第 51 卷 第 10 期/2024 年 5 月/中国激光 综 述

中国激光

增材制造自支撑设计综述

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摘要 增材制造(AM)的零件若存在悬垂部件，则往往需要添加额外的支撑结构，这不仅会影响打印效率，而且拆除支撑也会引发新的问题。结构自支撑设计能使增材制造摆脱对支撑结构的依赖，现已成为国内外的研究热点。本文首先总结了增材制造结构自支撑设计的原理，接着综述了增材制造零件整体结构自支撑设计的研究进展以及增材制造填充结构自支撑设计的研究进展。其中，根据不同的结构优化方式，将增材制造零件整体结构自支撑设计进一步划分为基于连续体结构拓扑优化、离散结构拓扑优化和形状优化的结构自支撑设计，并分析了各类优化方法的优缺点。最后，讨论了提升计算效率以及提升结构性能的解决方案，并对未来的应用场景以及未来的研究重点进行了展望。

关键词 增材制造；结构优化；拓扑优化；填充结构；结构自支撑

中图分类号 TH164；TN249 **文献标志码** A **DOI**：10.3788/CJL240434

1 引 言

增材制造(AM)，也称 3D 打印，通过逐层增加材料的方式制造具有复杂结构的零件[1]。目前，增材制造技术已被广泛应用于汽车[2]、电子[3]、航空航天[4-5]以及医药[6]等领域并在这些领域发挥着重要作用。但是，该工艺仍存在某些制造约束，如长度尺度约束[7-11]、连通性约束[12-15]、材料性能约束[16-18]和悬垂约束[19]等。其中，悬垂约束是最麻烦的制造约束。

在增材制造过程中，往往会遇到具有悬垂结构(如图 1 所示)的零件，而悬垂结构的存在会影响零件的打印质量[20]。如图 2 所示，在没有支撑的情况下，随着结构的悬垂角度减小，打印件的表面质量变差甚至会发生坍塌[21]。对于传统的 2.5 轴 3D 打印机，解决悬垂结构问题的主要方法有两种：一是在悬垂结构区域下方添加支撑结构，二是通过结构优化实现结构的自支撑[22]。添加支撑结构可以在一定程度上防止翘曲以及减少零件结构的变形，但也增加了制造时间和材料成本；此外，移除支撑结构的后处理工序不仅费时，而且会影响零件的表面粗糙度[23]。因此，实现打印零件结构的自支撑，对于节省材料成本、打印时间以及后处理时间都具有重要意义。

结构优化可以分为尺寸优化、拓扑优化以及形状优化三类[24]，其中的拓扑优化可以进一步分为连续体结构拓扑优化[25]和离散结构拓扑优化两类。就目前而言，基于拓扑优化的结构自支撑设计方法是实现增材制造零件整体结构自支撑设计的最主要方法，而增材制造填充结构的自支撑设计方法主要是基于形状优化以及拓扑优化的方法。这些方法将自支撑约束纳入到结构优化过程中，因而不依靠支撑结构就能成功打印零件。

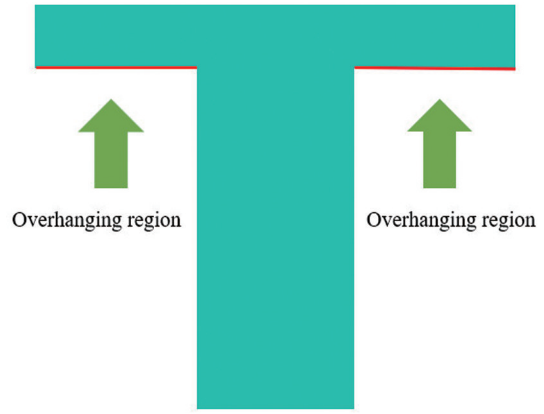

图 1 悬垂结构示意图，其中红色区域为悬垂结构区域

Fig. 1 Schematic diagram of the overhanging structure, where the red areas is the overhanging structure areas

本文对目前的研究热点——增材制造结构自支撑设计进行了系统性总结，首先介绍了增材制造结构自

收稿日期：2024-01-02；**修回日期**：2024-03-15；**录用日期**：2024-03-18；**网络首发日期**：2024-03-28

基金项目：国家重点研发计划(2022YFB4601601)、广西壮族自治区重点研发计划(GKAB23026101)、广西科技基地与人才专项项目(GKAD23026149)、广西自然科学基金(2023GXNSFBA026287)

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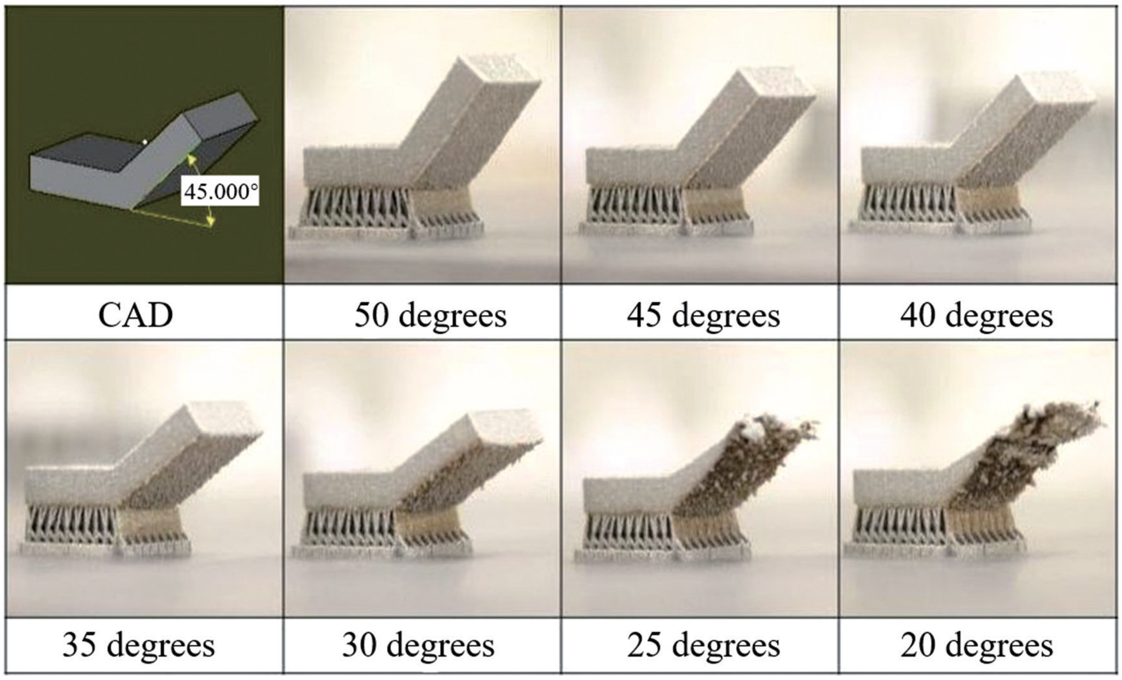


图2 7个不同的悬垂角度下，激光选区熔化工艺(SLM)打印情况[21]

Fig. 2 SLM printing at seven different overhang angles[21]

支撑设计的原理，之后以时间顺序为主线，综述了增材制造零件整体结构自支撑设计的研究进展，包括基于连续体结构拓扑优化的结构自支撑设计研究进展、基于离散结构拓扑优化的结构自支撑设计研究进展，以及基于形状优化的结构自支撑设计研究进展，然后综述了增材制造填充结构自支撑设计的研究进展，最后讨论了提升计算效率以及提升结构性能的解决方案，并对未来的应用场景以及未来的研究重点进行了展望。

2 增材制造结构自支撑设计的基本原理

在增材制造过程中，将结构进行切片后，每个打印层都能充分锚定在前一层而不坍塌的结构被认为是自支撑的，如图3所示。从几何角度来讲，结构表面的悬垂角度应大于一个特定的临界悬垂角度(一般以40°~50°为临界悬垂角[26-29])。

为了实现结构的自支撑，通常在优化过程中引入AM滤波器或纳入悬垂约束(包括悬垂角度和悬垂长度)来对违反悬垂约束的元素予以优化。目前，Langelaar等[30]已经初步实现了零件的自支撑打印，并且他们所取得的成果对以后的研究产生了较大影响，因此本节以他们的研究工作为例进行具体的原理讲解。Langelaar等设计了基于支撑区域的最大密度的自支撑数学模型，如图4所示。位置(i,j)处的黑色元素需要由$i=1$层中的元素对其提供充分的支撑(基板($i=1$)支撑的所有元素都可打印)；对于后续的层，定义元素的打印密度$\xi_{(i,j)}$不能高于其支撑区域$S_{(i,j)}$中存

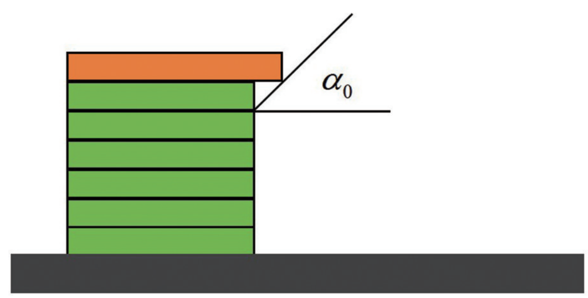


图3 自支撑示意图。橙色区域表示打印层，绿色区域表示打印完成层。当橙色区域可以实现打印时，则认为该结构是自支撑的

Fig. 3 Schematic diagram of self-supporting. The orange area represents the print layer, and the green areas represent the finish print layers. When the orange area can be printed, the structure is considered to be self-supporting

在的最大打印密度$\Xi_{(i,j)}$。以45°临界悬垂角作为约束条件，则支撑区域由被支撑元素下方的元素以及与其直接相邻的元素组成，对于违反约束的元素则进行删除。对于二维情况，自支撑约束的定义为

$$\xi_{(i,j)}=\min\left\{x_{(i,j)},\Xi_{(i,j)}\right\}\text{ with}$$
$$\Xi_{(i,j)}=\max\left\{\xi_{(i-1,j-1)},\xi_{(i-1,j)},\xi_{(i-1,j+1)}\right\},\tag{1}$$

式中：(i,j)表示元素位置；$\Xi_{(i,j)}$表示最大打印密度；$x_{(i,j)}$表示密度变量；$\xi_{(i,j)}$表示打印密度。

在三维情况下，Langelaar[31]提出了一种考虑悬垂约束的AM滤波器。该滤波器被定义在一个统一规则的网格内，如有$n_x\times n_y\times n_z$个立方体离散有限元的立方体设计域内。网格中的每个元素都与密度变量$b_{(i,j,k)}$相关联。这些坐标表示每个元素的位置，基板上

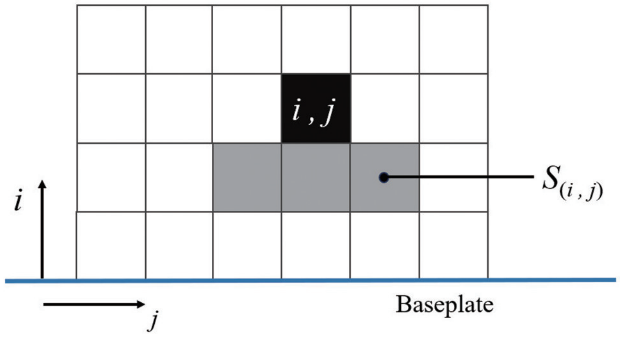


图 4　元素 (i,j) 的支撑区域 $S_{(i,j)}$ 的定义[30]

Fig. 4　Definition of supporting region $S_{(i,j)}$ for element (i,j)[30]

的第一层具有 z 方向坐标，即 $k=1$。

只有受底层打印元素充分支撑的元素才可被打印。根据定义，可以打印基板（$k=1$）支撑的所有元素。在随后的层中，每个元素都与一个支撑区域 $S_{(i,j,k)}$ 相关联，该支撑区域由所考虑元素正下方的元素以及与其直接相邻的4个元素组成，如图5所示。在该数学模型中，定义了每个打印密度 $p_{(i,j,k)}$ 不能高于其支撑区域的最大打印密度 $\hat{p}_s$，如式(2)所示。但由于式(2)不能连续可微，所以采用式(3)和式(4)进行平滑近似表示。

$$p_{(i,j,k)}=\min\left\{b_{(i,j,k)},\hat{p}_s\right\}\text{ with }\hat{p}_s=\max\left\{p_{(i,j,k)}\in S_{(i,j,k)}\right\},\tag{2}$$

$$\min\left\{b_{(i,j,k)},\hat{p}_s\right\}\approx s\cdot\min\left\{b_{(i,j,k)},\hat{p}_s\right\}=\frac{1}{2}\left\{b_{(i,j,k)}+\hat{p}_s-\left[\left(b_{(i,j,k)}-\hat{p}_s\right)^2+\varepsilon\right]^{\frac{1}{2}}+\sqrt{\varepsilon}\right\},\tag{3}$$

$$\max\left\{p_{(i,j,k)}\in S\right\}\approx s\cdot\max\left\{p_{(i,j,k)}\in S\right\}=\hat{p}_s=\left(\sum\nolimits_{e\in S}p_e^P\right)^{\frac{1}{Q}},\tag{4}$$

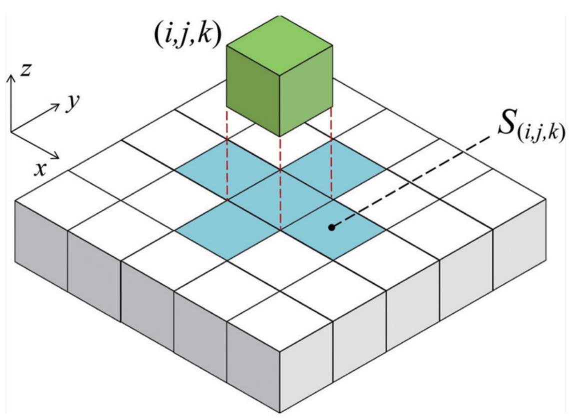


图 5　三维 AM 滤波器的定义，其中蓝色区域 $S_{(i,j,k)}$ 表示元素在网格中的位置 (i,j,k) 处的支撑区域[31]

Fig. 5　Definition of 3D AM filter, where the blue region $S_{(i,j,k)}$ denotes the supporting region of an element at position (i,j,k) in a mesh[31]

式中：$b_{(i,j,k)}$ 表示密度变量；$\hat{p}_s$ 表示最大打印密度；$p_{(i,j,k)}$ 表示打印密度；$S_{(i,j,k)}$ 表示支撑区域；p_e 表示元素的打印密度；参数 ε、P、Q 用于控制近似值的平滑度和准确性。

综上所述，打印层的元素或构件不能违反悬垂约束，应将违反悬垂约束的几何形状排除在设计空间之外，以便使整个结构实现自支撑。尽管设计原理一样，但不同的方法进行的自支撑设计都有其各自的优缺点以及不同的研究进展，因此接下来对不同自支撑设计方法的研究现状进行总结。

3　增材制造零件整体结构自支撑设计的研究进展

3.1　基于连续体结构拓扑优化的结构自支撑设计研究进展

目前，与增材制造零件整体结构的自支撑设计相关的多数工作是基于连续体结构拓扑优化方法进行的，并且已经取得了不错的成果。基于连续体结构拓扑优化的结构自支撑设计方法如表1所示，其中最常用的是固体各向同性材料惩罚法（SIMP 法）。

3.1.1　基于 SIMP 法及其改进方法的结构自支撑设计研究进展

固体各向同性材料惩罚法，简称密度惩罚法[32-33]或 SIMP 法。该方法通过定义每个单元的“伪密度”在0～1区间变动，建立伪密度与弹性模量的关联函数，通过调整惩罚因子 p 减小中间密度，获得较为清晰的拓扑结构。该方法容易实现并且计算效率高。

由于上述优点，基于 SIMP 法及其改进方法的结构自支撑设计已经引起了众多研究者的浓厚兴趣。早在2014年，Leary 等[34]就通过改变结构的几何形状、角度等参数并采用适当的后处理技术避免了大悬垂结构的材料坍塌现象，但并未完全实现自支撑。2016年，Langelaar[31]提出了一种与 SIMP 法相兼容的 AM 滤波器，严格地将违反悬垂约束的几何形状排除在设计空间之外，实现了自支撑、完全可打印的结构设计。此外，Brackett 等[35]和 Gaynor 等[36]分别提出了与悬垂角相关的检测程序和楔形空间滤波器，但前者出现了与约束相关的灵敏度分析在实施过程中发生延误的问题，而后者则出现了使用中间密度材料来支撑完全致密结构的问题。尽管上述工作实现了结构的自支撑设计，但仍存在临界悬垂角不能实现任意角度、出现 V 形区域、需要后处理来平滑边界以及打印性能与设计性能不匹配等问题。

针对不能实现任意临界悬垂角的问题，2018年，Garaigordobil 等[37]提出了一种基于材料属性有理近似模型（RAMP）的结构自支撑设计方法。该方法将悬垂角约束表述为可接受和不可接受的材料构件之间的比率（如式(5)所示），并利用轮廓检测算法评估构件的悬

表1 基于连续体结构拓扑优化的结构自支撑设计方法的优点与缺点

Table 1 Advantages and disadvantages of structural self-supporting design methods based on continuum structure topology optimization

Method	Advantages	Limitations
Based on SIMP method	(1) The optimization algorithm converges well and the sensitivity is simple and easy to calculate (2) Discrete design sensitivity calculations based on finite elements can be performed directly (3) Suitable for combining more complex nonlinear structural topologies, such as geometric and material nonlinear problems	(1) Numerical instability (2) Existence of intermediate densities (3) Prone to local minima
Based on the level set method	(1) Simple principles and clear boundaries (2) No numerical instability (3) No intermediate density	(1) Geometry is limited by existing boundaries (2) Weak convergence (3) Presence of initial dependencies
Based on bi-directional evolutionary structural optimization	(1) Practical principles, simple algorithms (2) Grid-independent (3) Easy to generate good solutions	(1) The more iterations there are, the less efficient the computation becomes (2) Instability of existing values (3) The optimization scheme depends on the type and size of the mesh
Based on feature-driven approach	(1) Co-design and topology optimization of features (2) Few design variables, computationally efficient, clear boundaries (3) Easy and seamless integration with mainstream CAD	(1) Stronger dependence on the number of features and layout (2) Presence of unsmooth boundaries

垂角度,实现不同临界悬垂角度的自支撑设计。其流程以及2D测试结果分别如图6和图7所示。2019年,Kuo等[38]提出了一种基于连续逻辑聚合函数的悬垂角约束,以解决临界悬垂角不能实现任意角度的问题。值得注意的是,其所设置的支撑元素之间的几何关系与文献[31,39]中设置的相同。

$$\tilde{\Phi}(\rho)=\frac{\varphi^{-}(\rho)}{\varphi^{-}(\rho)+\varphi^{+}(\rho)}, \tag{5}$$

式中:$\tilde{\Phi}(\rho)$描述的是结构的“悬垂率”;$\varphi^{-}(\rho)$表示自支撑轮廓线;$\varphi^{+}(\rho)$表示非自支撑轮廓线。

针对传统的基于密度的拓扑优化方法不可避免地需要进行后处理来平滑边界的问题,2019年,Fu等[40]提出了一种基于元素体积分数的SIMP方法。该方法将每个元素进一步划分成多个网格点,在网格点上执行固体/空隙设计,形成边界(如图8所示),实现了具有平滑边界的自支撑拓扑设计。此外,Fu等[41]基于实验仿真探讨了优化参数(滤波器半径、网格尺寸和目标体积分数)对自支撑拓扑和可制造性的影响,结果显示,较大的滤波器半径可以得到更简单的光滑自支撑拓扑。

针对打印出现V形区域的问题,2021年,Wang等[42]提出了一种基于B-样条函数(基函数如图9所示)的拓扑优化方法。该方法根据密度场的梯度来控制结构边界的悬垂角度,并通过约束检测点的密度值来检测和消除V形区域。此外,与其他基于密度的方法相比,基于B-样条函数的密度方法可以通过直接微分的方式计算密度场的梯度,避免了需要复杂线性插值的问题,但该方法获得的优化结果在很大程度上依赖于临界悬垂角、打印方向、节点区间的数量以及检测点之间的间距。

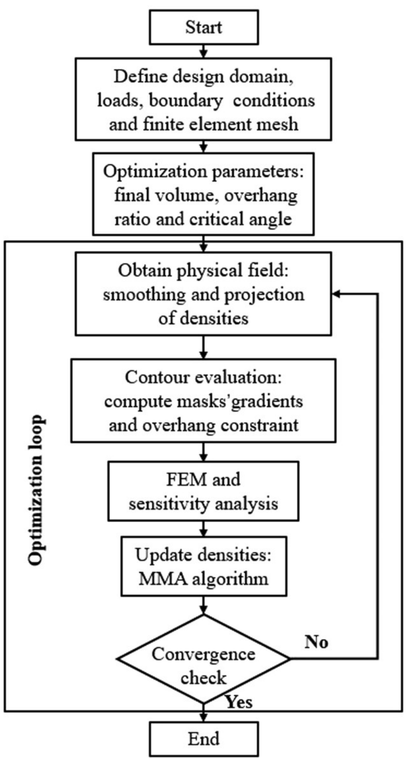


图6 具有悬垂约束的拓扑优化过程流程图[37](选择合适的参考域,定义结构分析的基础数据;然后进行优化循环,包括定义拓扑优化参数、获得物理密度场、轮廓评估、有限元方法计算以及灵敏度分析)

Fig. 6 Flowchart of the topology optimization process with overhang constraint[37] (After selecting the appropriate reference domain, define the underlying data for the structural analysis. Then, the optimization loop is performed, which includes defining the topology optimization parameters, obtaining the physical density field, profile evaluation, finite element method calculations, and sensitivity analysis)

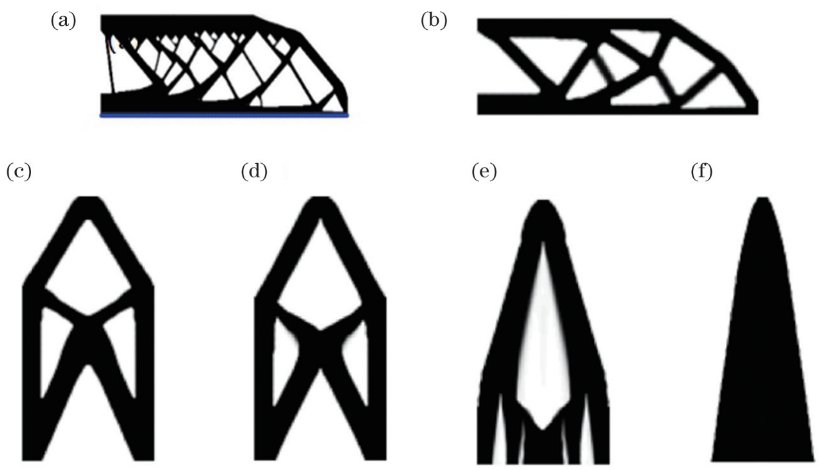


图7　MBB梁与悬臂梁的2D测试结果。(a) Langelaar[30]得到的MBB梁；(b) Garaigordobil等[37]得到的MBB梁；(c)～(f) Garaigordobil等[37]得到的临界角度分别为45°、60°、80°、90°的最佳拓扑结构

Fig. 7　Two-dimensional test results of MBB and cantilever beams. (a) MBB beams obtained by Langelaar[30]; (b) MBB beams obtained by Garaigordobil *et al.* [37]; (c) – (f) optimal topology structures with different critical angles of 45°, 60°, 80°, and 90° obtained by Garaigordobil *et al.* [37]

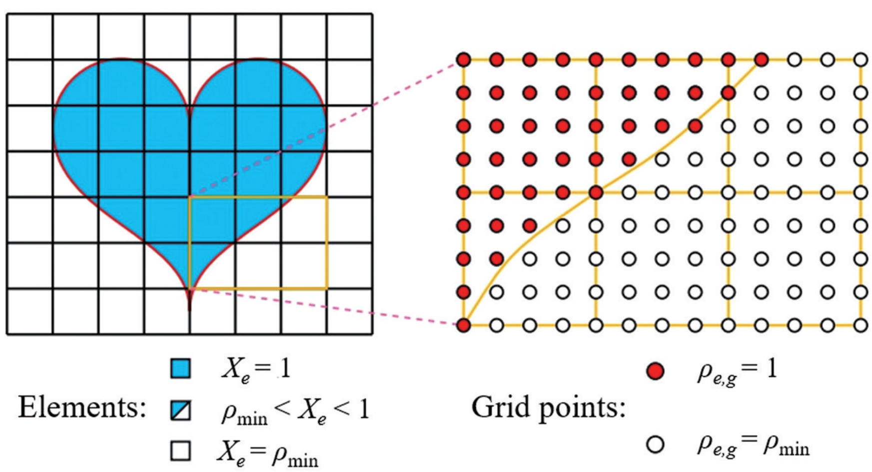


图8　平滑的拓扑结构以及元素内网格点的密度[40](将元素点划分成N个网格点。当$\rho_{e,g}=1$时网格点为固体点，当$\rho_{e,g}=\rho_{min}$时网格点为空隙点)

Fig. 8　Smooth topology structure and density of grid points within elements[40] (Divide the element points into N grid points. When $\rho_{e,g}=1$, grid points are solid points; when $\rho_{e,g}=\rho_{min}$, the grid point is a void point)

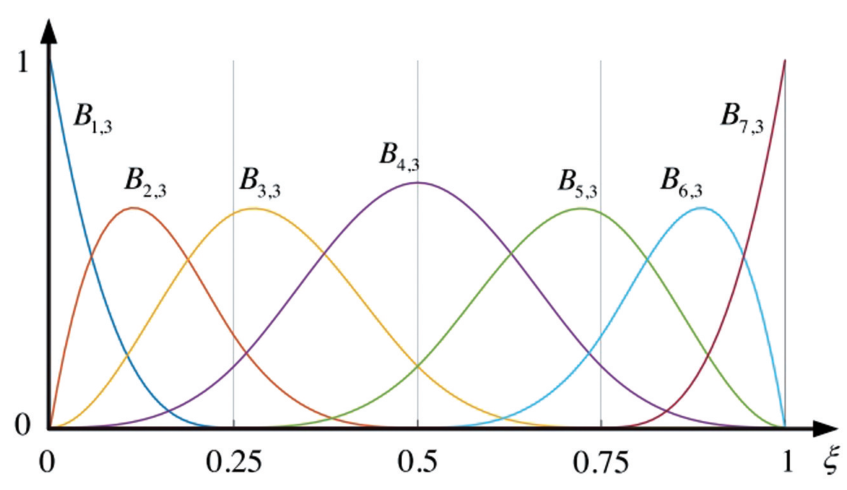


图9　具有均匀开节点向量的三次单变量B-样条基函数[42]

Fig. 9　Cubic univariate B-spline basis functions with uniform and open knot vectors[42]

针对设计与制造之间的约束不一致导致的增材制造很难获得与设计性能相匹配的可制造结构的问题[43]，2022 年，Wu 等[44]提出了一种包含悬垂角度、悬垂长度以及打印方向三个自支撑因素的密度拓扑优化方法。该方法将悬垂角和悬垂长度分别内化为当前层网格与其支撑网格的相邻单元之间的密度映射关系以及支撑网格相邻单元之间的密度映射关系，严格禁止无法打印的设计进入设计空间，实现了设计与制造之间约束一致的自支撑设计。

除了上述传统的三轴自支撑结构设计外，2023 年，Ye 等[45]提出一种基于 SIMP 优化框架，同时利用旋转底座改变打印构件和重力方向之间的角度来降低结构性能损失的自支撑设计方法。相较于无约束的最佳悬臂梁（如图 10 所示），考虑悬垂约束后的悬臂梁的最终柔度为 332.26 N·mm（如图 11 所示），增幅仅为 1.9%，几乎可以忽略。

图 10　无约束条件下悬臂梁的最佳结构构型[45]

Fig. 10　Optimal structural configuration of the cantilever beam without constraints[45]

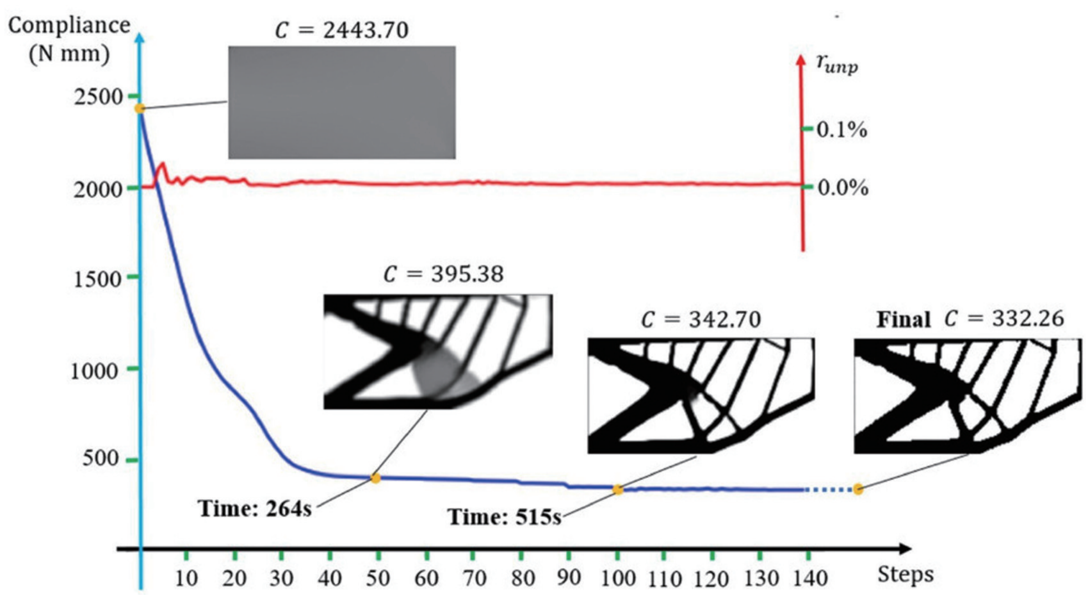


图 11　悬臂梁再优化步骤的收敛历史和计算时间图[45]

Fig. 11　Graph of convergence history and calculation time of the cantilever beam re-optimization step[45]

目前，基于 SIMP 法的结构自支撑设计已成为一个热门的发展方向。由表 2 可见，该方向已部分实现了自支撑的打印效果，但基于该法的研究还存在一定问题，比如额外计算成本高、结构性能损失严重等。在未来的工作中可以通过采用并行计算的方式、综合考虑打印方向以及纳入其他约束来解决相应的问题。此外，目前的研究成果多局限于 2D 案例上的测试，3D 案例扩展研究成果较少，未来的研究工作还需向 3D 案例拓展。

3.1.2　基于水平集法的结构自支撑设计研究进展

水平集方法是由 Sethian[46]提出的一种具有清晰结构边界并且无数值不稳定现象的曲线（或曲面）演化方法，其定义如式（6）所示。与密度法相比，水平集方法能够更自然地处理结构边界的演化和几何信息。因此，有学者利用水平集法进行结构自支撑设计。

$$\Phi(x)=\begin{cases} d(x),\ \text{if}\ x\in \Omega\backslash\partial\Omega \\ 0,\ \text{if}\ x\in\partial\Omega\cap D \\ -d(x),\ \text{if}\ x\in D\backslash\Omega \end{cases},\tag{6}$$

式中：$d(x)$表示点x到材料边界的欧氏距离；Ω表示材料域；D表示设计域。

2017 年，Liu 等[47]提出了一种基于多层水平集框架的自支撑设计方法，该方法通过在多层水平集函数（如图 12 所示）中加入悬垂约束阈值，同时利用基于结构骨架的沉积路径规划方法（如图 12(a)、(b)所示）辅助结构拓扑优化，实现了结构自支撑并解决了材料各向异性问题。但该方法在结构性能评估的准确性、三维设计的数值稳定性以及计算效率上均有待进一步提升。2018 年，Wang 等[48]提出了一种基于水平集函数梯度积分域的结构自支撑设计方法，该方法使用单域积分（如式(7)所示）代替传统的点约束，利用有符号距离的性质简化悬垂约束的形状导数，避免了由惩罚参

表 2 基于SIMP法的自支撑设计的优缺点

Table 2 Advantages and disadvantages of self-supporting design based on SIMP

Ref.	Author	Printing platform	Advantages	Limitations
[30-31]	Matthijs Langelaar	Selective laser melting (SLM)	(1) Overcomes non-printability and related inefficiencies (2) Process simulations can be performed to strictly consider overhang constraints and ensure self-support at each layer (3) Extended to 3D design	(1) Rectangular grid only (2) Limited to specified critical overhang angle
[34]	Martin Leary, *et al.*	Fused deposition modeling (FDM)	(1) Collapse of large overhanging areas is avoided	(1) Not fully self-supporting printing
[37]	Alain Garaigordobil, *et al.*		(1) Precise detection of contours (2) Any critical overhang angle can be specified (3) The proposed constraints are easy to add to a topology optimization program and easy to incorporate with any generic optimizer	(1) Not extended to 3D design
[38]	Yu Hsin Kuo, *et al.*	FDM	(1) The self-supporting index is continuous and can be directly differentiated for sensitivity analysis (2) Easily adapted to different overhang angles or self-supporting design domains	(1) Imposed length constraints are not considered
[40-41]	Yun-Fei Fu, *et al.*	FDM/SLM	(1) The jagged and fuzzy boundary problems caused by the traditional SIMP method can be solved (2) Lower compliance can be obtained	(1) AM-oriented topology optimization requires more material to form a complete self-supporting structure when the structure volume fraction is relatively small
[42]	Wang Che, *et al.*		(1) The number of design variables is substantially reduced, allowing easy and accurate calculation of density gradients (2) Overhang constraints are independent of the finite element mesh and are suitable for design domains with irregular boundary shapes	(1) Not extended to 3D design (2) The optimization results are highly dependent on the print direction and critical overhang angle
[44]	Wu Zijun, *et al.*		(1) Combined overhang angle, overhang length, and print orientation (2) Integration of structural design and manufacturing	(1) Computational efficiency needs to be improved (2) Stress constraints are not considered
[45]	Ye Jun, *et al.*		(1) Low loss of structural performance	(1) Not extended to 3D design

数值过大导致的弱收敛问题，获得了具有相对平滑、自然的自支撑结构。相较于逐点形式的悬垂约束，该所提约束检测非自支撑部位（如向下的尖点，如图 13 所示）的能力更强。2020 年，Liu 等[49]提出了一种基于骨架提取的结构分解方法，如图 14 所示。该方法根据连接性条件将结构划分为组件，通过水平集法对组件进行优化，同时综合考虑组件的悬垂长度与悬垂角度（违反阈值条件的组件激活自支撑约束，如图 15 所示），实现结构自支撑设计。与 Liu 等[47]所提基于多层水平集框架的自支撑设计方法相比，该方法不仅具有更大的设计空间，还可以实现临界悬垂角度为零的自支撑打印，并且适用于不同的增材制造工艺。

$$\int_D \left\{R\left[\nabla\Phi(x)\cdot d\right]-\cos\alpha_0\right\}^2\left[1-H(\Phi)\right]\mathrm{d}\Omega\leqslant 0,\quad(7)$$

式中：$H(\cdot)$表示 Heaviside 函数；$R(s)=(s+|s|)/2=\int_{-\infty}^{s}H(\zeta)\mathrm{d}\zeta$表示斜坡函数；$\alpha_0$表示临界悬垂角度；$d$表示打印方向。

表 3 给出了部分研究人员在基于水平集法的结构自支撑设计上取得的成果以及所提方法的优点。虽然水平集法已经应用在增材制造自支撑领域并且具有边界清晰的优势，但该类方法高度依赖于初始参数值，并且存在不能自主开孔与弱收敛等问题，Allaire 等[50]也指出过相应的问题。针对仅能实现孔洞融合而不能自主开孔的问题，可以采用拓扑导数、反应扩散方程进行解决。此外，可以采用共轭法计算二维与三维线弹性模型的形状导数，或者采用最速下降法更新设计变量，或者结合基于全局与局部元胞分割框架的遗传算法，来改善优化结果的初始依赖性。

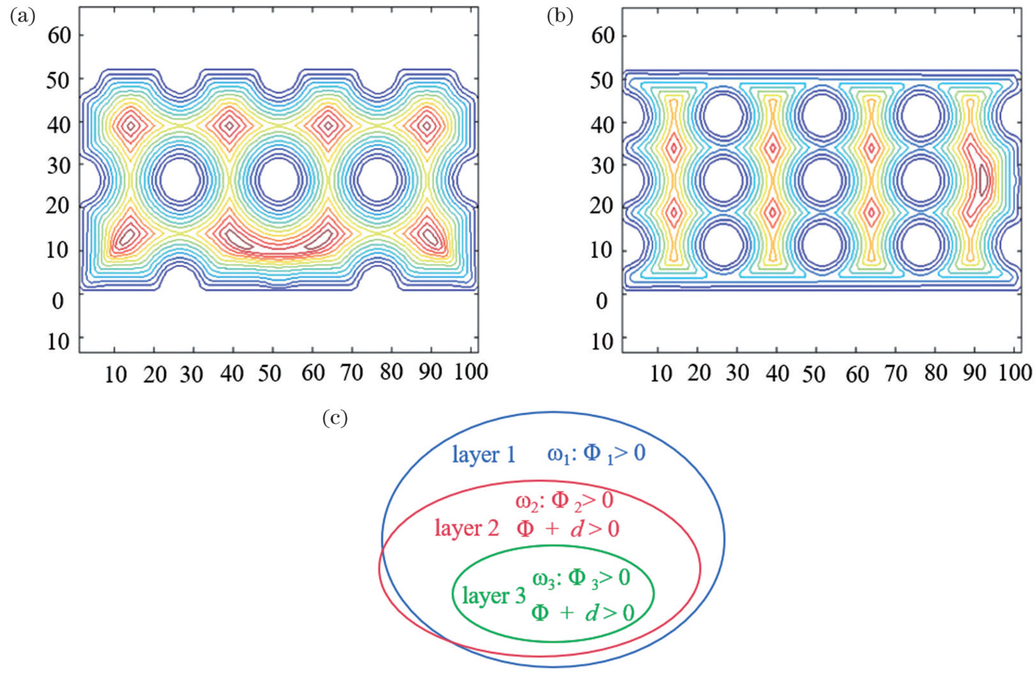


图 12　水平集下的结构骨架沉积路径以及基于多层水平集的悬垂约束建模[47]。(a)~(b)基于水平集的沉积路径的两个示例；(c)基于多层水平集的悬垂约束建模，其中 d 表示最大悬垂长度约束，临界悬垂角度设为 45°

Fig. 12　Structural skeleton deposition path under level set and overhang constraint modeling based on multi-layer level set[47]. (a)–(b) Two examples of a horizontal set-based deposition path; (c) modeling of overhang constraint base on multi-layer level set, where d represents the maximum overhang length constraint and the critical overhang angle is set to 45°

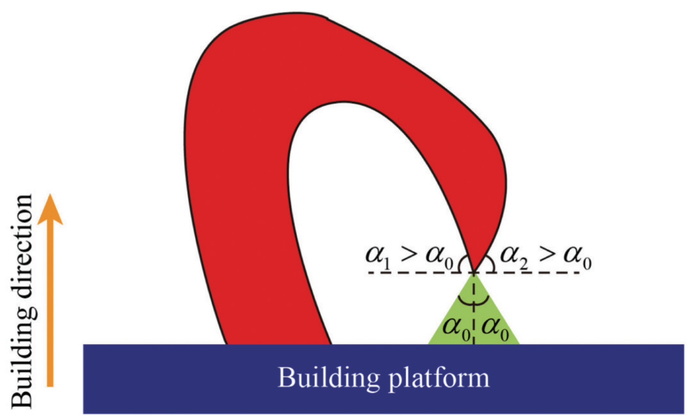


图 13　向下的尖点[48]

Fig. 13　Downward cusp[48]

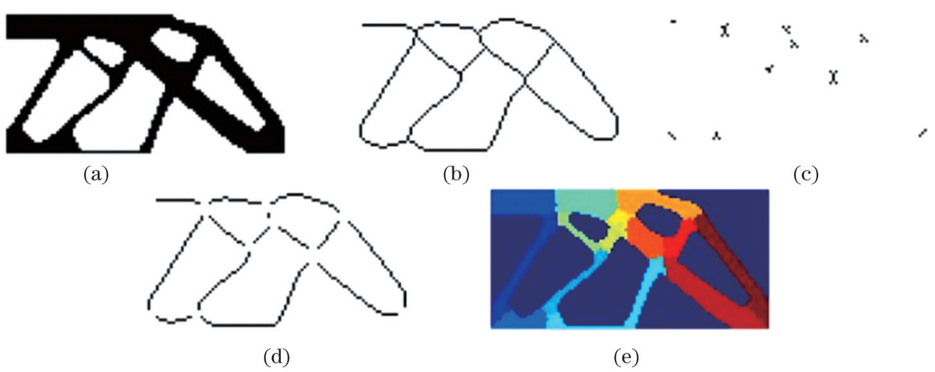


图 14　骨架分割[49]。(a)结构拓扑；(b)识别骨架；(c)识别交集和终点；(d)分割结构骨架；(e)分割结构区域

Fig. 14　Skeleton segmentation[49]. (a) Structural topology; (b) identified skeleton; (c) identified intersection and end points; (d) segmented structural skeletons; (e) segmented structural areas

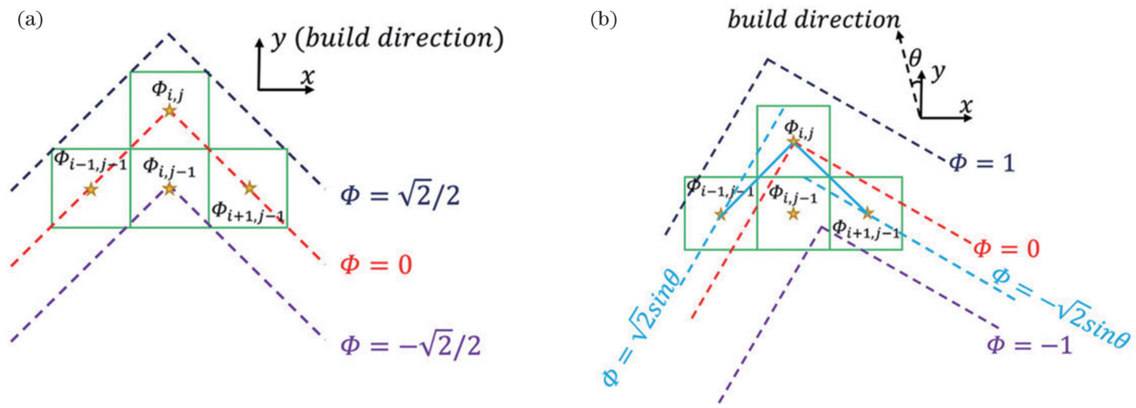


图 15　阈值自支撑条件[49]。(a)打印方向与 y 轴对齐时的阈值自支撑条件；(b)打印方向偏离 y 轴时的阈值自支撑条件

Fig. 15　Threshold self-supporting conditions[49]. (a) Threshold self-supporting condition when the building direction aligns with the y-axis; (b) threshold self-supporting condition when the building direction deviates from the y-axis

表 3　部分研究人员在基于水平集法的结构自支撑设计上取得的成果以及所提方法的优势

Table 3　Achievements of some researchers on structural self-supporting design based on level set and the advantages of the proposed methods

Ref.	Author	Printing platform	Achievement or advantages
[47]	Liu Jikai, *et al.*	FDM	(1) Proposing a structural skeleton based on deposition path planning to solve the material anisotropy problem (2) Proposing a multi-story horizontal set frame incorporating overhang length to solve the structural self-support problem
[48]	Wang Yaguang, *et al.*		(1) The overhang constraint is expressed as a domain integral of the gradient of the level set function, which helps to detect violations of the overhang angle (2) Can handle any initial design and overhang angle (3) Optimized design meets overhang constraints without much loss of stiffness
[49]	Liu Jikai, *et al.*	FDM	(1) Proposing new threshold conditions that synthesize overhang dimensions and inclination angles (2) The proposed method is applicable to a wide range of additive manufacturing equipment

3.1.3　基于双向渐进结构优化的结构自支撑设计研究进展

双向渐进结构优化法(BESO 法)作为一种理论简洁且优化效率高的结构拓扑优化方法，在结构拓扑优化中的地位不容忽视。此外，该方法还具备易与有限元分析程序连接、能够清晰地表示实体和孔洞边界以及可以很容易地识别和控制悬垂角等优点，因而有学者基于此方法进行自支撑设计。

2019 年，Han 等[51]基于混合增材减材制造技术，采用 BESO 法进行拓扑优化，综合考虑增材制造的自支撑约束和减材制造的铣削约束，实现了尺寸精度更高的自支撑结构设计。2020 年，Bi 等[52]提出了一种基于 BESO 法的三维结构自支撑设计方法。该方法通过在灵敏度分析框架中引入几何悬垂约束，在每次迭代中识别和控制悬垂角度(如图 16 所示)，同时通过引入卷积矩阵和矩阵最小函数来减少计算时间，实现了可打

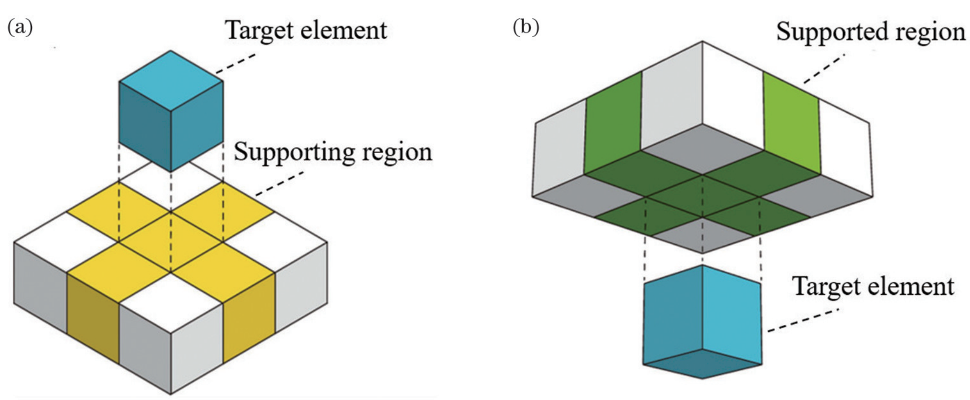


图 16　悬垂识别[52]。(a)支撑区域中的 5 个黄色元素可以支撑目标元素；(b)目标元素可以支撑被支撑区域中的 5 个绿色元素

Fig. 16　Overhang recognition[52]. (a) Five yellow elements in the supporting region can support the target element; (b) the target element can support five green elements in the supported region

印的自支撑设计。该方法的优点如下：1）允许对任意悬垂角度进行建模；2）悬垂问题背后的概念易于理解和实现；3）悬垂问题的表述在优化过程中不需要多目标搜索；4）不需要对几何形状进行后处理调整；5）使用卷积矩阵和矩阵最小函数，额外的计算成本低。与文献[31]中的悬臂梁优化结果相比，两者在顶部位置的结构区别很大，但两者的性能是相似的，如图 17 所示。

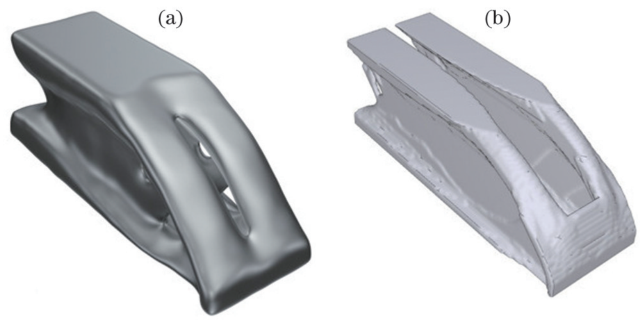


图 17　自支撑悬臂梁优化结果。(a)Bi 等所提自支撑悬臂梁[52]；(b)Langelaar 所提自支撑悬臂梁[31]

Fig. 17　Optimization results of the self-supporting cantilever beams. (a) Self-supporting cantilever beam proposed by Bi *et al.* [52]; (b) self-supporting cantilever beam proposed by Langelaar[31]

目前，基于 BESO 法已经实现了增材制造的自支撑打印，但其只考虑了规定的打印方向，综合考虑优化的打印方向或许会带来更优异的性能。

3.1.4　基于特征驱动优化的结构自支撑设计研究进展

不同于以上逐层设计的拓扑优化方法，特征驱动优化方法通过一组构造的实体与孔洞的几何特征运动和变形来驱动结构的拓扑优化。该方法具有较高的计算效率，并且有效融合了结构特征与拓扑优化的优点，因而有学者基于此方法进行自支撑设计。

2017 年，Guo 等[53]提出了基于移动可变形组件（MMC）和移动可变形空隙（MMV）的自支撑设计方法，该方法引入了大量的非线性约束对悬垂角度进行约束，可以以更明确的几何处理方式达到结构自支撑的目的，如图 18 所示。与文献[30]中的方法相比，该方法的显著特点是可以从根本上解决边界扩散以及存在灰度单元等问题。2018 年，Zhang 等[54]基于固定网格和高阶 B 样条曲线，引入多边形特征孔作为基本设计单元（如图 19 所示），以其运动、变形和交点控制拓扑结构，同时在几何描述中直接引入悬垂约束，使沿悬垂边界的倾斜角度大于或等于临界悬垂角，并对多边形进行修改和重新优化，消除了由多边形相交引起的不可打印的 V 形区域，实现了自支撑设计。但是，该方法所实现的结构自支撑是以降低结构性能为代价的，并且临界悬垂角的大小和打印方向的选择对优化结果的影响很大。2021 年，Zhou 等[55]对该方法[54]进行了优化，采用实心多边形和多面体特征作为二维和三维结构自支撑拓扑优化的基本设计单元，通过约束实体特征的位置，以几何的方式消除了 V 形区域，避免了重新

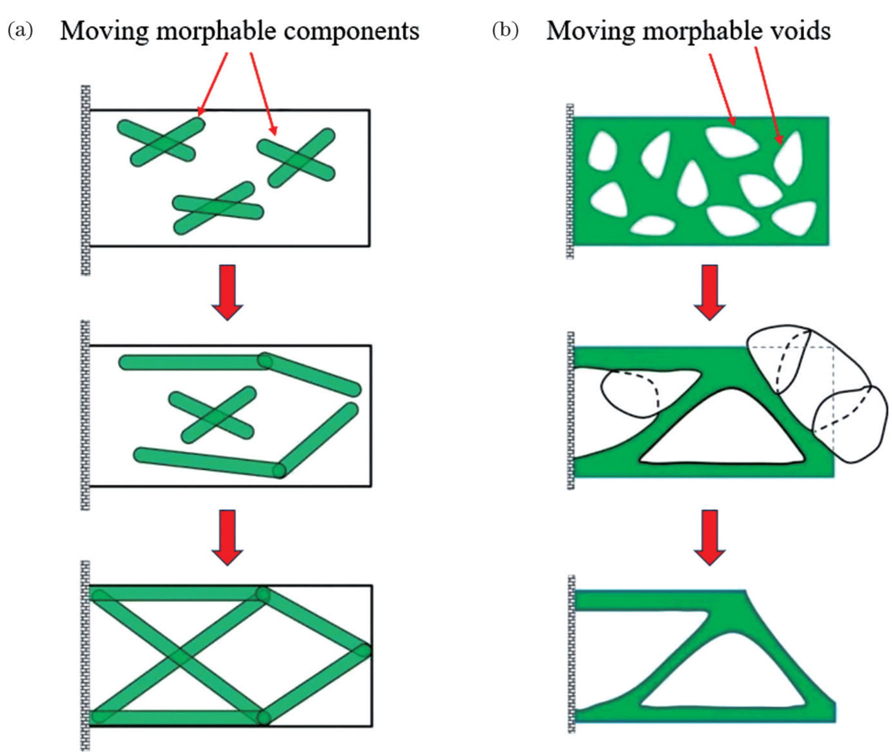


图 18　基于 MMC 和 MMV 的拓扑优化方法的基本思想[53]。(a)基于 MMC 的拓扑优化演化过程；(b)基于 MMV 的拓扑优化演化过程

Fig. 18　Basic idea of the MMC-based and MMV-based topology optimization approaches[53]. (a) Topology optimization evolution process based on MMC; (b) topology optimization evolution process based on MMV

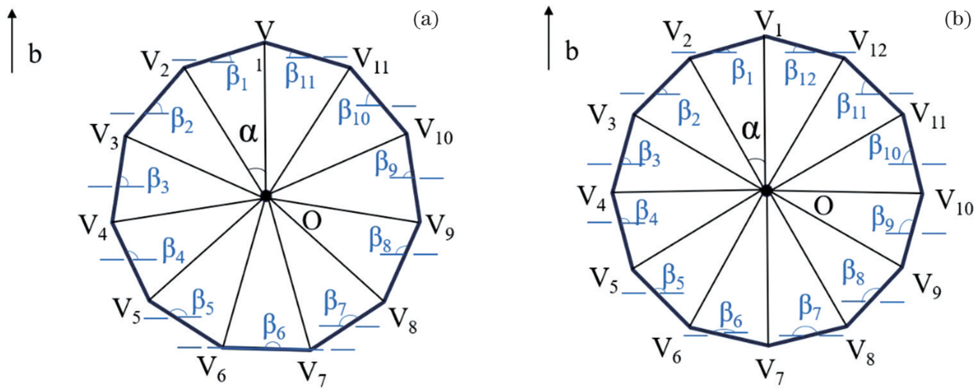


图 19　奇偶多边形的定义[54]。(a) 11边多边形;(b) 12边多边形

Fig. 19　Definition of polygons with odd and even sides[54]. (a) An 11-side polygon; (b) a 12-side polygon

优化的步骤并且优化结果具有更好的刚度。其设计方法如图 20所示。

表 4是特征驱动优化方法的优缺点。特征驱动优化方法可以实现结构自支撑设计,并且可以很容易地进行三维案例的扩展。但是,目前基于该方法的研究还有许多局限性,如结构性能的损失较大等。在未来的工作中,需要综合考虑不同打印方向以及不同临界悬垂角度等因素,以获得更优的结构自支撑设计。

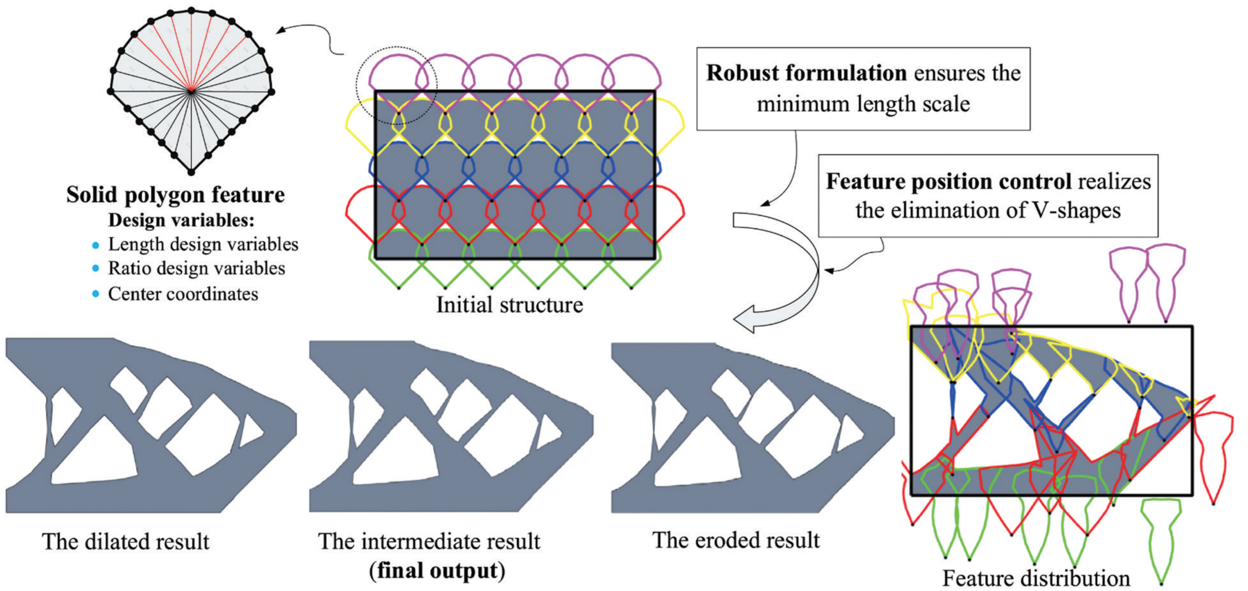


图 20　基于实心多边形特征提出的悬臂梁自支撑设计方法的说明[55]

Fig. 20　Illustration of proposed approach for self-supporting design of cantilever beam proposed based on solid polygon features[55]

表 4　特征驱动优化方法的优缺点

Table 4　Advantages and disadvantages of feature-driven optimization methods

Ref.	Author	Advantages	Disadvantages
[53]	Guo Xu, *et al.*	(1) Some of the inherent difficulties associated with stress-constrained topology optimization (*e. g.*, locally stress-constrained singularities, accuracy of stress calculations) can be directly eliminated (2) A direct link can be established between the optimization results and the CAE system (3) Improve accuracy of stress calculations along structural boundaries (4) Greatly reduces the computational effort of finite element analysis	(1) A smooth transition of the boundary contour around the intersecting portion of the component is not achieved to mitigate stress concentrations
[54]	Zhang Weihong, *et al.*	(1) Eliminate V- area not printable problem (2) Easily scalable to 3D cases	(1) Reduces the performance of the structure
[55]	Zhou Lu, *et al.*	(1) Precise overhang angle control is available (2) Small overhang angles can be printed (3) Fine topology with more features can be designed	(1) Reduced structural stiffness

3.2 基于离散结构拓扑优化的结构自支撑设计研究进展

基于连续体结构拓扑优化方法的自支撑结构设计存在结构边界获取困难的问题，为此，相关学者提出了密度信息法、轮廓检测法和拟合密度分布法等方法来解决此问题。但是，这些方法需要先求解单元密度才能确定结构边界，因此优化效率低下。此外，针对该问题，有学者采用卷积算子以及连续逻辑聚合函数等方法对非自支撑单元数量进行控制，但这样会显著增加优化问题的求解规模。相比之下，基于离散结构拓扑优化的结构自支撑设计方法在结构边界获取问题上具有更高的效率。此外，引入打印方向约束也不会大幅增加计算成本。

2017 年，Mass 等[56]提出了一种基于离散结构和连续体结构的混合拓扑优化模型。在离散模型的优化过程中，通过引入基于几何参数的悬垂约束，将优化的离散图案投影到连续体上，使其影响连续体优化中的材料分布，从而实现结构自支撑设计。该模型对悬臂梁的优化结果如图 21 所示。与基于连续体结构拓扑优化的自支撑设计相比，该项设计的计算成本低，并且可以提供更好的结构布局。2019 年，He 等[57]提出了一种在布局优化和几何优化过程中考虑悬垂约束的方法，该方法在实现自支撑设计的同时进一步提升了计算效率。与 SIMP 法相比，该方法耗时明显更短并且结构柔度更好，如图 22 所示。2023 年，林晓阳等[22]也提出了一种基于布局优化和几何优化的自支撑优化框架，通过布局优化移除不满足悬垂约束的构件，同时通过几何优化将所有构件的悬垂角度约束在可打印范围内，实现了结构的自支撑设计，打印结果如图 23 所示。

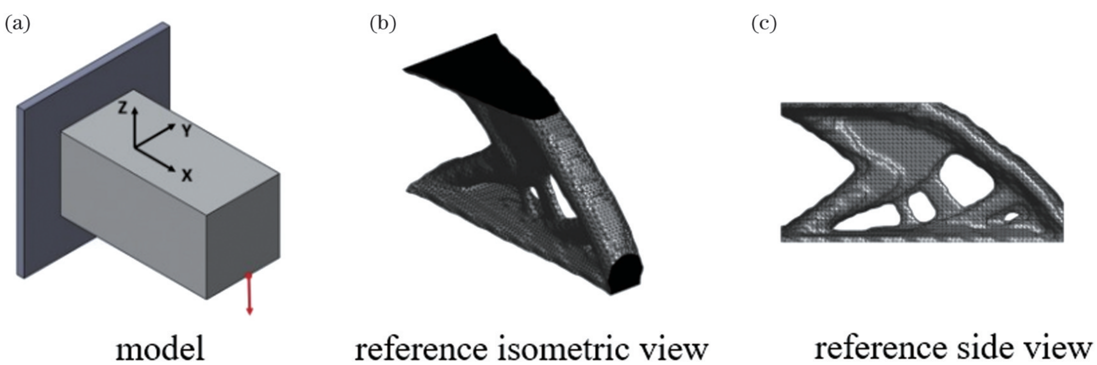
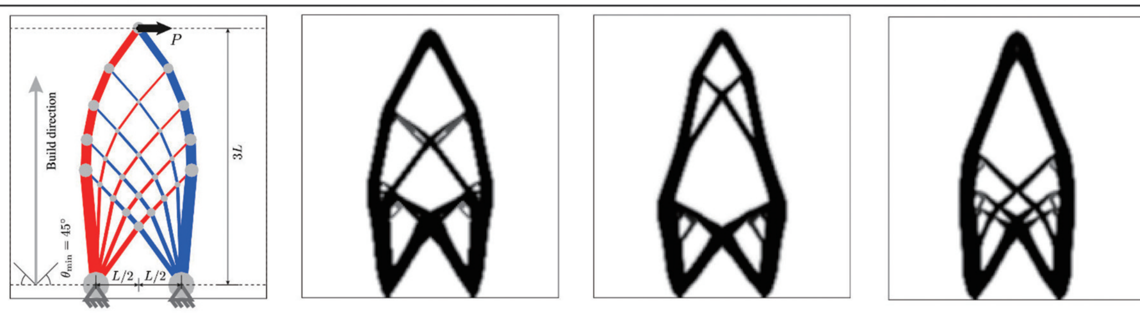


图 21　具有虚拟骨架的 3D 悬臂梁[56]

Fig. 21　Three-dimensional cantilever beam with virtual skeleton[56]



	Layout optimization	SIMP (OC)	SIMP (MMA)	SIMP (MMA: tightened bounds)
Case	I	II	III	IV
Compliance	Diff = 0%	Diff = 0.655%	Diff = 7.14%	Diff = 3.56%
Nodal grid	16 × 16	151 × 166	151 × 166	151 × 166
No. variables	40534 (all potential)	50132	50132	50132
Max iterations	6 (LO) + 14 (GO)	200	198	181
CPU cost	1.2s (LO) + 2.4s (GO)	32.9s (FEM) + 187.3s (OC)	26.5s (FEM) + 38.7s (MMA)	24.8s (FEM) + 29.4s (MMA)

LO - layout optimization; GO - geometry optimization; FEM - finite elemet solver; OC - optimality criteria method; MMA - the method of moving asymptotes

图 22　大麻悬臂：通过布局优化和连续拓扑优化获得的解决方案的比较[57]

Fig. 22　Hemp cantilever: comparison of solutions obtained through layout optimization and continuous topology optimization[57]

由上述可见，虽然基于离散结构拓扑优化的结构自支撑设计的研究还比较少，但目前已经实现了三维案例的打印。相较于连续体结构拓扑优化的结构自支撑设计方法，其优点是显而易见的，如计算成本低、性能下降有限。在未来的研究工作中，还可以进一步降低结构性能的损失。

3.3 基于形状优化的结构自支撑设计研究进展

形状优化是结构优化方法之一，它通过单元节点

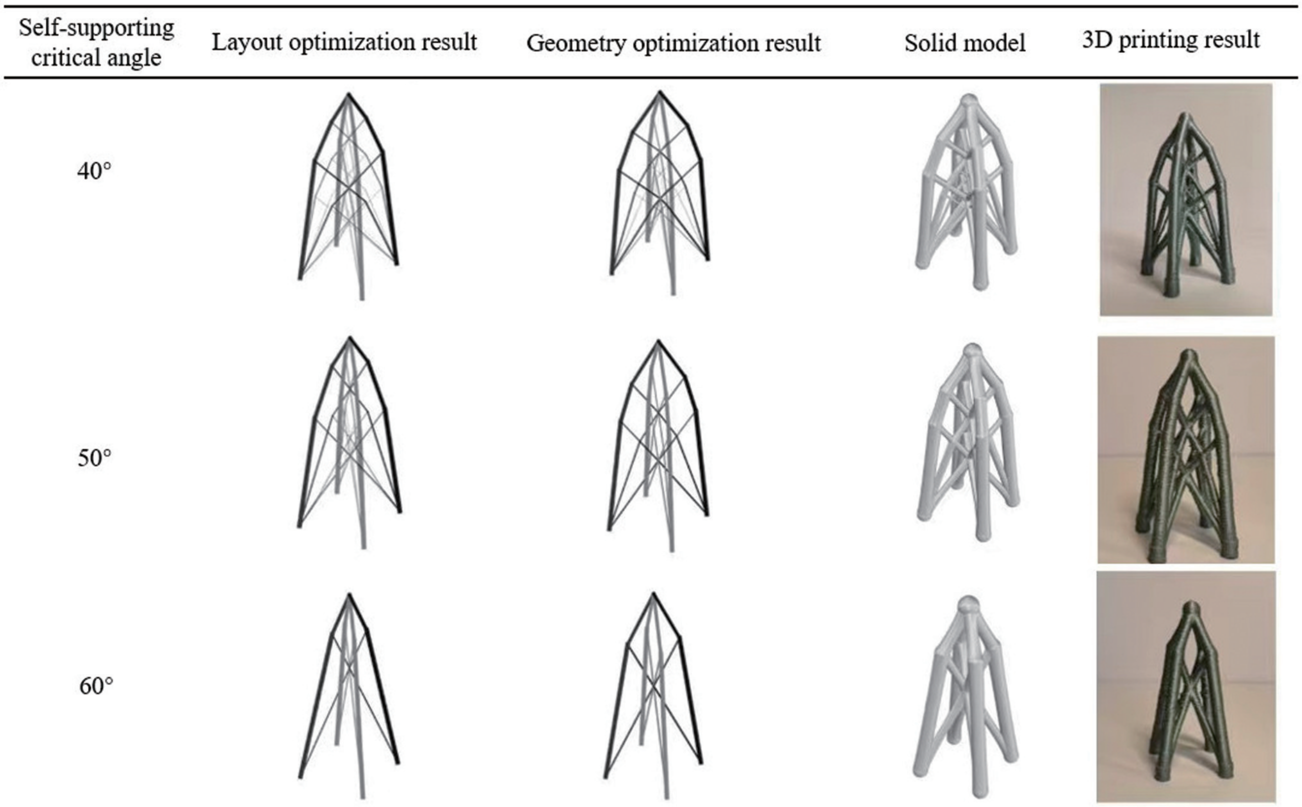


图 23　双向中心受力竖直桁架在考虑不同自支撑临界角下的结构布局、几何优化及 3D 打印测试结果[22]

Fig. 23　Test results of the structural layout, geometric optimization and 3D printing of the bidirectional center-stressed vertical truss considering different self-supporting critical angles[22]

移动到另一个新位置或者通过单元变形来实现结构形状的改变，从而实现相应的性能。然而，在许多情况下，设计人员需要手动更改设计的形状，然后通过应用支撑生成工具来验证结构自支撑性。这样的操作非常繁琐。2015 年，Hu 等[58]提出了一种基于形状优化的结构自支撑设计方法，该方法通过在优化流程中提供一个支撑结构瘦身的优化器来帮助设计人员生成更好的自支撑结构模型，该模型可作为最终的设计参考。这项研究工作使得支撑结构的材料使用量与初始设计相比减少了 70% 以上（其中蓝色表示支撑材料），如图 24 所示。尽管优化后的模型还需要使用支撑结构，但不可否认的是，剩余的支撑结构可以起到将工艺热量散发到打印平台从而避免零件局部变形的作用。

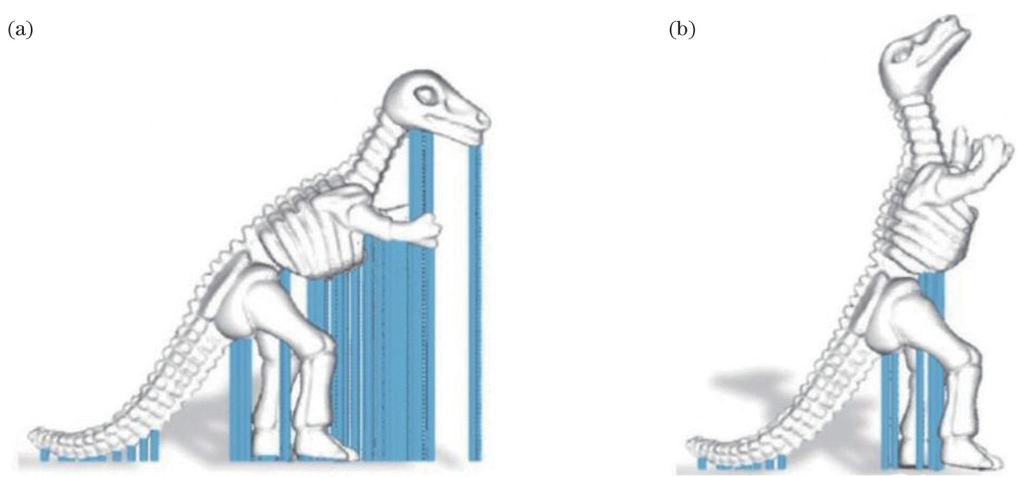


图 24　一种方向驱动的形状优化程序，可以显著减少支撑材料的使用[58]。(a)初始设计；(b)调整后的新方案，支撑结构以蓝色表示

Fig. 24　A direction-driven shape optimization program that significantly reduces the use of support materials[58]. (a) Initial design; (b) adjusted new scheme, with the support structure indicated in blue

4　增材制造填充结构自支撑设计的研究进展

在增材制造过程中，填充结构起着承受外力负载、支撑给定外壳悬空区域的重要作用[59]。由于填充结构与外部支撑结构不同（填充结构作为本体结构的一部分），填充结构的自支撑性往往会影响模型的打印成功率。当填充结构难以打印时，易导致模型表面坍塌[60]。针对此问题，2016 年，Wu 等[61]提出了一种基于菱形单元自动生成满足最大悬垂角度和壁厚可制造性的填充结构，如图 25 所示。2017 年，Wang 等[62]提出了一种自支撑空心填充结构（如图 26 所示），通过稀疏性优化消除了冗余内支柱和不满足自支撑约束的支柱，同时通过悬垂角度优化步骤优化了内支柱之间的角度，获得了最佳的内部自支撑框架。2018 年，Martínez 等[63]提出了一种严格执行悬垂角度约束的多面 Voronoi 结构，实现了填充结构自支撑，如图 27（a）所示。但该结构存在以下缺点：1）挤出路径不是连续的；2）结构缩回量会降低可靠性并增加打印时间；3）在高密度下，可能会产生重叠的挤出路径，导致过度挤出，从而导致打印缺陷。相较于 Martínez 等提出的 Voronoi 结构[63]，Kuipers 等[64]于 2019 年提出的 CrossFill 泡沫状空间填充结构（如图 27（b）所示）则没有出现这样的问题。2022 年，Xu 等[65]提出了一种基于层构建的变截面自支撑填充结构，其支撑单元如图 28 所示。该结构的层从下到上在三角形和六边形之间连续和周期性地转换，因而整体结构更具稳定性和轻量性。相较于前面所述的填充结构，该项研究中打印的物体在结构刚度方面

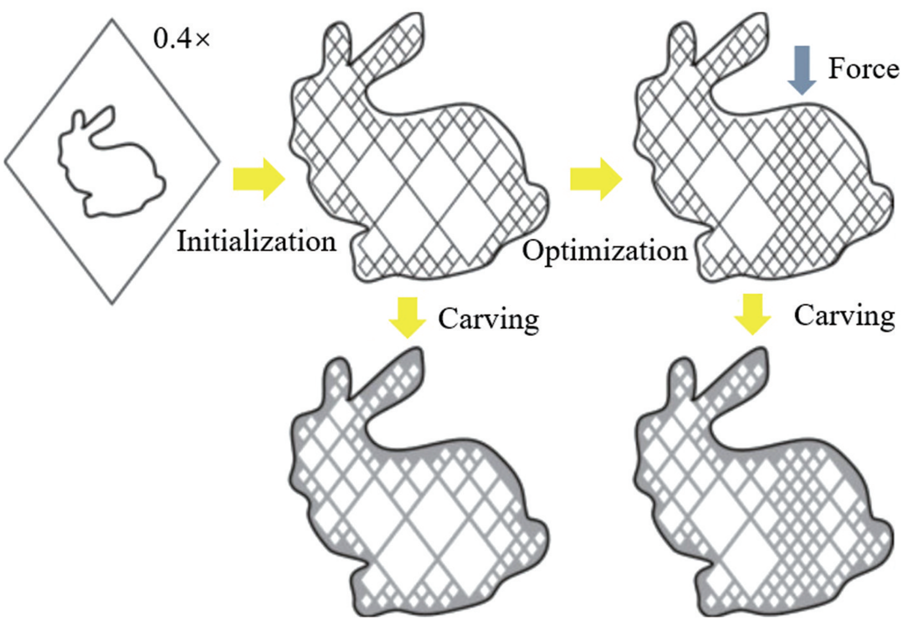


图 25　使用菱形结构的填充优化过程：通过对菱形树的每个叶节进行所谓的雕刻操作，菱形单元被转换为具有给定壁厚的菱形外壳[61]

Fig. 25　Filling optimization process using a rhombic structure: by performing a so-called carving operation on each leaf node of the rhombic tree, the rhombic element is converted into a rhombic shell with a given wall thickness[61]

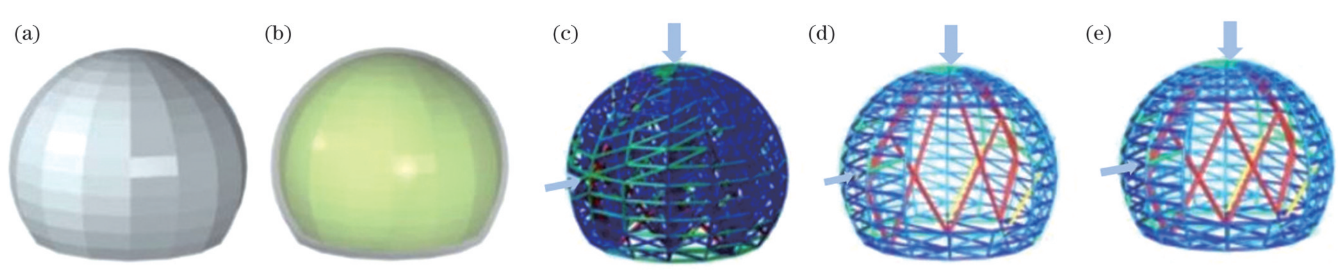


图 26　自支撑空心填充结构算法的流程图[62]。（a）输入三角形网格，自支撑填充结构在其偏置版本中生成；（b）随机生成大量的内支柱和节点，并初始化所有支柱的半径；（c）取消所有冗余支柱和非自支撑支柱；（d）进一步优化内支柱和节点，以减少材料的使用；（e）该模型由三个力生成，其中一个在顶部，另外两个在两侧

Fig. 26　Flow diagram of the self-supporting hollow filling structure algorithm[62]. (a) A triangular mesh is first entered, and the self-supporting infill structure is generated in its offset version; (b) randomly generate a large number of inner pillars and nodes, and initialize the radius of all pillars; (c) elimination of all redundant struts and non-self-supporting struts; (d) further optimization of inner pillars and joints to reduce material usage; (e) the model is generated by three forces: one at the top and the other two on the sides

更具优势。此外，Wu 等[66]提出的与骨骼相似的多孔结构以及 Lee 等[67]提出的椭圆形空心结构均实现了自支撑，打印效果如图 29 所示，但上述结构存在不具备连通性的问题。

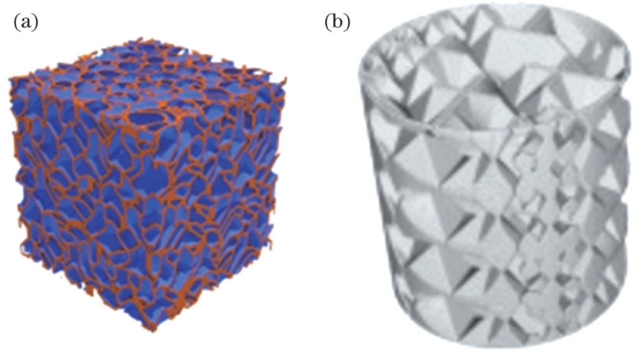


图 27 微观填充结构。(a)多面 Voronoi 结构[63]；(b)类似于泡沫的 CrossFill 填充结构[64]

Fig. 27 Microscopic infill structures. (a) Multi-faceted Voronoi structure[63]; (b) CrossFill-filled structure similar to foam[64]

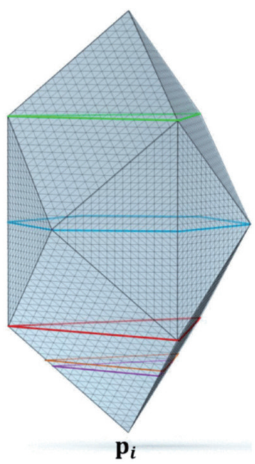


图 28 基于层构建填充结构的晶胞由横截面重建得到，其中：p_i 表示起点，蓝色多边形是六边形横截面，红色和绿色多边形是两个等边三角形横截面，橙色和紫色多边形是两个相邻的横截面[65]

Fig. 28 Unit cells of the layer-based infill structure are reconstructed by cross-sections, where p_i represents the starting point, the blue polygon is the hexagonal cross-section, the red and green polygons are two equilateral triangular cross-sections, and the orange and purple polygons are two adjacent cross-sections[65]

针对连通性问题，徐文鹏等[68]于 2023 年提出了一种基于层构建的变截面自支撑填充结构，如图 30 所示。在该结构中，层正三角形通过连续的周期性变化来实现填充结构的自支撑性和连通性。

上述结构多是通过引入自支撑单元来设计的，与这些方法相比，基于拓扑优化的设计方法更具设计自由度。2021 年，Liu 等[69]提出了一种基于密度法的填充结构自支撑设计方法。该方法通过引入一种基于

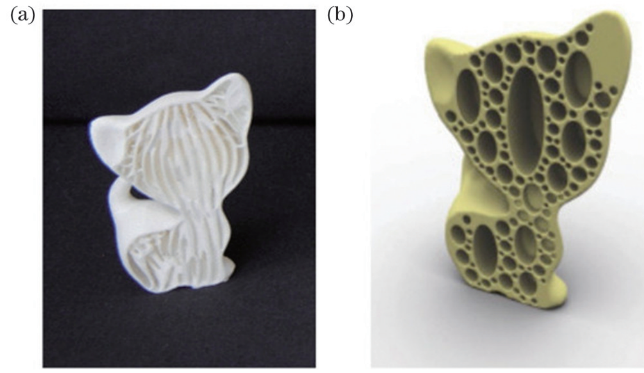


图 29 小猫模型的打印效果。(a)与骨骼相似的多孔结构[66]；(b)椭圆形空心结构[67]

Fig. 29 Printing effect of a kitten model. (a) A porous structure similar to a skeleton[66]; (b) elliptical hollow structure[67]

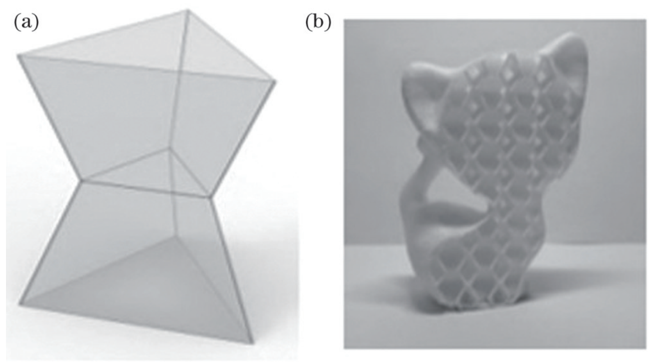


图 30 基于层构建的填充结构单元与打印结果[68]。(a)填充单元；(b)打印结果

Fig. 30 Filling structural elements based on layers and the printed result[68]. (a) Filling elements; (b) print result

AM 滤波器的悬垂约束（如图 31 所示）来确保填充结构在指定的打印方向上自支撑，同时通过引入最小长度约束来避免出现不切实际的单节点连接特征，利用局部体积约束来实现多孔填充模式，最后通过求解优化问题实现具有极少悬垂单元的壳体填充设计。2022 年，Zhou 等[70]采用密度法对壳与填充结构进行并行拓扑优化，引入悬垂约束来保证填充结构的自支撑性，利用自适应参数更新策略来稳定优化过程，引入基于双场公式的参数化方案（如图 32 所示）来控制最小长度尺度，然后通过模型重建算法将拓扑优化结果重新构造为边界表示（B-rep）模型，使锯齿形边界转化为平滑的几何形状，最终实现了具有优异力学性能的壳体-填充结构的填充结构自支撑设计。

由表 5 可见，目前填充结构的自支撑设计可以分为两种方法：一是通过引入自支撑单元进行填充结构自支撑设计，二是利用拓扑优化进行填充结构自支撑设计。前者的形状多依赖于工程经验，设计较为困难，而后者则拥有更大的设计空间，但目前基于拓扑优化的填充结构自支撑设计仍处于起步阶段，大多数研究只进行了 2D 案例的测试。

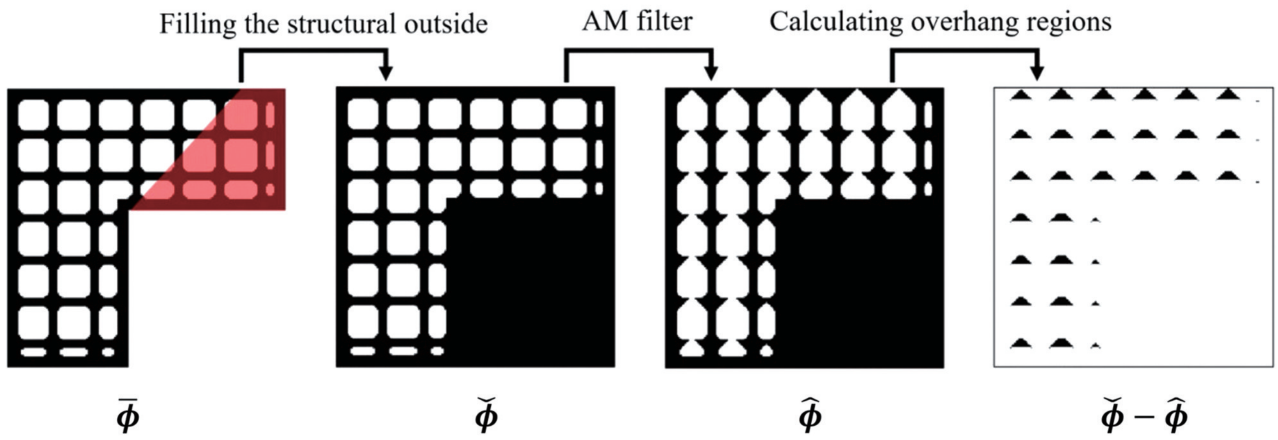


图 31　基于 AM 滤波器的悬垂约束[69]

Fig. 31　Overhang constraints based on AM filter[69]

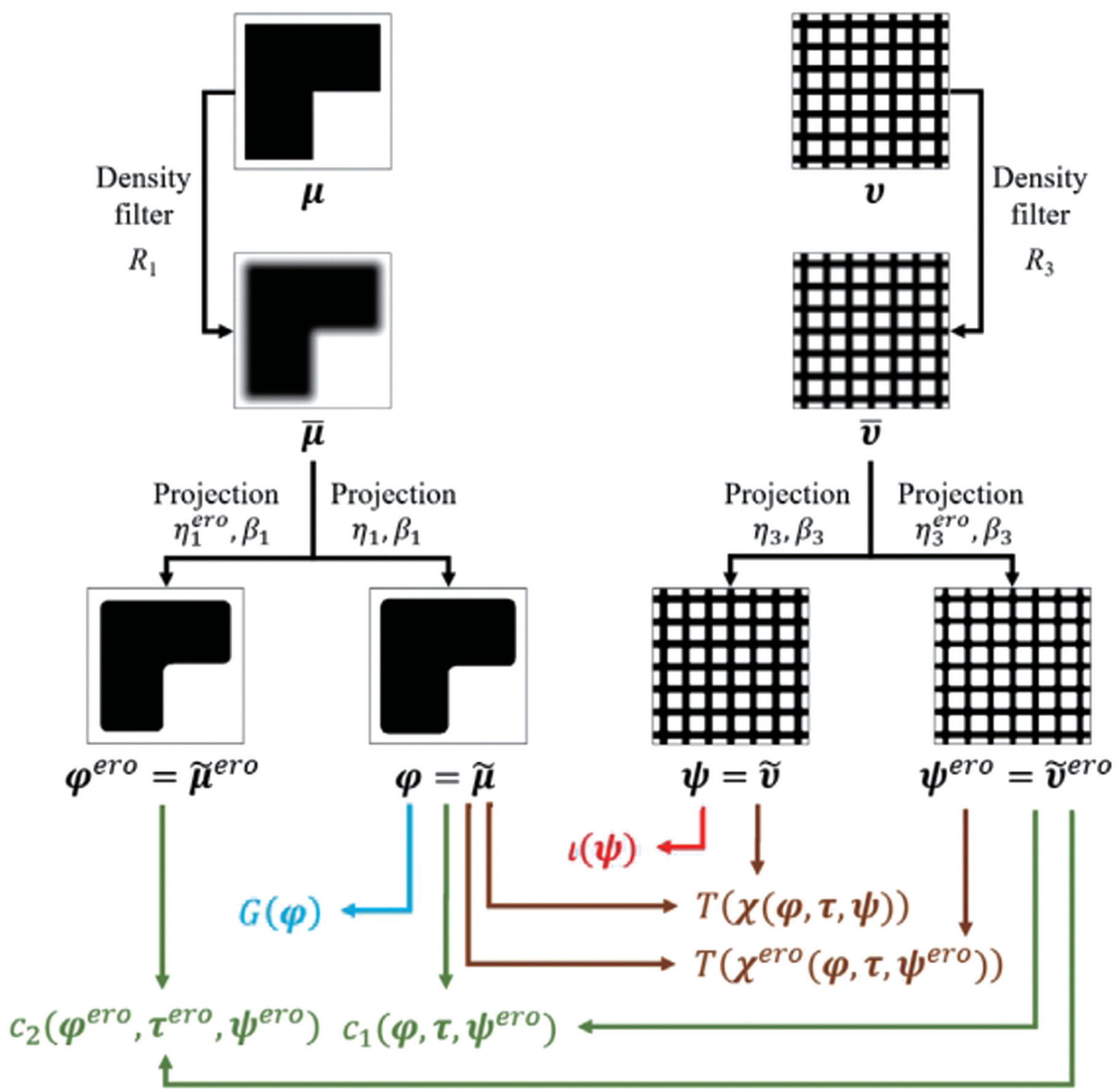


图 32　基于双场公式的改进参数化方案(绿色:目标函数;蓝色:全局体积约束;红色:局部体积约束;棕色:悬垂约束)[70]

Fig. 32　Improved parametrization scheme based on the two fields formulation (green: the objective function; blue: global volume constraint; red: local volume constraint; brown: overhang constraint)[70]

表5　填充结构自支撑设计的内容及优点比较

Table 5　Comparison of the contents and advantages of the self-supporting design of the filling structure

Ref.	Author	Details	Advantages
[61]	Wu Jun, *et al.*	A filling structure based on the generation of self-support on rhombic cells is proposed	(1) Boundaries that ensure optimized maximum overhang angles and minimum wall thicknesses for internal structures (2) Good mechanical stiffness and static stability
[62]	Wang Weiming, *et al.*	A sparsity optimization method is proposed to eliminate redundant and unsupported struts, and overhang angle optimization is proposed to achieve unsupported design	(1) More material saving
[63]	Jonàs Martínez, *et al.*	A microstructure based on Voronoi diagrams is proposed which strictly enforces the three constraint requirements of continuity, self-support and overhang angle	(1) Good elastic properties
[64]	Tim Kuipers, *et al.*	A foamy CrossFill structure with a single, continuous, non-overlapping layer in each layer is proposed to realize self-supporting of the filled structure	(1) The structure is more supple and suitable for the application of objects such as shoes
[65]	Xu Wenpeng, *et al.*	A novel lightweight infill structure based on a layer structure whose layers are continuously and periodically transformed between triangles and hexagons is presented	(1) No additional slicing process is required, reducing time-consumption (2) The proposed structure has comparable structural performance under different loading conditions
[66]	Wu Jun, *et al.*	A method for filling bone-like porous structures based on the voxel topology optimization method is proposed	(1) Good mechanical properties (2) Good resistance to damage
[67]	Mokwon Lee, *et al.*	An elliptic Voronoi filling structure based on greedy algorithm is proposed	(1) Compared to Ref. [61], the problem of stress concentration is avoided
[68]	Xu Wenpeng, *et al.*	A layer-based infill structure is proposed to realize the self-supporting and connectivity of the infill structure by adjusting the parameters to control the continuous periodic changes of the ortho-triangles of different layers	(1) Good spatial connectivity
[69]	Liu Yichang, *et al.*	An infill structure design method that introduces overhang constraints and minimum length scale constraints and is based on the density method is proposed, and self-supporting of infill structures has been realized	(1) More design freedom (2) Exhibits better mechanical properties compared to predefined periodic fill patterns
[70]	Zhou Mingdong, *et al.*	A self-supporting infill structure design method based on the density method is proposed, where overhang constraints are introduced to ensure accurate control of overhangs and dual-field parameters are introduced to control the minimum length scale	(1) Full self-support of the structure in the actual print can be ensured

5　增材制造结构自支撑设计的发展方向以及未来的应用场景

尽管许多研究工作实现了结构的自支撑设计并且对 2D 或 3D 案例进行了测试，但还存在不足。本节主要讨论增材制造结构自支撑设计未来的发展方向以及未来的应用场景。

5.1　提升灵敏度计算效率

灵敏度分析是结构优化过程中的重要环节，而灵敏度分析的计算成本可以通过采用效率更高的分析方法来降低。2021 年，Zou 等[71]利用梯度优化算法来提高灵敏度分析的计算效率，同时采用了并行求解的方式（如图 33 所示），以极大地降低计算成本。

5.2　悬垂特征和打印方向综合考虑

相对于只考虑悬垂约束，综合考虑打印方向与拓扑结构在实现更大的设计空间和更好的结构性能方面更具优势。

综合考虑悬垂特征：2019 年，Zhang 等[72]提出了一种同时考虑悬垂角度和悬垂长度的拓扑优化方法，该方法可以有效地抑制过薄构件的形成；2020 年，Wang 等[73]提出了一种考虑悬垂角度和悬垂高度的拓扑优化方法，该方法在实现结构自支撑的同时还可以获得更好的结构性能（与仅有悬垂角约束的方法相比），如图 34 所示。

打印方向与悬垂角度综合考虑：2022 年，Zou 等[74]通过将设计域离散化以及自动修改元素长度比以适应不同的悬垂角度，同时通过在拓扑优化过程中考虑不同的打印方向来实现更优的结果。综合考虑打印方向和悬垂角度后，在相同的滤波半径下，MBB 梁的性能损失得以降低，最优情况下的最小柔度只损失了 0.4%，如图 35 所示。

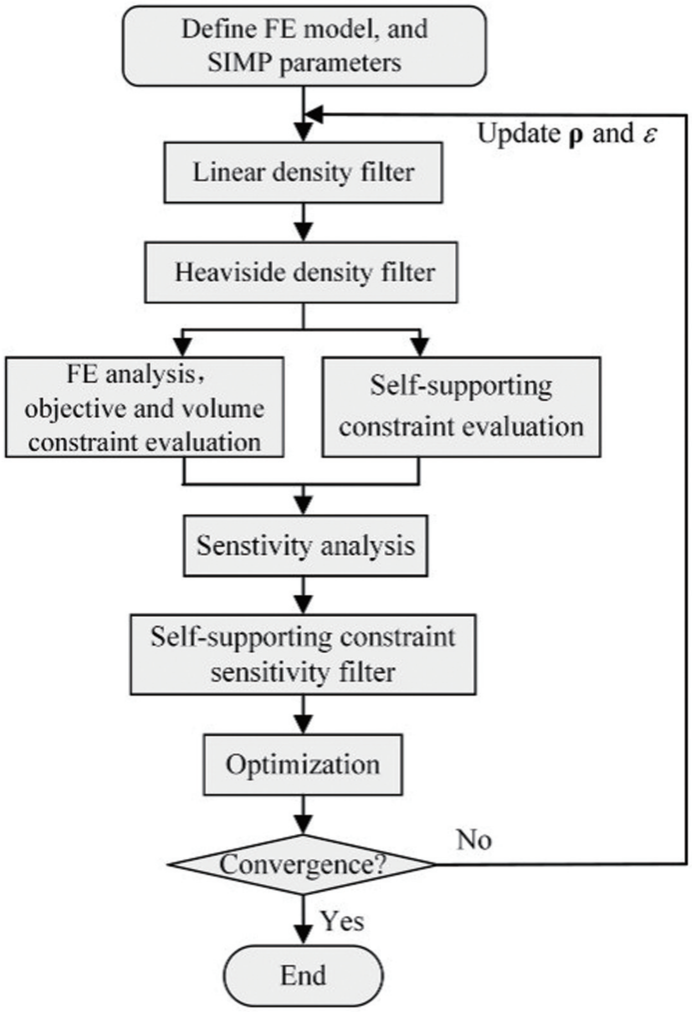


图 33　灵敏度并行求解流程图[71]

Fig. 33　Sensitivity parallel solving flowchart[71]

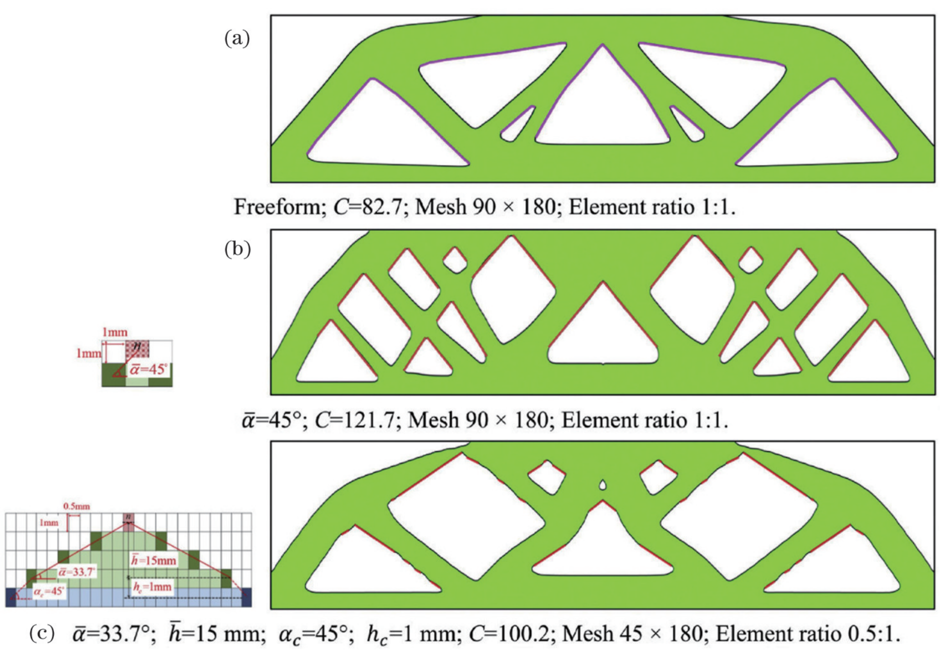


图 34　MBB 梁的优化效果[73]。(a) 无约束；(b) 悬垂角度约束；(c) 悬垂角度约束与悬垂高度约束

Fig. 34　Optimization effect of MBB beam[73]. (a) Unconstrained; (b) overhang angle constraints; (c) overhang angle and height constraints

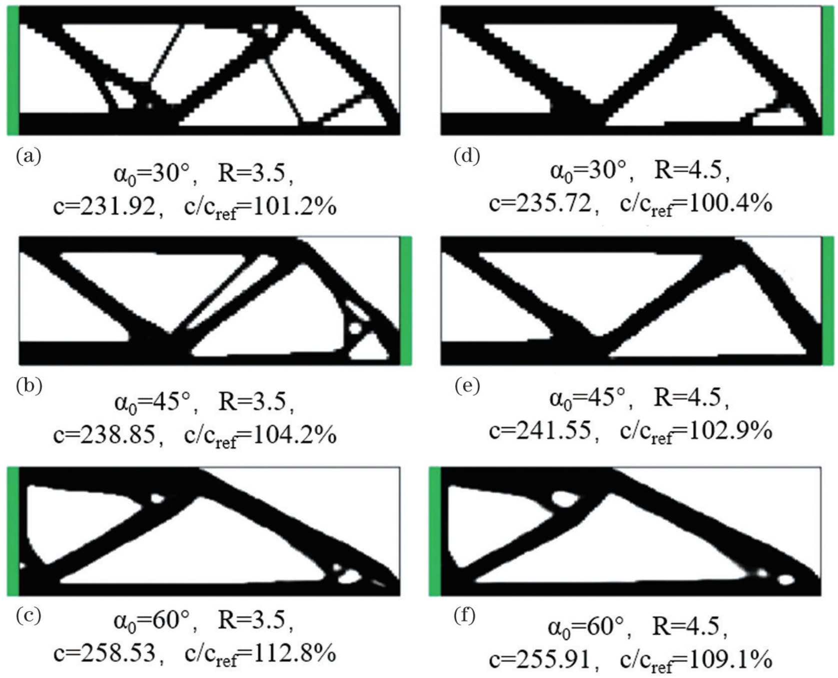


图 35　综合考虑打印方向以及悬垂角度后，自支撑约束下 MBB 梁的优化结果：基板的变化代表着不同的打印方向[74]

Fig. 35　Optimized MBB beam results under self-support constraint, considering the printing direction and the overhang angle: the change of the substrate represents different printing directions[74]

5.3　自支撑设计与其他性能设计相结合

轻量化设计在航空航天领域占有重要地位，是研究热点之一。在设计自支撑结构时还可以同时考虑轻量化设计。2017 年，Li 等[75]提出了一种基于密度法的轻量化自支撑结构设计方法。该方法以最小化体积为目标函数，并将悬垂约束纳入考虑，实现了自支撑结构的轻量化设计。相比于原模型，最终打印的模型在实现自支撑的情况下体积减小了 34%，如图 36 所示。但是，该方法需要复杂的重新设计过程，会增加时间消耗，因而 Li 等[76]于 2018 年对该方法进行了改进。

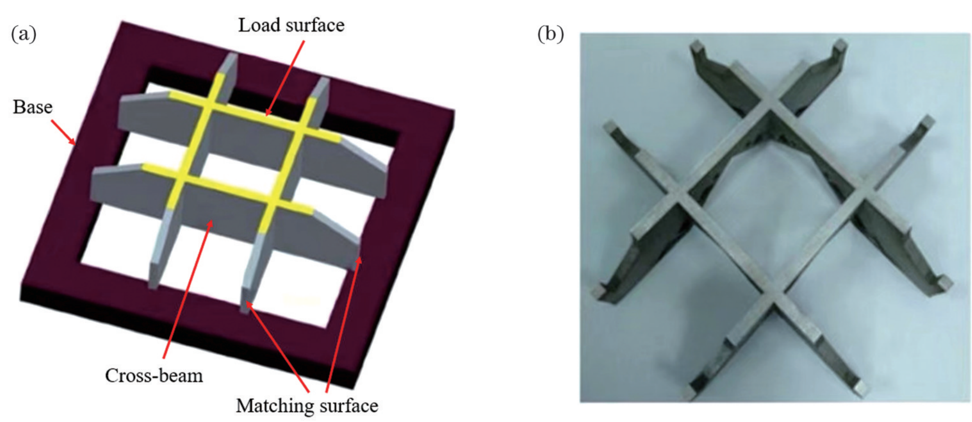


图 36　横梁部件的打印情况[75]。(a)原模型；(b)打印模型

Fig. 36　Printing of beam parts[75]. (a) Original model; (b) printed model

残余应力、变形和过热一直是人们关注的焦点，在增材制造过程中会引起残余应力和变形，从而对制造零件的力学性能和尺寸精度产生不利影响。2022 年，Xu 等[77]基于 RAMP 框架，综合考虑自支撑约束与残余应力约束，实现了结构的自支撑并且避免了零件的开裂、分层或翘曲失效等问题。图 37 显示了在 MBB 梁结构左上角施加垂直力(F=800 N)后残余应力分布的仿真测试结果。2023 年，Miki 等[78]提出了一种考虑失真约束的自支撑拓扑优化方法。该方法通过基于固有应变法的解析模型预测残余应力和变形，并将该模型纳入拓扑优化过程，以获得最佳的高性能配置，解决了增材制造过程中零件变形的问题。

5.4　未来的应用场景

增材制造结构自支撑设计的应用可以分为两类：金属增材制造结构自支撑设计的应用以及非金属增材制造结构自支撑设计的应用。金属增材制造结构自支

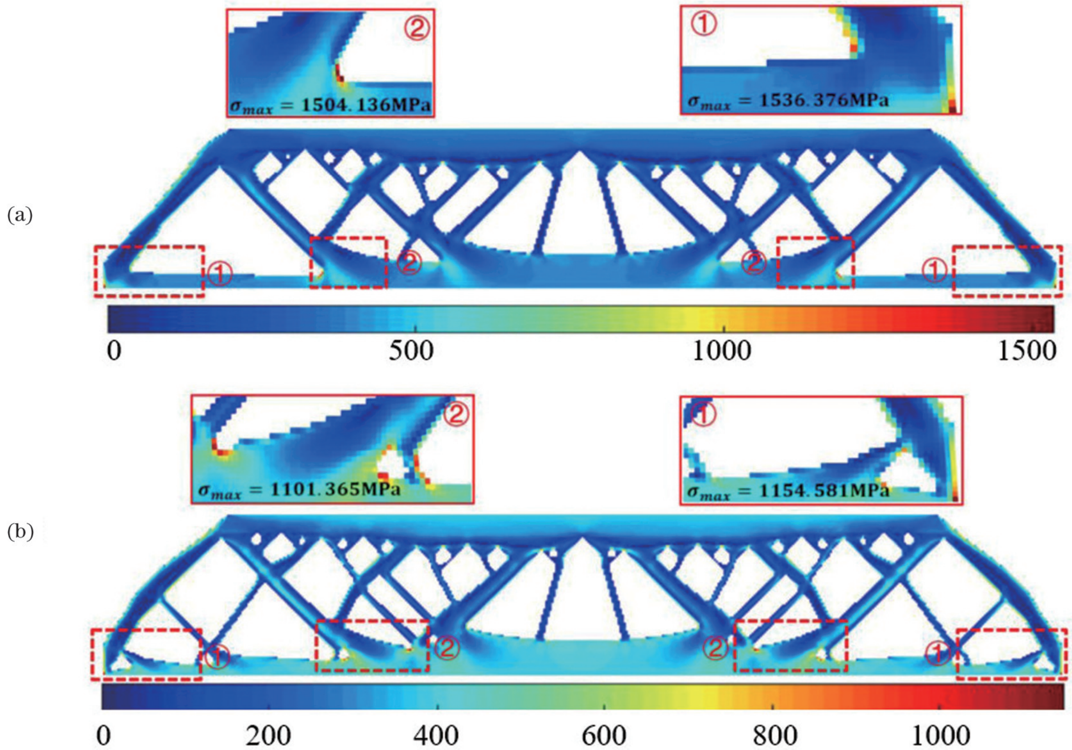


图 37　MBB 梁残余应力分布的仿真测试结果[77]。(a)有自支撑但无残余应力约束；(b)有自支撑和残余应力约束

Fig. 37　Simulation results of residual stress distribution of MBB beam[77]. (a) Self-supporting but without residual stress constraints; (b) self-supporting and residual stress constraints

撑设计的应用场景包括：1) 航空航天领域。可以用于制造航空航天部件，如复杂的燃烧室、发动机喷嘴和涡轮叶片等。2) 汽车工业。可以用于汽车制造并可用于制造形状复杂的零部件，如发动机排气系统、座椅结构和刹车组件等。3) 医疗领域。可以用于骨科植入物、牙科支架和人工关节等的制造。非金属增材制造结构自支撑设计的应用场景包括：1) 3D 打印领域。适用于各种 3D 打印应用，如打印聚合物零件、陶瓷件和复合材料构件等。2) 制造业。可以用于制造各种结构复杂的零部件，如模具、工装夹具和传感器外壳等。3) 文化艺术领域。可以用于雕塑、艺术品和装饰品等的制造，实现形状和结构复杂的艺术设计。

6　总结和展望

增材制造结构自支撑设计在提升打印效率以及降低打印成本方面具有重要价值，但目前缺少系统性的总结。本文首先对增材制造结构自支撑设计的原理进行阐述，随后对增材制造零件整体结构自支撑设计的研究进展进行总结，总结分为三部分：基于连续体结构拓扑优化的结构自支撑设计、基于离散结构拓扑优化的结构自支撑设计和基于形状优化的结构自支撑设计。现有的研究大部分是基于连续体结构拓扑优化展开的，对于基于连续体结构拓扑优化的结构自支撑设计研究进展，本文分为四部分进行介绍，即基于 SIMP 法及其改进方法的结构自支撑设计研究进展、基于水平集法的结构自支撑设计研究进展、基于 BESO 法的结构自支撑设计研究进展，以及基于特征驱动优化的结构自支撑设计研究进展。然后，对增材制造填充结构自支撑设计的研究进展进行了综述。最后，对增材制造结构自支撑设计进行了总结与展望。对于增材制造结构自支撑设计的发展，笔者提出了以下几个可以进一步研究的方向：

1) 进行 3D 案例的扩展。尽管结构自支撑设计的研究发展迅速，但目前所提方法仍处于起步阶段，且主要针对 2D 案例进行了测试，并且是基于可打印悬垂角度的“经验法则”，在 3D 案例的扩展上仍需继续努力。

2) 提升灵敏度的计算效率。目前大多数的研究是基于连续体结构拓扑优化进行的，拓扑优化设计存在设计变量巨大等问题，同时灵敏度计算涉及的元素过多，往往会造成较大的计算成本。因此，改进灵敏度的计算方法、提高计算效率具有重要意义。

3) 综合考虑悬垂特征约束、打印方向以及拓扑布局。相较于仅考虑悬垂角度约束，对悬垂特征约束、打印方向以及拓扑布局进行综合考虑可以更好地降低结构性能损失。并且，悬垂角度的阈值往往取决于打印方向。因此，在未来的研究工作中，综合考虑打印方向和拓扑布局是未来的研究重点之一。

4) 将结构自支撑设计与其他性能设计相结合。在金属材料的增材制造过程中，材料的熔化与凝固常常会引起残余应力和变形，从而造成打印失败或者打印件强度及尺寸精度下降。因此，将自支撑设计与结构中的残余应力以及结构变形等相结合是未来发展的

一个重要方向。此外,轻量化设计在航空航天领域具有重要的现实意义,在进行自支撑设计过程中亦可结合轻量化进行考虑。

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Review of Self-Supporting Design for Additive Manufacturing

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Abstract

Significance Additive manufacturing can be used to construct complex structures and facilitate the design of an overall structure by adding materials layer-by-layer to form parts. Additive manufacturing technology has been widely used in the automotive, electronics, aerospace, and medical fields and plays a crucial role.

However, during the additive manufacturing process, parts with overhangs are often encountered and cannot be successfully printed without considering the overhangs. For traditional 2.5-axis 3D printers, two methods are used to solve the problem of overhanging structures that cannot be printed. One method involves adding support structures below the area with the overhanging structures, and the other requires achieving self-support of the structures through structural optimization. Adding support structures can prevent warping and reduce the structural deformation of a part. However, this method increases the production time and material costs. In addition, further postprocessing is required to remove unwanted support structures, which is time-consuming and affects the surface accuracy of the part. Therefore, it is important to achieve self-support of a printed part to reduce the material cost, printing time, and postprocessing time.

Progress We summarize the research progress in structural self-supporting design for additive manufacturing. First, the principle of the structural self-supporting design of additive manufacturing is summarized, and the research progress in the self-supporting design of the overall structure of additive manufacturing parts and the self-supporting design of additive manufacturing infill structures are reviewed. Based on different structural optimization methods, it is further divided into structural self-supporting design using continuum structural topology optimization, discrete structural topology optimization, and shape optimization. Next, the advantages and disadvantages of each method are analyzed. Finally, solutions to improve computing efficiency and structural performance are discussed, along with future application scenarios and research priorities.

Conclusions and Prospects Additive manufacturing of structural self-supporting designs is critical for saving printing time and material, but it has not been systematically reviewed. This paper first summarizes the structural self-supporting design principle of additive manufacturing and reviews the research progress of the self-supporting design of the overall structure of the part, which is divided into three parts: research progress in structural self-supporting design based on continuum structure topology optimization, discrete structural topology optimization, and shape optimization. Previous studies were mainly based on continuum structure topology optimization, and the research progress in structural self-supporting design based on continuum structure topology optimization is presented in four parts: research progress in structural self-supporting design using the SIMP method and its improved version, the level set method, the BESO method, and feature-driven optimization. Subsequently, the research progress in the self-supporting design of additive manufacturing infill structures is reviewed. Finally, self-supporting designs of additive manufacturing structures are summarized and discussed. The structural self-supporting design of additive manufacturing is still in its infancy, and the following prospects are proposed to further develop this field.

(1) Perform 3D case extensions. Despite the rapid development of structural self-supporting design, the proposed method is still in its infancy and has been mainly applied to 2D cases based on the "rule of thumb" of printable overhang angles. Therefore, the extension to 3D cases still requires further investigation.

(2) Improve the computational efficiency of sensitivity. Previous studies were mainly based on continuum structure topology optimization, and topology optimization design has problems, such as large design variables, which often leads to high computational costs owing to the excessive number of elements in the sensitivity calculation design. Therefore, it is necessary to improve the sensitivity calculation method and increase calculation efficiency.

(3) Comprehensive consideration of the overhang feature constraints, printing direction, and topological layout. Compared with considering only the overhang angle constraint, a comprehensive consideration can further reduce the loss of structural performance. Moreover, the threshold value of the overhang angle often depends on the direction of printing. Therefore, in future research, the integrated consideration of printing direction and topological layout should be the focus.

(4) Combine self-support with other structural properties. During the melting and solidification of metallic materials printed by additive manufacturing, residual stresses and deformations are typically induced, resulting in printing failure or a decrease in strength and dimensional accuracy. Therefore, considering a self-supporting design that considers the residual stress and deformation of the structure is an important direction for future development. In addition, lightweight design is required in the aerospace field and should be considered in combination with light weight during the self-supporting design process.

Key words additive manufacturing; structural optimization; topology optimization; infill structure; self-supporting of structures