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Design optimization of composite structures composed of dissimilar materials based on a free-form optimization method

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ABSTRACT

Design optimization of composite structures has been a significant topic of research over the recent years. In the present work, we propose a developed free-form optimization method for designing the shape of composite structures composed of dissimilar materials (*A* and *B*). In this shape design optimization, we use compliance as the objective function and minimize it under two volume constraints (total volume and volume of material *A*). According to the proposed free-form optimization method, we theoretically derive the shape gradient function used in the compliance minimization problem, and determine the optimal interface and surface shapes of composite structures under external loading or body force without any shape parameterization. The optimal results of numerical examples show that the compliance of composite structures composed of dissimilar materials can be significantly reduced by using the proposed free-form optimization method.

1. Introduction

Designing new structures to satisfy specific requirements has been a hotpot since a long time ago. For instance, structures may need high-temperature resistance in one part, whereas need toughness or wear resistance in another location. According to that, designers consider composite structures composed of dissimilar materials to fit this requirement. With the development of adhesive techniques, dissimilar materials, such as ceramic–metal, carbide-steel, and carbon fiber-polymer composites, have been widely applied for strengthening and lightening the composite structures [1–3]. One of the most widely utilized structures composed of dissimilar materials is the reinforced concrete structure [4], in which concrete with lower tensile strength and ductility is reinforced by rebar having higher tensile strength and ductility. The most notable feature of dissimilar materials is that new properties can be obtained by combining different constituent materials together. Nowadays, automotive bodies are fabricated using dissimilar materials. The design for automotive bodies involves the use of dissimilar lightweight materials such as advanced high-strength steel, aluminum alloys, and carbon fiber reinforced plastic [5].

Mechanical properties of composite structures composed of dissimilar materials have been studied based on theoretical approaches and experiments [6–10]. For example, Ranjith et al. [6] studied the stability and well-posedness of steady frictional sliding along the interface between dissimilar elastic solids. Lee et al. [7] performed a combined numerical/experimental study to analyze the ballistic efficiency of a ceramic/metal composite armor system against 7.62 AP and 40.7 g steel projectiles. For designing the armor systems made of ceramic–metal composite in ballistic applications, Krishnan et al. [8] made an explicit analysis based on finite element method (FEM), and verified the results by laboratory testing. The results showed that the finite element analysis of damage by understanding the various nuances of projectile-armor interaction and finding effective ways to develop light weight solutions is in good agreement with the experimental data. In the design of dissimilar materials, structural design optimization is an effective mean and has been seriously considered among designers [11].

Structural design optimization is a procedure to improve or enhance the performance of structures by changing design parameters [12,13]. As the development of computer-aided engineering, structural design optimization has been widely utilized in mechanical, civil, aerospace, automotive engineering, and so on [14]. In structural design optimization, an objective function should be optimized to minimize the cost or to maximize the efficiency of

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the production. Up to now, some works in terms of structural design optimization of composite structures have been carried by using topology optimization [15–19]. For instance, Rodrigues et al. [15] presented a method of topology optimization for dissimilar materials by predicting both local properties and topology for the dissimilar materials. Kato et al. [16] addressed a topology optimization method of textile fiber reinforced concrete to improve the structural ductility. This method was based on multiphase material optimization and extended to a damage formulation. Huang and Xie [17] developed a new bi-directional evolutionary structural optimization method with a penalization parameter for achieving convergent optimal solutions for structures composed of dissimilar materials.

On the other hand, shape optimization also plays an important role in structural optimization design. There are two classifications of shape optimization, which are parametric method and non-parametric method. The parametric shape optimization method depending on the parameters, such as basis shapes or boundary splines, has been widely used [20–23]. However, the parametric method requires expert knowledge of designers to construct the basis shapes or a large number of degrees of freedom in a boundary spline. Different from the parametric method, non-parametric shape optimization method does not require a shape design parametrization or constructing the basis shapes, and can be used more conveniently. The non-parametric shape optimization method is based on the variational method, so that the smooth and free-form optimal shapes can be determined without requiring shape parameterization. According to the non-parametric method, de Gournay et al. [24] presented a novel application of shape optimization tools in the case of biphasic domains and performed the shape sensitivity analysis with respect to the evolution of the interface between the fluid phase and solid phase.

The free-form optimization method used in the present work belongs to non-parametric method that consists of sensitivity analysis, derivation of shape gradient functions, and a gradient method with a P.D.E. (Partial Differential Equation) smoother in the Hilbert space for shape optimization of continua. This method is also called the H^1 gradient method or the traction method that was firstly proposed by Azegami [25]. In our previous works, we proposed the free-form optimization method for designing interface shape of sandwich structures [26] and shell structures consisting of composite materials [27]. In the present work, we aim to develop this free-form optimization method for shape design (including interface and surface shapes) of composite structures composed of dissimilar materials under external loading or body force.

The rest of the paper is arranged as follows. In Section 2, domain variation and formulation of compliance minimization problem are introduced, respectively. In Section 3, we develop the free-form optimization method for composite structures composed of dissimilar materials to minimize their compliance. Using the developed shape optimization method, four design problems of structures composed of dissimilar materials are analyzed in Section 4. At last, we present concluding remarks in Section 5.

2. Shape optimization problem of dissimilar materials

2.1. Domain variation

Before formulating the optimization problem of composite structures composed of dissimilar materials, domain variation in dissimilar materials used in the shape gradient method needs to be introduced briefly. As shown in Fig. 1, an elastic solid body with an initial global domain of $\Omega \subset \mathbb{R}^3$ (where $\mathbb{R}$ is a set of real numbers) and boundary $\Gamma \equiv \partial\Omega$ is composed of two different materials A and B. This elastic solid body undergoes variation (i.e., the design velocity field) $\boldsymbol{V}$, so that its domain and boundary become Ω_s and Γ_s. Sub-domain and its boundary of sub-material A (or B) are defined as Ω_A (or Ω_B) and Γ_A (or Γ_B), respectively. The interface between sub-domains Ω_A and Ω_B is $\Gamma_{AB} \equiv \Gamma_A \cap \Gamma_B$. The domain variation is expressed by a one-to-one mapping $T_s(\boldsymbol{X}) : \boldsymbol{X} \in \Omega \mapsto x \in \Omega_s,\ 0 \leqslant s < \varepsilon$, where the notations s and ε indicate the iteration history (or the design time) of domain variation and a small positive number, respectively. $\boldsymbol{f}(\boldsymbol{x})$ is the body force per unit volume of the dissimilar materials, $\boldsymbol{P}(\boldsymbol{x})$ is the surface forces per unit area acting on the sub-boundary Γ_1 and $p(\boldsymbol{x})\boldsymbol{n}$ is the pressure acting on the sub-boundary Γ_2. Assuming a constraint acting on the variation in the domain $\Theta \subset \Omega$, the domain variation can be given by:

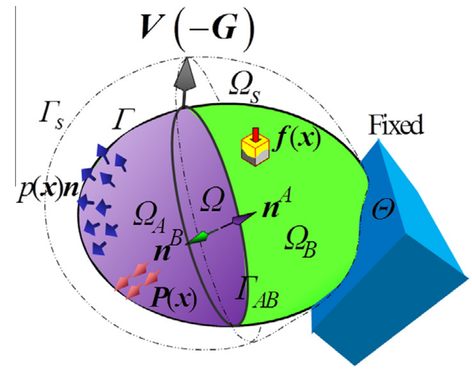

Fig. 1. Domain variation of a composite structure composed of dissimilar materials A and B.

$$T_{s+\Delta s}(\boldsymbol{X}) = T_s(\boldsymbol{X}) + \Delta s\boldsymbol{V} \tag{1}$$

where the design velocity field $\boldsymbol{V}$ is given as a derivative of $T_s(\boldsymbol{X})$ with respect to s, shown as:

$$\boldsymbol{V}(\boldsymbol{x}) = \frac{\partial T_s}{\partial s}(T_s^{-1}(\boldsymbol{x})), \quad x \in \Omega_s,\ \boldsymbol{V} \in C_\Theta = \{\boldsymbol{V} \in C^1(\Omega;\mathbb{R}^3) | \boldsymbol{V} = \boldsymbol{0} \text{ in } \Theta\} \tag{2}$$

where C_Θ is the suitably smooth function space that satisfies the constraints of domain variation. The optimal design velocity field $\boldsymbol{V}$ can be determined based on a developed free-form optimization method which will be introduced in Section 3.

2.2. Compliance minimization problem

We consider a free-form optimization method for minimizing the compliance in the present work. Letting $l(\boldsymbol{v})$ denote the compliance as an index of rigidity, the compliance minimization problem of composite structures composed of dissimilar materials is formulated as:

$$\text{Find} \quad \boldsymbol{V} \tag{3}$$
$$\text{that minimizes} \quad l(\boldsymbol{v}) \tag{4}$$
$$\text{subject to} \quad M = \hat{M}, \quad M_A = \hat{M}_A \tag{5}$$
$$\text{and} \quad a_A(\boldsymbol{v},\boldsymbol{w}) - h_A(\boldsymbol{v},\boldsymbol{w}) + a_B(\boldsymbol{v},\boldsymbol{w}) - h_B(\boldsymbol{v},\boldsymbol{w}) = l(\boldsymbol{w}), \quad \forall \boldsymbol{w} \in U \tag{6}$$

where M and M_A are the total volume and the volume of material A, respectively. The notation $(\hat{\ })$ indicates the constraint value. U denotes the kinematically admissible displacement space that satisfies the Dirichlet boundary condition. The forms $a_m(\boldsymbol{v},\boldsymbol{w})$, $h_m(\boldsymbol{v},\boldsymbol{w})$