

不同初始设计状态下材料与结构一体化设计

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[摘 要] 通过双向渐进结构优化算法提出了一种复合宏观结构与周期性材料微结构的拓扑优化方法,以材料体积比为约束条件,以结构的柔顺度为目标函数建立了宏观结构与材料微结构的并行拓扑优化数学模型。研究了不同初始设计状态条件下的宏观结构与材料微结构的并行拓扑优化问题。结果表明,宏观结构与材料微结构的最优拓扑优化结果、目标函数与对应的等效弹性矩阵独立于初始设计状态。

[关键词] 双向渐进结构优化法;材料体积比;柔顺度;不同初始设计状态

引言

拓扑优化技术在过去的几十年中已经取得了巨大的发展。现如今拓扑优化方法比如均匀化方法、SIMP法、BESO法等都已经成功应用于连续体结构的设计当中,从而提高了结构的特性或功能或减轻了结构的重量。Suzuki[1]等人讨论了基于均匀化方法的线性弹性结构的形状和拓扑优化。为了使磁场柔顺度最大化,在磁场领域内对结构的拓扑优化采用了均质化设计方法[2]。均匀化的方法扩展到最小应力设计,其中部分技术被用于连续层压复合材料[3]。Tcherniak[4]等采用了SIMP方法来获得谐振执行器的优化布局。相应地,SIMP方法的理论收敛特性由Martinez[5]等进行了研究。Wang[6]等人表示使用的是嵌入在一个更高的层面。水平集模型灵活处理复杂的拓扑变化,简洁的描述结构的边界形状。水平集方法也通过激发频率或频率范围最小化用于指定的点或表面的频率响应上的结构[7]。郭[8]等指出,水平集方法在与压力有关的拓扑优化问题上面是一个行之有效的手段。Xie和Steven提出了被称为渐进结构优化(ESO)的简单拓扑优化方法。但使用这种方法时,在优化过程中材料只能被删除,而不能被添加。后来基于此提出了一种双向渐进结构优化(BESO)方法,使用此方法材料不仅可以添加,还可以删除被开发。Huang和Xie[9-11]基于BESO方法研究了一些连续体结构拓扑优化的设计问题,包括几何和材料非线性,二维和三维周期性材料和结构与一种或多种材料结构设计研究。

1 两尺度刚度优化问题

考虑多尺度下的复合宏观结构和周期性多孔材料优化问题。以结构刚度最大化为目标,以材料体积比为约束条件建立优化数学模型,从而进行两尺度下的拓扑优化设计。

2 材料插值函数

本质上来说,宏观结构和周期性材料微结构的并行拓扑优化设计其实就是对材料进行分配从而找到最优的材料布局,给定设计域 Ω ,哪些点 \mathbf{x} 是材料点,哪些点是孔洞,其数学模型可以表述为:

$$\mathbf{x}:\alpha(\mathbf{x})=\begin{cases} 0 & \rightarrow \text{no material} \\ 1 & \rightarrow \text{material} \end{cases} \quad \alpha \in L^{\infty}(\Omega) \quad (3.1)$$

$\alpha(\mathbf{x})=0$,表示该处没材料; $\alpha(\mathbf{x})=1$ 表示该处有材料。总之,这是一个0-1的整体拓扑优化问题,很容易导致高度非凸变分问题。为了确保0-1解的存在性,必须采用一些正规化或者平滑技术。

本文采用SIMP材料插值模型,质量矩阵 $\mathbf{M}(\alpha)$ 和刚度矩阵 $\mathbf{K}(\alpha)$ 分别可以由单元质量矩阵和单元刚度矩阵组装而成。

3 数值算例及分析

通过数值算例对宏观材料以及微观胞体材料的分布进行优化设计从而使得结构刚度最大化。结构模型底座为4节点的离散细胞四边形元件,表示的是材料的微观结构。每个 V_1^* 、 V_1^{mic} 和 V_2^{mic} 等于0.5。 $n_1=n_2=3$ 。所提出的BESO技术使用下列参数: $\alpha_1+\alpha_2+\alpha_3+\alpha_4+\alpha_5+\alpha_6+\alpha_7+\alpha_8+\alpha_9+\alpha_{10}+\alpha_{11}+\alpha_{12}+\alpha_{13}+\alpha_{14}+\alpha_{15}+\alpha_{16}+\alpha_{17}+\alpha_{18}+\alpha_{19}+\alpha_{20}+\alpha_{21}+\alpha_{22}+\alpha_{23}+\alpha_{24}+\alpha_{25}+\alpha_{26}+\alpha_{27}+\alpha_{28}+\alpha_{29}+\alpha_{30}+\alpha_{31}+\alpha_{32}+\alpha_{33}+\alpha_{34}+\alpha_{35}+\alpha_{36}+\alpha_{37}+\alpha_{38}+\alpha_{39}+\alpha_{40}+\alpha_{41}+\alpha_{42}+\alpha_{43}+\alpha_{44}+\alpha_{45}+\alpha_{46}+\alpha_{47}+\alpha_{48}+\alpha_{49}+\alpha_{50}+\alpha_{51}+\alpha_{52}+\alpha_{53}+\alpha_{54}+\alpha_{55}+\alpha_{56}+\alpha_{57}+\alpha_{58}+\alpha_{59}+\alpha_{60}+\alpha_{61}+\alpha_{62}+\alpha_{63}+\alpha_{64}+\alpha_{65}+\alpha_{66}+\alpha_{67}+\alpha_{68}+\alpha_{69}+\alpha_{70}+\alpha_{71}+\alpha_{72}+\alpha_{73}+\alpha_{74}+\alpha_{75}+\alpha_{76}+\alpha_{77}+\alpha_{78}+\alpha_{79}+\alpha_{80}+\alpha_{81}+\alpha_{82}+\alpha_{83}+\alpha_{84}+\alpha_{85}+\alpha_{86}+\alpha_{87}+\alpha_{88}+\alpha_{89}+\alpha_{90}+\alpha_{91}+\alpha_{92}+\alpha_{93}+\alpha_{94}+\alpha_{95}+\alpha_{96}+\alpha_{97}+\alpha_{98}+\alpha_{99}+\alpha_{100}+\alpha_{101}+\alpha_{102}+\alpha_{103}+\alpha_{104}+\alpha_{105}+\alpha_{106}+\alpha_{107}+\alpha_{108}+\alpha_{109}+\alpha_{110}+\alpha_{111}+\alpha_{112}+\alpha_{113}+\alpha_{114}+\alpha_{115}+\alpha_{116}+\alpha_{117}+\alpha_{118}+\alpha_{119}+\alpha_{120}+\alpha_{121}+\alpha_{122}+\alpha_{123}+\alpha_{124}+\alpha_{125}+\alpha_{126}+\alpha_{127}+\alpha_{128}+\alpha_{129}+\alpha_{130}+\alpha_{131}+\alpha_{132}+\alpha_{133}+\alpha_{134}+\alpha_{135}+\alpha_{136}+\alpha_{137}+\alpha_{138}+\alpha_{139}+\alpha_{140}+\alpha_{141}+\alpha_{142}+\alpha_{143}+\alpha_{144}+\alpha_{145}+\alpha_{146}+\alpha_{147}+\alpha_{148}+\alpha_{149}+\alpha_{150}+\alpha_{151}+\alpha_{152}+\alpha_{153}+\alpha_{154}+\alpha_{155}+\alpha_{156}+\alpha_{157}+\alpha_{158}+\alpha_{159}+\alpha_{160}+\alpha_{161}+\alpha_{162}+\alpha_{163}+\alpha_{164}+\alpha_{165}+\alpha_{166}+\alpha_{167}+\alpha_{168}+\alpha_{169}+\alpha_{170}+\alpha_{171}+\alpha_{172}+\alpha_{173}+\alpha_{174}+\alpha_{175}+\alpha_{176}+\alpha_{177}+\alpha_{178}+\alpha_{179}+\alpha_{180}+\alpha_{181}+\alpha_{182}+\alpha_{183}+\alpha_{184}+\alpha_{185}+\alpha_{186}+\alpha_{187}+\alpha_{188}+\alpha_{189}+\alpha_{190}+\alpha_{191}+\alpha_{192}+\alpha_{193}+\alpha_{194}+\alpha_{195}+\alpha_{196}+\alpha_{197}+\alpha_{198}+\alpha_{199}+\alpha_{200}+\alpha_{201}+\alpha_{202}+\alpha_{203}+\alpha_{204}+\alpha_{205}+\alpha_{206}+\alpha_{207}+\alpha_{208}+\alpha_{209}+\alpha_{210}+\alpha_{211}+\alpha_{212}+\alpha_{213}+\alpha_{214}+\alpha_{215}+\alpha_{216}+\alpha_{217}+\alpha_{218}+\alpha_{219}+\alpha_{220}+\alpha_{221}+\alpha_{222}+\alpha_{223}+\alpha_{224}+\alpha_{225}+\alpha_{226}+\alpha_{227}+\alpha_{228}+\alpha_{229}+\alpha_{230}+\alpha_{231}+\alpha_{232}+\alpha_{233}+\alpha_{234}+\alpha_{235}+\alpha_{236}+\alpha_{237}+\alpha_{238}+\alpha_{239}+\alpha_{240}+\alpha_{241}+\alpha_{242}+\alpha_{243}+\alpha_{244}+\alpha_{245}+\alpha_{246}+\alpha_{247}+\alpha_{248}+\alpha_{249}+\alpha_{250}+\alpha_{251}+\alpha_{252}+\alpha_{253}+\alpha_{254}+\alpha_{255}+\alpha_{256}+\alpha_{257}+\alpha_{258}+\alpha_{259}+\alpha_{260}+\alpha_{261}+\alpha_{262}+\alpha_{263}+\alpha_{264}+\alpha_{265}+\alpha_{266}+\alpha_{267}+\alpha_{268}+\alpha_{269}+\alpha_{270}+\alpha_{271}+\alpha_{272}+\alpha_{273}+\alpha_{274}+\alpha_{275}+\alpha_{276}+\alpha_{277}+\alpha_{278}+\alpha_{279}+\alpha_{280}+\alpha_{281}+\alpha_{282}+\alpha_{283}+\alpha_{284}+\alpha_{285}+\alpha_{286}+\alpha_{287}+\alpha_{288}+\alpha_{289}+\alpha_{290}+\alpha_{291}+\alpha_{292}+\alpha_{293}+\alpha_{294}+\alpha_{295}+\alpha_{296}+\alpha_{297}+\alpha_{298}+\alpha_{299}+\alpha_{300}+\alpha_{301}+\alpha_{302}+\alpha_{303}+\alpha_{304}+\alpha_{305}+\alpha_{306}+\alpha_{307}+\alpha_{308}+\alpha_{309}+\alpha_{310}+\alpha_{311}+\alpha_{312}+\alpha_{313}+\alpha_{314}+\alpha_{315}+\alpha_{316}+\alpha_{317}+\alpha_{318}+\alpha_{319}+\alpha_{320}+\alpha_{321}+\alpha_{322}+\alpha_{323}+\alpha_{324}+\alpha_{325}+\alpha_{326}+\alpha_{327}+\alpha_{328}+\alpha_{329}+\alpha_{330}+\alpha_{331}+\alpha_{332}+\alpha_{333}+\alpha_{334}+\alpha_{335}+\alpha_{336}+\alpha_{337}+\alpha_{338}+\alpha_{339}+\alpha_{340}+\alpha_{341}+\alpha_{342}+\alpha_{343}+\alpha_{344}+\alpha_{345}+\alpha_{346}+\alpha_{347}+\alpha_{348}+\alpha_{349}+\alpha_{350}+\alpha_{351}+\alpha_{352}+\alpha_{353}+\alpha_{354}+\alpha_{355}+\alpha_{356}+\alpha_{357}+\alpha_{358}+\alpha_{359}+\alpha_{360}+\alpha_{361}+\alpha_{362}+\alpha_{363}+\alpha_{364}+\alpha_{365}+\alpha_{366}+\alpha_{367}+\alpha_{368}+\alpha_{369}+\alpha_{370}+\alpha_{371}+\alpha_{372}+\alpha_{373}+\alpha_{374}+\alpha_{375}+\alpha_{376}+\alpha_{377}+\alpha_{378}+\alpha_{379}+\alpha_{380}+\alpha_{381}+\alpha_{382}+\alpha_{383}+\alpha_{384}+\alpha_{385}+\alpha_{386}+\alpha_{387}+\alpha_{388}+\alpha_{389}+\alpha_{390}+\alpha_{391}+\alpha_{392}+\alpha_{393}+\alpha_{394}+\al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如图1所示,本算例是对一个悬臂梁结构进行复合宏观结构和胞体材料的多尺度设计。设计尺寸为长0.3m,宽0.2m,厚

0.002m。在自由端的中心施加了一个负y方向上的静荷载,大小为 1.0×10^5 N。相材料1和3的弹性模量分别为 1.5×10^{11} Pa和 7.0×10^{10} Pa。相材料2和4是无效的多孔材料。

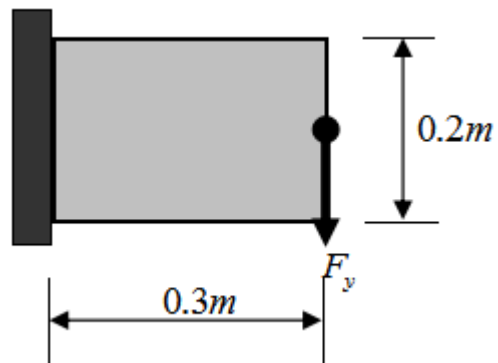


图1. 悬臂梁的设计尺寸、边界及荷载

表1. 不同初始设计下的六种工况

	宏观水平	微观水平
工况1	初始设计1	初始设计1
工况2	初始设计1	初始设计2
工况3	初始设计1	初始设计3
工况4	初始设计2	初始设计1
工况5	初始设计2	初始设计2
工况6	初始设计2	初始设计3

通过计算得出六种工况下宏观结构的柔顺度分别为 $1445.2 N \cdot m$, $1432.2 N \cdot m$, $1431.1 N \cdot m$, $1446.9 N \cdot m$, $1429.0 N \cdot m$ 和 $1430.9 N \cdot m$ 。因此从中可以得出,六种工况下的最优目标函数值之间只存在很小的差异。

结束语

(1) 对于在静载作用下宏观结构与微观结构的多尺度设计产生了一种新方法。基于宏观结构的刚度最大化,以结构的柔顺度作为目标函数进行优化设计研究。

(2) 基于BESO方法得出了宏观结构和材料微结构的最优拓扑,可以看出结构的最优目标函数和最优弹性矩阵是由结构的初步设计决定的。事实上,在单独外力作用下,胞体材料1和2的最优拓扑结果在每种工况下都是相同的。

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