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Topology optimization for continuous and discrete orientation design of functionally graded fiber-reinforced composite structures

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ABSTRACT

This paper presents a topology optimization method for the sequential design of material layout and fiber orientation in functionally graded fiber-reinforced composite structures. Specifically, the proposed method can find the optimal structural layout of matrix and fiber materials together with optimal discrete fiber orientations. In this method, an orientation design variable in the Cartesian coordinate system is employed with a conventional density design variable. The orientation design variable controls not only the fiber orientation, but also fiber volume fraction. The fiber volume fraction control can be used to relax the orientation design problem and simultaneously design a functionally graded structural layout of fiber material. To avoid intermediate fiber orientations and achieve discrete fiber orientation design, a penalization scheme is applied to the orientation design variable. For solving the optimization problem which involves multiple design variables such as the density variable, fiber orientation variable, and target discrete orientation set, a three-step sequential optimization procedure is proposed. In this procedure, the result for each step provides the isotropic design, continuous fiber orientation design, and functionally graded discrete orientation design, respectively. To validate the effectiveness of the proposed approach, numerical examples for structural compliance minimization and compliant mechanism design are provided.

1. Introduction

The functionalization of advanced materials and structures, e.g. for enhanced strength-to-mass ratio, is central to improving efficiency in next generation land vehicles, aircraft, and robotics applications. Traditionally, two paradigms have co-existed in the design of such structures. On the one hand, progress in material science related to advanced steel [1] plus aluminum and magnesium [2] has led to significant improvements in the capability of generally isotropic metals for structural design. On the other hand, sophisticated fiber-reinforced composite materials [3], with targeted anisotropic physical properties, have emerged as viable and in some cases preferred alternatives to isotropic materials. In either case, the use of an isotropic material or anisotropic composite is often coupled with a structural optimization method to determine the best use or layout of the material.

Topology optimization [4] is one such method that has been successfully applied to the design of structures involving both isotropic and anisotropic materials, and the research field is now rich with examples. With regard to topology optimization involving isotropic materials, the literature is overflowing with studies focused on the solid isotropic material with penalization (SIMP) approach. The SIMP method has been notably applied to the design of structures [5], compliant mechanisms [6], vehicle chassis [7], and aerospace frames [8], to name a few examples.

As described in [9], structural optimization of fiber-reinforced composites typically involves the determination of the fiber angle orientation, fiber volume fraction, and laminate stacking sequence. The prior art for the structural optimization of fiber-reinforced composites is also expansive including the continuous fiber angle optimization (CFAO) approach [10–12], the free material optimization (FMO) strategy [13–15], or the discrete material optimization (DMO) technique [16–20]. Each of these composite structure design methods has its challenges including the 2π ambiguity for CFAO, fabrication feasibility for FMO, or the *a priori* specification of fiber angle options in the case of DMO. Furthermore, works related to common composite panel design problems [18,21,22] or continuum-based structural studies [23–25] have revealed difficulties in the simultaneous design of the fiber orientation and structural topology. Specifically, the fiber

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orientation design variable may become trapped at a local optima due to coupling between the fiber orientation and topological changes. Thus, prior work by the authors [26] has focused on a versatile method for the design of a structural continuum that addresses the aforementioned challenges, while allowing for simultaneous optimization of structural topology and composite material fiber layout.

The work presented in this article suitably expands upon the method introduced in [26], while further developing an approach to the co-design of both isotropic and functionally graded fiber-reinforced composite material layout with structural topology. Note that multi-material structures [27–31] and actuators plus compliant mechanisms [32,33] have been previously optimized and designed using two or more isotropic materials as discrete phases. The layout and material gradation in topology optimization of structures [34,35] and compliant mechanisms [36] has also been explored. However, the method described herein is unique in that it allows for the simultaneous design of structural topology, continuous or discrete composite fiber angle layout with or without a predetermined angle set, and a functionally graded fiber distribution. In such a manner, structural and compliant mechanism designs are synthesized, where portions of each design comprise isotropic matrix material, while the remaining portions of each structure optimally integrate fiber-reinforced composites with optimized fiber angle orientation plus layout. Such designs may leverage state-of-the-art additive manufacturing technology, and related tools have been previously put to good use in the three-dimensional (3D) printing of multi-material structures [37] and active composites [38].

The paper is organized as follows. Section 2 explains the formulation of the composite structure design problem including the topological design of the matrix material, the orientation design of the fiber material, and the design for discrete fiber orientations. In Section 3, the optimization strategies employed to solve the composite structure design problem are explained. Numerical examples related to structural compliance minimization and compliant mechanism design are then provided in Section 4. Conclusions are provided in Section 5.

2. Formulation

This section explains a proposed formulation for the continuous and discrete orientation design of functionally graded fiber-reinforced composite structures. Fig. 1 shows an abstract schematic representation of the design optimization problem settings. In order to solve this problem, the optimization algorithm should find the optimal values for design variables with different characteristics such as matrix material density, fiber material density and orientation, and target discrete fiber orientation angles. The simultaneous treatment of these multiple design variables is difficult in the optimization procedure. Specifically, the simultaneous optimization of matrix density, and fiber orientation easily falls into an undesired local optimum. To overcome this problem, the continuation scheme of density penalty parameter was proposed in [26]. Now, the fiber material density and target discrete fiber orientation angles are added in this work. For the stable treatment of these multiple design variables, a sequential three-step optimization procedure is proposed in this work as a regularization process for the optimization problem with a sacrifice of the exploration of new topology optimal for anisotropic materials. The first step aims to find the optimal topology design of matrix material when the volume fraction of fiber material is set as zero. After the optimal design of the matrix material is determined, the second step aims to determine the optimal density distribution and orientation of fiber material. In this step, the fiber orientation in the design result is continuous, which is not preferable with regard to feasibility of fabrication. Thus, intermediate fiber orientations between target orientations, are penalized in the third step, and finally the discrete orientation design result is achieved. In addition, the target fiber angle orientation set is also optimized as additional design variables during the third step. The detailed formulation for each step follows.

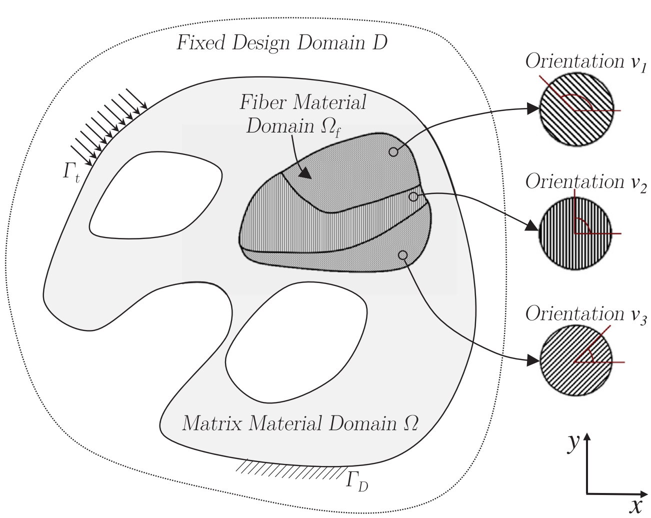

Fig. 1. Abstract schematic representation of orientation design problem in composite structures.

2.1. Topology design of matrix material

For the topology design of matrix material, a conventional scalar density design variable with a Partial Differential Equation (PDE) based filter [39] is utilized in this work. In general, topology optimization aims to solve the material distribution problem within a fixed design domain, D, defined as

$$\inf_{\chi(\vec{x})} F = \int_\Omega f_d(\vec{u},\chi(\vec{x}))d\Omega + \int_\Gamma f_b(\vec{u},\chi(\vec{x}))d\Gamma \tag{1}$$

where f_d and f_b are real functions, respectively, defined at domain Ω filled with a material and boundaries Γ, and $\vec{u}$ represents the vector of state variables. Here, the characteristic function χ at location $\vec{x}$ is defined to indicate the structural topology:

$$\chi(\vec{x}) = \begin{cases} 0 & \text{for} \quad \forall\, \vec{x} \in D\backslash\Omega \\ 1 & \text{for} \quad \forall\, \vec{x} \in D \end{cases} \tag{2}$$

The above characteristic function χ can be represented as the Heaviside function of implicit scalar density design variable ϕ.

$$\chi(\vec{x}) = H(\phi(\vec{x})) = \begin{cases} 0 & \text{for} \quad \forall\, \vec{x} \in D\backslash\Omega \\ 1 & \text{for} \quad \forall\, \vec{x} \in D \end{cases} \tag{3}$$

The raw design variable ϕ may produce severely oscillating designs like a checkerboard or corrugated shape. Thus, the variable ϕ is regularized by a Helmholtz PDE based filter [39] to consequently produce the smoothed variable $\tilde{\phi}$

$$-R_\phi^2 \nabla^2 \tilde{\phi} + \tilde{\phi} = \phi \tag{4}$$

where R_ϕ is the filter radius for density design variable ϕ.

To apply a gradient based optimization algorithm, the characteristic function χ is relaxed to the material density field $\rho(\vec{x})$:

$$\rho = \chi(\vec{x}) = H_r(\tilde{\phi}(\vec{x})) \tag{5}$$

where a regularized Heaviside function H_r of filtered density design variable $\tilde{\phi}$ is defined as [39]:

$$H_r(\tilde{\phi}) = \begin{cases} 0 & (\tilde{\phi} < -h) \\ \frac{1}{2} + \frac{15}{16}\left(\frac{\tilde{\phi}}{h}\right) - \frac{5}{8}\left(\frac{\tilde{\phi}}{h}\right)^3 + \frac{3}{16}\left(\frac{\tilde{\phi}}{h}\right) & (-h \leqslant \tilde{\phi} \leqslant h) \\ 1 & (h < \tilde{\phi}) \end{cases} \tag{6}$$

where h is a positive parameter representing the bandwidth between