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Full Length Article

Strength-based topology optimization for anisotropic parts

Amir M. Mirzendehdel, Behzad Rankouhi, Krishnan Suresh*

Department of Mechanical Engineering, University of Wisconsin-Madison, WI 53706, United States

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ABSTRACT

Additive manufacturing (AM) is emerging as a promising technology to fabricate cost-effective, customized functional parts. Designing such functional, i.e., load bearing, parts can be challenging and time consuming where the goal is to balance performance and material usage. Topology optimization (TO) is a powerful design method which can complement AM by automating the design process. However, for TO to be a useful methodology, the underlying mathematical model must be carefully constructed. Specifically, it is well established that parts fabricated through some AM technologies, such as fused deposition modeling (FDM), exhibit behavioral anisotropicity. This induced anisotropy can have a negative impact on functionality of the part, and must be considered. To the best of our knowledge, a robust TO method to handle anisotropy has not been proposed. In the present work, a strength-based topology optimization method for structures with anisotropic materials is presented. More specifically, we propose a new topological sensitivity formulation based on strength ratio of non-homogeneous failure criteria, such as Tsai-Wu. Implementation details are discussed throughout the paper, and the effectiveness of the proposed method is demonstrated through numerical and experimental tests.

1. Introduction

Additive manufacturing (AM) is becoming increasingly popular for fabricating prototypes, and customized production parts. Furthermore, AM is well-suited for small-batch production and on-spot fabrication where transporting built parts is expensive or even impossible. Currently, the most accessible AM technology is Fused Deposition modeling (FDM) where material is extruded from a nozzle, and the part is built layer by layer. FDM is fairly robust with respect to build scale and material [1]. This, along with other advantages such as ease of use, portability, affordability, and safety make FDM very promising in producing functional parts in applications such as:

a) Large-scale printing (cars and houses) [1,2]
b) Biomedical customized parts [3]
c) Electronics-embedded designs, e.g. Fig. 1 [4]
d) Printing in hostile places, e.g. space missions [5]

Topology optimization (TO) [6–8] is used at early stages of design to automatically reduce weight and material usage while satisfying constraints on performance. AM and TO complement each other in that organic and complex designs generated through TO can be manufactured through AM technologies. On the other hand, the cost of AM parts increase significantly with material usage. Thus optimizing designs can be crucial in saving material usage, build time, and post-process time [9].

However, there are certain challenges in TO for AM which need to be addressed before the two fields can be seamlessly integrated. Material anisotropy and weakness along build direction, especially in FDM, is an important consideration. This issue becomes more critical when the part is functional and has to satisfy strength-related constraint. There are mainly two types of anisotropy, namely 1) intrinsic e.g. composites and 2) process induced. Intrinsic anisotropy is often favorable since it can provide more freedom through intentionally creating directional preference in behavior. On the other hand, process-induced anisotropy is the result of process limitations and is often unfavorable. In this paper, we focus on addressing material anisotropy induced throughout FDM process due to lack of interlayer fusion as illustrated in Fig. 2. Note that anisotropy in FDM could manifests itself in two ways: 1) anisotropic constitutive properties relating stress and strain, and 2) directional strengths. However, current experimental results suggest that in some cases (see Section 4), printed parts exhibit isotropic constitutive properties [10]. The focus of this paper is on strength anisotropy.

In Section 2 we will review literature on stress-constrained TO for both isotropic (2.1) and anisotropic (2.2) materials. In Section

* Corresponding author.
E-mail address: ksuresh@wisc.edu (K. Suresh).

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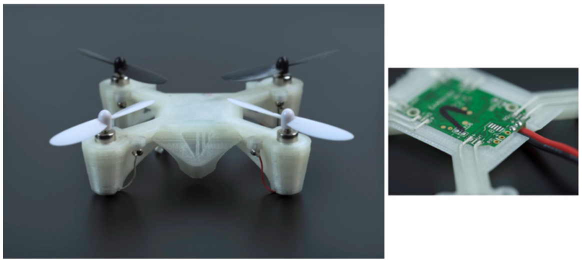

Fig. 1. FDM printed functional quadcopter. Printed via Voxel8 with embedded electronics and endures structural loading [4].

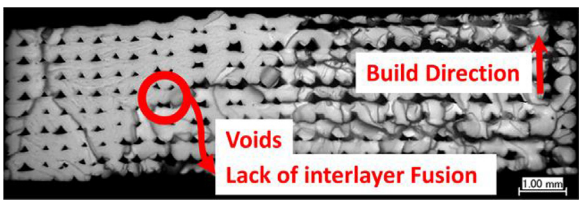

Fig. 2. Micro fractographs of 3D printed samples using FDM. Different raster orientations plays and important role in mechanical behavior of parts [11].

3 we will describe the proposed method and define the strength-based TO problem (3.1), perform sensitivity analysis (3.2 and 3.3), and present the proposed optimization algorithm (3.4). Finally, in Section 4 we demonstrate the effectiveness of the proposed method through numerical and experimental results.

2. Literature review

A typical TO problem can be posed as follows: given an initial design space $\mathcal{D}$, we want to find an optimal topology that minimizes an objective while satisfying several constraints,

$$\begin{aligned} &\underset{\Omega \subset D}{\text{minimize}} \quad f(\Omega, \boldsymbol{u}) \\ &g_i \leq 0 \qquad i = 1, \ldots, N \\ &\text{subject to} \\ &\mathbf{Ku} = \boldsymbol{f} \end{aligned} \tag{1}$$

where:

$$\begin{aligned} &D: \ \text{Design space} \\ &\Omega: \ \text{Optimized design} \\ &f: \ \text{Objective} \\ &g_i: \ \text{Constraints : volume, displacement,...} \\ &\boldsymbol{u}: \ \text{Displacement vector} \\ &\boldsymbol{K}: \ \text{Stiffness matrix} \\ &\boldsymbol{f}: \ \text{External force vector} \end{aligned} \tag{2}$$

Perhaps the most common objective is compliance for which the TO is fairly straight forward [12]. However, in order to design functional parts, we must consider minimizing stress where sensitivity analysis can be quite challenging due to locality and non-linearity of stress with respect to design variables. The former results in a huge number of constraints for even moderately complex problems, and the latter affects the convergence of the optimization process. Due to these challenges, there have been fewer attempts focusing on strength optimization compared to stiffness, and even less using anisotropic material properties.

2.1. Strength optimization for isotropic materials

There are numerous failure criteria that have been developed for isotropic materials over the years; the most common ones are based on maximum principal stress by Rankine, maximum principal strain by St. Venant, total strain energy by Beltrami, maximum shear stress by Tresca, and octahedral shear stress by von Mises. Among these, Rankine is best suited for brittle materials and von-Mises agrees best with ductile materials [13].

Earlier attempts towards producing strength-based optimum structural designs were mainly focused on shape optimization [14,15] and topology optimization of trusses [16]. It was believed by many [17–20] that the optimal design might be an isolated or singular point in the design space. For instance for truss optimization, as was shown by Kirsch [19], a singularity phenomenon occurs as the cross-section of a bar reaches its lower bound of zero. This, as explained later by Cheng and Jiang [21], was due to discontinuity of the stress function and the fact that the constraint function of the optimization problem becomes undefined. Cheng and Guo [22] proposed an ε-relaxation method as a solution to this issue, where the singular optimum design was eliminated from the design space; consequently, sizing and topology optimization could be unified in a single framework (also see [23,24]).

Since the development of homogenization method by Bendsøe and Kikuchi [25] and Solid Isotropic Material with Penalization (SIMP) method by Bendsøe [26], many different strategies have been proposed for stress-based TO. For instance, Xie and Steven [27] proposed an evolutionary method, in which elements with lower von-Mises stress are gradually rejected. This approach could lead to sub-optimal designs, due to locality nature of stress [28].

Perhaps the most popular TO method is SIMP, where a pseudo-density variable ρ $(0 \leq \rho \leq 1)$ is used to describe material distribution. Yang and Chen [29] used a global stress measure such as Kreisselmeier-Steinhauser or Park-Kikuchi as the objective function. In particular, their objective was a weighted average of compliance and the p-norm of a stress measure.

It is well-known that as ρ approaches 0, the stress values can become singular, which results in the same type of singularity phenomenon discussed above. In order to overcome this problem, Duysinx and Bendsøe [30], proposed an ε-relaxation scheme for SIMP. Bruggi and Venini [31] and Bruggi [32] proposed an alternative qp-approach to remedy the singularity problem, which required less computational effort. Le et al. [33] proposed a formulation based on normalized stress p-norm and a density filter to control length scale. París et al. [34], proposed a TO method considering local and global stress constraints. They later extended their work in [35] by developing block aggregated approach, where one stress constraint was assigned to a group of elements. As was shown in [30], TO with a global stress constraint can be too coarse and might yield results similar to those of stiffness optimization. The clustered approach can avoid stress concentrations and give better designs while not being too expensive. Along these lines, in [36], the number of stress constraints are reduced by clustering several stress evaluation points into groups.

The level-set (LS) method [7,37,38] is another popular approach for TO, where the boundaries of the design are defined as zero level sets of a scalar level-set function. In the conventional form, the Hamilton-Jacobi partial differential equations have to be solved to update design boundaries.

In [39], Miegroet and Duysinx proposed a LS method to minimize the stress concentration of 2D fillets. The approach uses X-FEM, which enriches classical finite element method (FEM) with several discontinuous shape functions. Svanberg and Werme [40], presented two sequential integer programming methods, where a sequence of linear or quadratic sub-problems with decreasing mesh sizes are solved and on the fine level. A LS method was pro-