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Two-scale optimal design of structures with thermal insulation materials

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ABSTRACT

This paper introduces a two-scale topology optimization approach by integrating optimized structures with the design of their materials. The optimization aims to find a multifunctional structure composed of homogeneous porous material. Driven by the multi-objective functions, macrostructural stiffness and material thermal conductivity, stiff but lightweight structures composed of thermal insulation materials can be achieved through optimizing the topologies of the macrostructures and their material microstructure simultaneously. For such a two-scale optimization problem, the effective properties of materials derived from the homogenization method are applied to the analysis of macrostructure. Meanwhile, the displacement field of the macrostructure under given boundary conditions is used for the sensitivity analysis of the material microstructure. Then, the bi-directional evolutionary structural optimization (BESO) method is employed to iteratively update the macrostructures and material microstructures by ranking elemental sensitivity numbers at the both scales. Finally, some 2D and 3D numerical examples are presented to demonstrate the effectiveness of the proposed optimization algorithm. A variety of optimal macrostructures and their optimal material microstructures are obtained.

1. Introduction

In engineering applications, material selection is a long and complex process which involves not only material properties but also the service conditions such as structural configuration, applied loads and boundary conditions for a specific product. Integrating designs of structure and material will be of great significance to the fields of structural engineering and materials engineering [1]. Porous materials are receiving increasing attention because of their ability to combine good properties with light-weight. They have been used in diverse areas of applications such as thermal insulation, energy absorption, buoyancy and soundproofing, and they also exist as biomaterials [2–3]. To meet multifunctional requirements of engineering structures, this paper will investigate the concurrent design of structure and its porous material so that the resulting structure has multifunctional properties.

Structural topology optimization aims to find optimal topology to maximize structural performance while satisfying various constraints such as a given amount of material. Compared with size and shape optimization, topology optimization provides much more freedom and allows the designer to create totally novel and highly efficient conceptual designs for structures. Over the last two decades, various topology optimization algorithms, e.g. homogenization method [4], solid isotropic material with penalization (SIMP) [5,6], evolutionary structural optimization (ESO) [7,8], and level set technique [9] have been developed. Unlike the continuous density-based topology methods, the ESO/BESO method represents the structural topology and shape with discrete design variables (solid or void) with a clear structural boundary [10,11]. It was originally developed based upon a simple concept of gradually removing redundant or inefficient material from a structure so that the resulting topology evolves towards an optimum [7]. The later version of the ESO method, namely bi-directional ESO (BESO), allows not only to remove elements from the least efficient regions, but also to add elements in the most efficient regions simultaneously [12–15]. It has been demonstrated that the BESO method is capable of generating reliable and practical topologies for various types of structures with high computational efficiency.

To date, topology optimization techniques are mainly used to solve one-scale design problems either for the macrostructures to improve their structural performance or for the materials to develop new microstructures with prescribed or extreme properties

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[16–20]. An ideal design should be that structures with different boundary conditions and geometries have their own optimal macrostructural topologies, meanwhile are composed of tailored materials with optimal microstructures. It is understandable that the concurrent design of structures and materials could be more effective since it provides more design freedoms on multiple scales to achieve an efficient solution. However, the research on topology optimization considering structure and material at both scales simultaneously is still limited. Rodrigues et al. [21,22] proposed a hierarchical computational procedure by integrating macrostructures with local material microstructures. This methodology treats the material design in a point wise manner within the macrostructure. Therefore the result brings up extra difficulties in manufacturing. Coelho et al. [23] extended this hierarchical procedure to three-dimensional elastic structures. Another type of the approach for concurrent design at two scales assumes that material is uniformly distributed in the macrostructure such as in Liu et al. [24] and Yan et al. [25]. Similarly, Deng et al. [26] studied the design of a thermoelastic structure by minimizing its structural compliance and thermal expansion simultaneously.

This paper attempts to propose a multi-objective and multi-scale topology optimization approach based on the BESO method. The optimization objective is to design the structure with multi-functional applications that require not only maximum structural stiffness but also superior thermal insulation capabilities. As we know, most engineering structures are expected to function under different physical conditions. The design just considering one single criterion is often unable to satisfy the multifunctional requirement for engineering structures [27,28]. To achieve the multifunctional needs, here we adopt a multi-objective and multi-scale optimization method, where two conflicting design objectives are taken into account to maximize structural stiffness at the macro level and minimize material thermal conductivity at the micro level.

In this paper, it is assumed that a macrostructure is uniformly composed of lightweight porous material and the optimization needs to find the optimal topologies for the macrostructure and for the microstructure of the porous material. The homogenization theory will be used to calculate the effective properties of porous material so as to establish a link between the macro level and the micro level. The BESO algorithm with binary design variables is employed to obtain clear solid-void solutions for the macrostructure and the microstructure simultaneously. Finally, 2D and 3D examples are presented to validate the proposed design method. Following this introduction section, the paper presents a multi-objective concurrent optimization model, and conducts its two-scale sensitivity analysis based on finite element method in Section 3. The concurrent optimization procedure based on the BESO method is detailed in Section 3. Finally, several typical 2D and 3D examples are discussed in Section 4 and some conclusions are drawn in Section 5.

2. Multi-objective concurrent optimization models

2.1. Optimization formulation

In the concurrent optimization, macro structural design and micro material design are combined into one system by using the homogenization theory and optimization is conducted at both levels simultaneously. Consider a structure with known boundary conditions and external forces as illustrated by Fig. 1. The macrostructure is composed of uniformly distributed porous material with microstructures periodically repeated by the unit cell. In the unit cell of the porous material, the base material is represented with black and the void with white. Two types of finite element

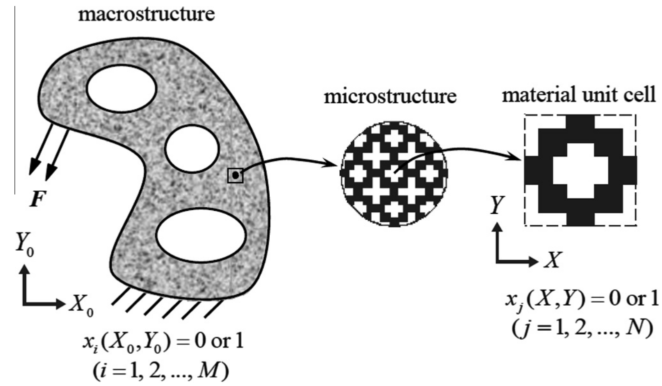

Fig. 1. Illustration of two-scale design for a structure composed of a porous material.

models, namely a macro FE model and micro FE model are employed to represent the macrostructure and material microstructure respectively. The macro and micro relative densities, x_i and x_j, are considered to be the macro and micro design variables, respectively.

In this paper, the optimization objective is to seek for a lightweight structure which is not only with maximum structural stiffness (or minimum compliance) but also composed of porous material with minimum thermal conductivity so that the resulting structure has multiple functions, i.e. best load-bearing and superior thermal insulation capabilities simultaneously. The macrostructural mean compliance can be expressed as

$$f_1(x_i, x_j) = \frac{1}{2}\boldsymbol{F}^{\mathrm{T}}\boldsymbol{U} \Big/ C_0 = \frac{1}{2}\sum_{i=1}^{M}\boldsymbol{U}_i^{\mathrm{T}}\boldsymbol{K}_i(x_i, x_j)\boldsymbol{U}_i \Big/ C_0 \tag{1}$$

where $\boldsymbol{F}$ and $\boldsymbol{U}$ represent the external force vector and the nodal displacement vector of the macrostructure, respectively. U_i is the displacement vector of the ith element in the macrostructure. $\boldsymbol{K}_i$ is the stiffness matrix of the ith macrostructural element. M is the total number of finite elements in the macro FE model. C_0 is the mean compliance of the full design. x_i is the binary design variables for the macro FE model. $x_i = 1$ means element i is porous or solid and $x_i = 0$ means element i is void. The summation of the diagonal elements in the effective thermal conductivity matrix can be used to measure the overall conduction capability for the orthotropic material design [29,30], as

$$f_2(x_j) = \sum_{m=1}^{2\text{ or }3}\kappa_{mm}^{\mathrm{H}}(x_j) \Big/ \kappa_s 0 \tag{2}$$

where κ_{mm}^{H} is the mth diagonal element in the effective thermal conductivity matrix of the porous material. κ_{s0} represents the summation of the diagonal elements in the base material thermal conductivity matrix. x_j is the binary design variables for the micro FE model. $x_j = 1$ means element j is solid and $x_j = 0$ means element j is void. Thus, to achieve the multifunctional designs for the structure and material, a multi-objective design problem can be formulated in terms of a weight average as

$$\text{Minimize}: \; f(x_i, x_j) = \eta f_1(x_i, x_j) + (1-\eta)f_2(x_j) \tag{3-a}$$

$$\text{Subject to}: \; \boldsymbol{K}(x_i, x_j)\boldsymbol{U} = \boldsymbol{F} \tag{3-b}$$

$$V_f = \frac{\sum_{i=1}^{M}x_iV_i}{\sum_{i=1}^{M}V_i}\frac{\sum_{j=1}^{N}x_jV_j}{\sum_{j=1}^{N}V_j} = V_f^{\mathrm{mac}}V_f^{\mathrm{mic}} = V_f^{*} \tag{3-c}$$

$$x_i, x_j = 0 \text{ or } 1, \quad (i = 1,\ 2,\ \ldots,\ M; j = 1,\ 2,\ \ldots,\ N) \tag{3-d}$$