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Maximum length scale control in density-based multi-material topology optimization

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Abstract

In this work, the method of the maximum length scale control is proposed for density-based multi-material topology optimization. The three-field approach of multi-material topology optimization is presented, which includes the density filter, the projection with Heaviside function, and the uniform multiphase materials interpolation (UMMI) scheme. Then, the local constraints are built by introducing porosity and aggregated by p-mean function to achieve maximum length scale control for the solid phase. Besides, three control schemes are studied and compared. The maximum length scale constraint for single solid phase (MaxLSC-S) and for entire solid phases (MaxLSC-U) are proposed. Based on them, the maximum length scale constraint with hybrid control scheme (MaxLSC-H) are presented. The proposed schemes realize the independent maximum length scale control of a certain material, the simultaneous control of multiple materials, and the maximum length scale control of the joints between two candidate materials. The optimization formulations and the sensitivity analysis of the related optimization responses are subsequently given. Numerical tests demonstrate that the proposed method can contribute to improving the manufacturability of length scale constrained designs and provides possibilities to achieve the desired properties on the design.

Keywords: topology optimization, multi-material, density-based, maximum length scale control.

1 Introduction

The multi-material topology optimization has attracted a great deal of attention over the last decades. Particularly, length scale control could be owed not only to manufacturing limitations but also to include indirect desired properties on the design. The maximum length scale constraint avoids the accumulation of a large amount of design material. Guest[1] firstly proposed a technique based on the design domain that is researched to create the local constraints, which prevent the formation of features that are larger than the prescribed maximum length scale. Several numerical examples prove the robustness of the method, but it demands a big computational cost due to the large number of local constraints that are introduced in the optimization problem. Then Zhang et al. reduced the number of local constraints by collecting those that belong to the structural skeleton[2]. Later, Lazarov and Wang[3] presented two alternatives based on the construction of a band pass filter in the frequency domain and morphological operators respectively to eliminate a large number of constraints and reduce the computational cost. More recently, Carstensen and Guest[4] proposed a projection-based method based on the multiple phase projection strategy to control the maximum length scale, and they reduced the number of design variables using weighting functions. Fernández[5] took over the maximum length scale formulation proposed by Guest to perform an efficient aggregation of the local constraints. Besides, a new test region that a ring replaces a circle around the element under analysis is proposed to slightly reduce the introduction of holes in the optimized designs.

For maximum length scale control in multi-material topology optimization, as far, the method proposed by Liu[6] based on level set functions considers the length scale control in level set topology optimization. The maximum length scale control has rarely been studied for density-based multi-material topology optimization. In this work, based on the three-field approach and UMMI scheme, we propose a method to control the maximum length scale for the solid phase in density-based multi-material topology optimization. In this method, the relationships between different solid phases are considered and three different control schemes are presented to realize the independent control of a certain material and simultaneous control of multiple materials, as well as the length scale control of the joints between two different materials for solid phase.

2 Methods

The three-field topology optimization approach is comprised of design variable field $\mathbf{x}$, filtered density field $\tilde{\mathbf{x}}$, and physical density field $\bar{\mathbf{x}}$. The weighting coefficient of element *k* related to element *i* in density filter is expressed as

$$W_{ik} = \frac{W_i\left(\mathbf{c}_k\right)V_k}{\sum_{\xi=1}^{n} W_i\left(\mathbf{c}_\xi\right)V_\xi}, \tag{1}$$

where $\mathbf{c}_k$ is the centroid coordinate of element *k* and V_k is its volume. $W_i\left(\mathbf{c}_k\right)$ is defined as

$$W_i\left(\mathbf{c}_k\right) = \max\left\{R_\mathrm{f} - d, 0\right\} \tag{2}$$

with R_f being the prescribed filter radius. $d = \| \mathbf{c}_k - \mathbf{c}_i \|$ is the distance between the centroids of elements i and k. The smoothed Heaviside function defined as

$$\bar{x}_{ij} = H(\tilde{x}_{ij}) = \frac{\tanh(\beta\eta) + \tanh(\beta(\tilde{x}_{ij} - \eta))}{\tanh(\beta\eta) + \tanh(\beta(1-\eta))}, \tag{3}$$

in which β and η control the steepness and the threshold of the projection, respectively.

Besides, the UMMI scheme with mass constraint is used. For the optimization problem of m solid materials, the UMMI interpolation of Young's modulus can be expressed as the weighted sum of all candidate material phases.

$$E_i = \sum_{j=1}^{m} \lambda_{ij} E^{(j)}, \tag{4}$$

where λ_{ij} is the weighting function of the design variable x_{ij}. $E^{(j)}$ is the Young's modulus of material j. The SIMP model is used in this work, the definition of the weighting function λ_{ij} can be presented as

$$\lambda_{ij} = \bar{x}_{ij}^{p} \prod_{\substack{\xi=1 \\ \xi \neq j}}^{m} (1 - \bar{x}_{i\xi}^{p}), \tag{5}$$

in which p is the penalty factor of SIMP model and $\bar{x}_{i\xi}$ presents the design variable of element i associated with material ξ. To control the maximum length scale, the method that introduces porosity in Ω_i field around i-th element is used. And then the *p-mean* aggregation function is used here to reduce the number of local constraints. Three kinds of Maximum length scale constraints, MaxLSC-S, MaxLSC-U, and MaxLSC-H are proposed based on different control schemes respectively.

1. Maximum length scale constraint for single solid phase (MaxLSC-S)

Generally, the Ω_i is a circular region of radius R_{Max} and controls the maximum length scale of the solid phase. Based on the UMMI scheme, the porosity of j-th material ζ_{ij} is introduced in Ω_i field around i-th element, which is defined as

$$\zeta_{ij} = \frac{\sum_{k \in \Omega_i} v_k (1 - \bar{x}_{kj})^p}{\sum_{k \in \Omega_i} v_k}. \tag{6}$$

2. Maximum length scale constraint for entire solid phases (MaxLSC-U)

The uniform expression to control the maximum local solid feature size of all candidate materials subjecting to element i is presented as

$$\zeta_i = \frac{\sum_{k \in \Omega_i} v_k \prod_{j=1}^{m} (1 - \bar{x}_{kj})^p}{\sum_{k \in \Omega_i} v_k}, \tag{7}$$

where m is the total number of candidate materials.

3. Maximum length scale constraint with hybrid control scheme (MaxLSC-H)

MaxLSC-H is proposed by combining MaxLSC-S with MaxLSC-U and thus two constraints at least should be imposed to the optimization problem.

$$G_{\text{MaxLCS-S}}^{(1)} < \varepsilon_{\text{MaxS}}^{(1)} \text{ and } G_{\text{MaxLCS-U}} < \varepsilon_{\text{MaxS}}^{(0)} \tag{8}$$

where ε is a small positive value that is close to zero.

3 Results

A three-point-load beam structure with two candidate materials VM1 and VM2 (cf. table 1) respectively is optimized. The initial design domain, boundary conditions, and the mesh are provided in Fig. 1.

Virtual material	Young's modulus (GPa)	Density (kg/m^3)	Color
VM1	70	2700	
VM2	120	5400	

Table 1: Basic material properties of the candidate materials

The comparison of optimized configurations is shown in Fig. 1. The optimized configurations are nearly symmetric. The strong material (VM2) mainly distributes around the loading areas and the constraint boundary areas where the deformation tends to be larger. However, the weak material (VM1) mainly plays a connection role in the optimized configuration and the structural feature of weak material is obviously larger than about strong material. Besides, the history iteration of the objective and the mass constraint in the optimization case without considering length scale control is shown in Fig. 1 (c).

For MaxLCS-S, Fig. 1 (d), Fig. 1 (e), and Fig. 1 (f) show the optimizations with MaxLSC of both materials, VM1, and VM2, respectively. Compared with configuration without considering length scale control, the optimized configurations with MaxLCS-S show the length scale constraint works well in the optimizations. Obviously, the size of the configuration features is changed but the material layout of different candidate materials is roughly the same. Because of the influence from the uncontrolled material, the effectiveness of controlling both materials' maximum size is more remarkable than controlling one of the material's maximum length scales. The size of the structural features is not uniform enough when controlling the maximum size of one material, especially in Fig. 1 (e).

For MaxLCS-U, the optimization with maximum length scale control of both materials is presented in Fig. 1 (g). Compared with the configuration with MaxLCS-S of both materials, the length scale of the joints between two different materials is controlled in the optimized configuration with MaxUCS-S as the circled features shown (cf. Fig. 1 (d) and Fig. 1 (g)) and the effectiveness of the length scale control is more conspicuous.

For MaxLCS-S, the MaxSCS-S of VM1 and MaxUCS-S of both materials are imposed to the optimization to control the maximum length scale of each material individually. The size of the length scale control area of VM1, VM2, and joints are 0.3, 0.5, and 0.5, respectively. The optimized configuration is shown in Fig. 1 (h).

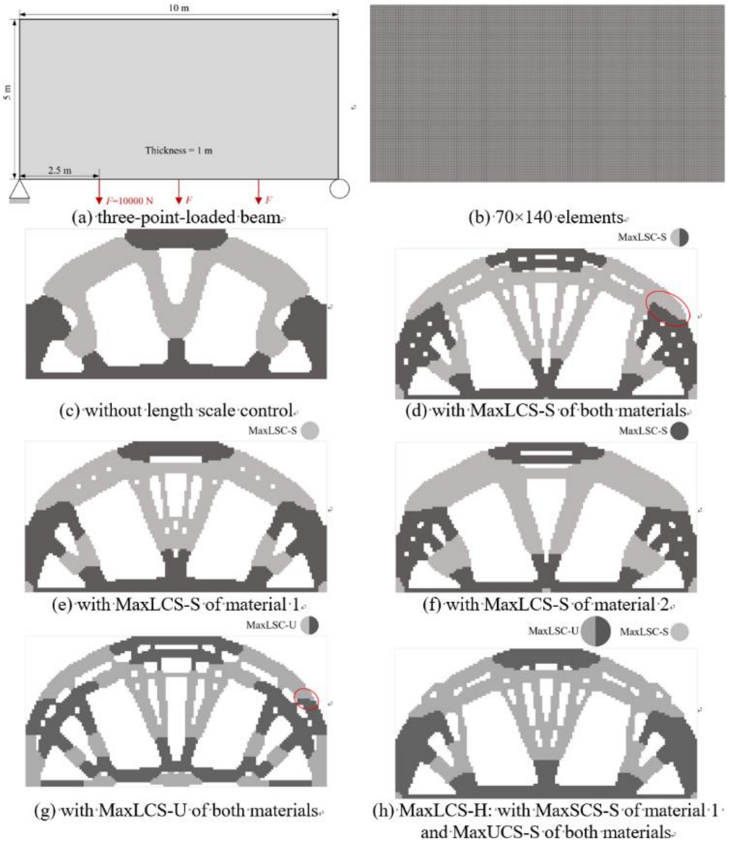

Fig. 1: The comparison of optimized configurations

4 Conclusions and Contributions

In this work, the maximum length scale control for the solid phase is imposed to density-based multi-material topology optimization. The relationships between different solid phases are considered. Thus, separate control scheme, uniform control scheme, and hybrid control scheme three control schemes are used and then MaxLSC-S, MaxLSC-U, and MaxLSC-H are proposed. The proposed method realizes the independent maximum length scale control of a certain material, the simultaneous control of multiple materials, and the maximum length scale control of the joints between two different materials. The results of the example show that the effectiveness of length scale control is remarkable and it improves the manufacturability of the structural design. Besides, the compromised structural compliance is also acceptable. For MaxLCS-S, because of the influence from the uncontrolled material, the effectiveness of controlling all materials' maximum length scale is more remarkable than controlling one of the materials. For MaxLCS-U, all of the materials and the joints between different materials are controlled with a uniform size of length scale control area. For MaxLCS-H, each material and the joints can be controlled with different sizes of length scale control areas via the combination of MaxLCS-S and MaxLCS-U. In a word, the maximum length scale constraints with three different control schemes are proposed for the multi-material problem not only to meet the manufacturing limitations but also to provide more possibilities for structural design in engineering.

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