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Exploiting Additive Manufacturing Infill in Topology Optimization for Improved Buckling Load

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ABSTRACT

Additive manufacturing (AM) permits the fabrication of functionally optimized components with high geometrical complexity. The opportunity of using porous infill as an integrated part of the manufacturing process is an example of a unique AM feature. Automated design methods are still incapable of fully exploiting this design freedom. In this work, we show how the so-called coating approach to topology optimization provides a means for designing infill-based components that possess a strongly improved buckling load and, as a result, improved structural stability. The suggested approach thereby addresses an important inadequacy of the standard minimum compliance topology optimization approach, in which buckling is rarely accounted for; rather, a satisfactory buckling load is usually assured through a post-processing step that may lead to sub-optimal components. The present work compares the standard and coating approaches to topology optimization for the MBB beam benchmark case. The optimized structures are additively manufactured using a filamentary technique. This experimental study validates the numerical model used in the coating approach. Depending on the properties of the infill material, the buckling load may be more than four times higher than that of solid structures optimized under the same conditions.

1. Introduction

Additive manufacturing (AM, also known as 3D printing) enables the fabrication of components with a geometrical complexity far beyond what can be achieved with conventional manufacturing technologies. Topology optimization, which is particularly known for creating lightweight mechanical components in the aerospace and automotive industries, provides a means for intelligently exploiting this design freedom, making these two technologies an ideal fit. So far, however, topology optimization approaches have only been adapted to a minor degree to the new opportunities and the manufacturing constraints relevant for AM. Infill is an example of a unique feature of extrusion-based AM methods. It allows the creation of structures that are composed of a solid shell with a porous interior, as opposed to completely solid components (Fig. 1). The authors of this paper have recently introduced the so-called coating approach to topology optimization [1]. While standard topology optimization approaches produce solid structures (Fig. 1(a)), the coating approach results in structures with a solid shell and a porous interior, exactly as when using infill (Fig. 1(b)). The coating approach offers no stiffness improvement. However, as shown in this study, it results in a strongly improved buckling load, which is an important element of structural stability. We therefore demonstrate an adaption of topology optimization to AM that has great potential.

Topology optimized components achieved through a standard minimum compliance approach [2] do not take buckling into account. On the contrary, the approach results in tension/compression-dominated configurations and avoids bending members. As the buckling load is closely related to bending stiffness (being proportional for the simple Euler column case), these structures may very well end up being failure-limited by the buckling load

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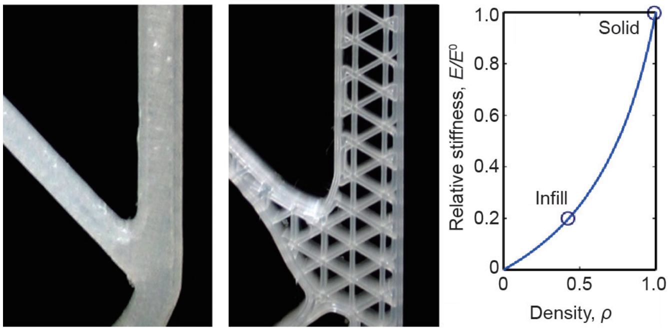

(a) (b) (c)

Fig. 1. Solid versus porous components. (a) Solid component; (b) porous component with solid shell and triangular infill; (c) Hashin-Shtrikman upper bound of stiffness as a function of material density, defining infill properties.

rather than by the fracture strength of the material. The problem becomes increasingly pronounced for smaller volume fractions.

Several works have treated the possibility of including a buckling constraint in the minimum compliance topology optimization problem. The approaches suggested so far, however, have not produced convincing results, or are challenged by clustering of a high number of eigenmodes at the lowest eigenvalue (the buckling load) [3–6]. This clustering implies a need for computing a large number of eigenvalues, leading to a prohibitively heavy computational burden. Instead, the mandatory buckling analysis is usually performed as a post-optimization step rather than as an integrated optimization constraint. If the elastic stability of the component is found to be insufficient, a post-processing may be applied to improve the minimum buckling load; however, this process may lead to sub-optimal components.

Nature provides a number of examples of structures that have an intrinsically high buckling load compared to weight. The most obvious examples are animal bone and plant stems, which are composed of a stiff, solid outer shell with a softer, porous interior. The same concept is exploited in sandwich structures, which are similarly characterized by a high bending stiffness-to-weight ratio and thereby a high buckling load. The high buckling load for structures obtained with the coating approach comes from the same principles. As demonstrated in this paper, the coating approach offers an effective and computationally cheap way of taking advantage of AM infill and thereby ensuring a high buckling load. The study is composed of both a numerical and an experimental part.

2. Methods

The objective of this paper is to prove the superior buckling performance of an infill structure compared to that of a solid structure with the same mass. We compare the following two density-based topology optimization approaches: ① a standard projection-based minimum compliance approach, resulting in an almost perfectly black and white structure, and ② the so-called coating approach, resulting in a structure composed of a solid shell with porous infill [1]. To this end, a standard optimization benchmark case is studied: a simply supported beam with a central load at the top edge, known as the MBB beam [7] (further details in Section 2.3). Compliance and buckling load are compared for the optimized structures. The buckling analysis involves both a numerical and an experimental comparison. The study is restricted to 2D for clarity. However, 3D effects from experimental tests are taken into account, and the full study can be readily extended to 3D.

2.1. Optimization problem

The optimization problem is a standard minimum compliance problem with a constraint on the volume. The discretized problem is defined as follows:

$$\begin{aligned} \min_{\boldsymbol{\mu}} :\ & c(\boldsymbol{\mu}) = \boldsymbol{U}^{\mathrm{T}}\boldsymbol{K}\boldsymbol{U} \\ \text{subject to: } & \boldsymbol{K}\boldsymbol{U} = \boldsymbol{F} \\ & g(\boldsymbol{\mu}) = V(\boldsymbol{\mu})/V^{*} - 1 \le 0 \\ & 0 \le \mu_e \le 1,\ \forall e \end{aligned} \tag{1}$$

where, $\boldsymbol{\mu}$ is the vector of design variables; c is the compliance; $\boldsymbol{K}$ is the global stiffness matrix (defined in the usual way for density-based topology optimization as a sum over element stiffness matrices, each depending on the interpolated stiffness); $\boldsymbol{U}$ and $\boldsymbol{F}$ are the global displacement and force vectors, respectively; g is the volume constraint; $V(\boldsymbol{\mu})$ is the material volume; V^* is the maximum allowed volume.

Design updates are performed based on analytically calculated gradients and a mathematical programming-based updating scheme, the method of moving asymptotes (MMA) [8]. Gradient expressions are omitted here for brevity (for details, see Ref. [2]).

2.2. Designing with the coating approach

Both the standard topology optimization approach and the coating approach permit the control of the macro-level structural feature size through the application of filters. These include smoothing using a partial differential equation (PDE)-based density filter [9] and projection of intermediate design fields in order to push the smoothed problem toward discrete designs [10–12]. The degree of smoothing is determined by the filter radius R (as defined in Ref. [11]), while the projection is determined by the threshold, η, and sharpness, β.

In addition to this control of the macroscopic feature size, the coating approach possesses several levers for designing solid shell structures with porous infill. The skin thickness, t_{ref}, determines the solid shell at the structural surface. Infill is modeled using the homogenized properties, that is, the effective macroscopic properties of the periodic infill structure. This permits the inclusion of the fine microstructure into the numerical model in a computationally feasible way. Two homogenized parameters are sufficient to describe the homogenized infill: density and stiffness. These parameters are expressed as ratios of the solid material's properties, noted as λ_{m} and λ_{E}, respectively. The relation between the two parameters must satisfy the Hashin-Shtrikman (HS) bounds in order to be physically meaningful [13]. We apply a triangular infill structure that is assumed to exactly reach the HS upper bound [14]. For the 2D case, the relation between the density and stiffness of the infill, shown in Fig. 1(c), is given by Ref. [15]:

$$\lambda_{\mathrm{m}} = \frac{3\lambda_{\mathrm{E}}}{1+2\lambda_{\mathrm{E}}} \tag{2}$$

Note that this relation is based on the assumption that the solid material has a Poisson's ratio of 1/3. However, for lower volume fractions where the infill structure behaves as a tension/compression-dominated triangular honeycomb, the influence of the Poisson's ratio of the solid material is negligible.

2.3. Test designs

The chosen test case is the so-called MBB beam benchmark problem: a simply supported beam of uniform thickness with a length-to-width ratio of 6∶1, loaded at the central point of the top edge. The numerically optimized structures are shown in Figs. 2(a) and (b). The domain size is 300 mm by 50 mm, with a thickness