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Multiscale isogeometric topology optimization for lattice materials

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Highlights

- A multiscale isogeometric topology optimization is presented for lattice materials.
- Asymptotic homogenization is coupled to topology optimization for lattice design.
- The role of cell topology is demonstrated in the optimal density distribution of lattices.
- Benchmark examples are presented to prove the efficiency of the proposed scheme.

Abstract

This paper presents isogeometric topology optimization (ITO) for periodic lattice materials, where non-uniform rational B-spline (NURBS) basis functions of CAD models are directly used in the finite element analysis to improve computational accuracy and efficiency. Two TO schemes that use asymptotic homogenization (AH) for the calculation of the mechanical properties are proposed for lattice materials with uniform and graded relative density respectively. To accelerate ITO for graded lattice materials, the mechanical properties are expressed as a function of the relative density of the unit cell, a step that avoids their iterative calculations during ITO. Three benchmark examples are presented to validate the proposed scheme with results that show tangible advantages, such as reduced computational time and faster convergence, of ITO over conventional TO.

Keywords: Topology optimization; Lattice material; Isogeometric analysis; Asymptotic homogenization; Multiscale mechanics

1. Introduction

Lattices are periodic materials that can be designed to obtain properties that primarily depend on the geometry of their repeating unit. The mechanical performance of lattice materials can be tailored to go beyond those of conventional materials, with structural advantages that are of interest in a large palette of applications, from aerospace lightweight components [1], to energy absorbing bumpers for vehicles [2], thermal insulation for civil engineering applications [3], as well as biomedical implants [4], among others. Compared to foams, generally characterized

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by a stochastic arrangement of cells, lattices allow better control of the cell arrangement, as they are generated by tessellating one porous unit along periodic vectors [5].

The mechanical properties of a lattice are mainly governed by the topology of the unit cell, whose characteristic length should be at least one order of magnitude below that of the component, should the periodic structure be considered as behaving as a material. Several theoretical approaches using the notion of Representative Volume Element have been proposed in the literature to calculate the mechanical properties of a lattice [6–9]. These schemes generally assume the unit cell walls behave like beams, following either Euler–Bernoulli or Timoshenko theory, and determine the elastic constants of the cell through the classical solution of deformation and equilibrium problems. These approaches provide accurate results for values of relative density below 0.3, above which beam theory looses accuracy. Furthermore, these theoretical approaches present limitations for unit cell with complex topology. On the other hand, homogenization methods (HMs), especially asymptotic homogenization (AH), have been proved to be able to rigorously predict the mechanical behavior of periodic materials [10–13]. In general, AH assumes that any field quantity can be described as an asymptotic expansion, which – replaced in the governing equations of equilibrium – allows to evaluate the effective properties of the material [14]. Since AH has neither limitation on the unit cell topology nor on the range of relative density, it has been widely used to calculate the properties of heterogeneous periodic materials [15–17].

Gradient based schemes for topology optimization (TO), such as the solid isotropic material with penalization (SIMP) [18,19], evolutionary methods for structural optimization (ESO) [20,21], as well as more recent strategies, such as the level set [22,23], have been extended to optimize the internal architecture of porous materials or composites [24–29]. TO contributions exist in the literatures that address the design of either the macroscale geometry or the unit cell of lattice materials. For example, Niu et al. [30] presented a two-scale optimization method to maximize the fundamental frequency of cellular materials, where the mechanical properties of the unit cell were obtained via HM and were used as homogeneous properties to design the macroscopic domain of the material. Coelho et al. [31] presented a hierarchical framework for concurrent material and TO of 3D cellular structures, where the optimization scheme comprises two main loops. The outer deals with the macroscale design of the material, whereas the inner one uses HM for the TO of the unit cell design Nakshatrala et al. [32] proposed another multiscale framework to couple macro and micro TOs for nonlinear structural problems. Here, the design domain was partitioned into subdomains where the microstructure is imposed to remain uniform so as to ensure ease in fabrication. Despite this advantage, the work of Nakshatrala et al. poses computational challenges due to the large computational power required to solve the coupled problem; hence the use of parallel computing and computer cluster was suggested [31,32]. More recently, Khanoki et al. [33] proposed a multiscale and multiobjective optimization for orthopedic hip implants with cellular material. In this work, the topology of the unit cell was predefined with mechanical properties expressed through fitting functions dependent on the relative density and directly used in the optimization loop, with the advantage of improved computational efficiency.

In recent years, isogeometric analysis (IGA) [34,35], where the basis functions of the geometric model are directly used for finite element computations, has much attracted the attention of researchers in a variety of domains, as an efficient alternative to other conventional methods [36–42]. The high accuracy and efficiency of IGA provide a number of advantages over the established finite element method (FEM). For example, whereas checkerboards appearing in FEA can be easily relieved with higher order elements [43,44], their use often requires high computational power [45]. IGA, on the other hand, can solve checkboard problems with much lower computational cost. Works that use IGA in structural optimization to capitalize on the IGA capability exist in literature, the first being the isogeometric TO (ITO) proposed by Seo et al. [46]. Later, Hassani et al. [47] proposed an isogeometric approach to TO where the so called control-point based SIMP was introduced to ease the interpolation of physical field quantities through the use of Non-uniform rational B-spline (NURBS). Dedé et al. [48] presented IGA for TO with a phase field model in both 2D and 3D problems, and demonstrated that IGA was particularly suitable for phase field problems as it allowed to handle exact CAD geometry. Very recently, Wang and Benson [49] proposed an ITO coupled with the level set method; here the NURBS basis functions of the CAD models are directly used for the parametrization of the level set functions and for the evaluation of the objective function. So far, however, all the ITO works existing in literature examine solid materials with isotropic properties. To the best of our knowledge, no work has so far extended ITO to porous materials, such as periodic lattices, with anisotropic properties.

In this paper, we present a framework that uses a multiscale ITO to optimize the relative density of lattice materials. Two schemes are proposed, one for homogeneous lattices and the other for graded lattices. AH is used to ease the

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