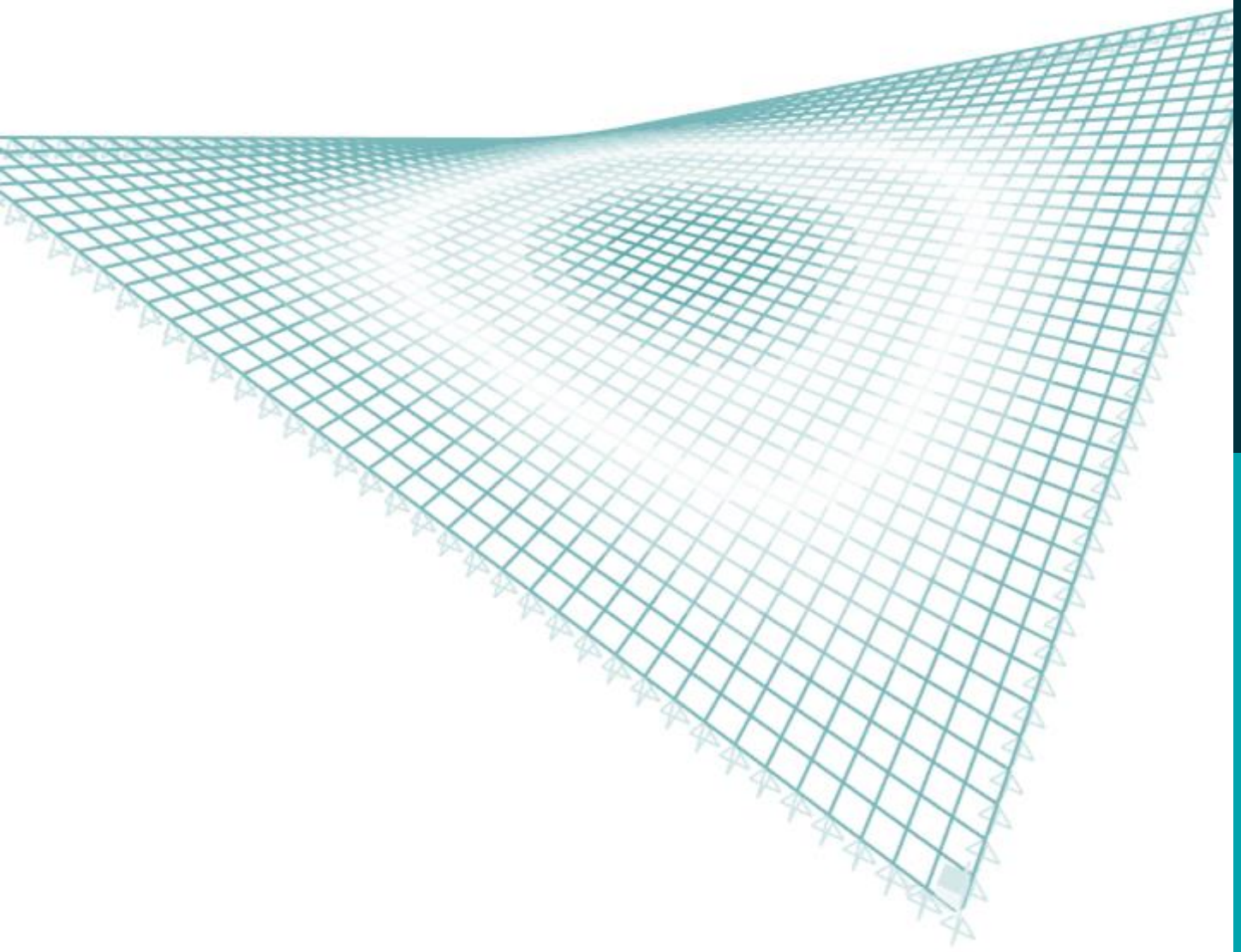


APRIL 30, 2022

力密度法结构找形研究与实现

Thornton Tomasetti

内容

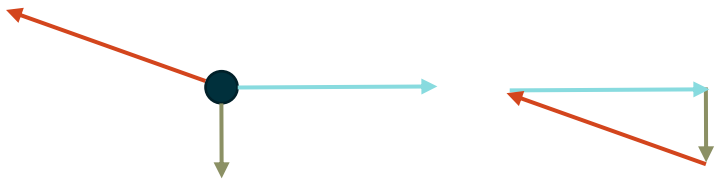
1. 力密度法介绍
2. 找形流程
3. 样例展示（轮辐式张拉屋盖）
4. 自重下找形
5. 结论和下一步工作

力密度法介绍

- 基于力和杆件长度的比值，即“力密度”

$$\rho = \frac{F}{L}$$

- 每个节点都处于轴力静力平衡，且杆件走向与其内力平行



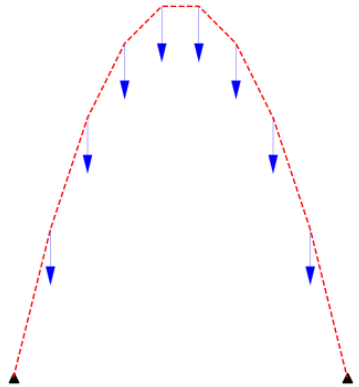
- 假设：拉杆力密度为正值，压杆力密度为负值

$$\rho \begin{cases} > 0 & if\ N > 0 \\ < 0 & if\ \mathrm{N} < 0 \end{cases}$$

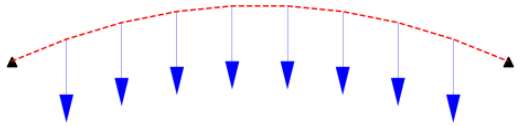
- 可假设所有杆件力密度为定值，或分组定值：杆件越长，轴力越大

力密度法介绍

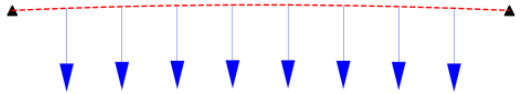
- 整体力密度越大，结构矢高越小；反之整体力密度越小，结构矢高越大



$\rho = -1$



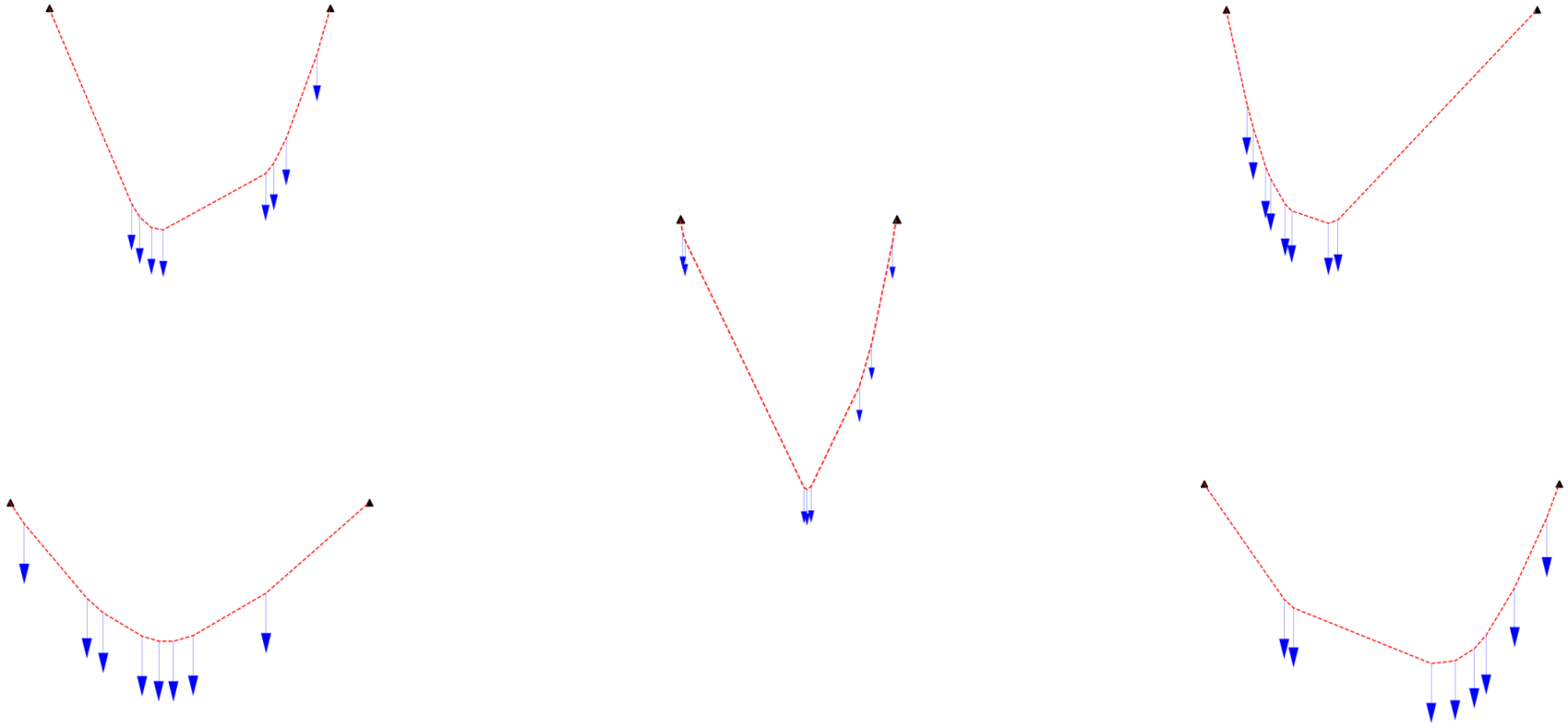
$\rho = -10$



$\rho = -100$

力密度法介绍

- 与某节点相连的杆件，力密度越大的杆件长度越小，力密度越小的杆件长度越大



找形流程

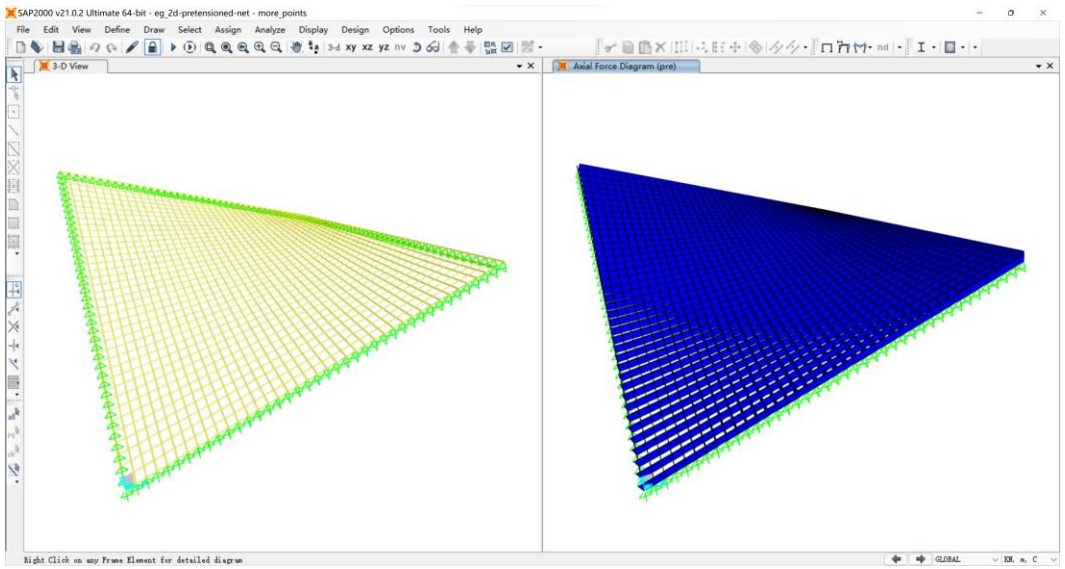
➢ **采用自编Python程序实现**

- **输入：**网格定义、边界约束、初始荷载、初始节点位置、力密度值　or　SAP2000初始模型
- **输出：**符合静力平衡的新节点位置和杆件内力

```
aaa = TwoDShapeFinding(m, n, 2)
aaa.set_fix(*constrain)
aaa.set_init_F(*loading)
aaa.set_init_z(*boundary_z)
aaa.set_connectivities()
aaa.set_force_density(1000)
```

OR

SAP2000®

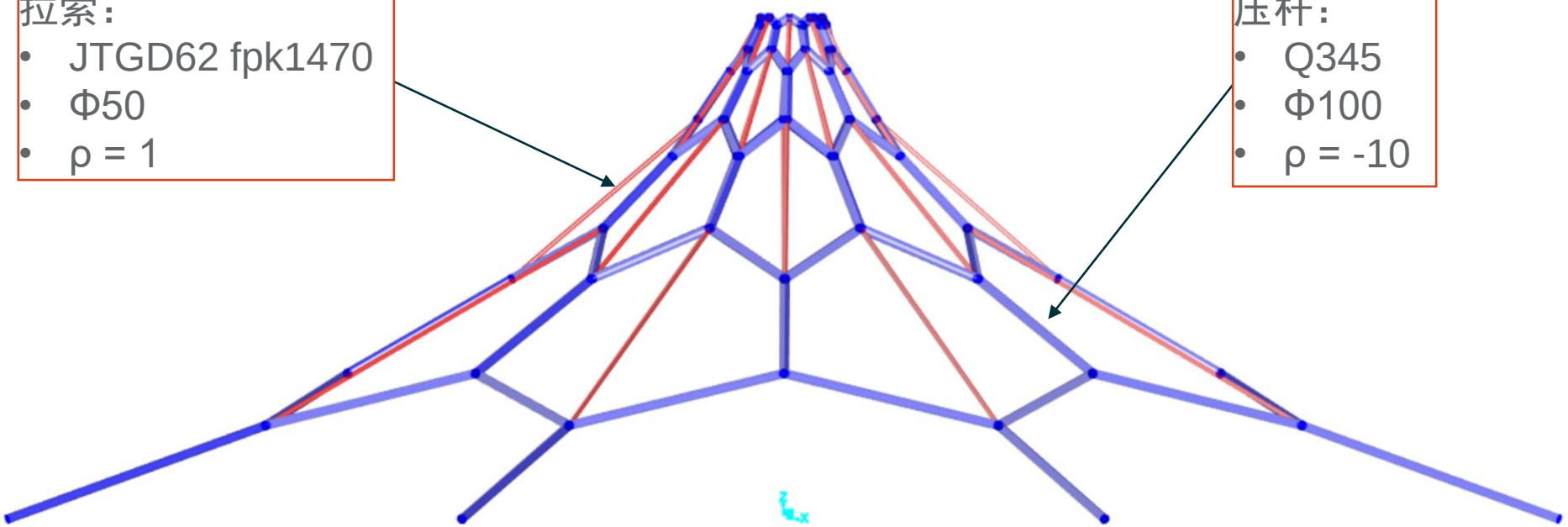


找形流程

- 可在SAP2000中对构件进行分组，指定不同的材料属性、截面和力密度值

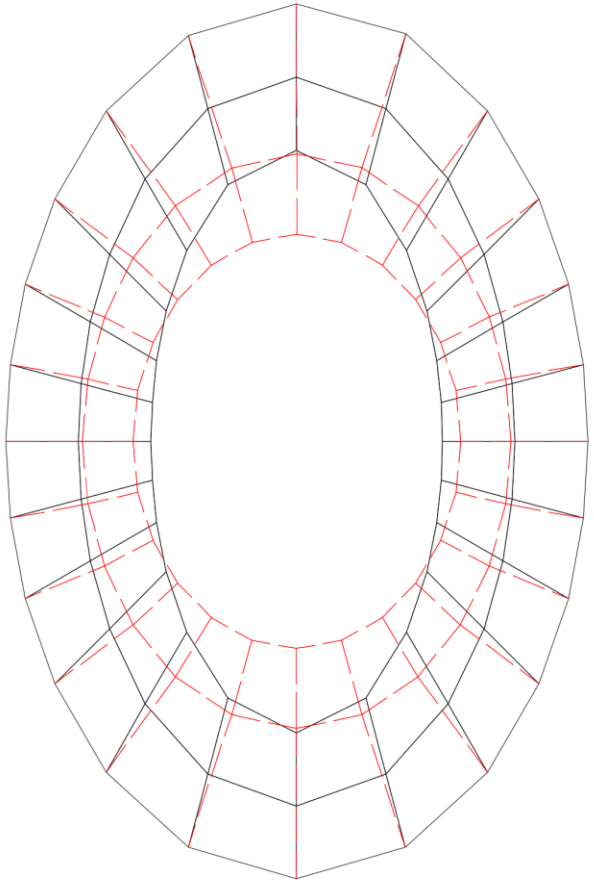
拉索：
- JTGD62 fpk1470
- Φ50
- ρ = 1

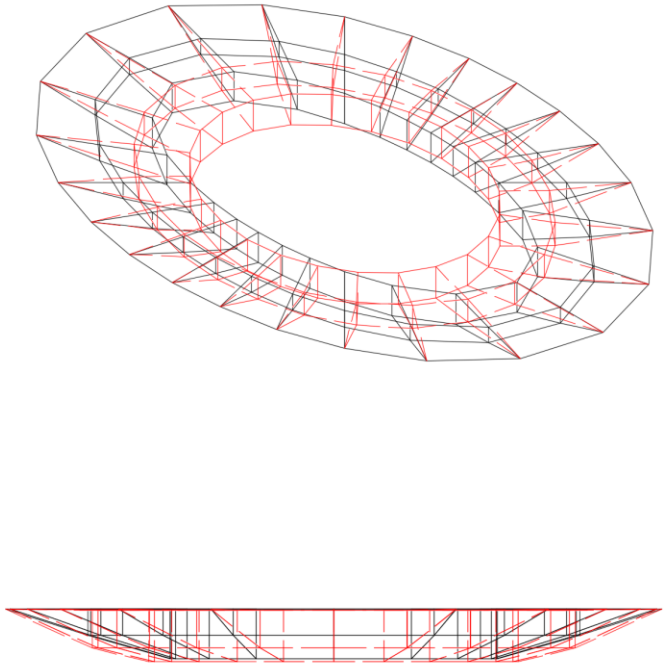
压杆：
- Q345
- Φ100
- ρ = -10



样例展示——轮辐式张拉屋盖

- 初始形状为同心椭圆
  - 外环300mx200m
  - 内环200mx100m，矢高15m
  - 径向索为直线
- 找形后
  - 外环为支座，形状不变
  - 内环142mx112m，矢高15.6m
  - 径向索为下凸折线，更加合理



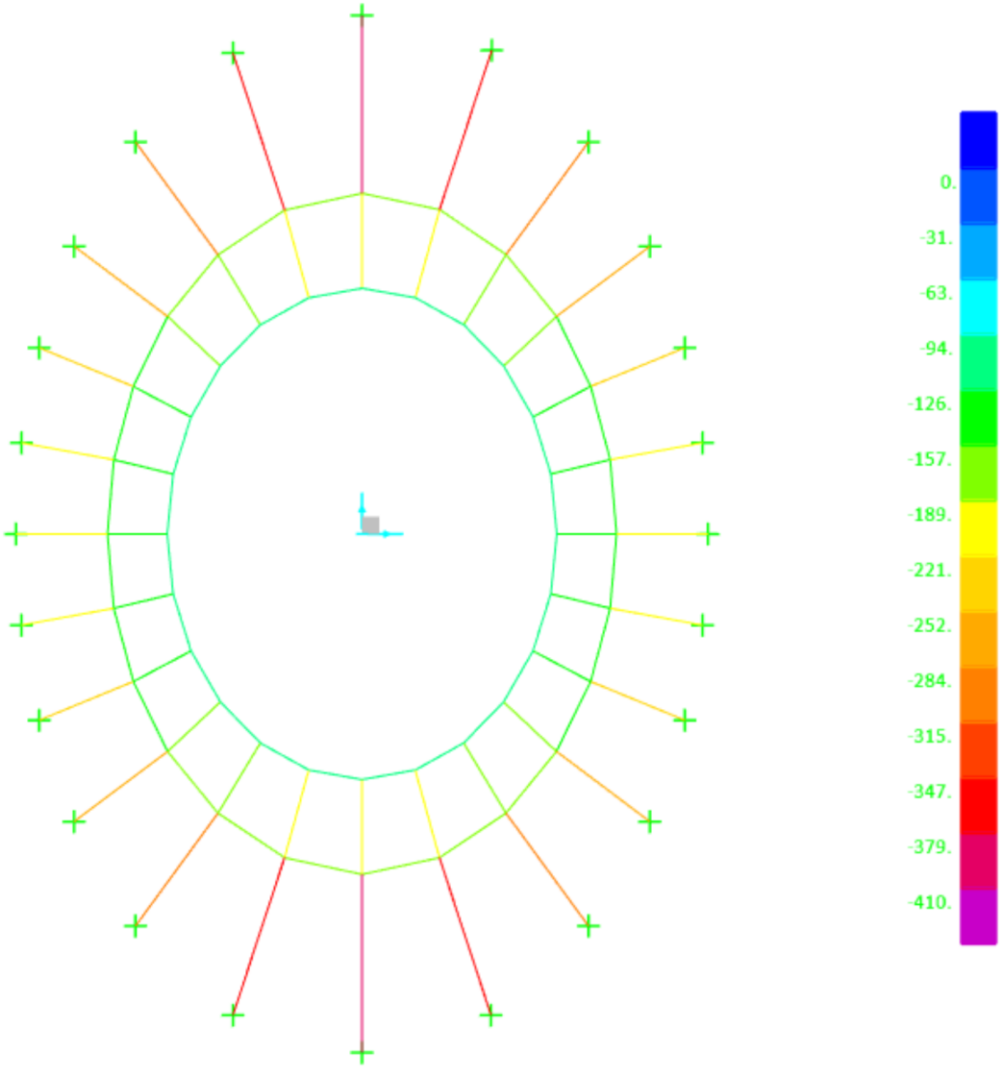


初始形状
找形后形状

样例展示——轮辐式张拉屋盖

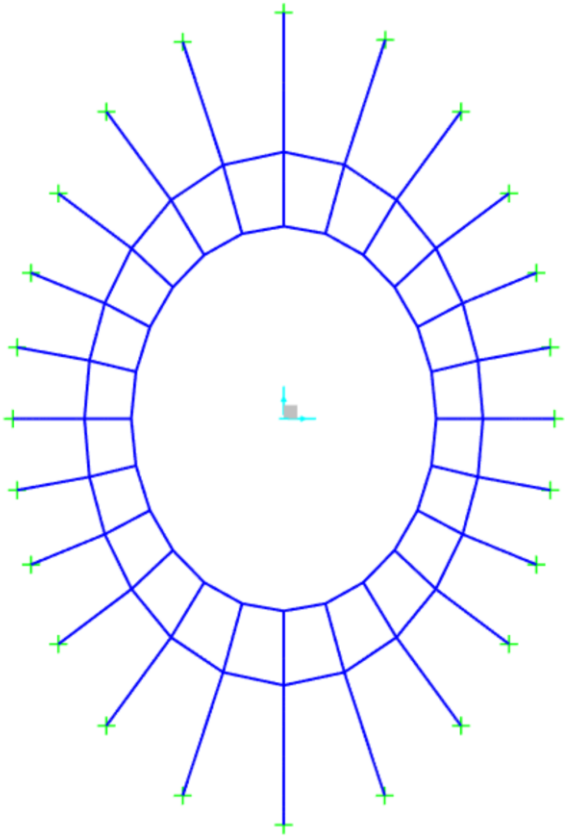
➢ 等效降温法初始温度的施加

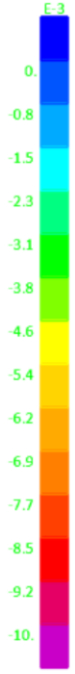
- 程序自动反算后输入到SAP2000
- 长轴向温度值最大大，短轴温度适当降低
- 中环索温度较低，内环索为最低

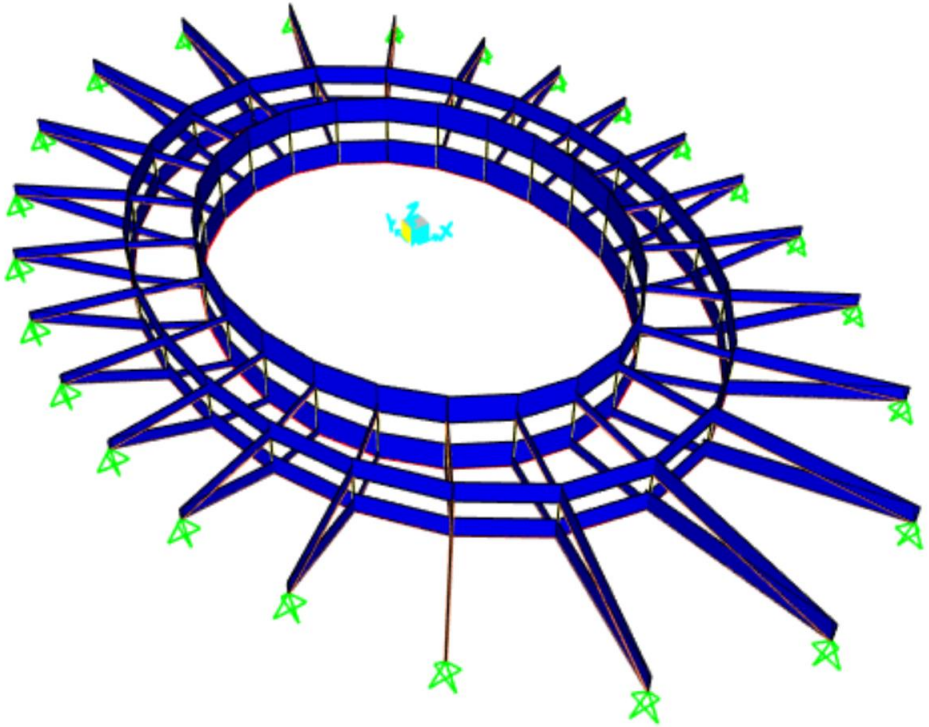


样例展示——轮辐式张拉屋盖

- 初始工况下变形为0
- Pre工况下(Pre_loading+Pre_temp)，所有索均受拉







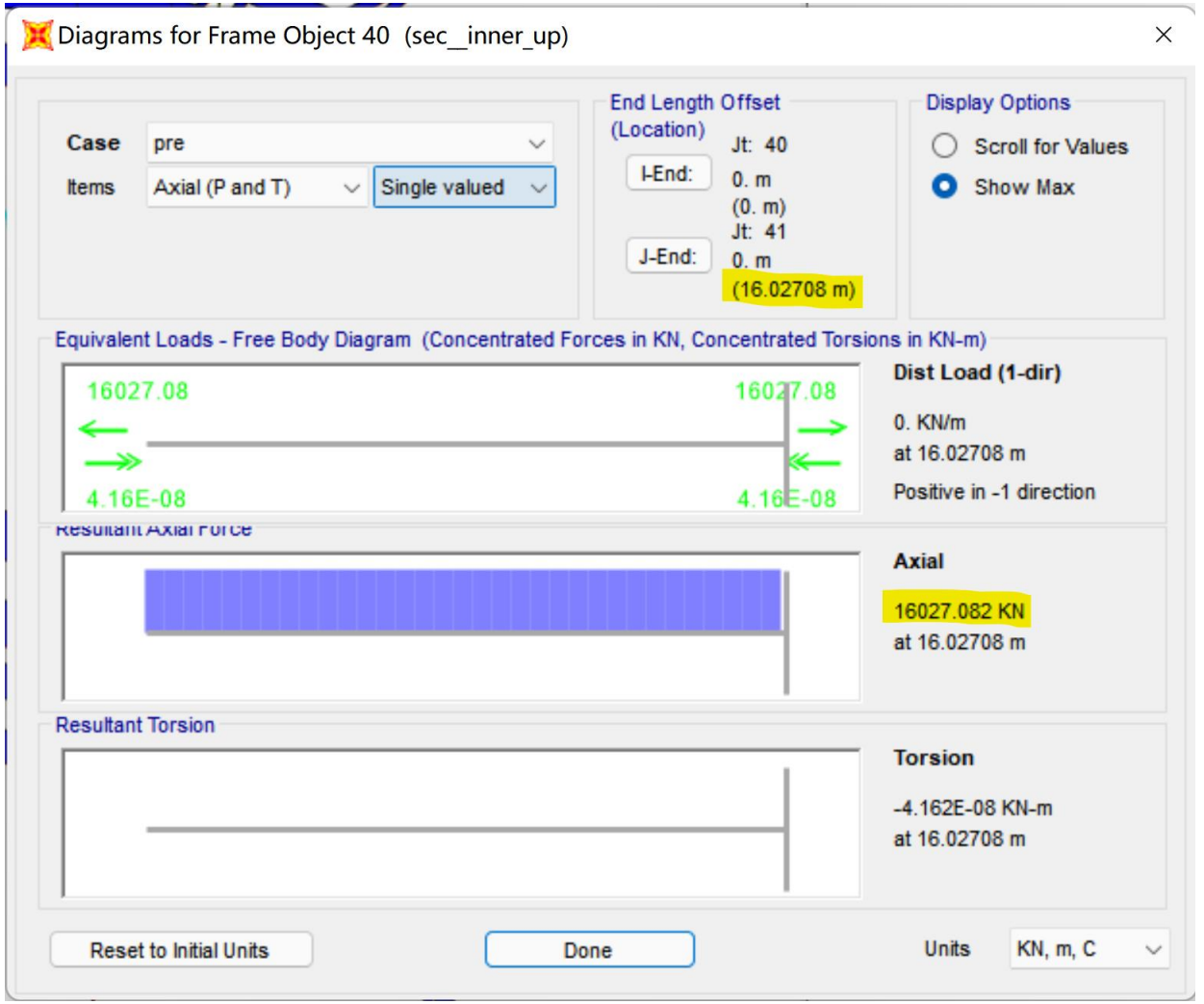
样例展示——轮辐式张拉屋盖

■ 力密度验证

$$l = 16.027m; F = 16027kN$$

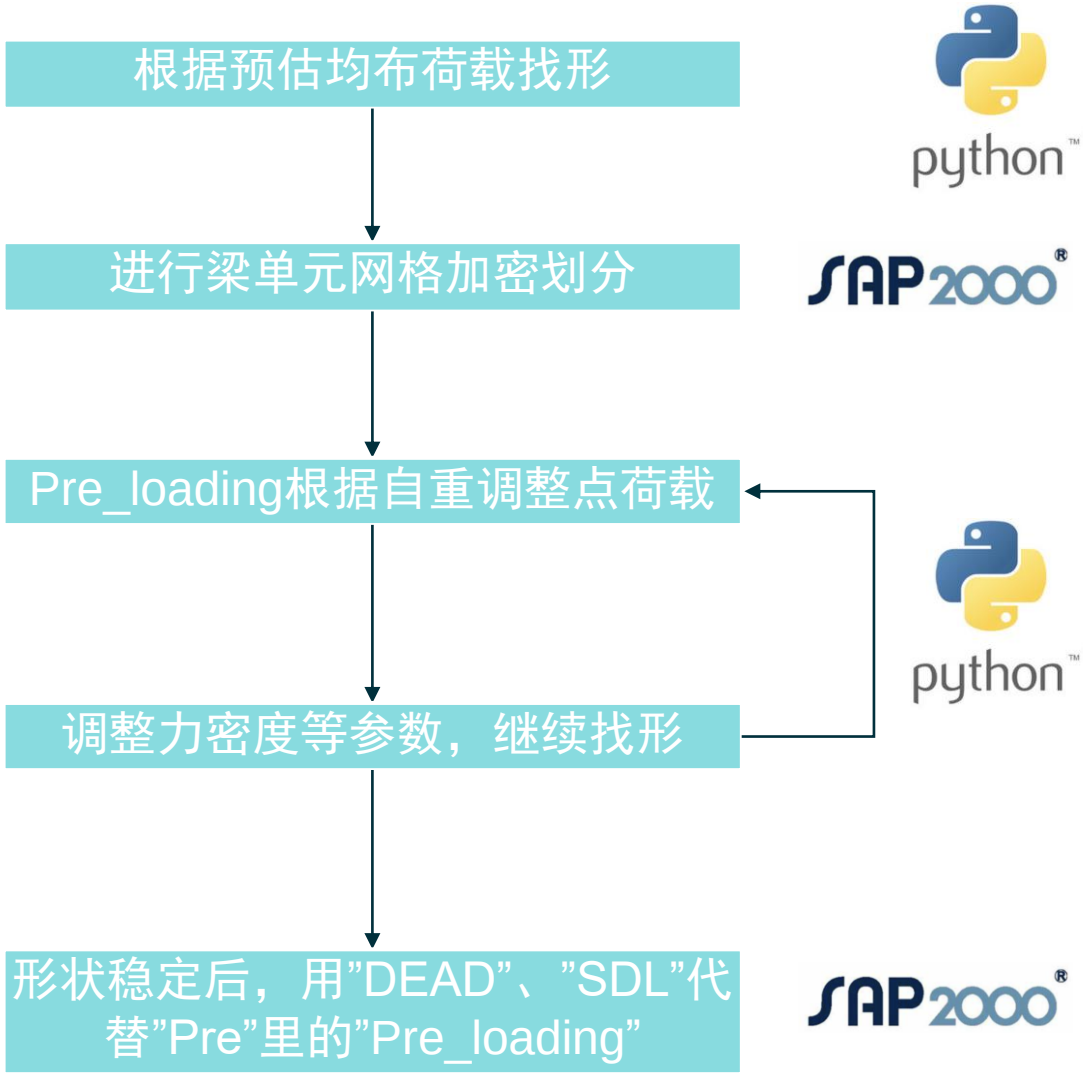
$$\rho = \frac{16027kN}{16.027m} = 1000kN/m$$

➢ Sap2000分析得到的力密度和初始输入完全一致




```
["inner_up", "China", "JTG", "JTGD62 fpk1470", 7,
 0.3, 1000],
```

自重下找形



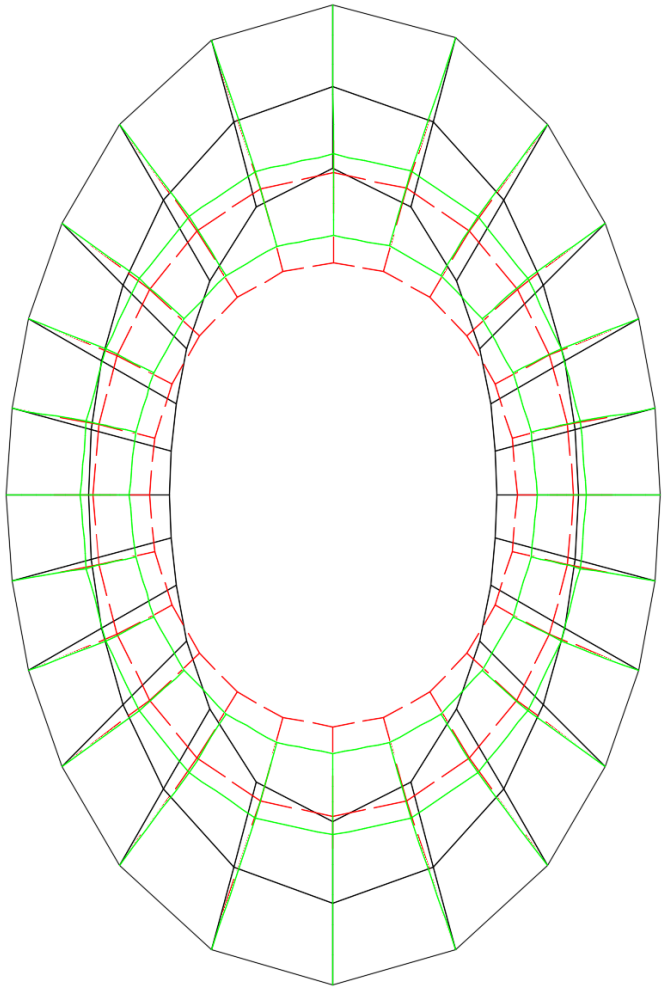

```
a.init_fr_sap2000("Pre_loading",
```

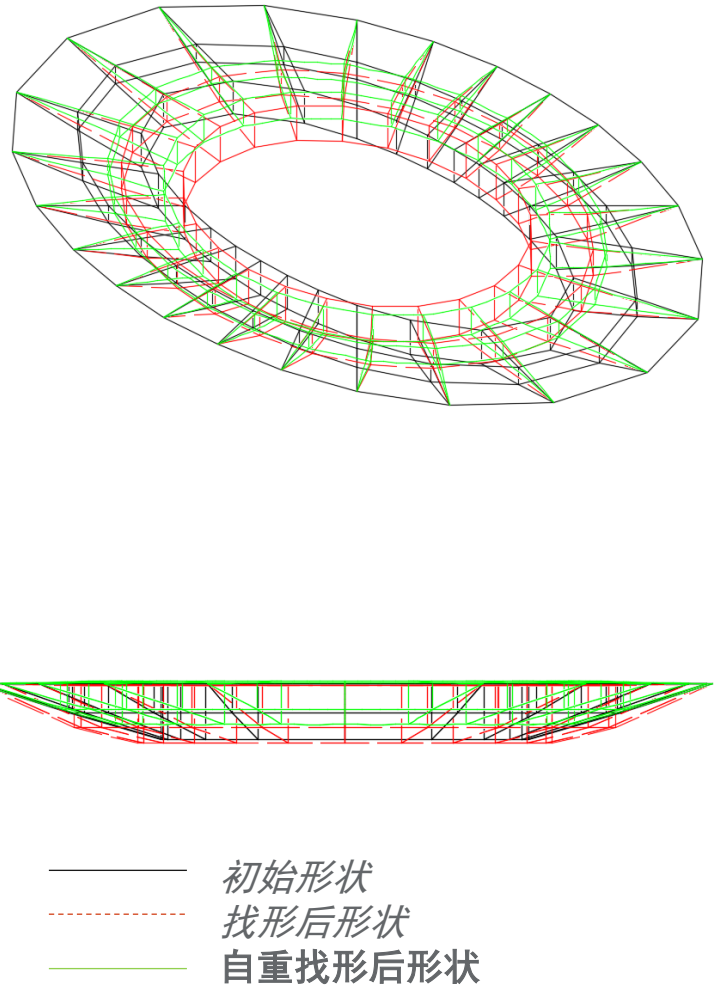
```
a.init_fr_sap2000(mass_assign(a.SapModel, "Pre_loading"),
```

- 循环计算次数越多，形状越准确

自重下找形——轮辐式张拉屋盖

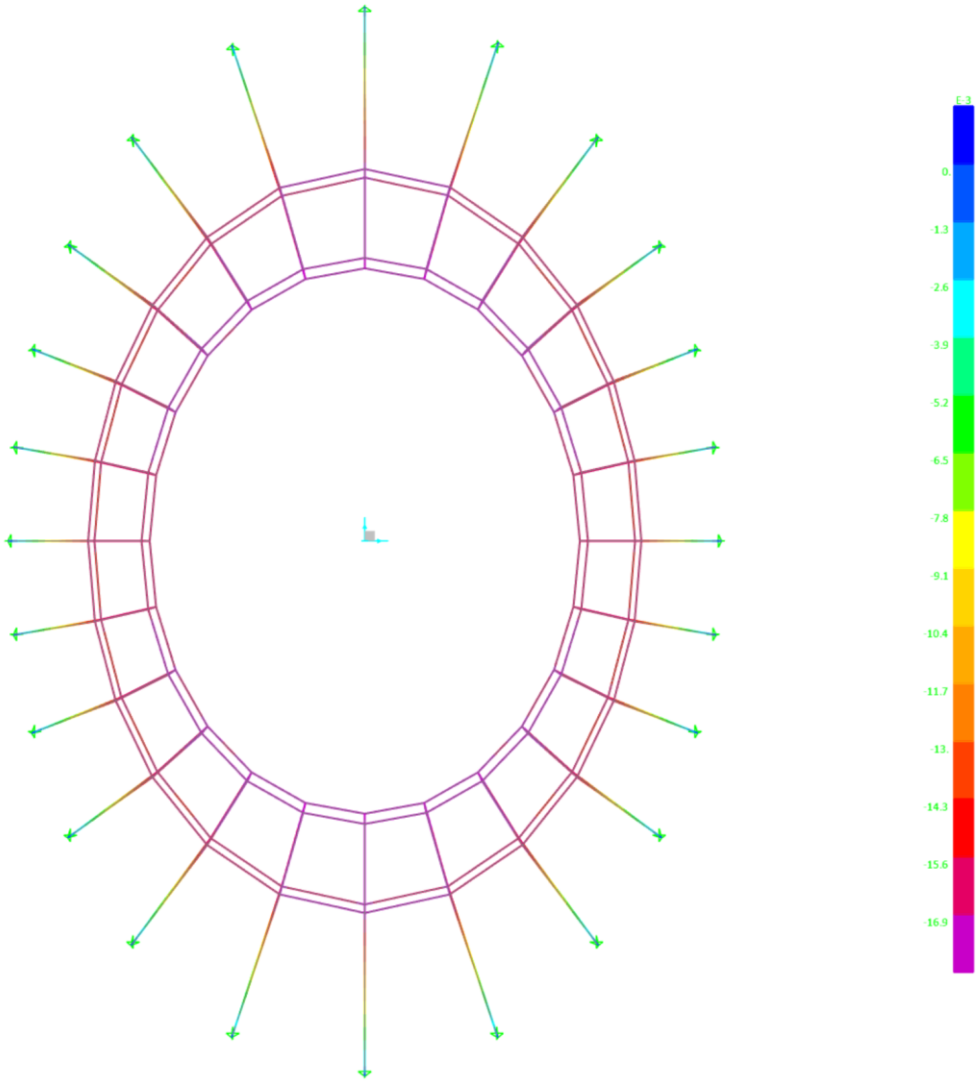
- 自重找形后
  - 内环尺寸增加到158x124
  - 结构上弦上鼓约1m
  - 矢高减小到10m





自重下找形——轮辐式张拉屋盖

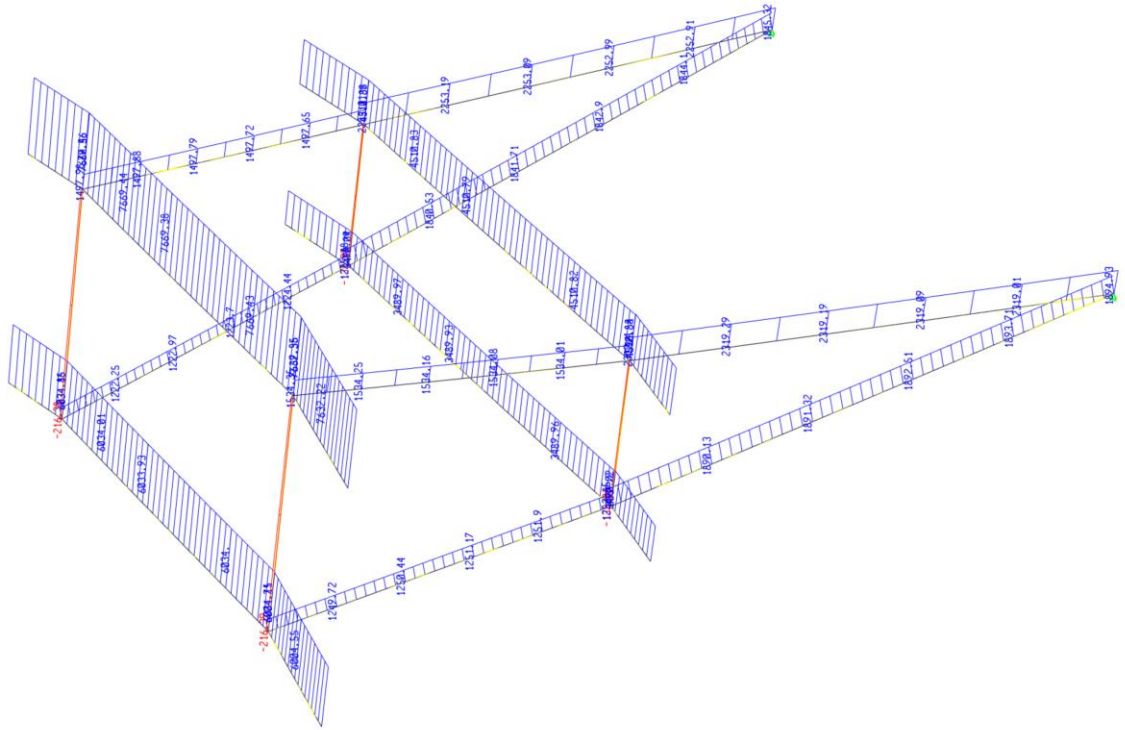
- 成型态下最大竖向变形仅约16.9mm
- 整体变形较为均匀



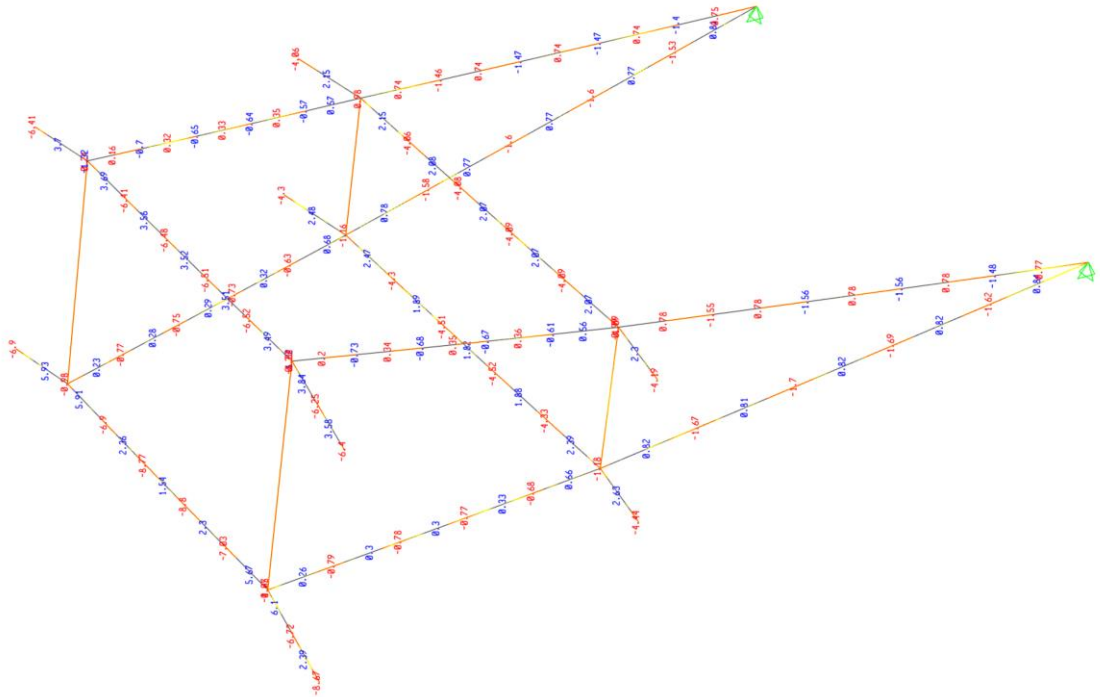
自重下找形——轮辐式张拉屋盖

- 结构仍受轴力为主，次内力可以忽略

■ Dead+SDL+pre_temp轴力图



■ Dead+SDL+pre_temp弯矩图



结论和下一步工作

- 经过算例验证，本程序找到的结构形状是正确的
- 针对广州体育场的建议：
  - 因上弦形状固定，可将上弦转化为点荷载进行下弦拉索的找形
  - 下弦形状确定后，进行上下弦模型组装和分析
  - 可能需多轮迭代，得到最终的屋盖形状

THANK YOU

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