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An application of multiscale topology optimization with loading uncertainty

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Abstract

A multi-scale topology optimization approach is investigated that grades the main geometrical feature of a porous microstructure within a design domain. Instead of using deterministic optimization, an efficient probabilistic framework is developed to account for uncertainty in the loading amplitude. Numerical homogenization is employed to derive the material schemes that interpolate the elastic properties of the period microstructure. A displacement-constrained minimum volume problem is implemented to control pointwise the displacement field and is endowed with an additional enforcement governing the minimum amount of graded porous material. The formulation is used to simultaneously define i) boundaries and ii) internal arrangements of circular holes with graded radius, for optimal 2D components (any object subject to loads and constraints, e.g. mechanical parts, structural components, elements of the building envelope, design pieces, industrial design objects...) Numerical tests are show investigating multi-scale layouts that are inherently robust with respect to loading uncertainty.

Keywords: topology optimization, multi-scale optimization, additive manufacturing, robust design, homogenization, mathematical programming.

1 Introduction

Topology optimization sketches lightweight components by searching the design domain for the distribution of material that minimizes a prescribed objective function given a set of constraints [1].

Techniques such as additive manufacturing (AM) are well-suited to bring optimal layouts from concept to reality, since they dramatically reduce restrictions imposed by traditional manufacturing techniques. Indeed, the combined use of tools of computational design and 3D printing allows for the fabrication of customizable objects that can be effectively tailored to meet given goals and performance needs [2]. In a classical topology optimization problem, the constitutive properties of the material to be distributed are scaled by the point-wise density, ranging between 0-1. A strong penalization of the intermediate densities is generally implemented to achieve optimal layouts made of void and solid material. Intermediate values of the density have no physical meaning unless composite materials are allowed within the optimization. Suitable periodic cells can be designed at the meso-scale to match the homogenized mechanical properties prescribed by the interpolation law when distributing material at the macro-scale. Hence, multi-scale approaches of topology optimization take advantage of numerical homogenization to define both the boundaries (macro level) and the inner lattices (meso level) of the optimal solution [3].

In this contribution, a novel approach based on multiscale optimization is proposed to design lightweight components that are endowed with a graded isotropic microstructure of given shape that can be easily handled in the optimization process and then exported as a printable geometry for AM.

Instead of working with a conventional volume-constrained minimum compliance problem, a displacement-constrained minimum volume problem is formulated, to control pointwise the displacement field also in case of distributed loads and loads with multiple point of applications [4] using a probabilistic optimization framework [5]. A peculiar feature of the proposed formulation is that it accounts also for an enforcement governing the minimum amount of graded porous material to be distributed in addition to the void phase and the solid one. Numerical simulations show that enforcing a minimum amount of graded material, layouts recalling sandwich structures may arise as optimal solutions. It is found that regions of solid material often lie along the perimeter of an inner core of graded porous phase. Such kind of layouts are inherently robust to loading uncertainty.

2 Methods

At first, numerical homogenization [6] is used to derive the values of two independent macro-scale elastic constants (bulk modulus K and shear modulus G) for the isotropic microstructure consisting in the distribution of circular holes with Hexagonal Close-Packed (HCP) arrangement. By varying the radius of the cavity, i.e. the density of the graded microstructure, suitable approximation laws are provided both for K and G. These take the role that the Solid Isotropic Material with Penalization (SIMP)[7] has in conventional problems of optimal design by distribution of isotropic material.

In the proposed formulation, two set of minimization unknowns are implemented: at each point of the design domain, it is possible to govern separately the arising of material/void and the type of material (full material/graded porous material). This allows to enforce an upper and a lower bound of the density of the graded material (as requested by the manufacturing process) and to control the amount of graded material arising in the optimal design in conjunction with full material and void.

A displacement-constrained minimum volume problem is herein implemented. It may be shown that, considering one point force only, this formulation is equivalent to a classical volume-constrained compliance minimization [4]. Unfortunately, the latter formulation does not allow for a local control of the displacement field in case of distributed loads and multiple load cases. To design lightweight components with local constraints on the displacement field, a multi-constrained optimization problem has to be solved efficiently. Recent contributions in the field of stress-constrained topology optimization have shown that a very large number of local enforcements can be efficiently tackled by combining sequential convex programming [8] and the augmented Lagrangian method [9]. This numerical approach is implemented herein to solve minimum volume problems with multiple displacement constraints, including the additional constraint governing the amount of graded porous material.

In this contribution, it is assumed that the loads are affected by uncertainties in their magnitude, such that their joint normal distribution function, mean values, and covariances are known. Instead of directly implementing the stochastic constraint on the allowed displacement limit, the automatic generation of stiff layouts under the effect of loads with uncertain amplitude is tackled embedding the minimum weight formulation with an equivalent determinist constraint following [5].

3 Results

A numerical example is considered addressing a cantilever beam. The cantilever is fully clamped along the edge on the left-hand side and is subjected to a uniformly distributed load acting vertically along the lower side. A preliminary numerical investigation considering deterministic loads is shown hereafter.

When the Solid Isotropic Material with Penalization (SIMP) is used, an optimal truss is expected to leverage the axial stiffness of each member to get a stiff minimum volume solution. The same layout is found if the multi-scale approach herein proposed is implemented and no constraint is adopted with respect to the minimum amount of graded material to be distributed.

However, if some porous graded material is forced to appear, solutions appear as the one shown in Figure 1 (left). Black stands for full material, white for void, whereas grey areas stand for regions in which an intermediate stiffness is beneficial, as provided by the graded porous isotropic microstructure. As in sandwich structures, an upper and lower chord of full material surround an inner weaker core. Among the benefits provided by composites, the inherent robustness is one of the most appreciated ones and exploited in structural applications. Indeed, if a variation affects the value and the position of the resultant of the uniformly distributed load applied at the bottom, the structure is not expected to lose its stability and stiffness. This is mainly due to the redundancy of load paths provided by the microstructure. A similar optimal design can be achieved by moving from the deterministic optimization to a probabilistic design problem, in which joint normal distribution function, mean values, and covariances of the load are explicitly taken into account.

Figure 1 (right) shows the blueprint of the design for manufacturing. Indeed, some straightforward post-processing is needed to place circular holes in a Hexagonal Close-Packed (HCP) arrangement with assigned reference dimension, using cavities whose radius depends on the material density of Figure 1 (left).

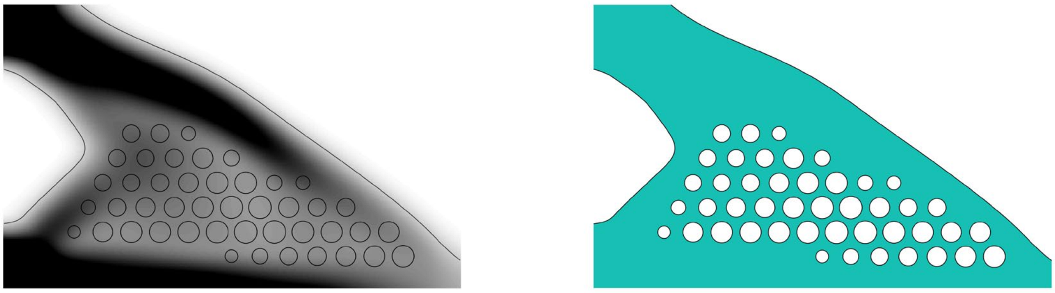

Figure 1: Optimal distribution of material density achieved through multi-scale optimization (left) and post-processed geometry for manufacturing (right).

4 Conclusions and Contributions

In this contribution, a multi-scale topology optimization approach is investigated that grades the main geometrical feature of an isotropic porous microstructure throughout the design domain. Instead of using deterministic optimization an efficient probabilistic optimization framework is developed to account for uncertainty in the loading amplitude.
Numerical homogenization is firstly employed to derive the material schemes that interpolate the elastic properties of a Hexagonal Close-Packed (HCP) arrangement of circular holes. Instead of working with a conventional volume-constrained minimum compliance problem, a displacement-constrained minimum volume problem is implemented, to control pointwise the displacement field also in case of distributed loads and loads with multiple point of applications.
The formulation is used to simultaneously define i) boundaries and ii) internal arrangements of circular holes with graded radius, for optimal 2D components (any object subject to loads and constraints, e.g. mechanical parts, structural components, elements of the building envelope, design pieces, industrial design objects...)
A peculiar feature of the proposed formulation is that it also embeds an enforcement governing the minimum amount of graded porous material to be distributed along with a void phase and a solid one.
Numerical tests show that enforcing a minimum amount of porous graded material, sandwich structures are likely to arise as optimal solutions. Such kind of layouts is inherently robust with respect to loading uncertainty.

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