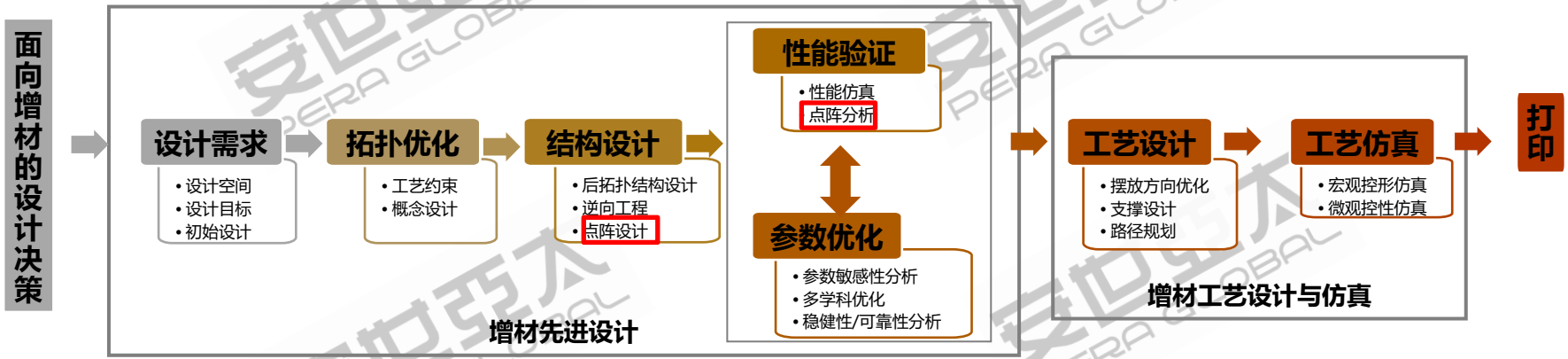
点阵结构设计与仿真分析

逯 璐

出品 安世亚太 PERA GLOBAL

增材先进设计与制造一体化解决方案



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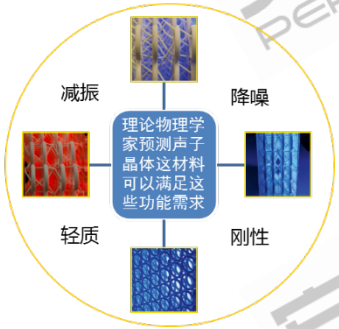
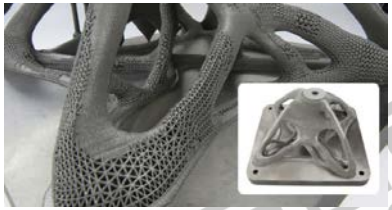
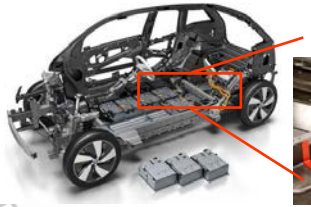
增材制造与点阵结构

- 增材制造技术使复杂点阵结构的大量生产及应用成为可能性。

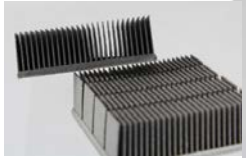


- 结构
  - 轻量化
  - 复合材料芯层
  - 变形隔离
  - 减振结构

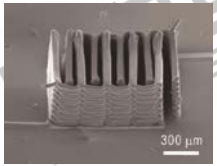


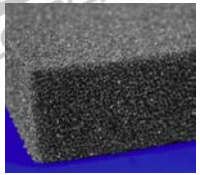


- 热
  - 热交换器
  - 阻火器
  - 隔热



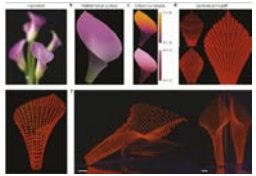
- 流体
  - 催化剂载体
  - 包装
  - 浮体





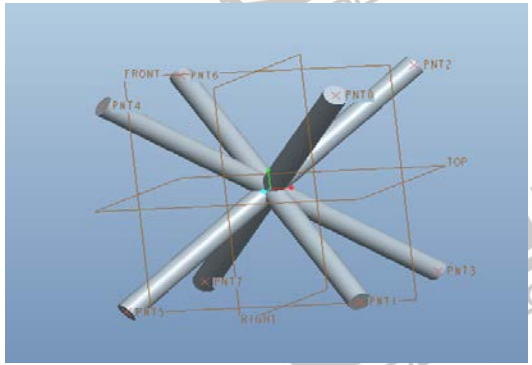
- 电磁
  - 电磁屏蔽
  - 电绝缘
  - 透电磁波

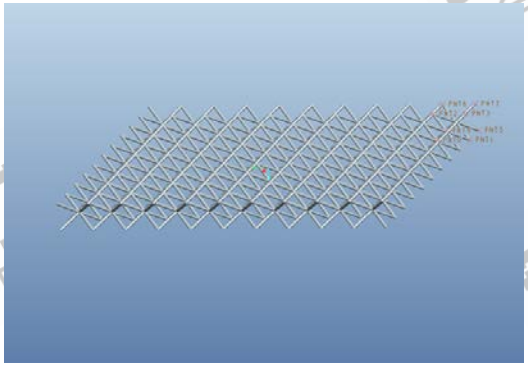
- 生物
  - 骨融合
  - 细胞生长
  - 仿生

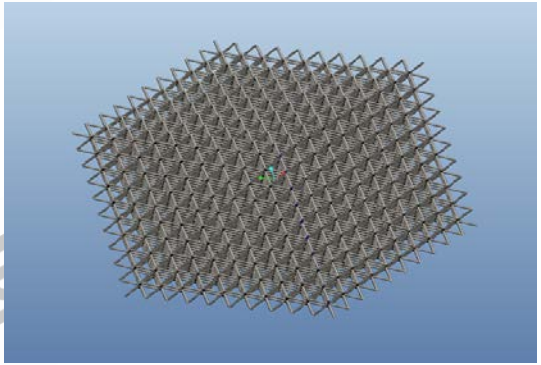


点阵结构建模

- 常规三维CAD软件，如UG, PRO-E,CATIA等。以体心立方结构为例：
  - 根据长方体体对角线，建立四根支架，形成体心立方单元；
  - 体心立方单元向x、y轴两个方向阵列，得到10×10个单元的“面” 。由于模型特征数目多，阵列时速度较慢。
  - 多个“面”通过装配形成待研究的体心立方点阵结构。由于单个“面”特征数目多，采用复制或者阵列命令会由于计算机的硬件限制而造成特征生成失败。



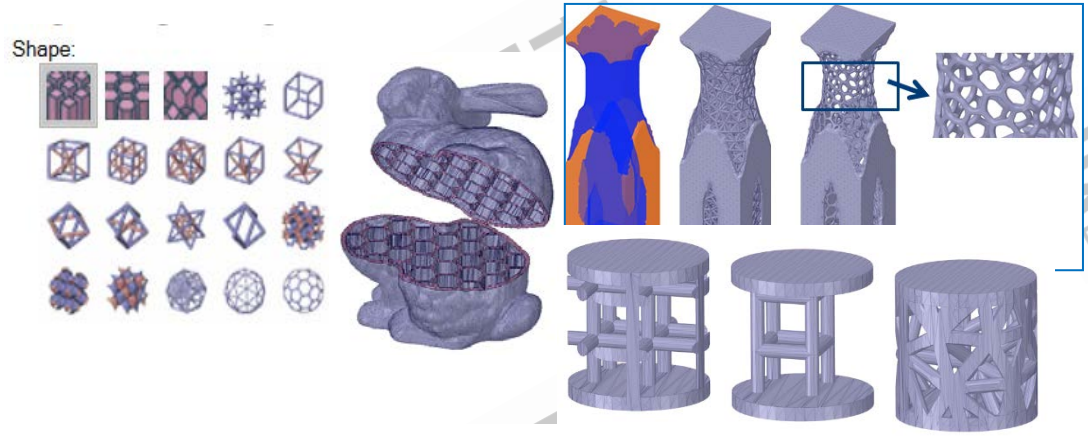


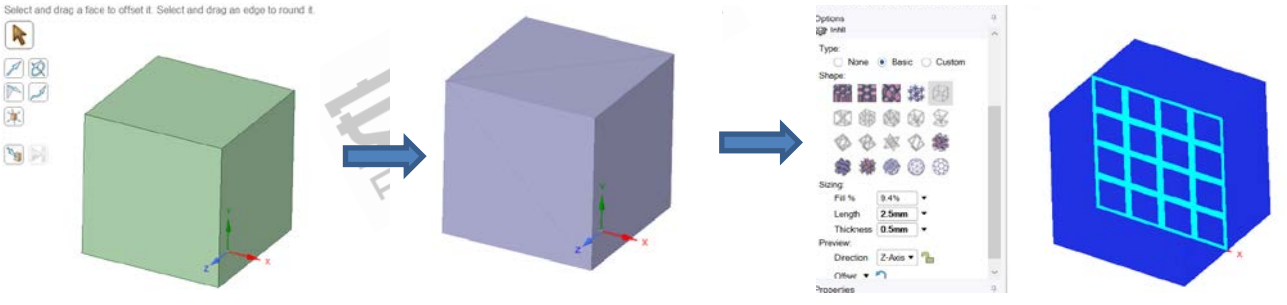


- 耗费资源、效率低，非常容易造成建模失败，甚至需要用二次开发或专用软件来解决建模问题。

点阵结构建模

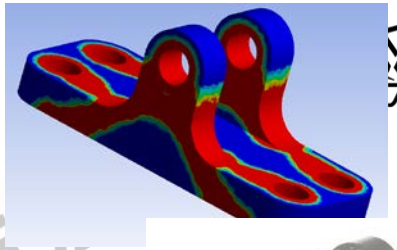
- 内置多种点阵结构，直接填充点阵结构建模



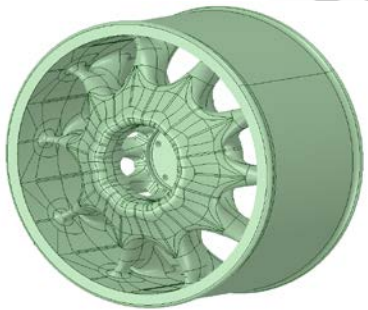
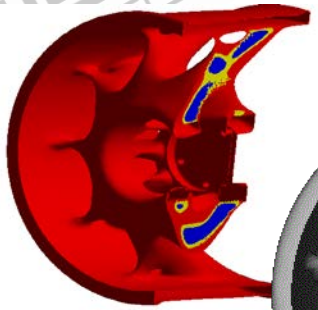
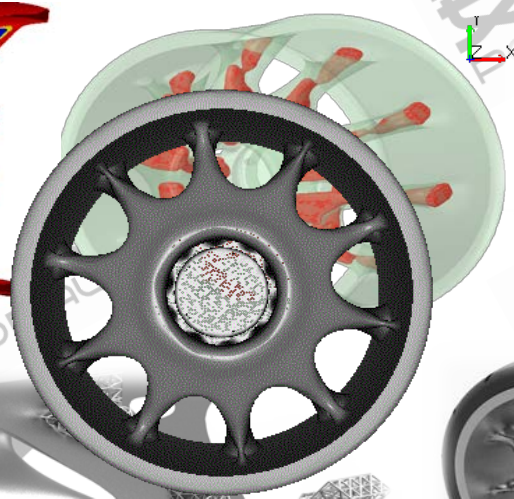


1. 点阵空间　2. 面片　3. 点阵参数　4. 点阵结构

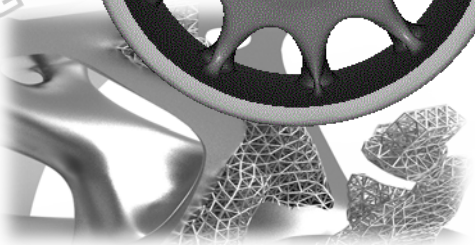
点阵结构优化设计



- **拓扑优化到点阵结构设计——基于填充率进行等密度填充**
  - 轻量化设计-选取合适区域填充点阵结构
    - 例如：质量密度0.4~0.6

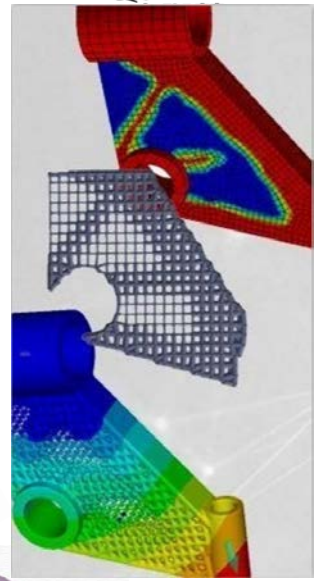




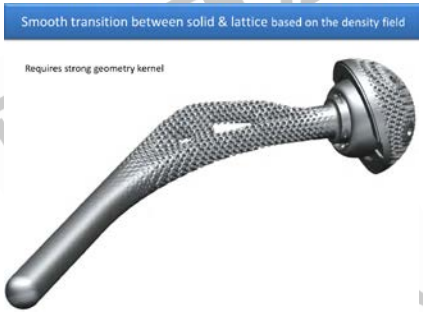



点阵结构优化设计

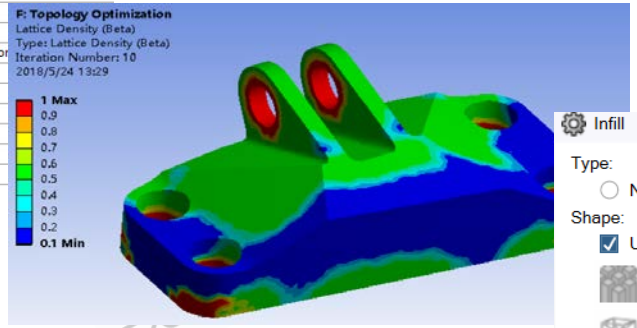
- **拓扑优化到点阵结构设计——基于有限元分析进行变密度填充**
  - ANSYS Topology提供点阵结构优化



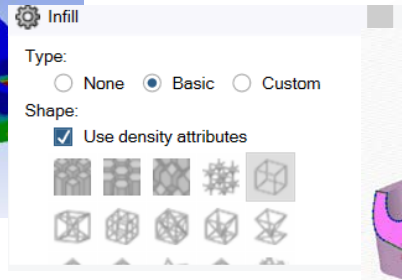


Details of "Optimization Region (Lattice)"	
Design Region	
Scoping Method	Geometry Selection
Geometry	1 Body
Exclusion Region	
Define By	Boundary Condition
Boundary Condition	All Boundary Condition
Optimization Option	
Optimization Type	Lattice Optimization
Lattice Type	Cubic
Minimum Density	0.1
Maximum Density	0.5
Lattice Cell Size	5. mm

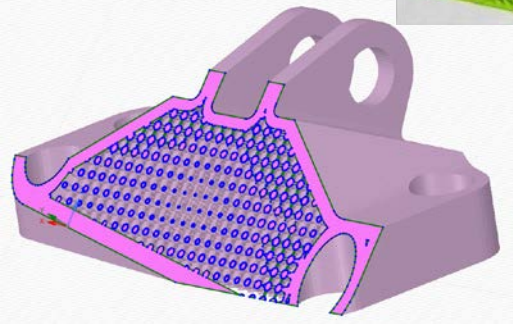
1. 点阵优化



2. 点阵密度（填充率）



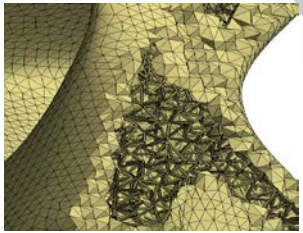
3. 基于点阵密度的Spaceclaim点阵生成

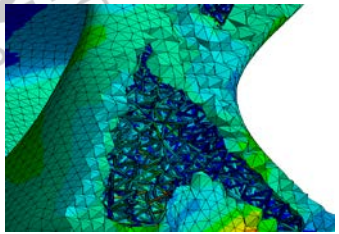


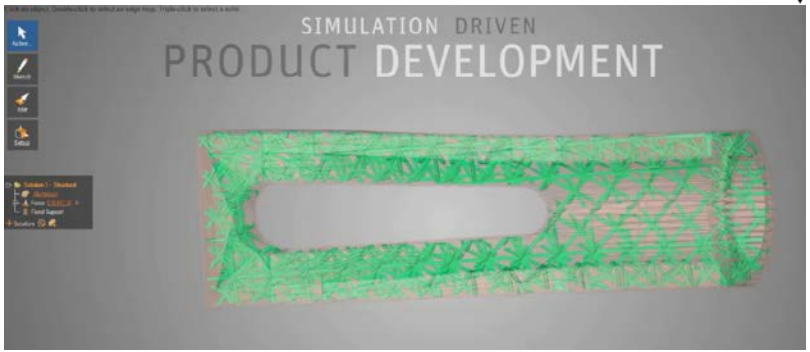
4. 变密度点阵

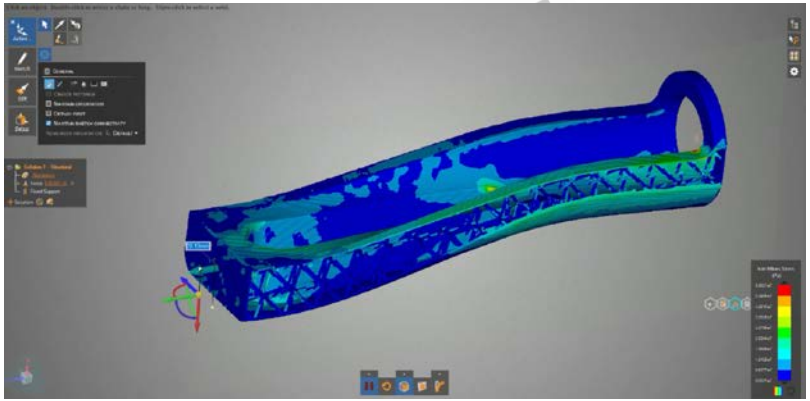
点阵结构仿真分析

- **全尺度实体建模仿真分析仅在理论上可行**
- **Discovery live有一些尝试，但其局限**
  - ✓ 大纵横比、网状结构是Discovery需要避免的结构，精度低，过于庞大的点阵结构还是有困难
  - ✓ 硬件要求高
- **具备实用潜力的点阵结构算法**
  - ✓ 梁模型
  - ✓ 多尺度算法



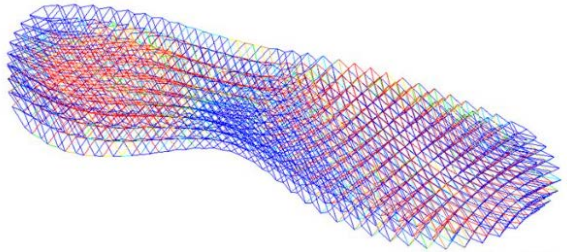




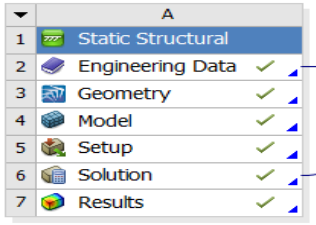


Discivery live点阵结构计算，难以大规模应用，
但可作为小规模测试模型验证手段

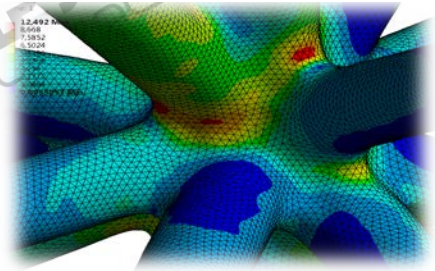
点阵结构仿真分析——梁模型算法

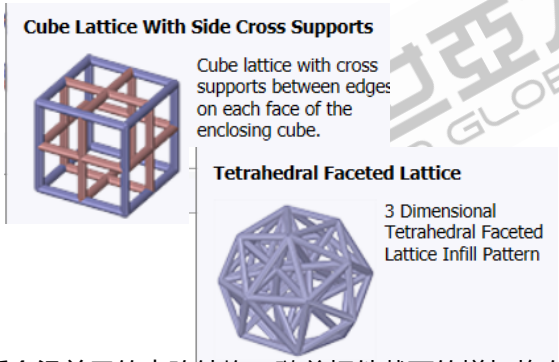


- **点阵结构抽取梁进行整体分析，结合子模型进行局部分析**
- **难点**
  - ✓ 梁模型的抽取通常并不容易
  - ✓ 梁模型与实体模型的装配关系的定义并不容易
  - ✓ 不具有普适性，很多点阵结构形式并不适合梁模型简化
  - ✓ 随着单胞的增加，计算量也成为一个问题

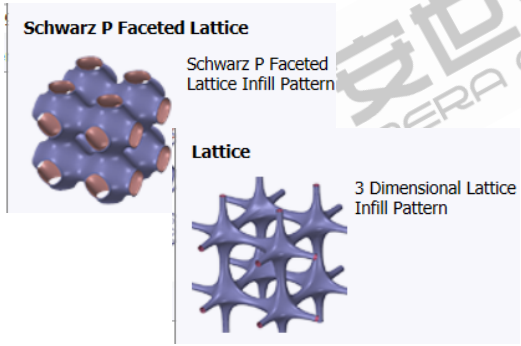


wheel rim with lattice　　submodel of lattice detail





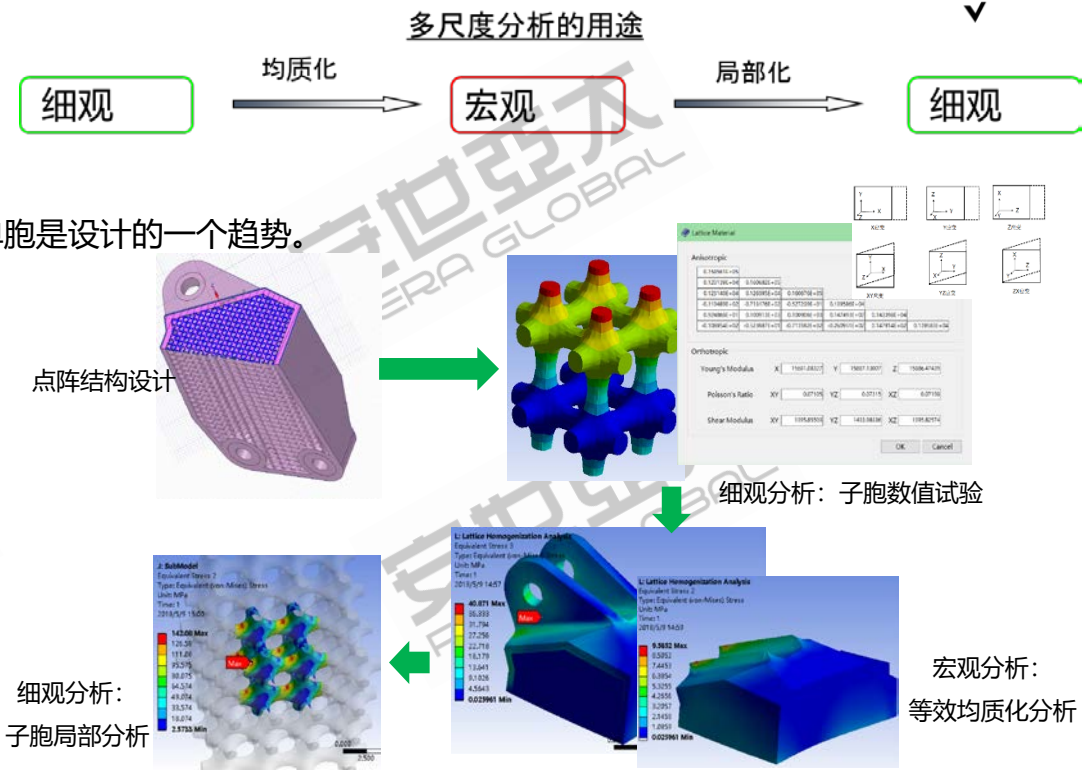
适合梁单元的点阵结构（随着杆件截面的增加趋向于不适用）



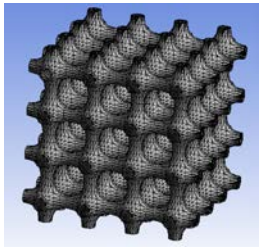
不适合梁单元的点阵结构

点阵结构仿真分析——多尺度算法

- **宏细观结合等效均质化算法**
- **具有普遍的适用性**
  - ✓ 对于大量单胞数量的情况优势明显，小型化单胞是设计的一个趋势。
  - ✓ 刚度准确，特别适合于刚度分析
  - ✓ 通过细观分析可以验算局部强度
- **难点**
  - ✓ 细观到宏观：等效均质化力学模型和参数
  - ✓ 宏观到细观：子模型算法
  - ✓ 变密度点阵结构的计算
- **多尺度算法适用性更广，作为首选，着手解决以上难点**



- **基于单个胞元结构，建立数值试验模型，采用约束方程定义周期边界计算等效材料属性**
- 等效均质化本构模型：
  - 各向异性是必须的
  - 正交各向异性（Orthotropic）：力学参数、热学参数
    - ✓ 正交各向异性在具有弹性对称面，在材料主轴方向正应变仅与正应力有关，剪应变仅与剪应力有关
  - 一般各向异性（Anisotropic）：弹性矩阵
    - ✓ 一般各向异性不具有弹性对称面，在任意方向正应力可能引起正应变或者剪应变，剪应力也可能引起正应变或者剪应变



$$\{\sigma\}=[D]\{\varepsilon^{el}\}$$

$$\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{xy}\\ \tau_{yz}\\ \tau_{xz}\end{Bmatrix}=\begin{bmatrix}D_{11} & & & & & \\ D_{21} & D_{22} & & & Symmetric & \\ D_{31} & D_{32} & D_{33} & & & \\ 0 & 0 & 0 & D_{44} & & \\ 0 & 0 & 0 & 0 & D_{55} & \\ 0 & 0 & 0 & 0 & 0 & D_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\\ \gamma_{xy}\\ \gamma_{yz}\\ \gamma_{xz}\end{Bmatrix}$$

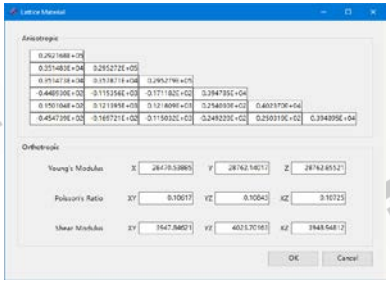
正交各向异性应力应变关系

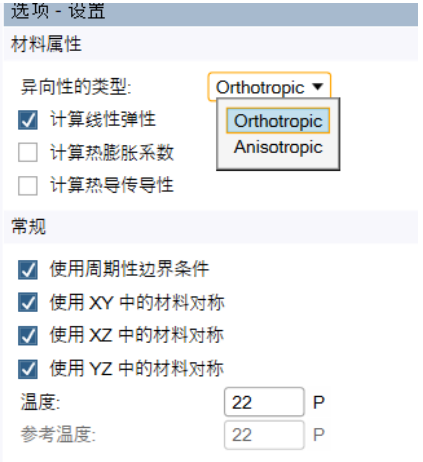
$$\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{xy}\\ \tau_{yz}\\ \tau_{xz}\end{Bmatrix}=\begin{bmatrix}D_{11} & & & & & \\ D_{21} & D_{22} & & & Symmetric & \\ D_{31} & D_{32} & D_{33} & & & \\ D_{41} & D_{42} & D_{43} & D_{44} & & \\ D_{51} & D_{52} & D_{53} & D_{54} & D_{55} & \\ D_{61} & D_{62} & D_{63} & D_{64} & D_{65} & D_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\\ \gamma_{xy}\\ \gamma_{yz}\\ \gamma_{xz}\end{Bmatrix}$$

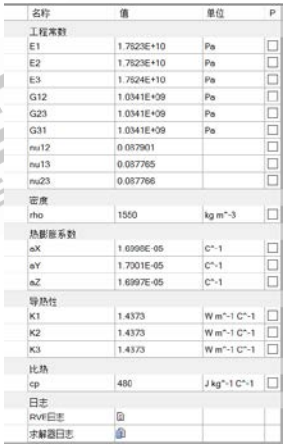
一般各向异性应力应变关系

I 细观分析-等效材料属性

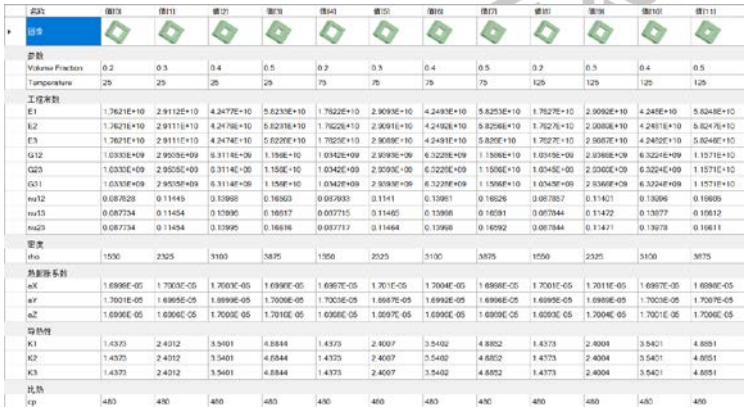
- **支持点阵结构：**
  - 内置点阵结构
  - 支持自定义
- **计算类型：**
  - 单一点阵密度
  - 多点阵密度





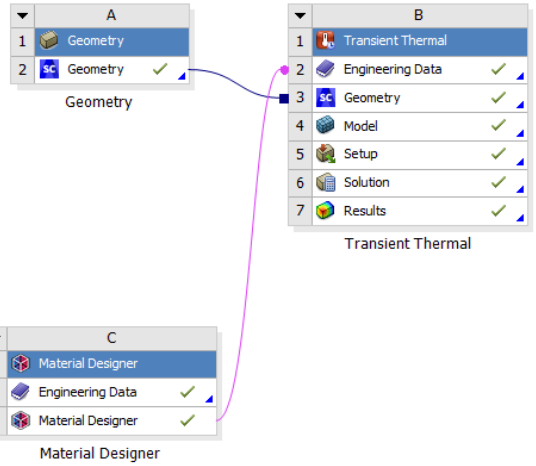


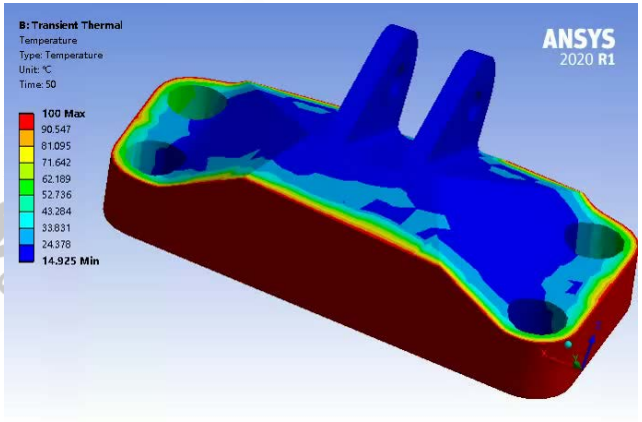
名称	值	单位	P
工程常数			
E1	1.7623E+10	Pa	
E2	1.7623E+10	Pa	
E3	1.7624E+10	Pa	
G12	1.0341E+09	Pa	
G23	1.0341E+09	Pa	
G31	1.0341E+09	Pa	
nu12	0.087901		
nu13	0.087765		
nu23	0.087766		
密度			
rho	1550	kg m^-3	
热膨胀系数			
aX	1.6998E-05	C^-1	
aY	1.7001E-05	C^-1	
aZ	1.6997E-05	C^-1	
导热性			
K1	1.4373	W m^-1 C^-1	
K2	1.4373	W m^-1 C^-1	
K3	1.4373	W m^-1 C^-1	
比热			
cp	480	J kg^-1 C^-1	
日志			
RVE日志			
求解器日志			

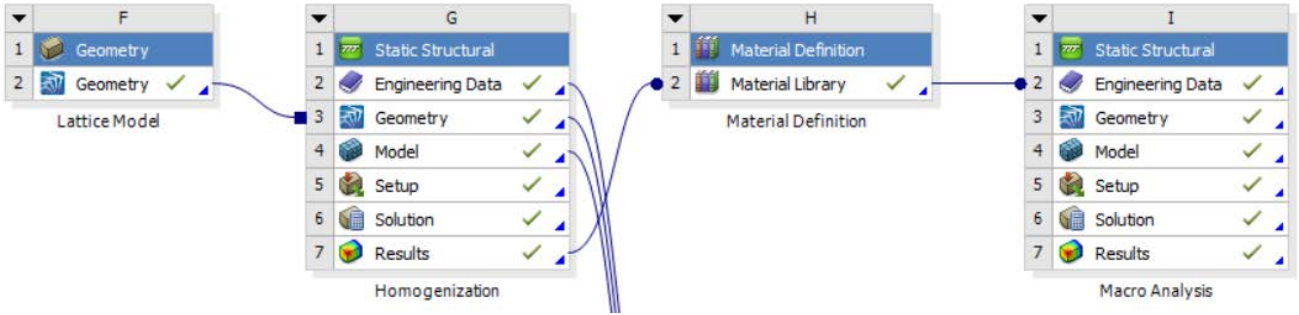


名称	值[0]	值[1]	值[2]	值[3]	值[4]	值[5]	值[6]	值[7]	值[8]	值[9]	值[10]	值[11]
目录												
参数												
Volume Fraction	0.2	0.3	0.4	0.5	0.2	0.3	0.4	0.5	0.2	0.3	0.4	0.5
Temperature	25	25	25	25	75	75	75	75	125	125	125	125
工程常数												
E1	1.7621E+10	2.9112E+10	4.2477E+10	5.8233E+10	1.7622E+10	2.9093E+10	4.2493E+10	5.8253E+10	1.7627E+10	2.9092E+10	4.248E+10	5.8248E+10
E2	1.7621E+10	2.9111E+10	4.2478E+10	5.8231E+10	1.7622E+10	2.9091E+10	4.2492E+10	5.8256E+10	1.7627E+10	2.9088E+10	4.2481E+10	5.8247E+10
E3	1.7621E+10	2.9111E+10	4.2474E+10	5.8229E+10	1.7625E+10	2.9089E+10	4.2491E+10	5.8256E+10	1.7627E+10	2.9085E+10	4.2482E+10	5.8246E+10
G12	1.0333E+09	2.9505E+09	6.3114E+09	1.156E+10	1.0342E+09	2.9093E+09	6.3229E+09	1.1506E+10	1.0345E+09	2.9368E+09	6.3224E+09	1.1571E+10
G23	1.0333E+09	2.9505E+09	6.3114E+09	1.156E+10	1.0342E+09	2.9093E+09	6.3229E+09	1.1506E+10	1.0345E+09	2.9368E+09	6.3224E+09	1.1571E+10
G31	1.0333E+09	2.9505E+09	6.3114E+09	1.156E+10	1.0342E+09	2.9093E+09	6.3229E+09	1.1506E+10	1.0345E+09	2.9368E+09	6.3224E+09	1.1571E+10
nu12	0.087628	0.11445	0.13998	0.16503	0.087933	0.1141	0.13981	0.16826	0.087857	0.11401	0.13996	0.16805
nu13	0.087734	0.11454	0.13996	0.16517	0.087715	0.11465	0.13998	0.16691	0.087844	0.11472	0.13977	0.16612
nu23	0.087734	0.11454	0.13995	0.16616	0.087717	0.11464	0.13998	0.16092	0.087844	0.11471	0.13978	0.16611
密度												
rho	1550	2325	3100	3875	1550	2325	3100	3875	1550	2325	3100	3875
热膨胀系数												
aX	1.6998E-05	1.7003E-05	1.7003E-05	1.6999E-05	1.6997E-05	1.701E-05	1.7004E-05	1.6998E-05	1.7001E-05	1.7011E-05	1.6997E-05	1.6998E-05
aY	1.7001E-05	1.6995E-05	1.6999E-05	1.7009E-05	1.7003E-05	1.6987E-05	1.6992E-05	1.6996E-05	1.6995E-05	1.6988E-05	1.7003E-05	1.7007E-05
aZ	1.6998E-05	1.6996E-05	1.7006E-05	1.7016E-05	1.6986E-05	1.6997E-05	1.6996E-05	1.6998E-05	1.6993E-05	1.7004E-05	1.7001E-05	1.7006E-05
导热性												
K1	1.4373	2.4012	3.5401	4.6844	1.4373	2.4007	3.5402	4.6852	1.4373	2.4004	3.5401	4.6851
K2	1.4373	2.4012	3.5401	4.6844	1.4373	2.4007	3.5402	4.6852	1.4373	2.4004	3.5401	4.6851
K3	1.4373	2.4012	3.5401	4.6844	1.4373	2.4007	3.5402	4.6852	1.4373	2.4004	3.5401	4.6851
比热												
cp	480	480	480	480	480	480	480	480	480	480	480	480

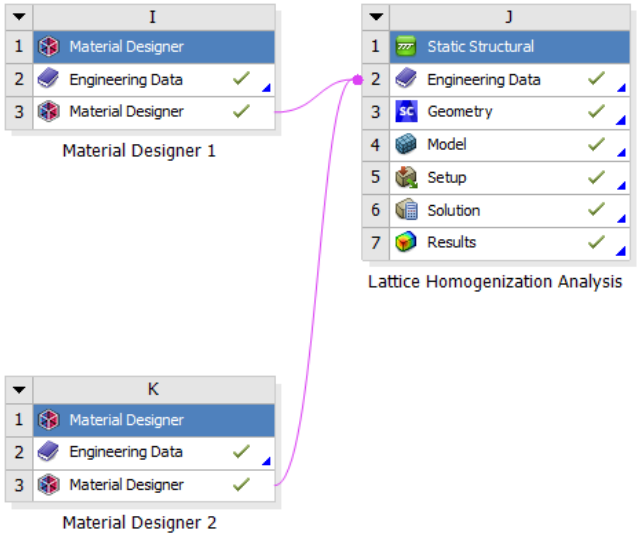
- **支持多种分析类型**
  - 热学分析
  - 力学分析

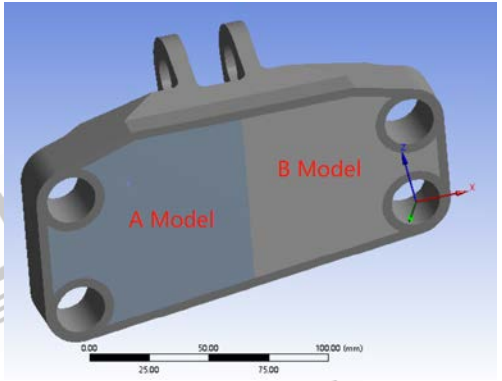


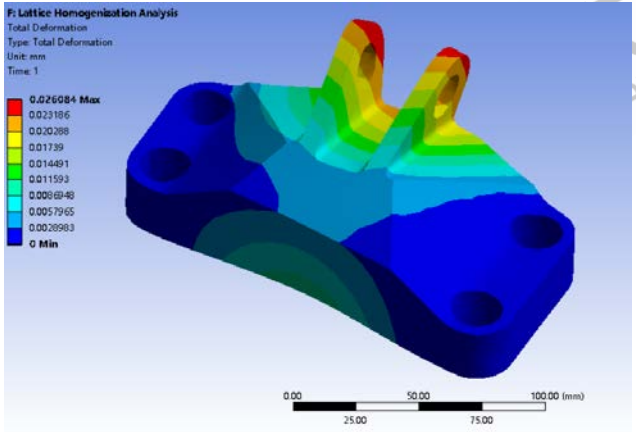




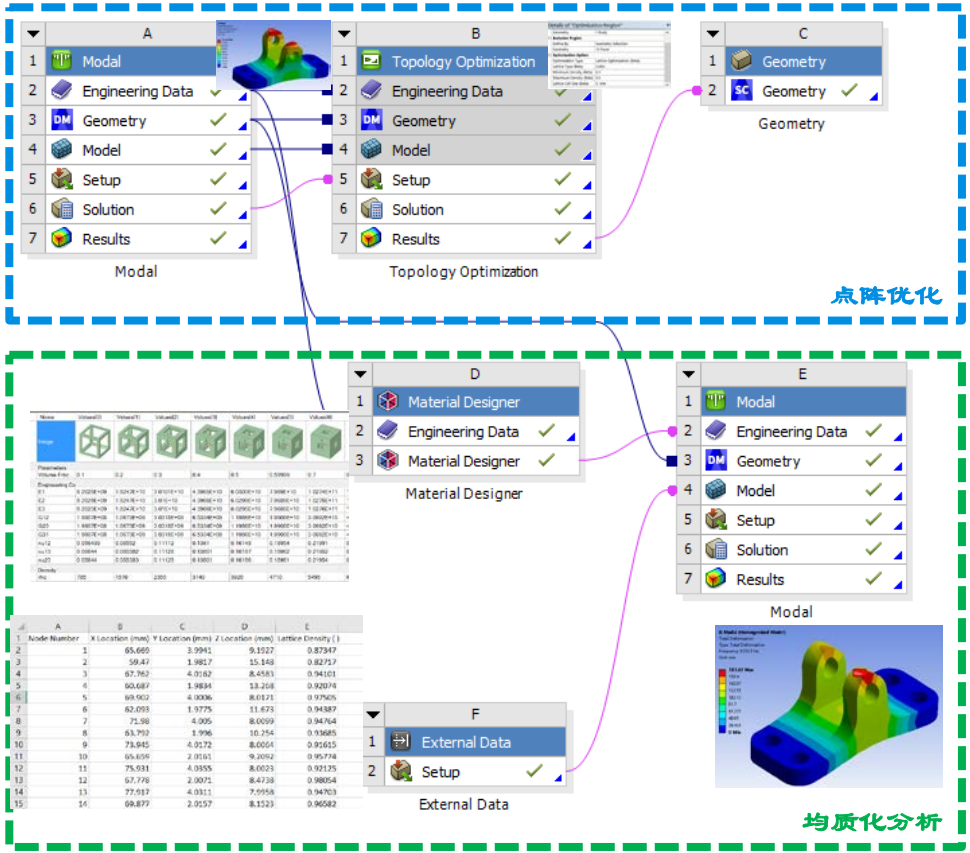
- 不同点阵结构/密度的宏观均质化分析



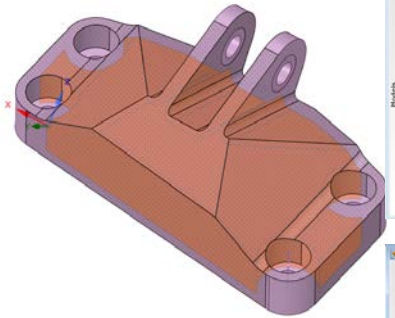


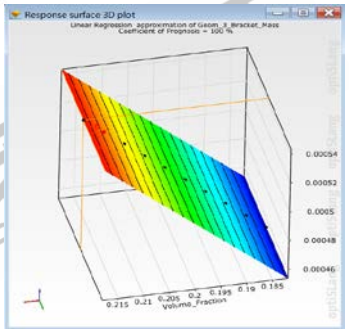


- 与点阵优化相结合，对优化的变密度点阵进行宏观均质化分析

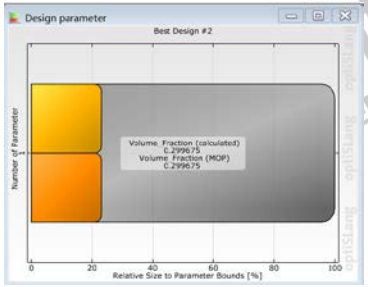


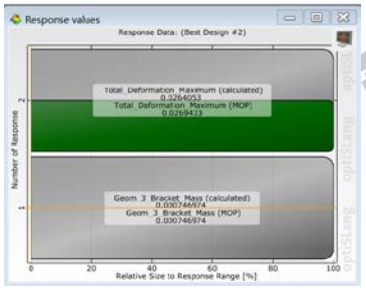
- 与参数优化相结合，进行点阵结构的参数优化



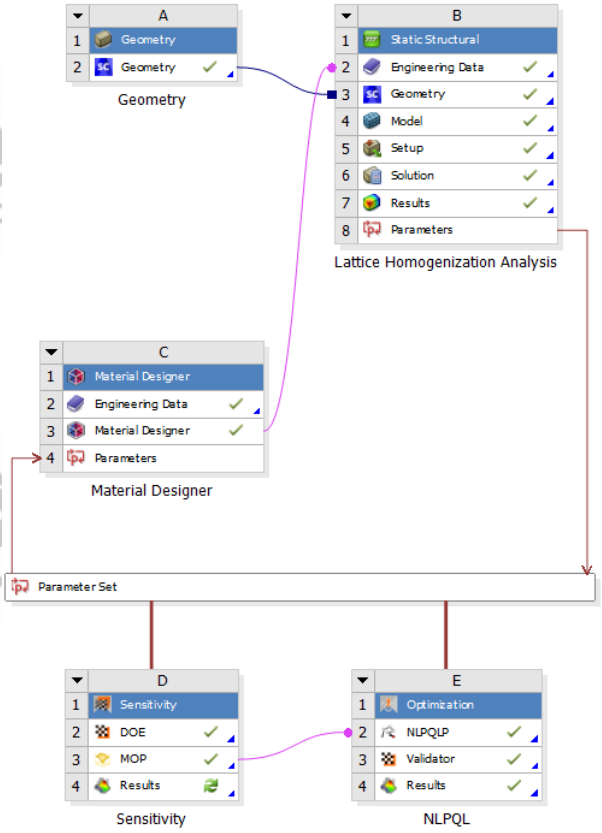


参数敏感性分析

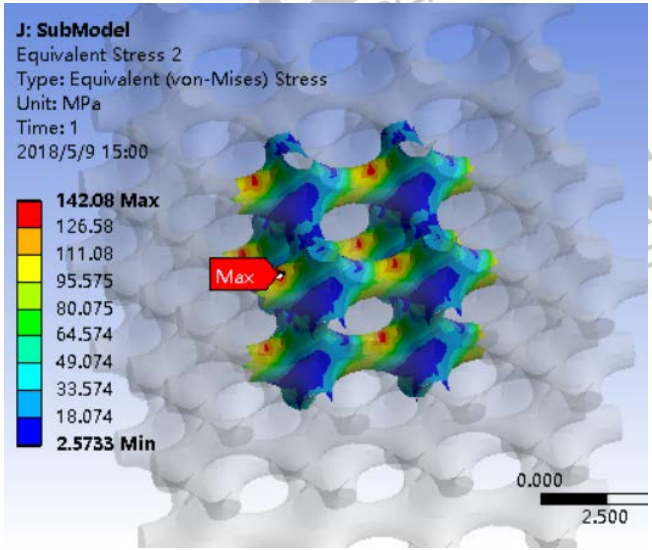


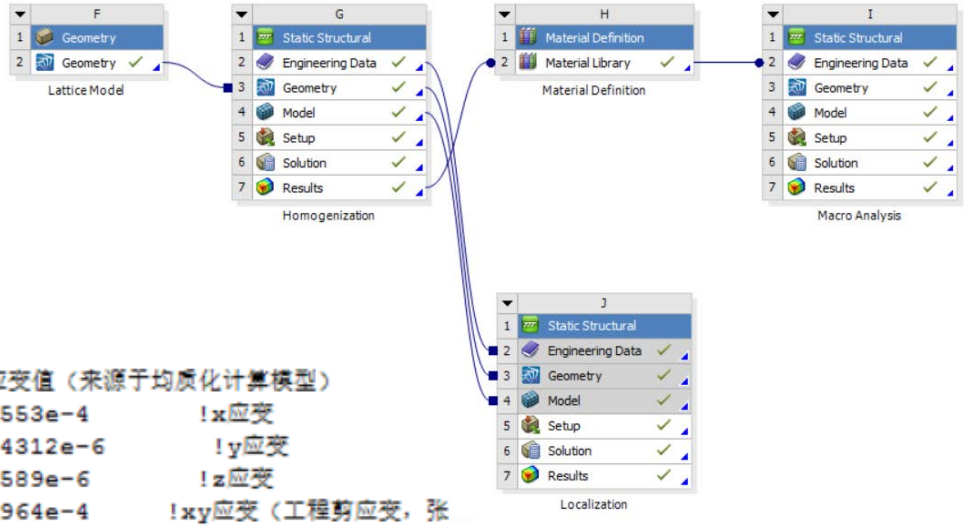


目标优化



- **局部细观分析进行应力校核**
  - 提取关键部位的六个应变分量
  - 该应变分量施加于胞元进行计算并确定局部应力

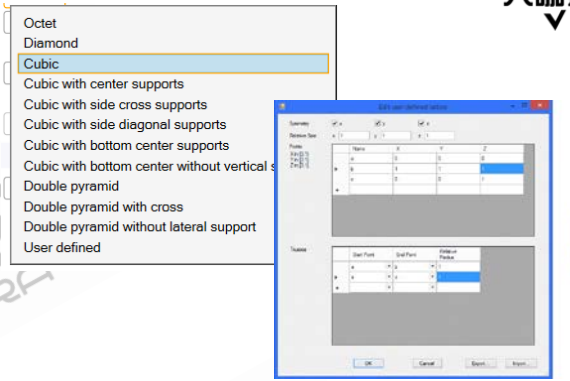


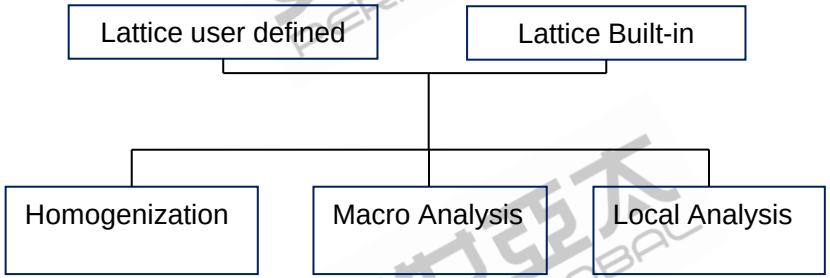


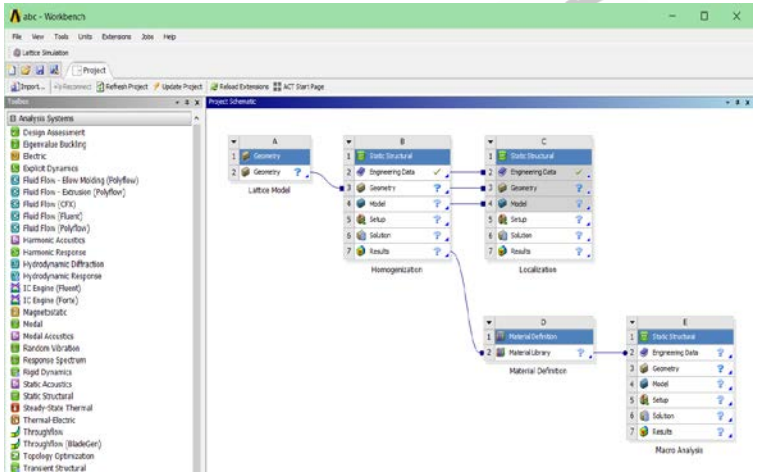

```
!---------应变值（来源于均质化计算模型）
epson_x=2.2553e-4          !x应变
epson_y=-7.4312e-6          !y应变
epson_z=9.0589e-6          !z应变
epson_xy=1.964e-4         !xy应变（工程剪应变，张
epson_yz=-7.2946e-5        !yz应变（工程剪应变，
epson_zx=-4.8083e-4        !zx应变（工程剪应变，
!--------------------------------------
```

点阵结构分析专用工具

- **Material Designer：计算点阵结构的等效材料属性**
- **Lattice Simulation：完整的细→宏→细观的多尺度分析**



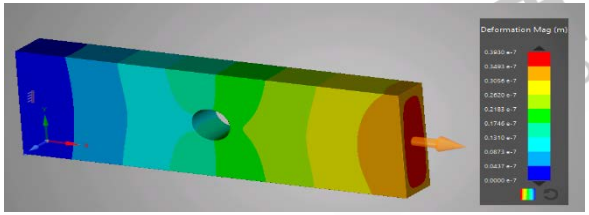


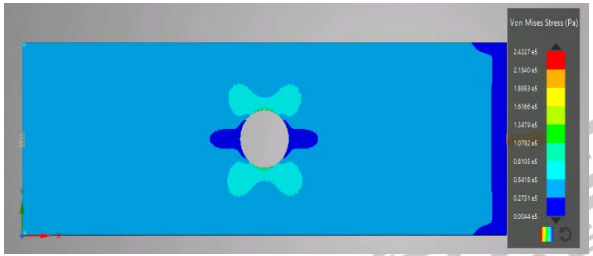


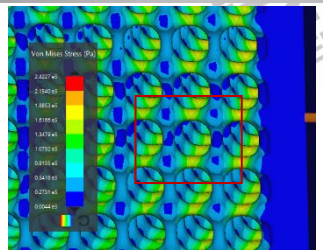
Lattice Simulation对比验证

- **刚度分析**

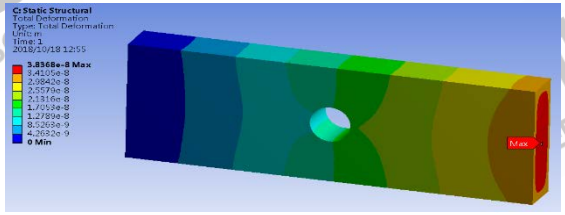
ANSYS Discovery

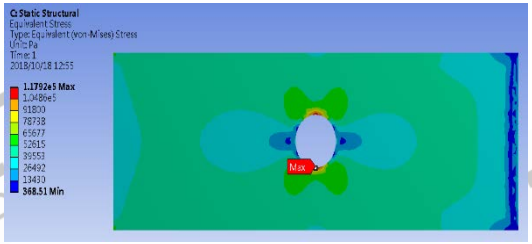


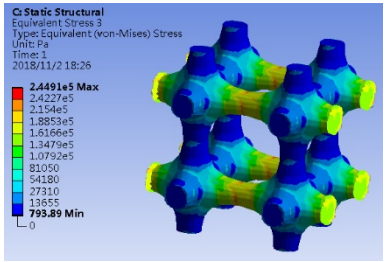


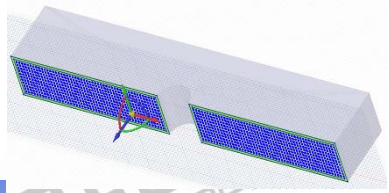


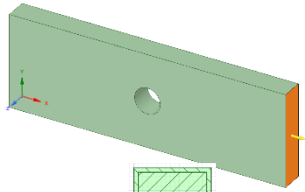
Lattice Simulation

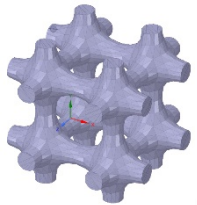


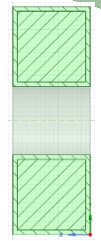












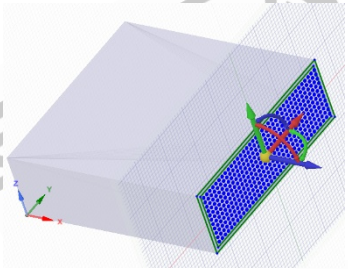
材料参数	几何参数	载荷
E=2.0e11Pa v=0.3	长度：150mm 宽度：50mm 厚度：17mm 孔径：15mm	P=-10000Pa

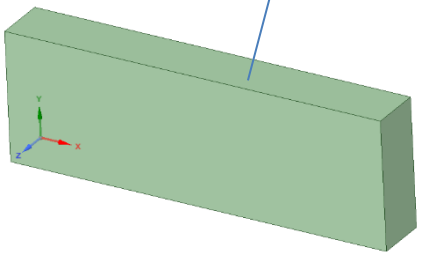
	ANSYS Discovery	Lattice Simulation	误差
最大变形	0.393mm	0.384mm	0.25%
最大应力	0.242MPa	0.2449MPa	0.11%

Lattice Simulation对比验证

- **模态分析：**

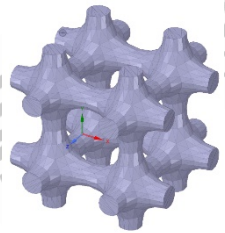
材料参数	几何参数	点阵参数	边界条件
E=2.0e11Pa v=0.3	长度：152.8mm 宽度：54mm 厚度：20.2mm	长度：1mm 壁厚：0.3mm 体积分数：21.2%	左端固定





等效均质化实体

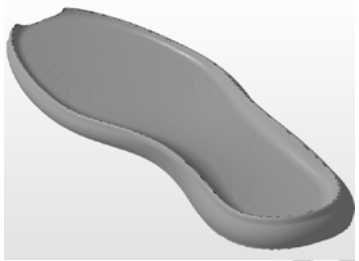
阶数	ANSYS Discovery	Lattice Simulation	误差
1	699.3Hz	698.6Hz	0.1%
2	1472.4Hz	1479.9Hz	0.5%
3	2851.3Hz	2778.1Hz	2.6%

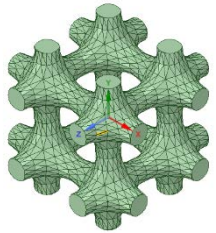


胞元结构

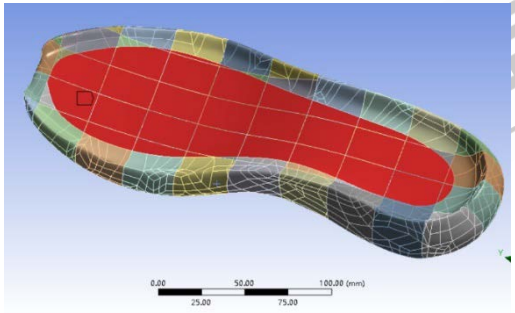
点阵结构剖面图

案例1：鞋中底优化设计





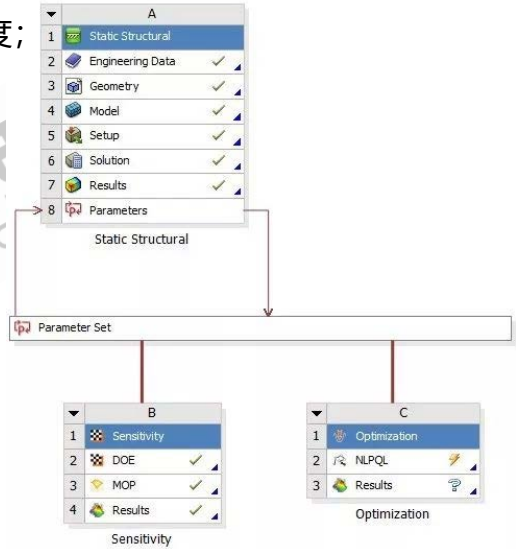
- **优化目标：**
  - 轻量化设计
  - 站立时，脚掌底部受力均匀
- **优化策略：**
  - 采用点阵结构进行优化设计使得**鞋底的重量尽可能低；**
  - 将鞋底划分为45个区域，不同区域填充不同体积分数的点阵结构，从而具有不同的刚度；
  - 通过插值可获得任意体积分数下的弹性矩阵；



f 体积分数

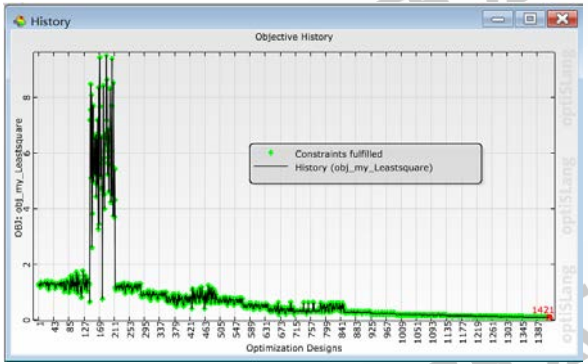
0.0540	0.0970	0.1550	0.2120	0.2660	0.3150	0.3600
3.77E-02	1.12E-01	2.24E-01	3.47E-01	4.73E-01	6.00E-01	7.30E-01
5.80E-04	4.47E-03	1.54E-02	3.27E-02	5.63E-02	8.43E-02	1.17E-01
5.80E-04	4.47E-03	1.54E-02	3.28E-02	5.63E-02	8.43E-02	1.17E-01
1.41E-04	1.01E-04	-7.87E-05	-3.50E-04	-6.80E-04	-1.02E-03	-1.38E-03
2.37E-05	6.97E-05	1.45E-04	2.10E-04	2.53E-04	2.69E-04	2.54E-04
1.41E-04	1.01E-04	-7.87E-05	-3.50E-04	-6.80E-04	-1.02E-03	-1.39E-03
3.93E-02	1.14E-01	2.26E-01	3.50E-01	4.80E-01	6.10E-01	7.37E-01
8.57E-04	4.00E-03	1.59E-02	3.33E-02	5.73E-02	8.60E-02	1.18E-01
-2.72E-04	-6.17E-04	-1.06E-03	-1.48E-03	-1.90E-03	-2.29E-03	-2.66E-03
4.47E-04	1.00E-03	1.60E-03	1.98E-03	2.15E-03	2.12E-03	1.93E-03
3.83E-05	1.89E-05	-5.30E-05	-1.57E-04	-2.78E-04	-4.03E-04	-5.20E-04
3.93E-02	1.14E-01	2.26E-01	3.50E-01	4.80E-01	6.10E-01	7.37E-01
3.83E-05	1.90E-05	-5.27E-05	-1.57E-04	-2.78E-04	-4.03E-04	-5.20E-04
4.47E-04	1.00E-03	1.60E-03	1.98E-03	2.15E-03	2.12E-03	1.93E-03
-2.72E-04	-6.20E-04	-1.06E-03	-1.49E-03	-1.90E-03	-2.29E-03	-2.66E-03
8.47E-04	5.13E-03	1.67E-02	3.50E-02	5.93E-02	8.83E-02	1.20E-01
2.63E-05	9.37E-05	2.06E-04	3.19E-04	4.17E-04	4.80E-04	5.13E-04
-8.33E-05	-2.40E-04	-4.13E-04	-4.93E-04	-4.70E-04	-3.70E-04	-2.33E-04
9.13E-04	5.37E-03	1.72E-02	3.57E-02	6.07E-02	8.97E-02	1.22E-01
2.62E-05	9.37E-05	2.06E-04	3.19E-04	4.17E-04	4.80E-04	5.13E-04
8.47E-04	5.13E-03	1.67E-02	3.50E-02	5.93E-02	8.83E-02	1.20E-01

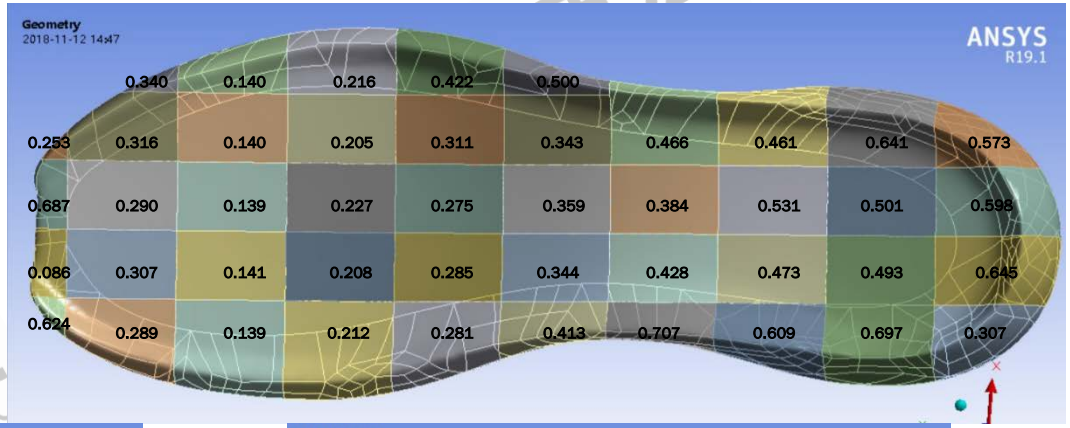
D_f 对应体积分数f的弹性矩阵

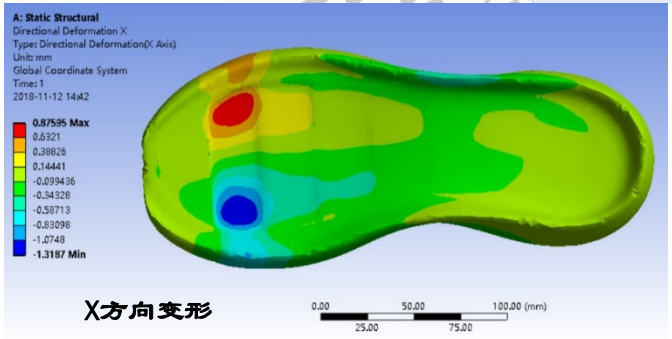


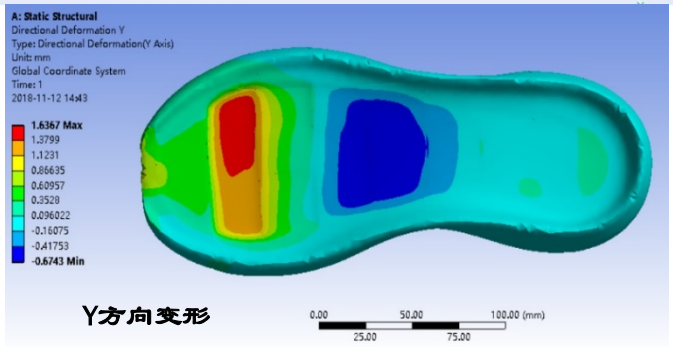
案例1：鞋中底优化设计

- 利用optiSLang进行优化以确定各子域对应的填充点阵的体积分数，获得满足目标函数的最优组合，使得鞋底上表面受均匀压力。





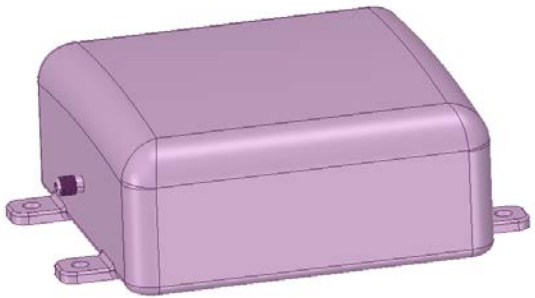




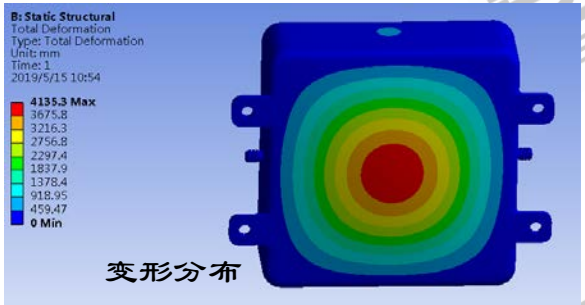
案例2：压力容器优化设计

- 材料：钛合金
- 优化目标：在有限的空间内尽可能地提高容积，并减小质量；
- 约束条件：
  - 四个螺孔设置固定约束
  - 内腔施加42MPa

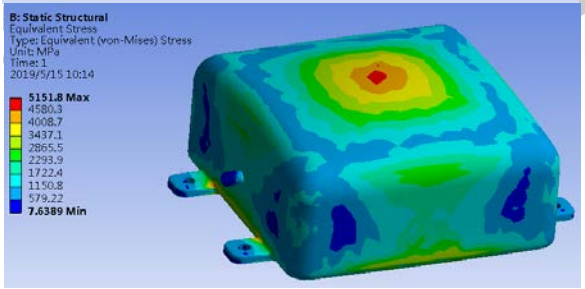
钛合金	
杨氏模量	107GPa
泊松比	0.32
屈服强度	1098MPa



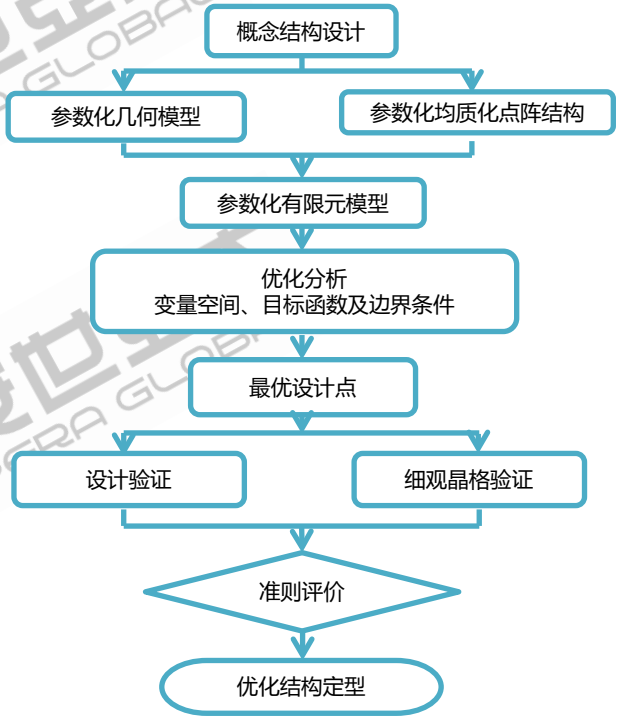
原始设计



变形分布

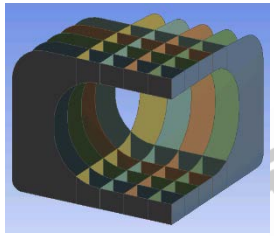


应力分布

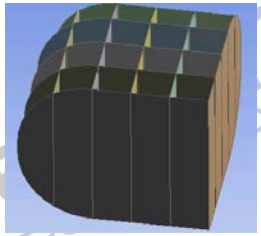


案例2：压力容器优化设计

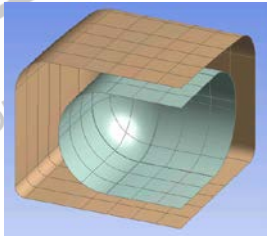
- 参数优化



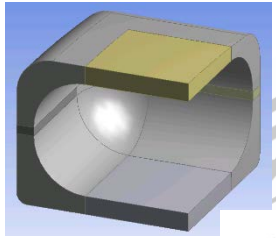
加强筋板



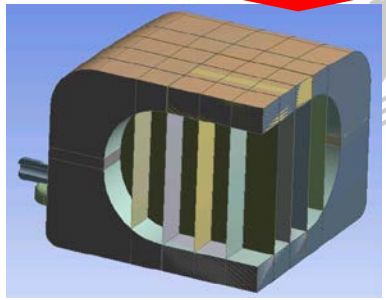
内部支撑筋板



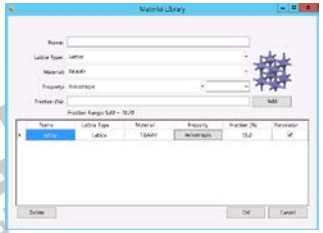
内、外壳体



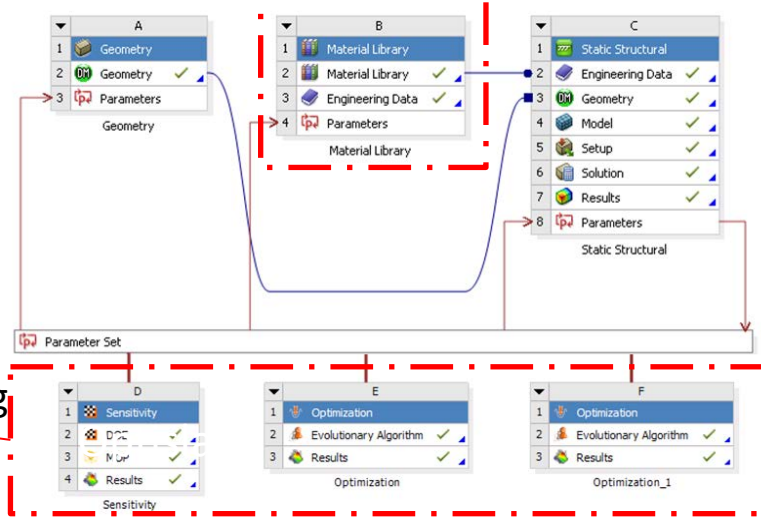
均质化点阵结构



Length_half	147.67 mm	Length	内腔半长度
Height	123.66 mm	Length	内腔高度
Width_half	147.67 mm	Length	内腔半宽度
Bend_R	56.806 mm	Length	内腔圆角半径
JianJu_L	30 mm	Length	长度方向加强筋间距
Num_Stiff_L	4	Dimensionless	长度方向加强筋个数
JianJu_W	30 mm	Length	宽度方向加强筋间距
Num_Stiff_W	4	Dimensionless	宽度方向加强筋个数



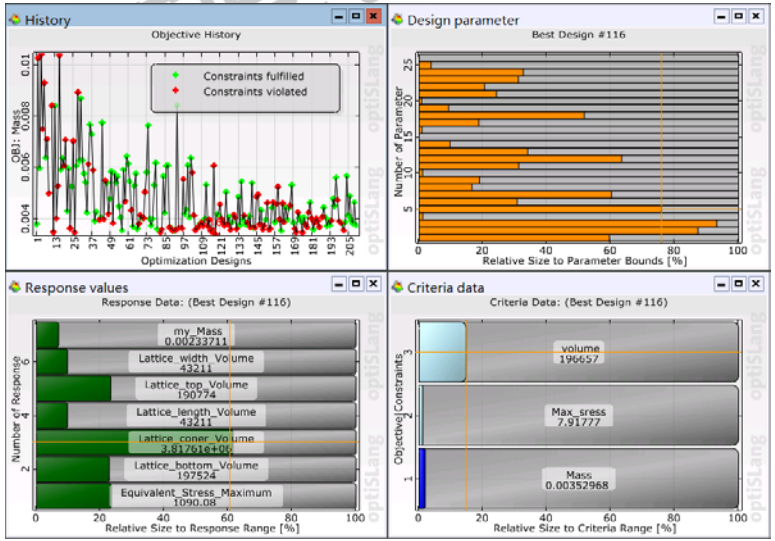
Lattice Simulation

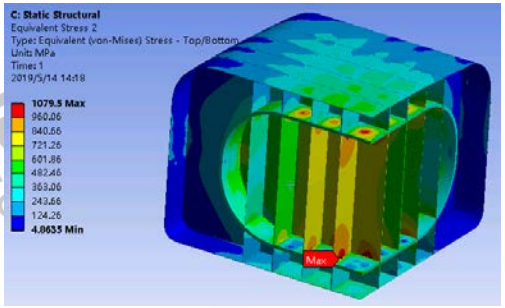


案例2：压力容器优化设计

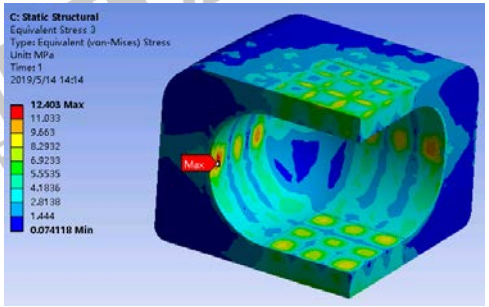
- 目标优化
  - 质量最小

名称	变量	函数表达式
目标函数	总质量	MIN
约束条件	容积	>2.5L
	最大等效应力	<1098MPa





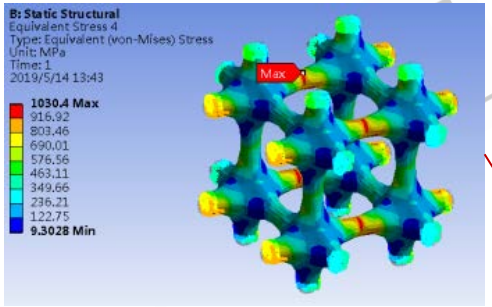
加筋壳体应力分布

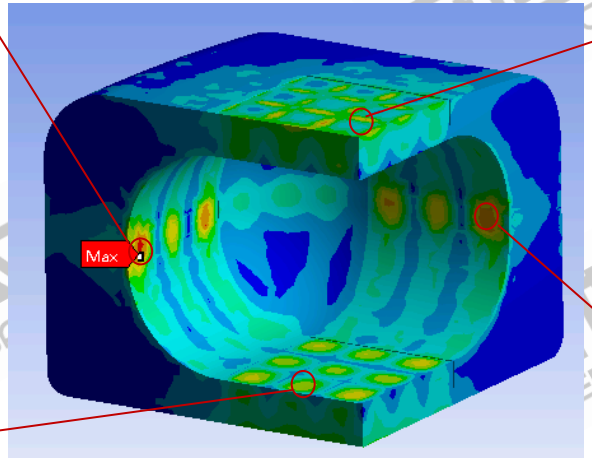


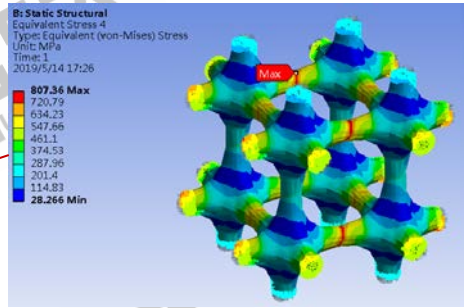
均质化点阵结构

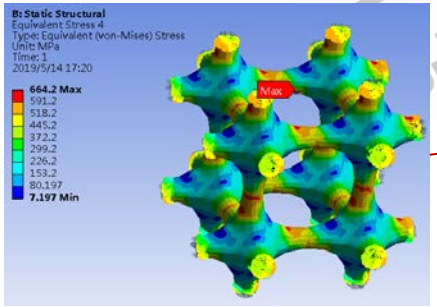
案例2：压力容器优化设计

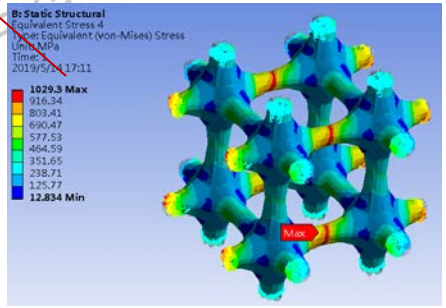
- 强度校核











总结

■支持点阵结构建模及设计优化

■多尺度算法基于细观-宏观-细观的分析方式，可准确、高效求解点阵结构的刚度及强度

■与拓扑优化相结合，进行变密度点阵结构设计及验证分析

■与参数优化相结合，进行点阵结构参数优化

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