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Concurrent topological design of composite structures and the underlying multi-phase materials

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ABSTRACT

This paper presents a concurrent topology optimization approach for simultaneous design of composite structures and their periodic material microstructures with three or more phases. The effective properties of multi-phase materials are obtained via homogenization technique which serves as a bridge of the finite element models of the macrostructure and the material microstructure. The base materials of periodic microstructures used in each phase of the macrostructure are divided into several groups and sensitivity analysis are carried out on them one by one. Meanwhile, the sensitivity number at the macrostructure is derived which is coupled with the designed material properties. Then, the composite configurations of material microstructures and macrostructures are inversely optimized concurrently based on the bi-directional evolutionary structural optimization (BESO) algorithm. Several 2D and 3D numerical examples are presented to demonstrate the effectiveness of proposed design approach.

1. Introduction

Structural topology optimization aims to find the optimal spatial material distribution within a given design domain for prescribed constraints, objectives, and boundary conditions. The original idea of this technique is to determine which points of the design domain should be material points and which points should remain void (no material) [1]. Over the past decades, topology optimization has undergone an extensive development in both fields of theoretical research and practical application [2]. Various topology optimization methods have been proposed, which include of homogenization approach [3], solid isotropic materials with penalization (SIMP) [4,5], level-set method (LSM) [6,7], evolutionary structural optimization (ESO) [8,9] and bi-directional ESO (BESO) method [10,11], etc. These methods have already demonstrated to be the flexible and reliable design tools in various industrial applications. An overview, comparison and critical review of the different topology optimization approaches was given in [12]. Among all exiting approaches for topology optimization, the ESO/BESO methods use an intuitive design strategy for the design of structural topology. The early ESO algorithms cannot recover the materials once it has been removed, however, in practice the materials that has been removed in an early stage might be required later. For this issue, its later version, namely BESO method allows materials to be added and removed simultaneously. It has been demonstrated that the new BESO method is capable of generating reliable and practical topologies for various types of structures with high computational efficiency [13–15].

Topology optimization has not only been applied for the design of monoscale structures, but also for the design of materials. By means of homogenization approach, one may evaluate the effective material properties of the considered microstructure or Representative Unit Cell (RUC) model [16]. The key hypotheses of the homogenization are that the characteristics of macroscopic structures are much larger than that of material microstructures, and the macrostructures are assembled by the RUC periodically. Sigmund [17,18] introduced an inverse homogenization technique to tailor materials with prescribed constitutive parameters and elastic properties using the SIMP method. Some studies were also investigated to tailor material microstructures with other extraordinary properties like thermal conductivity [19], permeability [20], and stiffness and conductivity [21]. Similar researches also were addressed using the level set-based methods [22] and the BESO method [23,24]. Some other works [25–28] also fall into this topic.

With such model for the design of material microstructures, one comes up naturally with ideas of integrate or concurrent designs of both structures and material microstructures. That is to say, the goal of topology optimization is to determine not only the optimal

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structural topology or material layout at the macrostructural scale, but also the optimal local use of the porous material or composite at the microstructural scale. Rodrigues at al [29] described a hierarchical computational procedure for optimization of material distribution as well as the local material properties of mechanical elements. Coelho at al [30] presented an extension of this hierarchical model for topology optimization to 3D structures. Ferreira et al. [31] performed the hierarchical optimization in laminated composite structures. Xia et al. [32–34] addressed concurrent design of material and structure within the FE^2 nonlinear multiscale analysis framework and applied lately in [35] a reduced database model [36] to circumvent the intensive computational cost. These works assumed that the materials/composites used in macrostructural construction vary pointwisely and require in general large amount of computational efforts.

The most commonly used strategy is designing a uniform material microstructure or RUC at the microscopic scale for a concurrently changed macrostructure at the macroscopic scale. Via this design strategy, concurrent design has been used for tailoring macrostructure and its material microstructures with minimum systematic mean compliances in [37,38], maximum fundamental frequencies in [39,40], and multi-objective functions, e.g. maximum stiffness and minimum resistance to heat dissipation [41], minimum structural compliance and minimum thermal expansion of the surfaces [42], and minimum structural mean compliance and material thermal conductivity [43]. Concurrent robust design and optimization considering load uncertainties was investigated in [44]. Concurrent design of composite macrostructure and cellular microstructure under random excitations was studied in [45]. But there is litter work on the concurrent topological design of composite structures and their multi-phase materials. In comparison with porous materials, composites consist of two or more phase materials are more attractive and advantageous from the perspective of engineering application. Designing new structures that are composed of multi-phase composite has already attracted much attentions, and a review of recent advances on mechanics of multi-functional composite materials and structures has been given in [46]. Based on the concept of topology optimization, Bendsøe and Sigmund [47] proposed a multi-phase material mixture model in SIMP, and such a model has been extended to various topology optimization problems [48–51]. Recently, different topology optimization methods were employed to design multi-phase material structures like level set-based methods [52–55] and the BESO method [56–58].

This paper builds on the earlier work [56] on multiple material design of monoscale structures using the BESO method where the constituent phases are divided into different groups. This model has already been extended for the design of multi-phase material microstructures [58]. The key contribution of this work is to integrate the BESO method, homogenization and multi-phase material interpolation scheme to carry out multiscale topology optimization with the consideration of multi-phase material microstructures at the lower scale, which has been rarely examined in the literature yet according to our best knowledge. Comparing with only two phase materials employed at microscopic scale in [57], we designed the underlying multi-phase material microstructures for both the solid material phase and the compliant material phase of the macroscale structure. The effective constitutive parameters of three or more materials are evaluated by the numerical homogenization analysis [59,60]. In addition, we have carried out the concurrent multi-phase topology optimization for both 2D and 3D cases, which makes this work distinguished from existing references. The remainder of this paper is organized as follows: concurrent optimization model of composite macrostructure and its multi-phase materials are drawn in Section 2. Section 3 formulates the material interpolation and gives the sensitivity analysis on macro and micro variables. The BESO method and numerical implementation procedure are introduced in Section 4. Section 5 presents several 2D and 3D numerical examples and discussions. Finally, conclusion part is given in Section 6.

2. Concurrent optimization formulation

The concurrent topology optimization problem considers a macrostructure composed of multi-phase materials with periodic microstructures illustrated in Fig. 1. Composite formulation is applied to both the macrostructure and material microstructures. The present work considers the macrostructure is composed of two nonzero periodic composites that both have three or more phase materials. Each multi-phase composite serves as a phase in the macrostructure. Then, there are totally three finite element (FE) models which include one macro model for the macrostructure and two micro models for the material RUCs correspondingly. RUC of the periodic multi-phase composite serves as the design

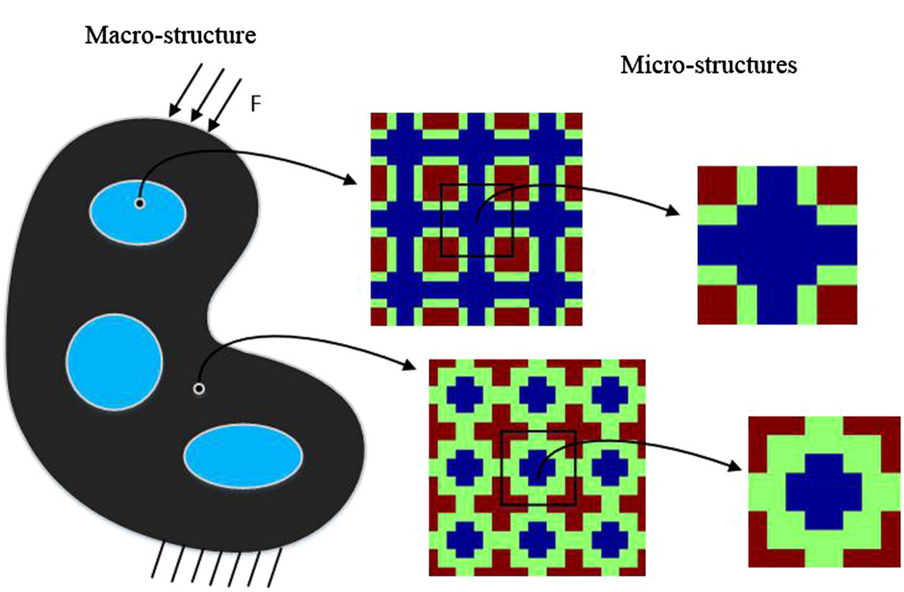

Fig. 1. An arbitrary macrostructure composed of periodic microstructures.