Computers and Structures 178 (2017) 119–128

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Concurrent topology design of structure and material using a two-scale topology optimization

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ARTICLE INFO

Article history:
Received 11 March 2016
Revised 25 August 2016
Accepted 5 October 2016

Keywords:
Topology optimization
Concurrent design
Algorithm
Homogenization
Response function

ABSTRACT

This paper presents new MIST (moving iso-surface threshold) formulation and algorithm for concurrent design of structural and cellular material topology. The material microstructure is assumed to be uniform in macro-scale, i.e. the macrostructure is composed of periodic unit cells. New formulations for the two physical response functions of macrostructure and microstructure (unit cell) are derived in terms of the results of finite element analyses of structure and material by using the homogenization theory. Several numerical examples are presented for optimum design solutions of the macrostructures and their corresponding material microstructures to illustrate the capability and efficiency of the present approach.

1. Introduction

The quest for high performance structures sets a requirement on concurrent design of both structure and material. Such concurrent design can be for structures and materials which are readily available, and can also be for structures and materials for which the most suitable material properties may not be available. As material properties are often dependent on the geometric topologies of a material microstructure at micro scale [1,2], the latter involves simultaneous design optimization of the structure's macrostructural topology and the materials' microstructural topologies. Thus concurrent design of structure and material in this context of pursuing for higher-performance structures is challenging and becomes a focus of recent studies.

Topology optimization is regarded as a powerful design approach for determining the best distribution of material via finding the optimum topology for maximizing selected structural performance with a given set of constrains [3]. Various topology optimization approaches have been developed over the last two decades, such as solid isotropic material with penalization (SIMP) [4,5], evolutionary structural optimization (ESO) [6], level set method (LSM) [7,8], and moving iso-surface threshold method (MIST) [9]. In MIST, a physical response for an objective function is used (similar to ESO); artificial densities are introduced on the elements to represent the material distribution (similar to SIMP); a moving iso-surface threshold is used to evolve design boundary (similar to LSM). Similar to LSM but unlike SIMP and ESO, MIST can generate optimal topology with clear and non-zig-zag material boundary that cuts through many elements; and similar to ESO but unlike SIMP and LSM, MIST avoids explicit sensitivity analysis, and thus yields another advantage of simplification in interfacing with an in-house or commercial finite element analysis program. This method has been used for maximizing structural stiffness [10,11], compliance mechanism problem [9], and single scale nonlinear topology optimization [13]. It will be further studied and used to investigate concurrent topology optimization design of macrostructure and material microstructure in this paper.

Until recently most of the studies with respect to topology optimization concentrate on one-scale design problem, either for the macrostructures to find the optimal structural layout or for the materials to design microstructures with prescribed or extreme properties. In pursuing higher-performance structures, it is desirable to conduct optimal designs at the structural scale and at the micro-scale for materials simultaneously. With such idea, one encounters two design problems coupled at two-scales. Moreover, the two-scale coupled design is different from either pure material design or pure structural topology optimization, because the essential influence of material microstructures on the global behavior of macrostructures requires that microstructures must be designed to optimally match the loading and boundary conditions of specific macrostructure. At present, the research on topology optimization considering structure and material at both scales

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http://dx.doi.org/10.1016/j.compstruc.2016.10.013
0045-7949/

simultaneously is still limited. Fujii et al. [14] studied the compliance minimization problem of the macrostructure through topology optimization of material microstructures using the homogenization method. Rodrigues et al. [15] proposed a hierarchical optimization of material and structure method in which the material properties at the macro-scale are allowed to be varied from point to point. Liu et al. [16] introduced a concurrent topology optimization method to simultaneously achieve the optimum structure and material micro-structure for minimum system compliance with uniform properties of microstructures on the macro-scale. In addition, using the same framework, Niu et al. [17] studied the problem of maximizing the fundamental eigen-frequency of the macrostructure, and Deng et al. [18] studied the multi-objective design of both the thermo-elastic structure composition and its material microstructure. Recently, Yan et al. [19] proposed an approach to the hierarchical concurrent design of a structure with thermal insulation materials by using BESO (bidirectional evolutionary structural optimization). Xia and Breitkopf [20,21] studied concurrent design of material and structure within FE^2 nonlinear multiscale analysis framework. Gao and Ma [22] proposed a modified model for concurrent topology optimization by introducing microstructure orientation angles as a new type of design variable. In addition, studies concerning the size-related topology optimization of materials and structures can be found in the work of Zhang and Sun [23], Liu and Su [24,25].

This paper presents a two-scale topology optimization approach based on the MIST method for concurrently designing structures and their material's microstructures. The macro-structure is assumed to be composed of uniform porous material, and the material microstructures are assumed to be periodically repeated by periodical unit cells. The optimization objective is to find the optimal topologies for both macrostructure and microstructure so that the resulting macrostructure has the best structural performance. In Section 2, A two-scale concurrent optimization model based on MIST method is established, the homogenization theory is used to calculate the effective properties of the material, and two physical response functions are derived by conducting finite element analyses of both structure and material. Then, details of MIST algorithm for two-scale optimization problem are introduced in Section 3. Section 4 gives several examples to demonstrate the effectiveness of the proposed algorithm. Conclusion is given in Section 5.

2. Problem statement and formulation

2.1. A brief overview of MIST

This paper extends the MIST [9] to the problem of designing a structure (macro scale) and its material (micro scale, i.e. unit cell) simultaneously. In MIST, a structural topology optimization problem can be formulated in the following general form:

$$\begin{aligned}
&\text{Find} && \rho(x)(x \in \Omega)\\
&\text{Min.} && J(\rho) = \int_\Omega \Phi(\rho) d\Omega\\
&\text{S.t.} && g_r(\rho) = 0\\
& && g_s(\rho) \leqslant 0
\end{aligned} \tag{1}$$

where ρ ranging between 0 and 1 is design variables or relative densities for defining a structural topology or material distribution, Ω is the design domain, J is the objective function in an integral form, $\Phi(\rho)$ is a response function estimated in the design domain from the weak solution of the governing equations of a physical system, $g_r = 0$ represent the governing equations of a physical system and g_s denote the constraints, such as volume fraction constraint.

The MIST algorithm finds solution of the above problem in a nested iterative process. In each iteration, for a response function Φ calculated from the system response using the design variables from previous iteration (or an initial guess in case of the first iteration), the level or threshold value t of the iso-surface can be determined via imposing the volume fraction or other constraint(s). Fig. 1 depicts that an iso-surface S intersects the Φ function and the projected contour of the intersection guides an update of design variables. As iteration progresses until convergence, elements with Φ at all nodes above the iso-surface harden toward solid material (relative densities tend to 1), those elements with Φ at all nodes below the iso-surface soften toward void material (relative densities tend to 0) and those elements with Φ partially above and below the iso-surface form structural boundary. It is evident that one key step in MIST is to choose an appropriate response function Φ.

2.2. Concurrent design optimization of structure and material

Concurrent design of structure and material refers to simultaneous design of the macrostructural topology of a structure and the microstructural topology of its uniform or non-uniform cellular material. If it is assumed that the macro-structure is composed of uniform porous material with a microstructure of repeated periodical unit cell (PUC), the concurrent design optimization of structure and material problem degenerates to a two-scale topology design problem. Fig. 2 depicts an example of such two-scale optimization problem that seeks simultaneously the optimum solutions for the macro-structure with given boundary conditions and external loadings and for the microstructure of a unit cell.

As shown in Fig. 2, two types of finite element models are required to represent the structural macrostructure and its material's microstructure of a unit cell respectively. If the macro design domain Ω is meshed with N elements and the micro design domain Y is meshed into n elements, we can assign each element in both domains a unique design variable ranging from 0 to 1 to describe the topologies of macrostructure and the micro unit cell. The optimization problem is formulated as to find the optimal topologies of both macro and micro structures so that the objective function can be maximized or minimized and the relevant constraints can be met.

Hence we can formulate the concurrent design optimization of structure and material problem as follows:

$$\begin{aligned}
&\text{Find} && \rho_i, \eta_j \ (i = 1,2,\ldots,N;\ j = 1,2,\ldots,n)\\
&\text{Minimize}: && C(\rho_i, \eta_j)\\
&\text{Subject to}: && \mathbf{K}(\rho_i, \eta_j)\mathbf{U} = \mathbf{F}\\
& && \frac{\int_\Omega \rho_i d\Omega}{\int_\Omega d\Omega} \frac{\int_Y \eta_j dY}{\int_Y dY} = v_f^{MA} v_f^{MI} \leqslant v_f^*\\
& && \frac{\int_Y \eta_j dY}{\int_Y dY} = v_f^{MI}\\
& && 0 < \delta \leqslant \rho_i \leqslant 1,\ 0 < \delta \leqslant \eta_j \leqslant 1
\end{aligned} \tag{2}$$

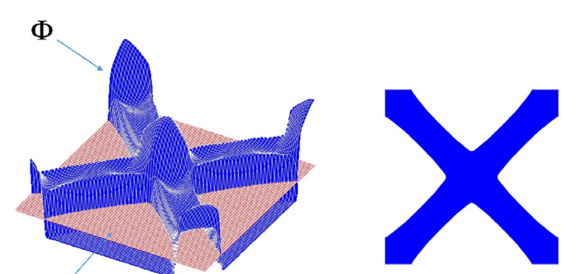

Fig. 1. Illustration of a response Φ, an iso-surface S and contour of the intersection.