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Christian Rye Thomsen, Fengwen Wang, Ole Sigmund

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Buckling strength topology optimization of 2D periodic materials based on linearized bifurcation analysis

Christian Rye Thomsen, Fengwen Wang*, Ole Sigmund

Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé, Building 404, 2800 Kgs. Lyngby, Denmark

Abstract

Low density cellular materials may offer excellent mechanical properties and find wide applicability in lightweight design and infill structures for additive manufacturing, yet currently existing material structures are still far away from their theoretical limit in terms of compressive strength. To explore the existing potential, this paper presents a topology optimization framework for designing periodic cellular materials with maximized strength under compressive loading. Under this condition, the limiting factor of strength is the failure mechanism of buckling instability in the microstructure. In order to predict microstructural buckling, a simplified model based on homogenization theory, a linearized stability criterion and Floquet-Bloch theory is employed. Subsequently, a gradient-based topology optimization problem is formulated to maximize the buckling strength of the most critical failure mode. The framework is utilized to optimize square, triangular and hexagonal microstructures for three different macroscopic load conditions including biaxial, uniaxial and shear loading, and performance assessments are conducted by computation of associated failure surfaces in macroscopic stress space. In all cases, the optimized designs turn out to be first-order hierarchical type microstructures which offer major improvements of strength compared to the initial zero-order designs, however, the gains come at the cost of reductions in stiffness. Furthermore, it is illustrated how imposing geometric symmetry constraints can be exploited to control the shape of the failure surfaces.

Keywords: Topology optimization, Periodic materials, Microstructural buckling instability, Floquet-Bloch theory, Macroscopic stress loading

1. Introduction

In recent years, artificially constructed materials have experienced a tremendous growth in popularity due to their large potential and customizability for a widespread range of applications, and due to the increased fabrication accessibility following advancement in additive manufacturing. This has resulted in a multitude of exotic materials which offer desirable properties ranging from low density with high strength, stiffness and recoverability [1, 2, 3] to excellent shock absorption capabilities [4, 5], wave-guiding [6], and materials which harness localized instability mechanisms to control the material properties [7, 8, 9]. The reader is referred to a recent review paper for additional references on the topic [10].

Of particular interest here is the subject of maximizing material strength in lightweight cellular materials through intelligent design of the microstructure. This constitutes a highly relevant objective, as material design without consideration of local stability is essentially only of theoretical interest, and as the current state of art is still orders of magnitude away from the theoretical limit of achievable strength [11]. For lightweight materials, the strength capacity is limited by the failure mechanism of microstructural buckling instability which occurs when its slender structural members are subjected to compressive loading. As this failure mode is highly dependent on geometry, previous studies have investigated a wide range of microstructure topologies in search for increased stability, including 2D honeycombs [12], lattice structures [13] and thin-walled structures [14]. Furthermore, studies have discovered certain

*Corresponding author.

Email address: fwan@mek.dtu.dk (Fengwen Wang)