ME 254

Subtleties in Finite Element Analysis of Compliant Mechanisms

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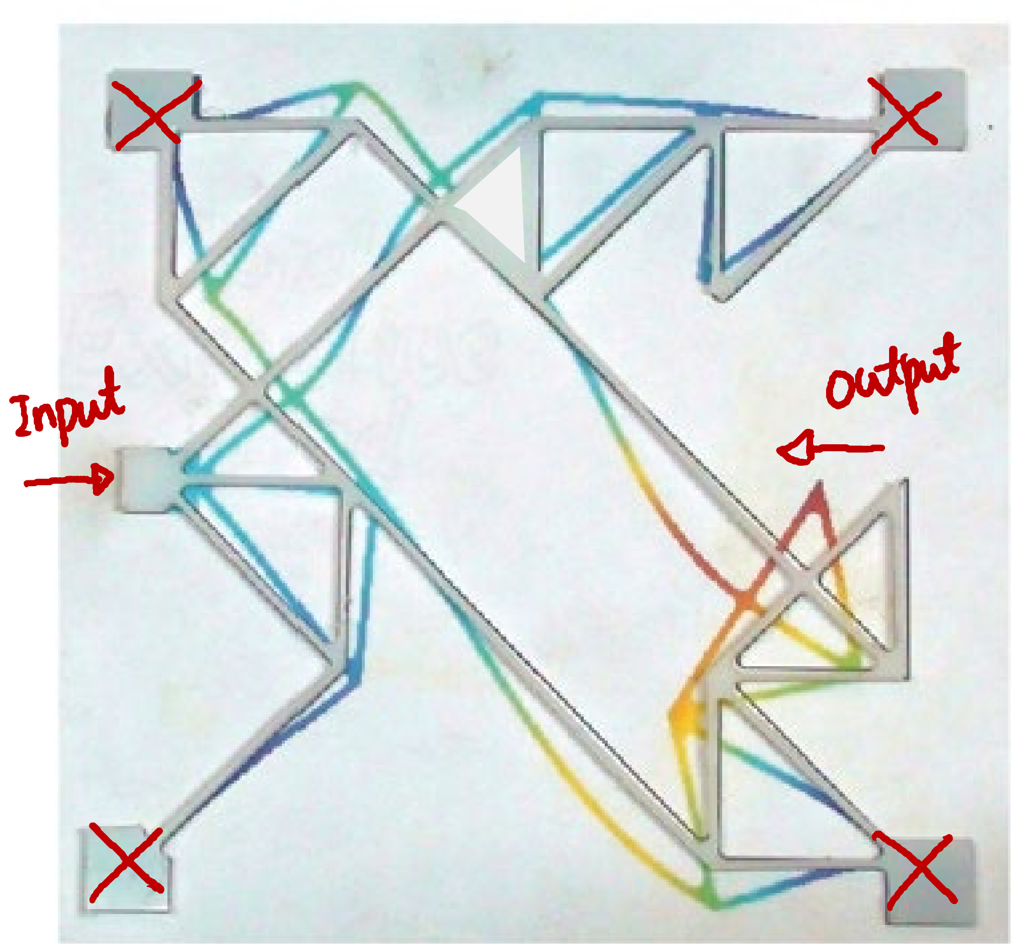
How do we tell linear and nonlinear analyses apart?

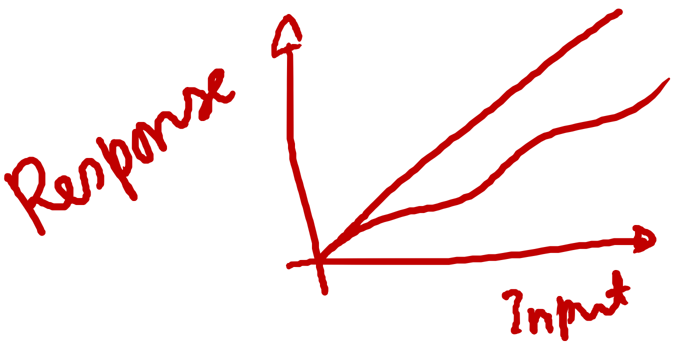


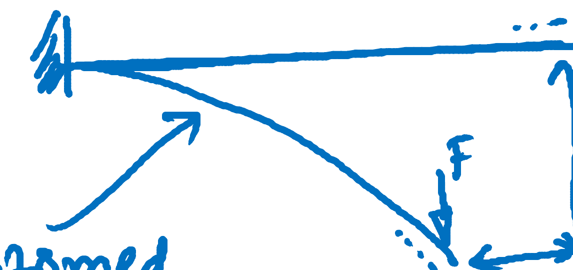
Sources of nonlinearity in elastic bodies

1. Geometric nonlinearity
   - Large displacements/rotations
   - Large strain
2. Material nonlinearity

$$\underset{3\times 1}{\bar{\sigma}} = \underset{3\times 3}{\bar{\bar{D}}}\ \underset{3\times 1}{\bar{\varepsilon}}$$

3. Boundary condition related nonlinearity (contact)
4. Stress-stiffening





"Deformed configuration"

Further reading

Geometrically Nonlinear Elastic Analysis of Frames with Application to Vision-Based Force-sensing and Mechanics of Plant Stems

A Project Report
Submitted in partial fulfilment of the requirements for the Degree of
Master of Engineering
in
Mechanical Engineering

by

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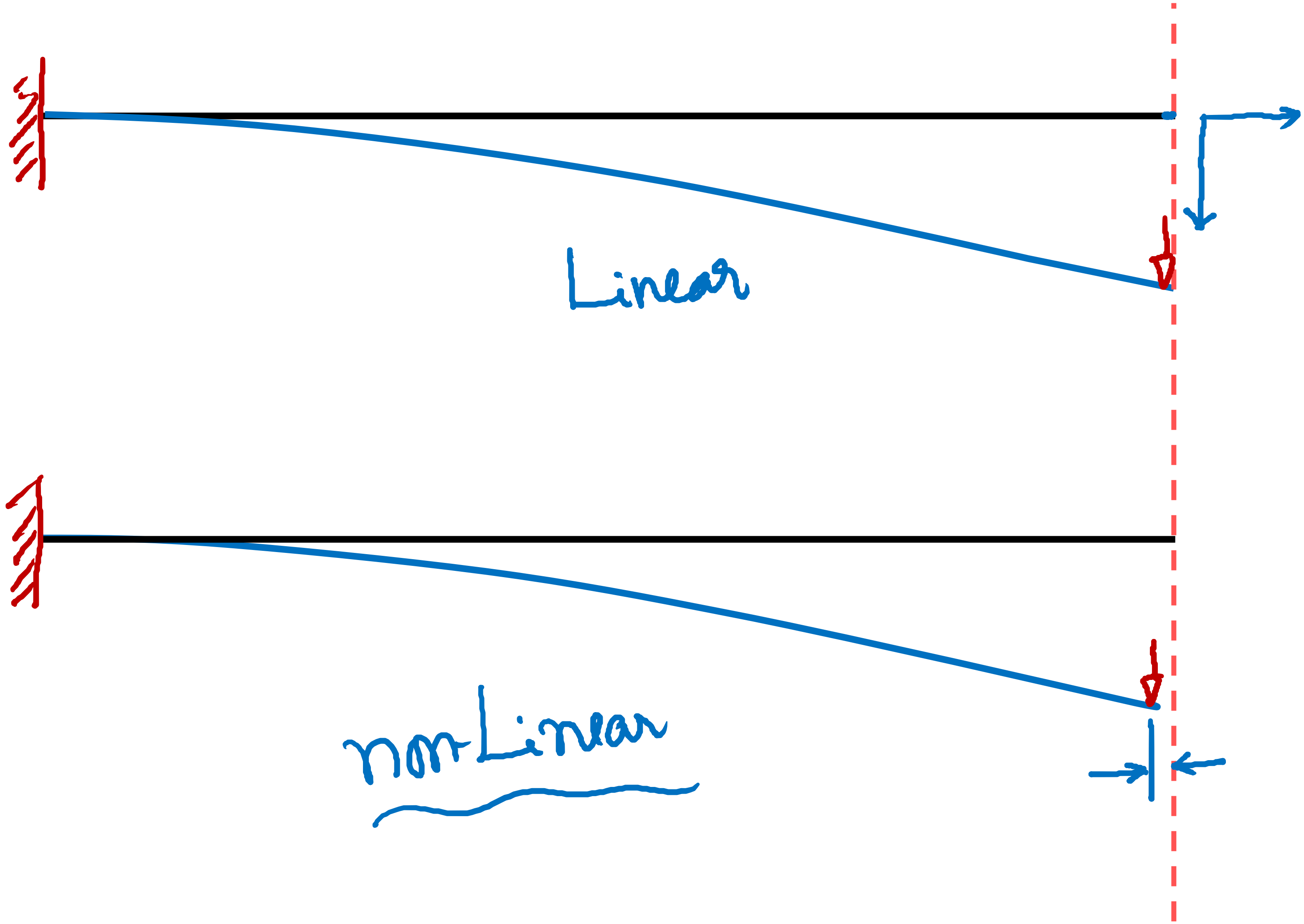
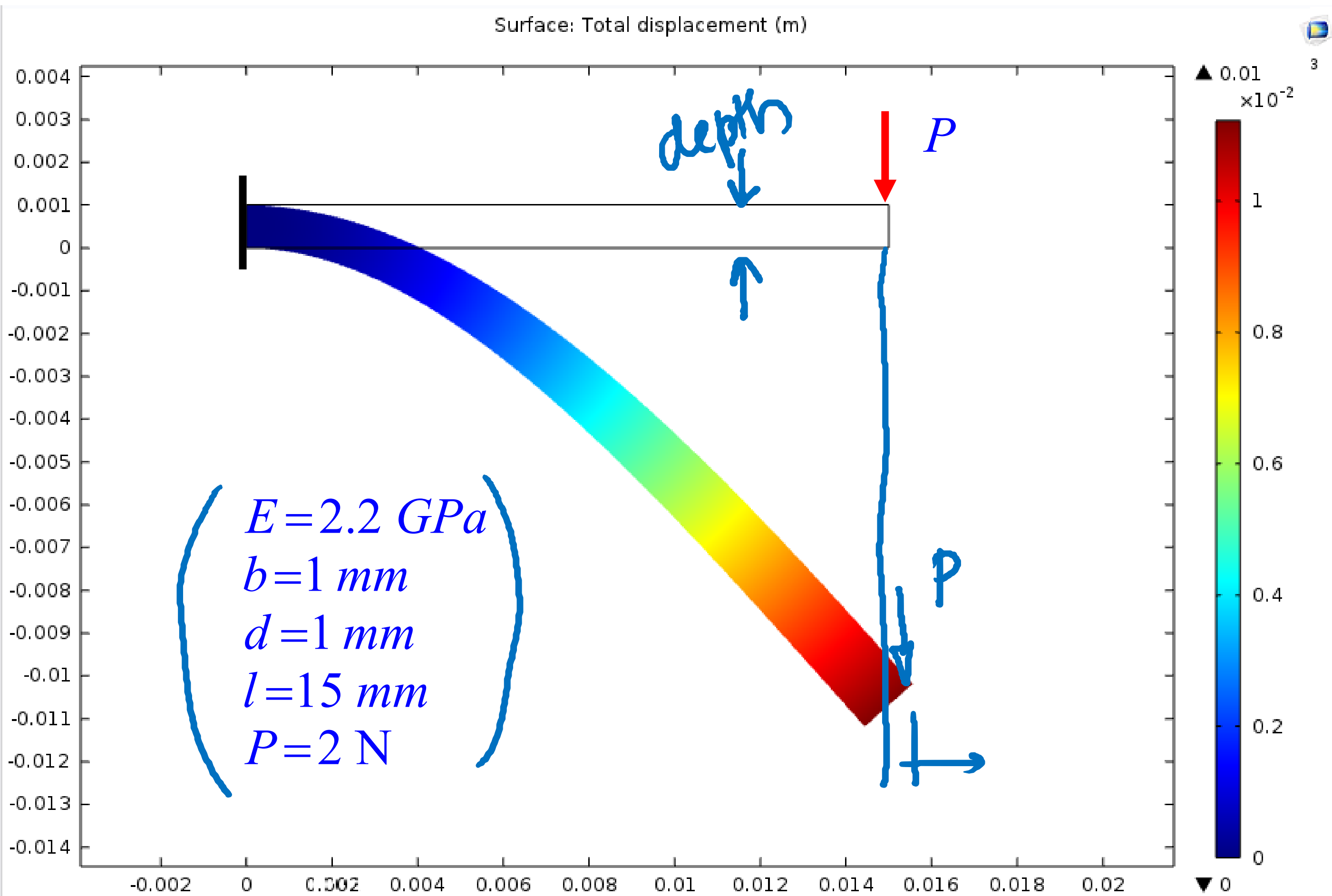
INDIAN INSTITUTE OF SCIENCE
BANGALORE – 560 012
JULY 2006

Section 4.10 in
"Micro and Smart Systems"
Wiley-India, 2010.

Deformation of a cantilever beam

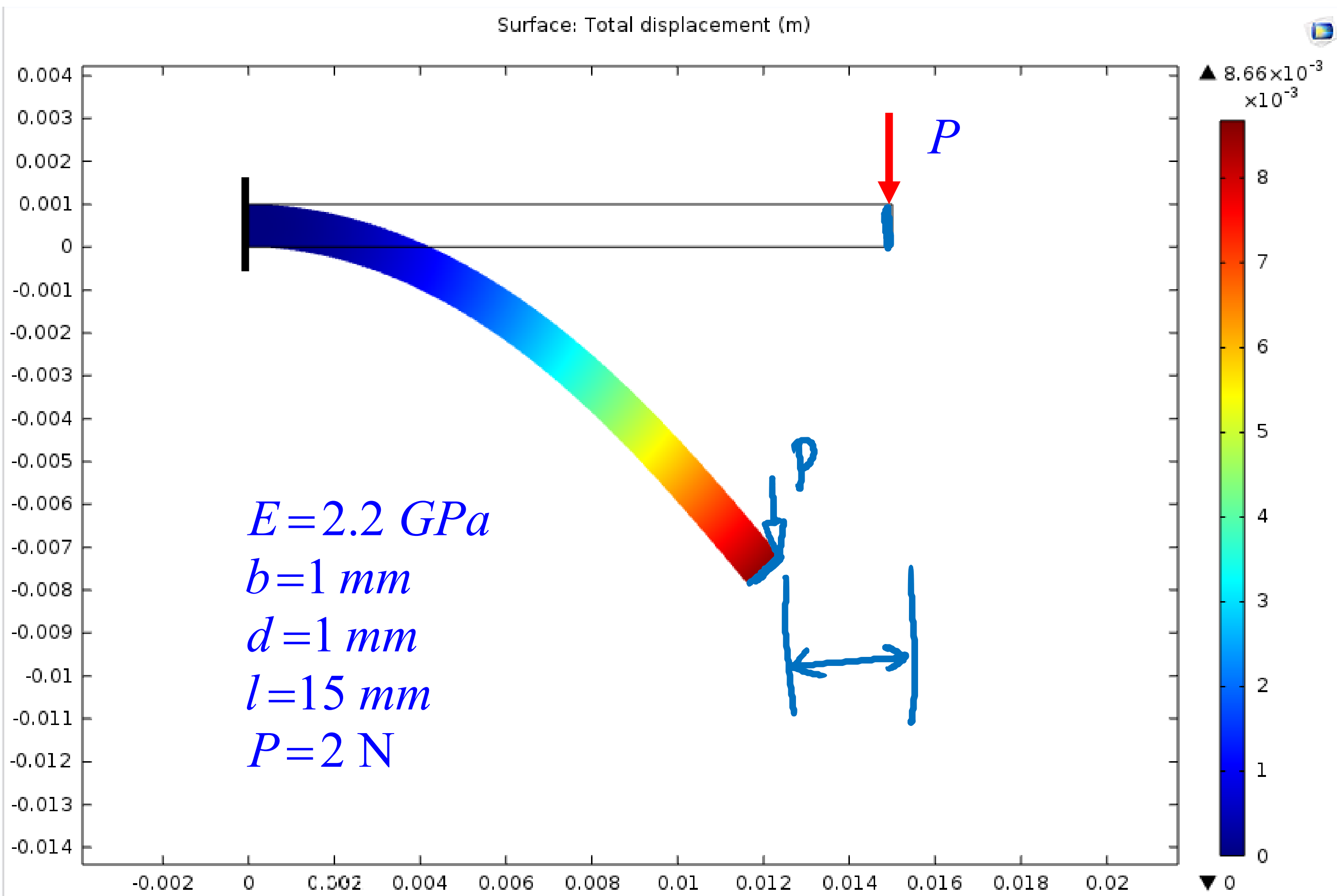


Linear Analysis



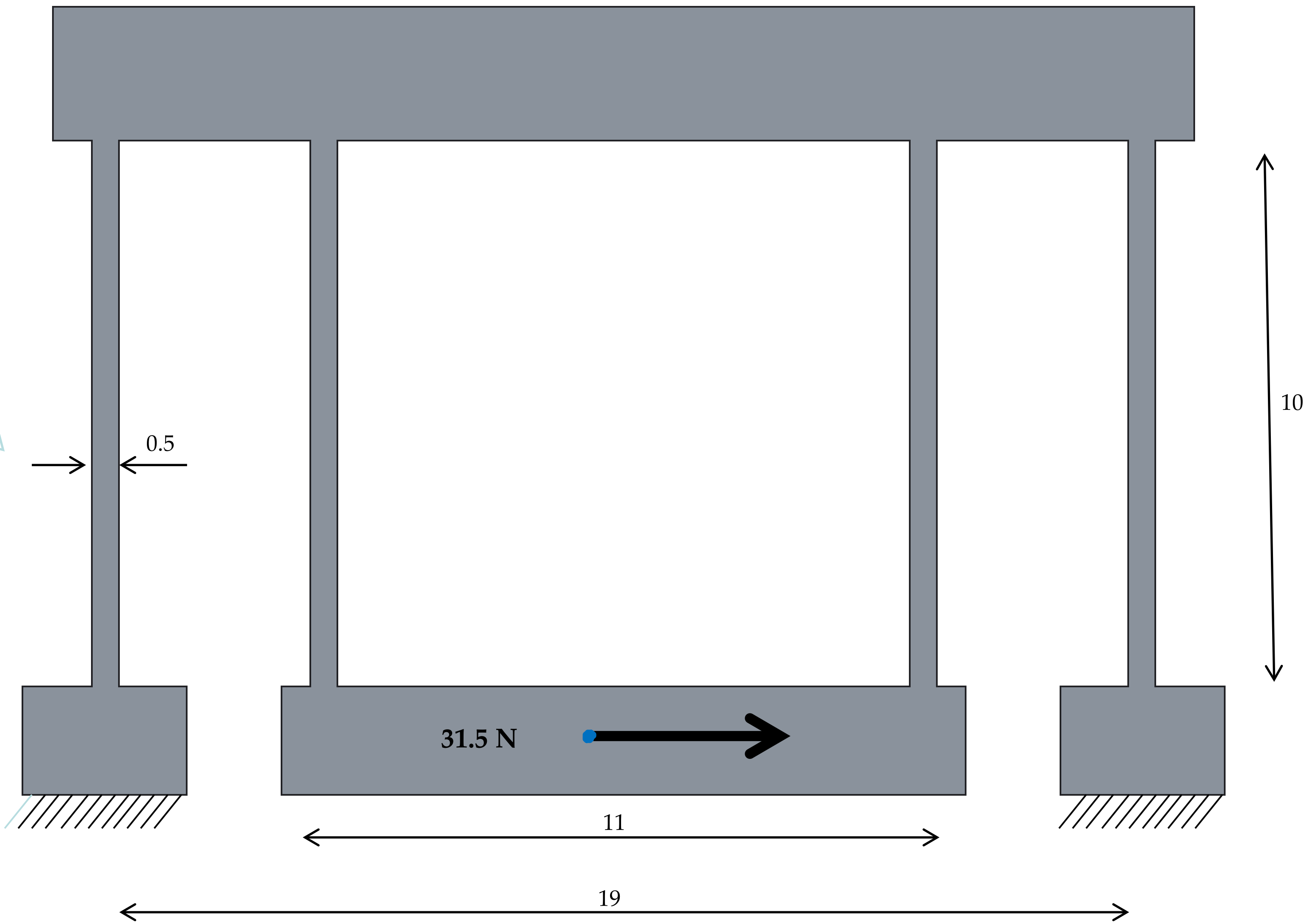
Nonlinear Analysis

Realistic picture

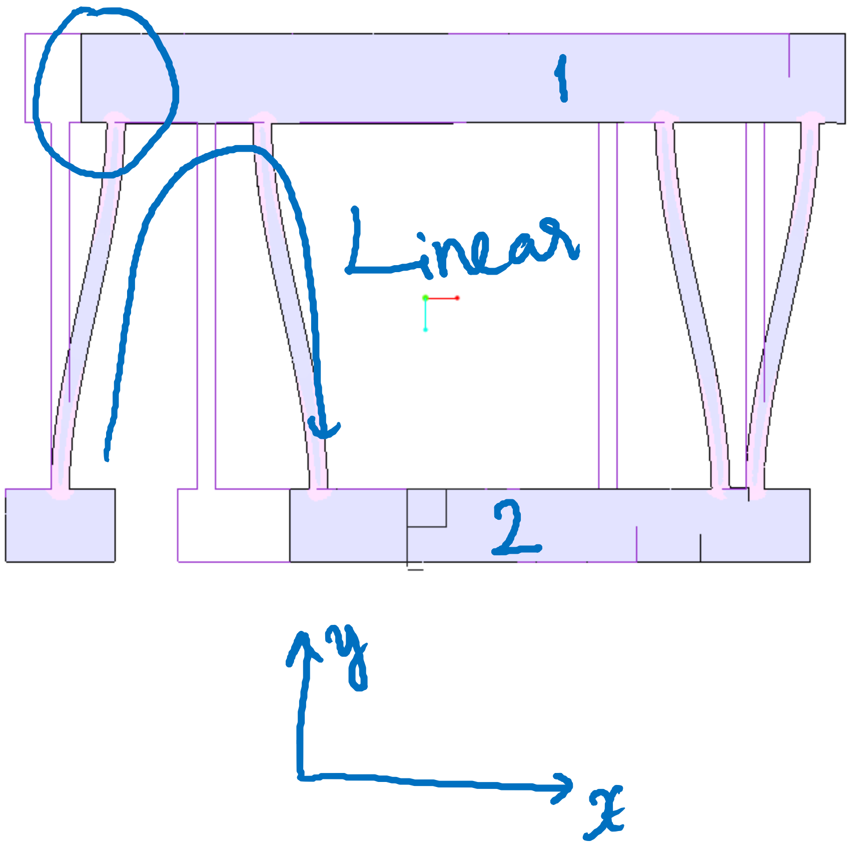


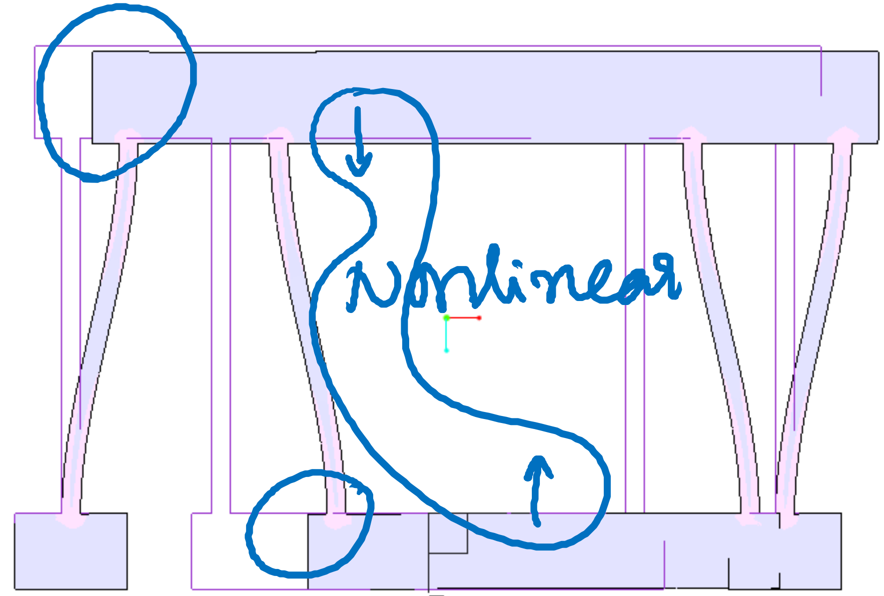
Double parallelogram: Simple ~~joints~~ beams

Elastic segments



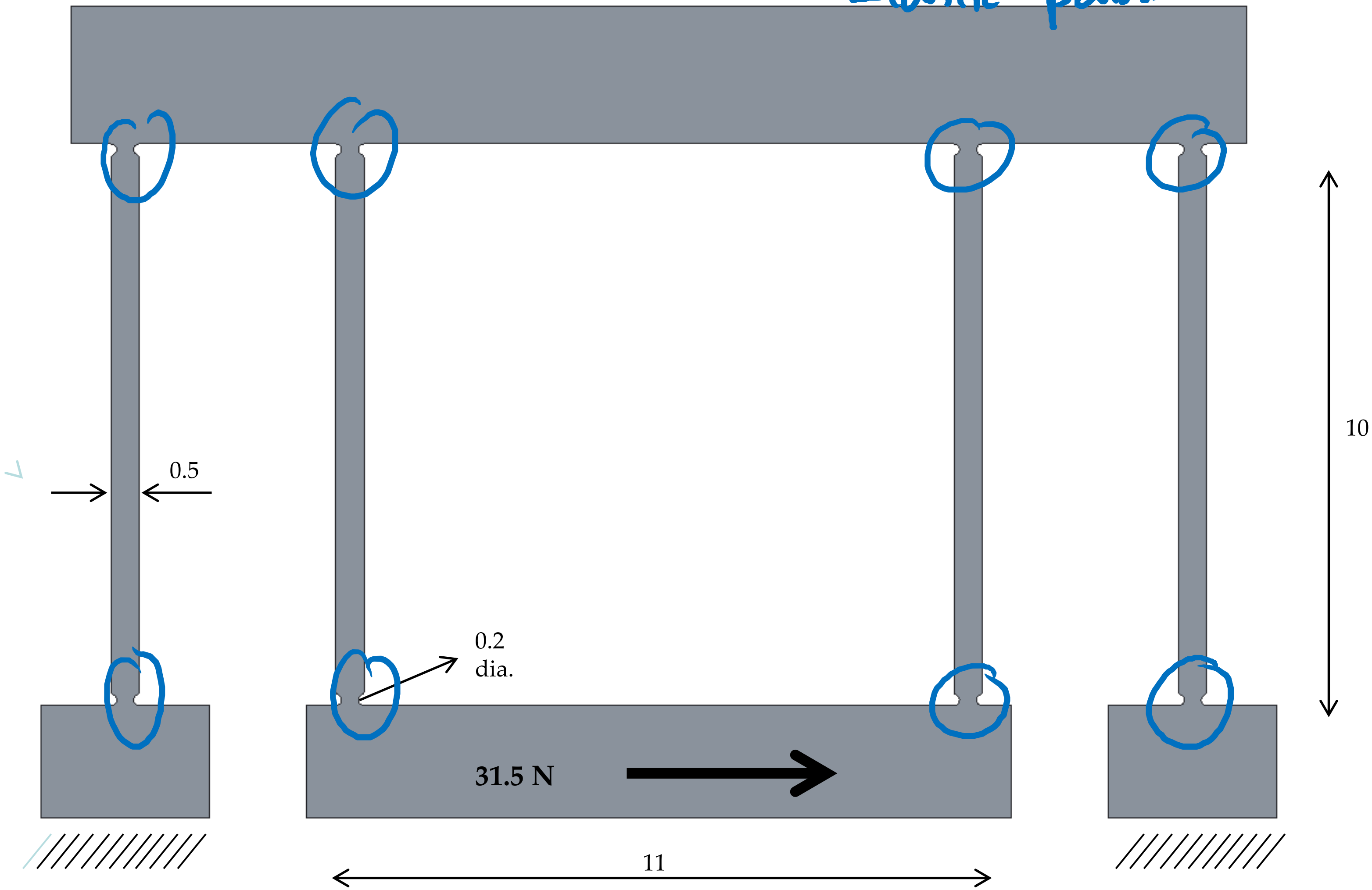
Results of FEA



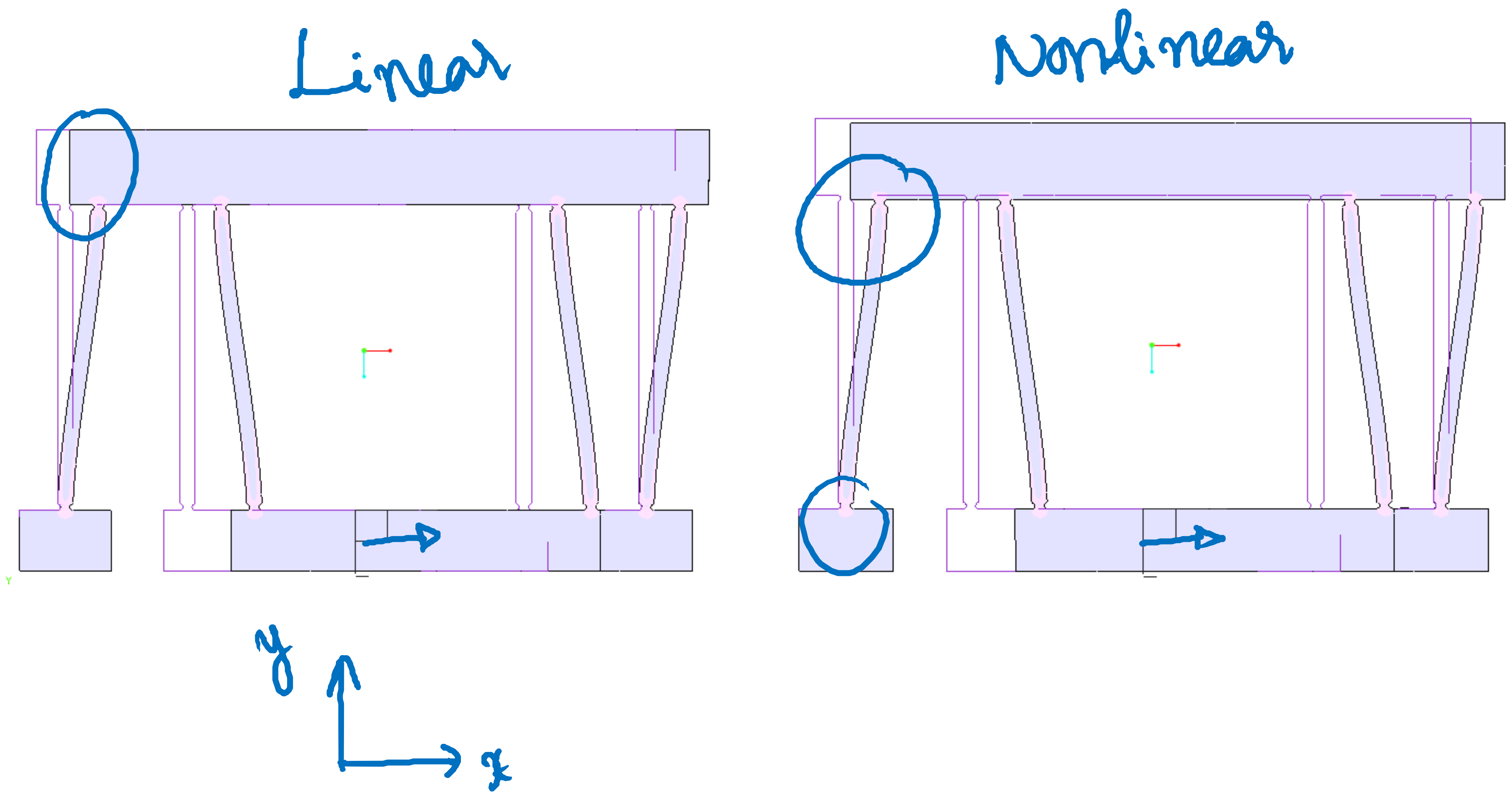


Double parallelogram: Notch flexures

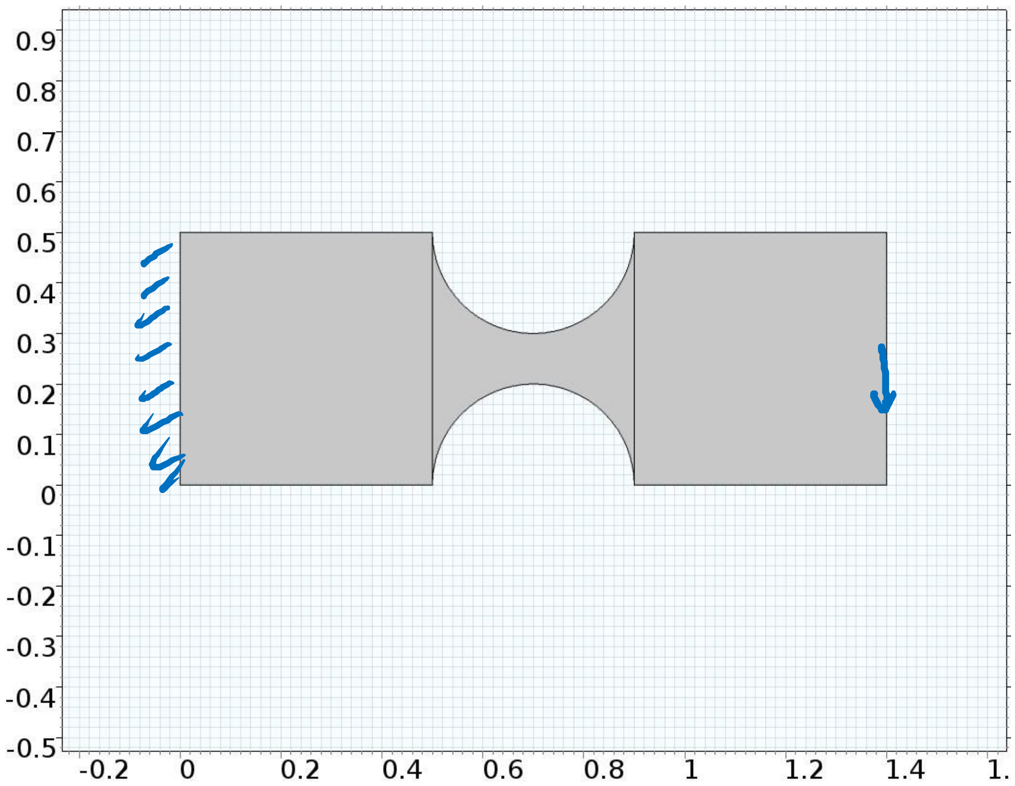
Elastic pairs



Results of FEA

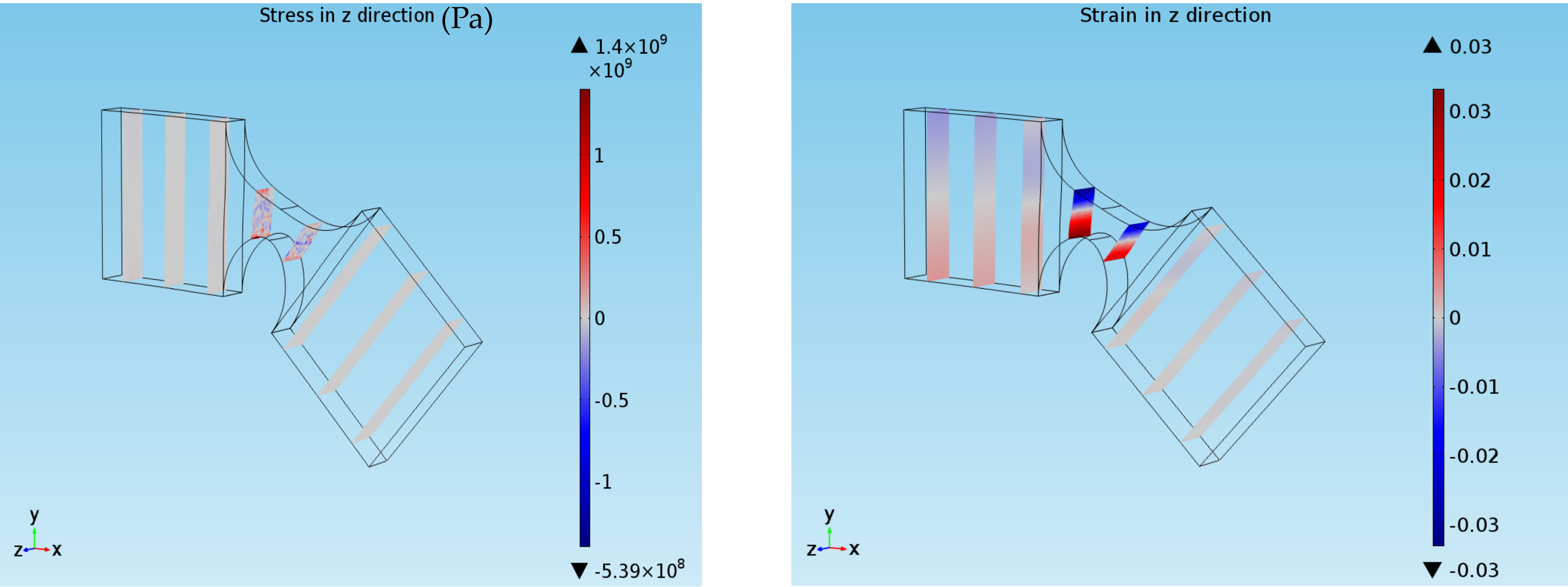


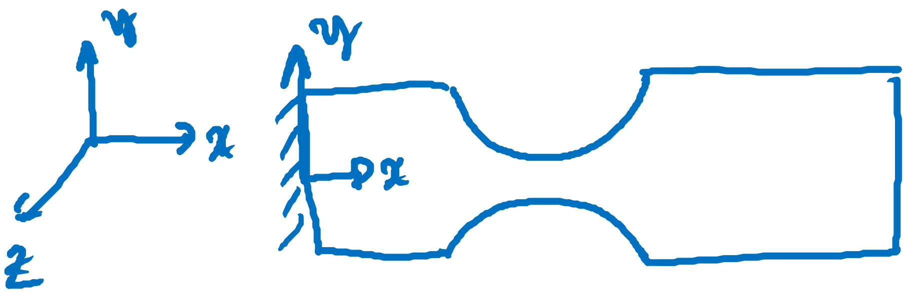
Circular flexure hinge



(All dimensions are in mm)

Plane-stress analysis





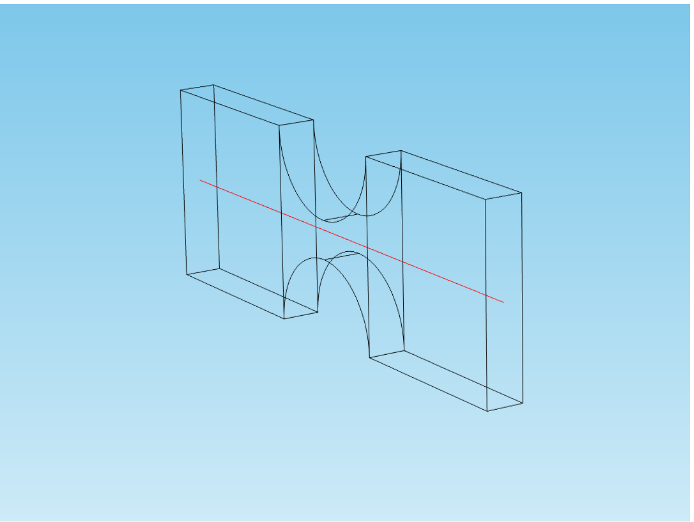
2D (planar)

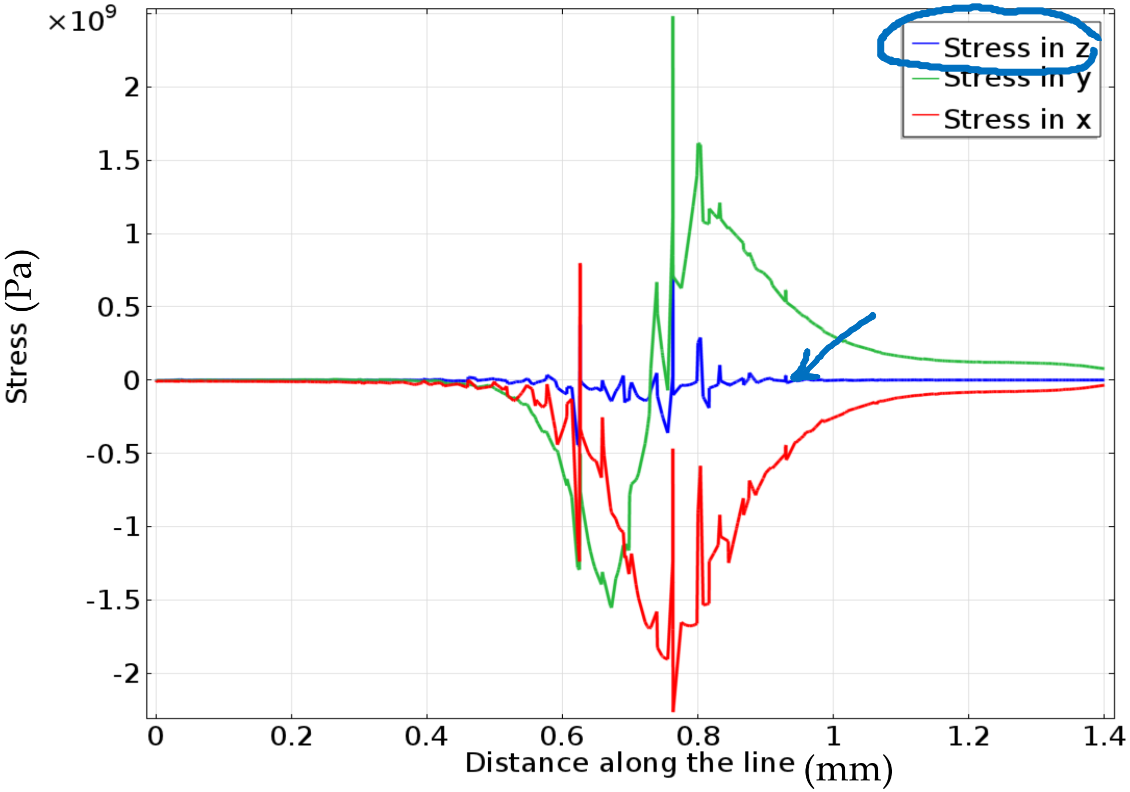
$\sigma_{zz} = 0$

$\sigma_{xz} = 0$

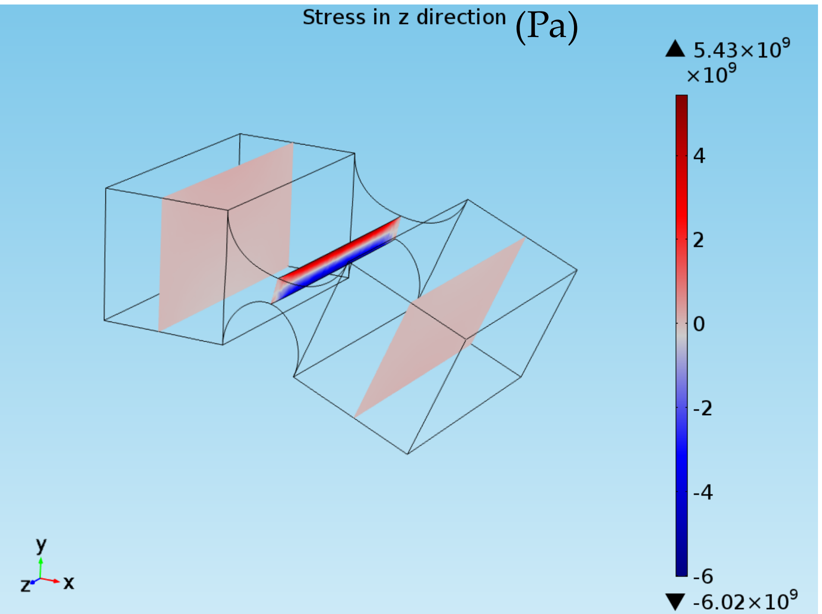
$\sigma_{yz} = 0$

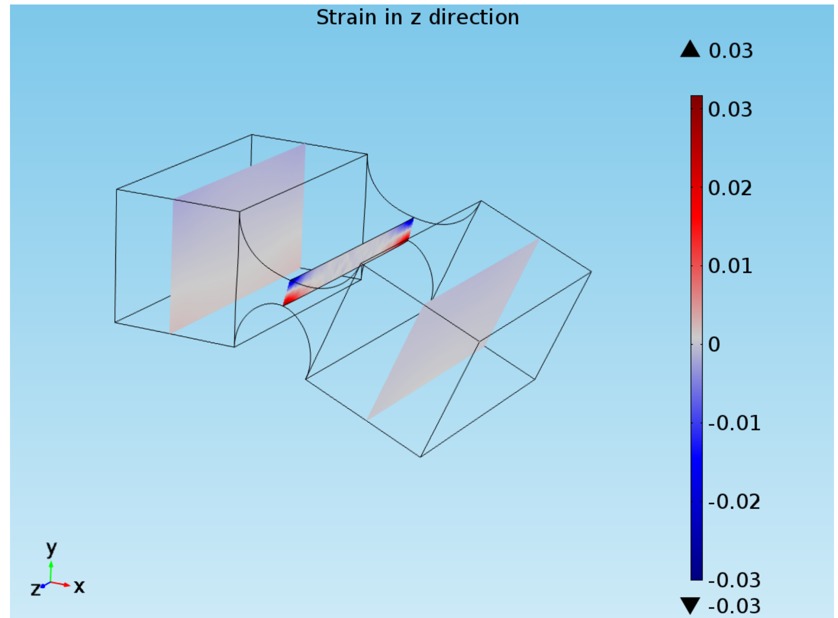
Plane-stress result





Plane-strain analysis

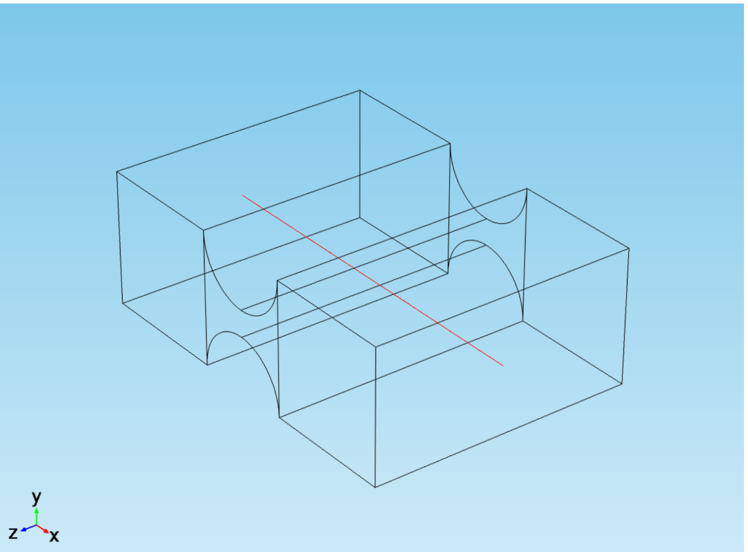


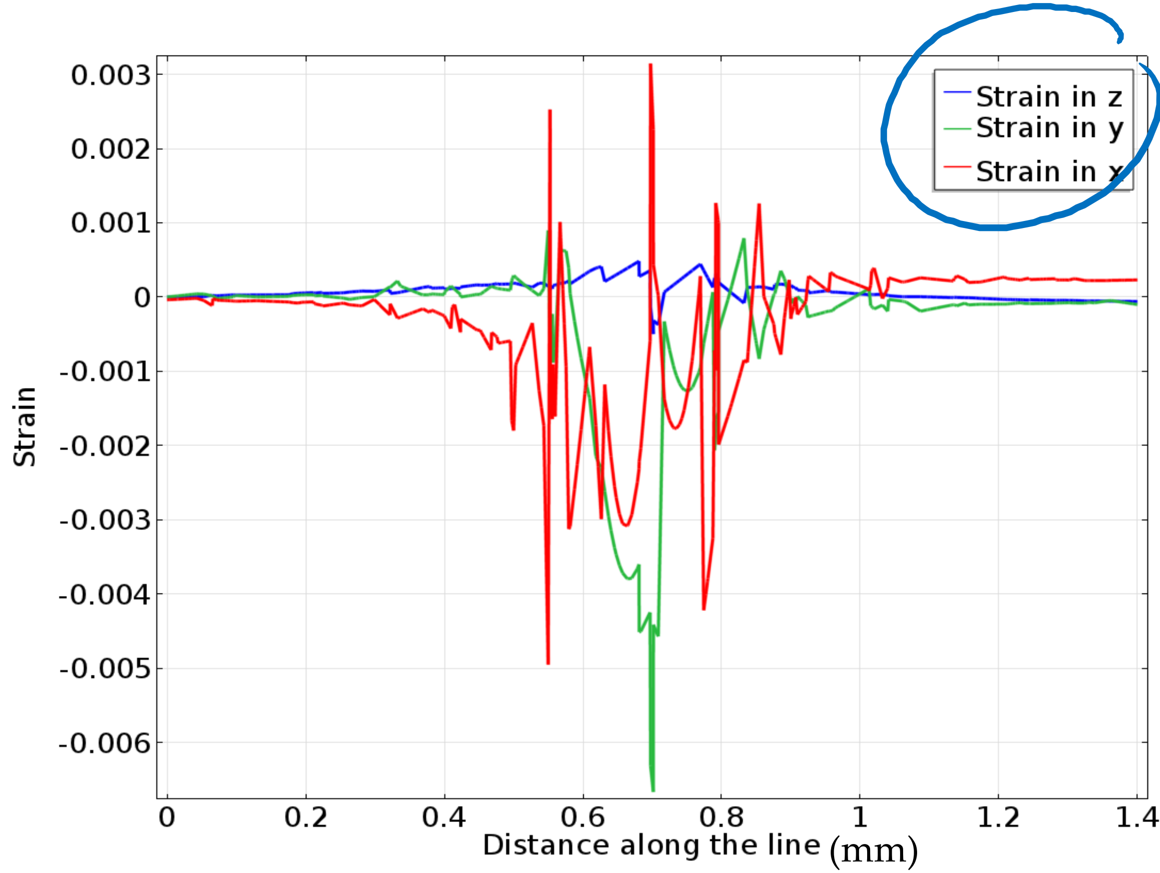


$$\boxed{\varepsilon_{zz} = \varepsilon_{zx} = \varepsilon_{yz} = 0}$$

Plane-strain condition

Plane-strain result





Plane-stress or plane-strain?

ASME Journal of Mech. Design 2004

On Systematic Errors of Two-Dimensional Finite Element Modeling of Right Circular Planar Flexure Hinges

B. Zettl

W. Szyszkowski

W. J. Zhang

Department of Mechanical Engineering,
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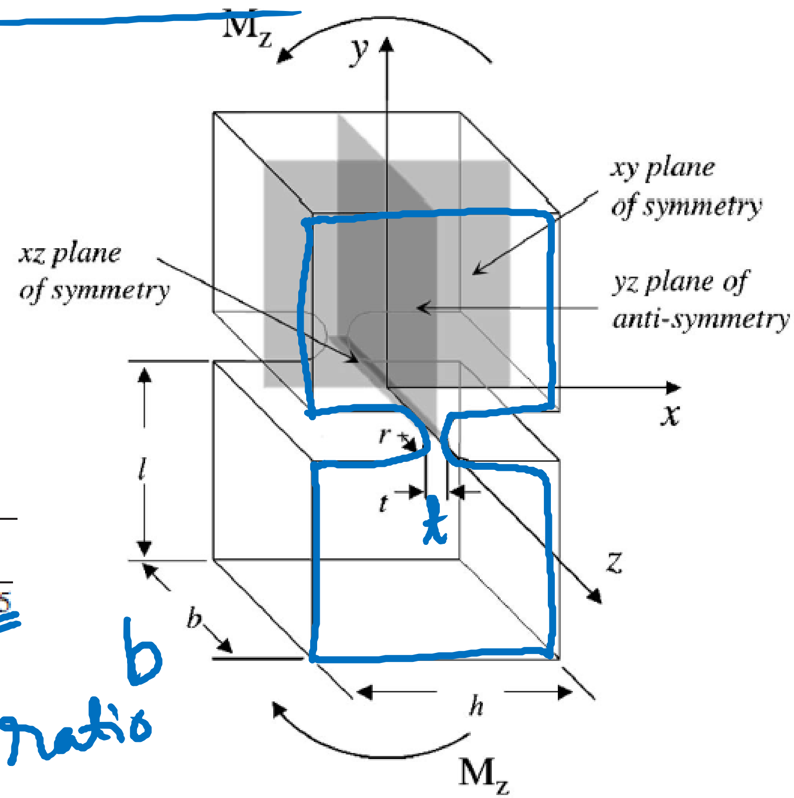
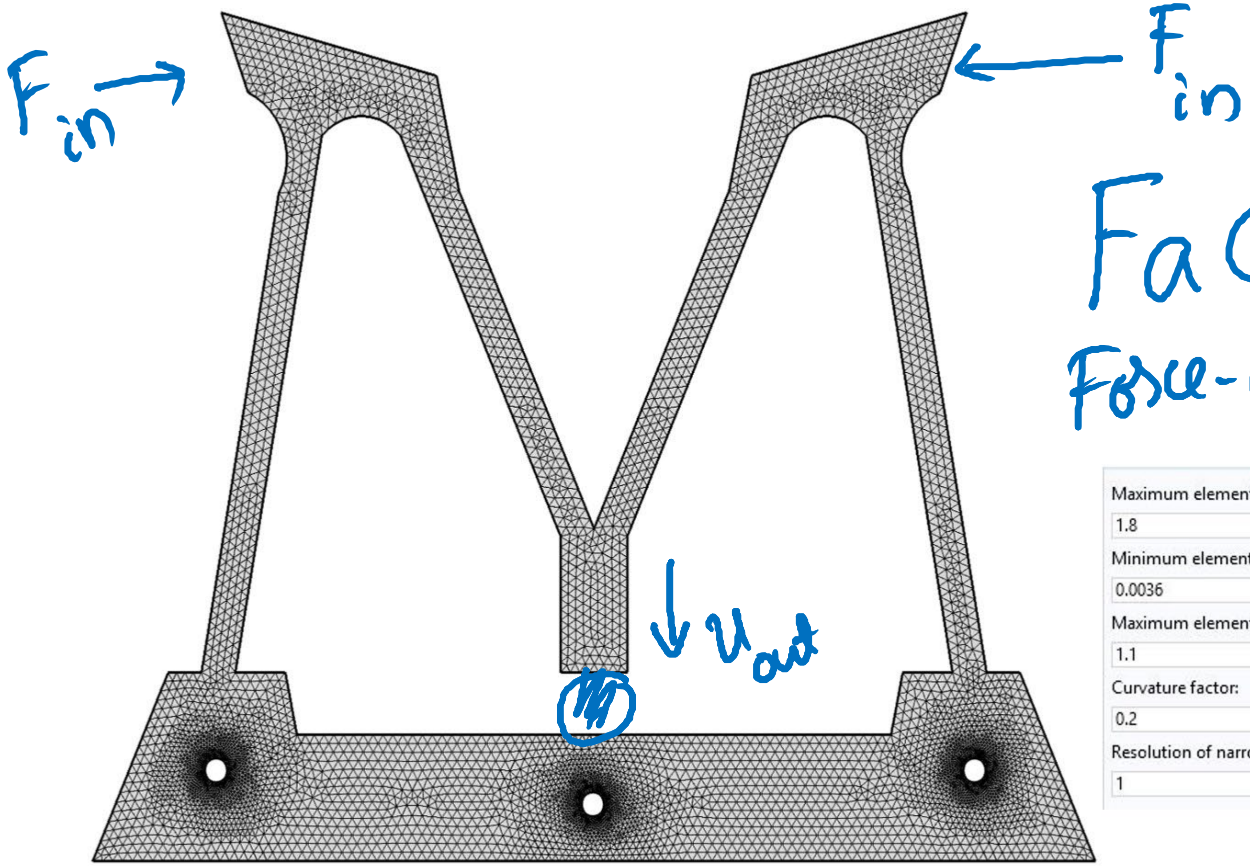
Saskatoon, S7N A9V, Canada



$$\frac{E_{\text{eff}}}{E} = \frac{k_\alpha^{3D}}{k_\alpha^{\sigma}} \cong \frac{1}{1 - \dfrac{\mu^2}{1 + 11.2\left(\dfrac{t}{b}\right)^{1.75}}}$$

b

μ = Poisson's ratio



FaCM

Force-amplifying CM

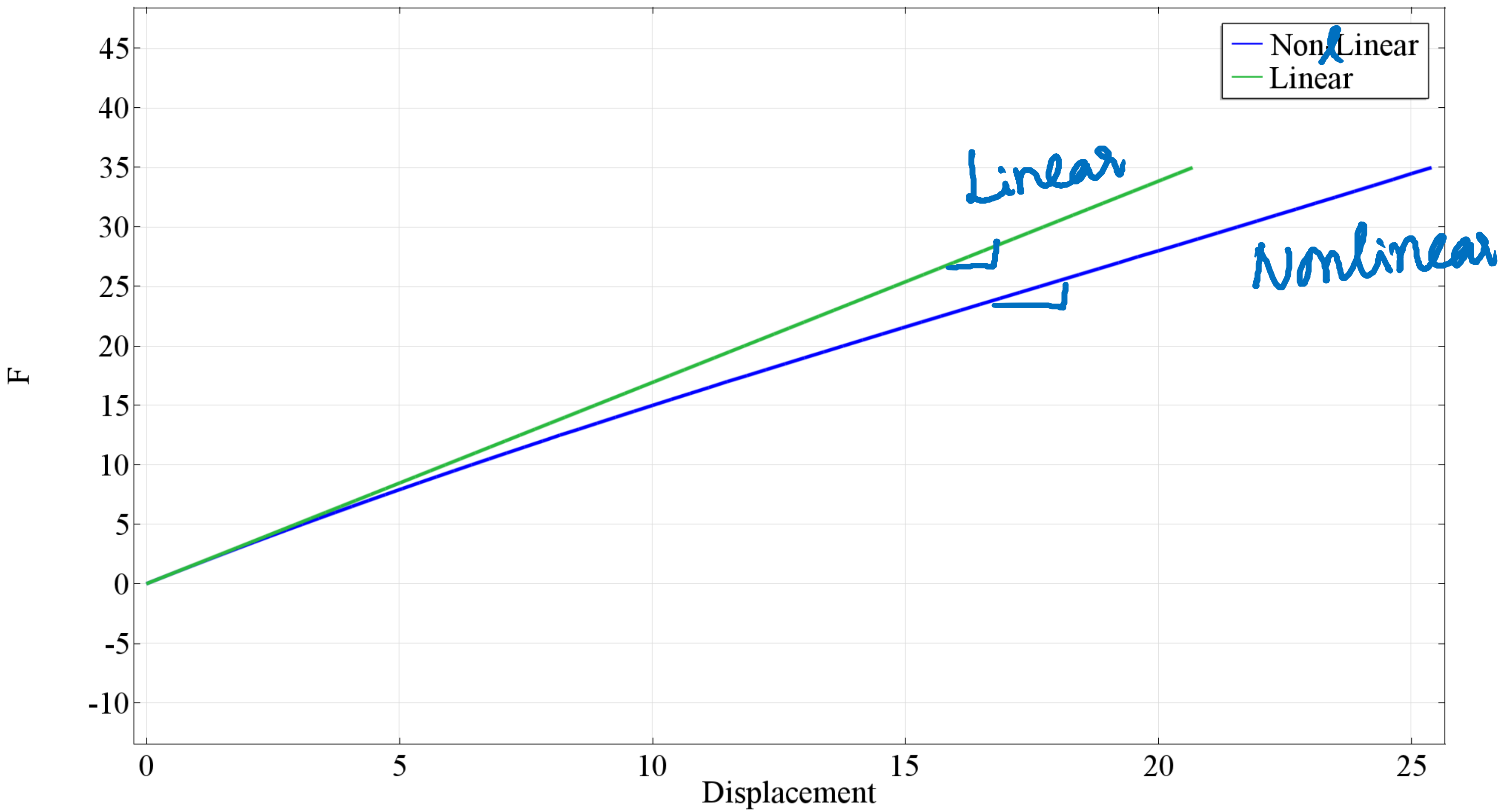
Maximum element size:
1.8 mm

Minimum element size:
0.0036 mm

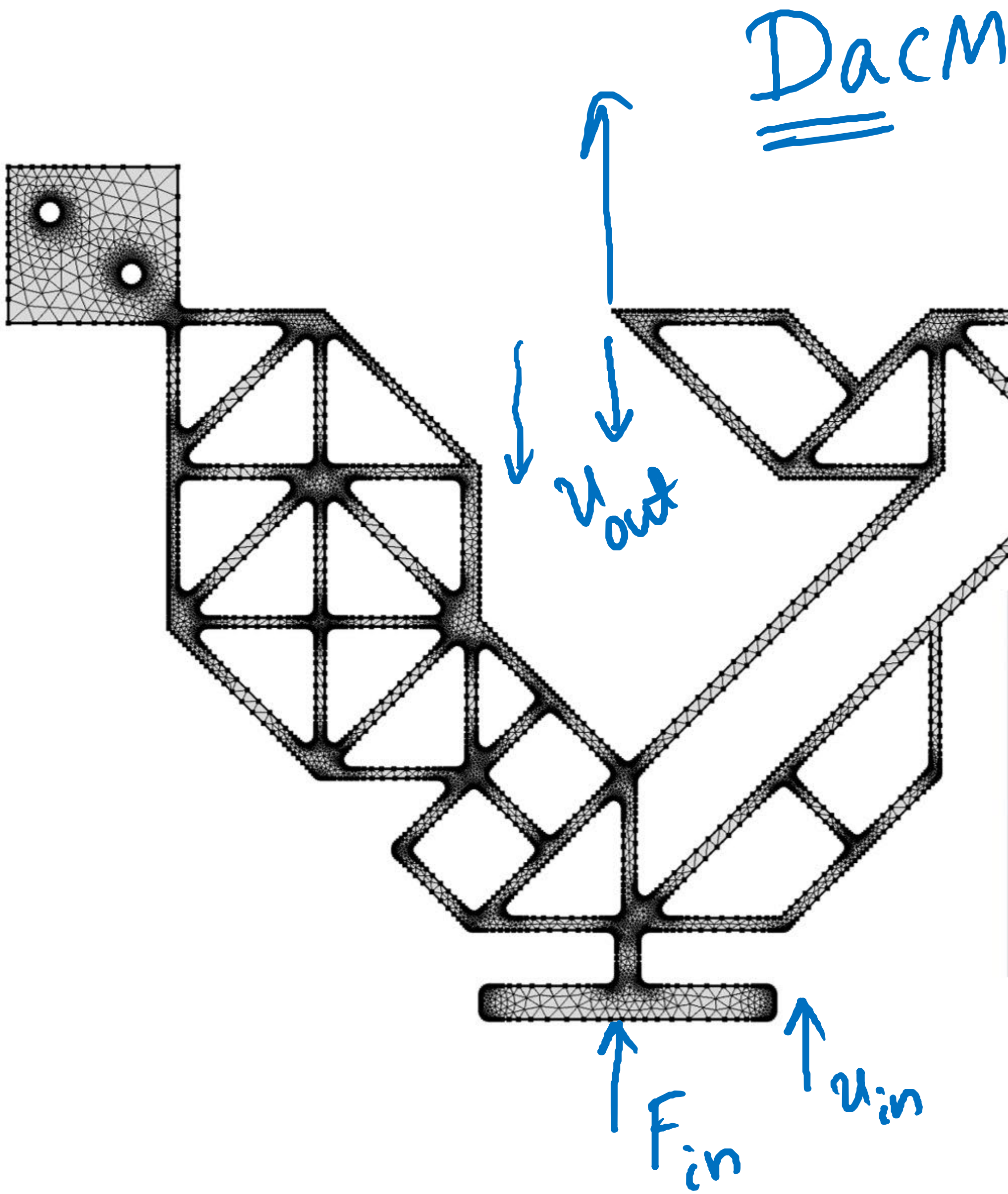
Maximum element growth rate:
1.1

Curvature factor:
0.2

Resolution of narrow regions:
1



Non-Linear
Linear
Linear
Nonlinear
F
Displacement
45
40
35
30
25
20
15
10
5
0
-5
-10
0
5
10
15
20
25



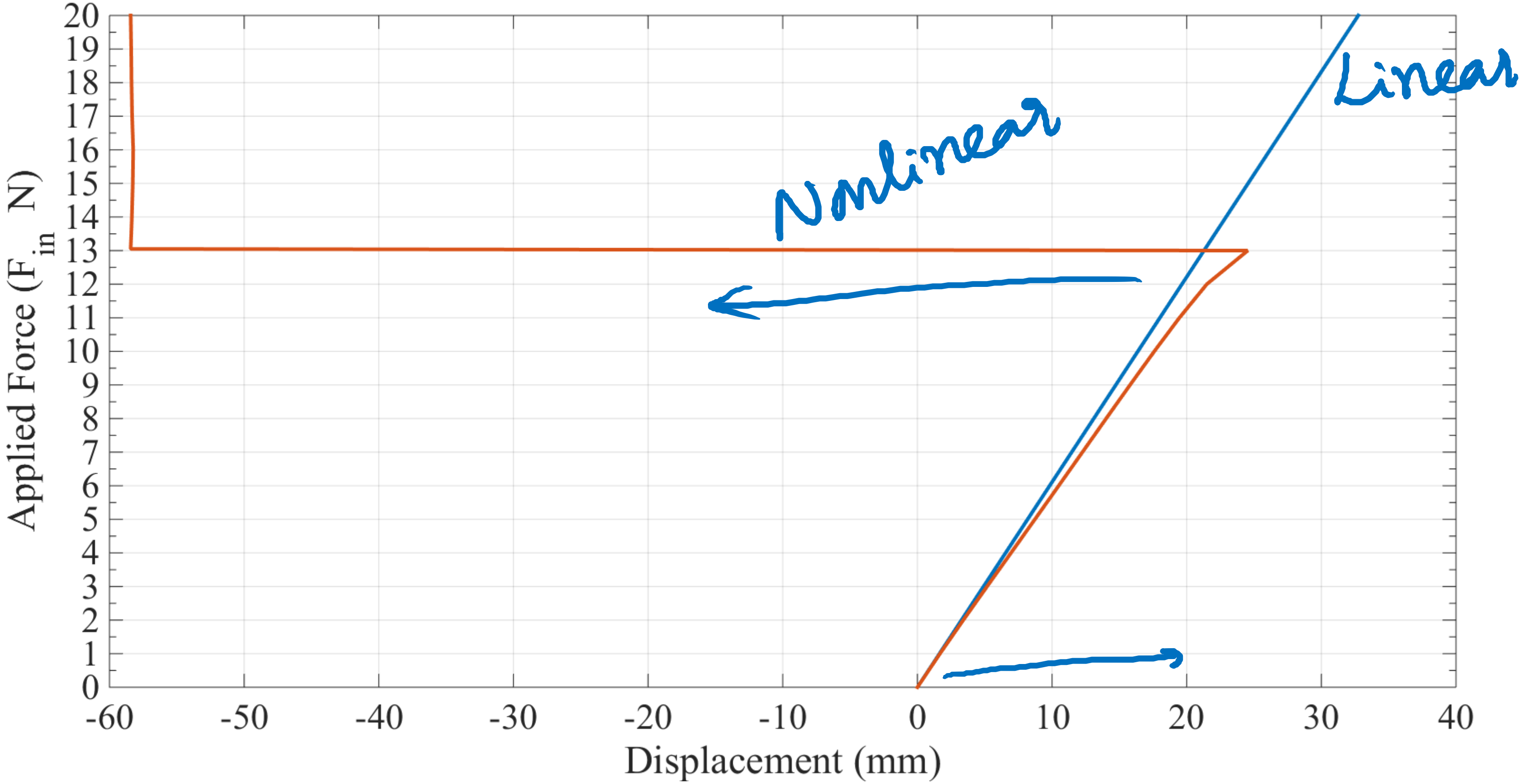
Maximum element size:
10.4 mm

Minimum element size:
0.0587 mm

Maximum element growth rate:
1.3

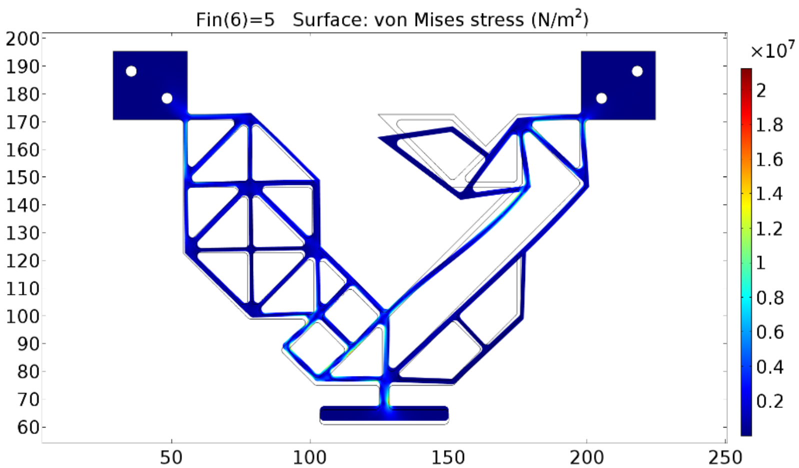
Curvature factor:
0.3

Resolution of narrow regions:
1

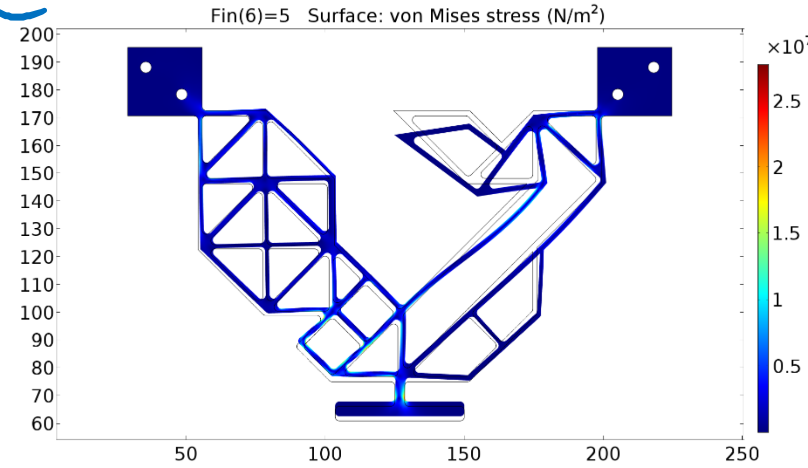


Linear
Nonlinear
Applied Force (F_{in} N)
Displacement (mm)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-60
-50
-40
-30
-20
-10
0
10
20
30
40

F_{in}= 5 N

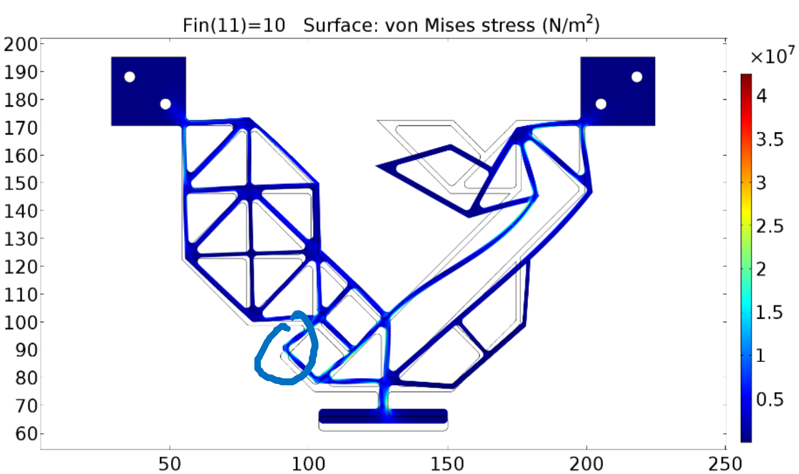


L

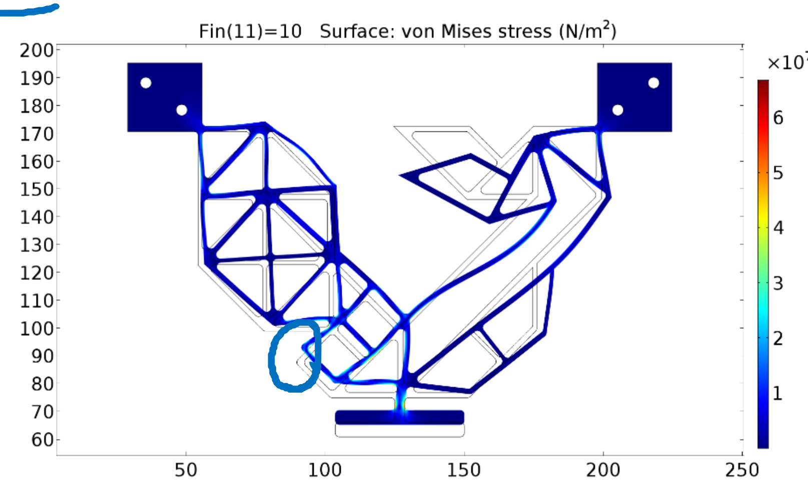


NL

F_{in}= 10 N

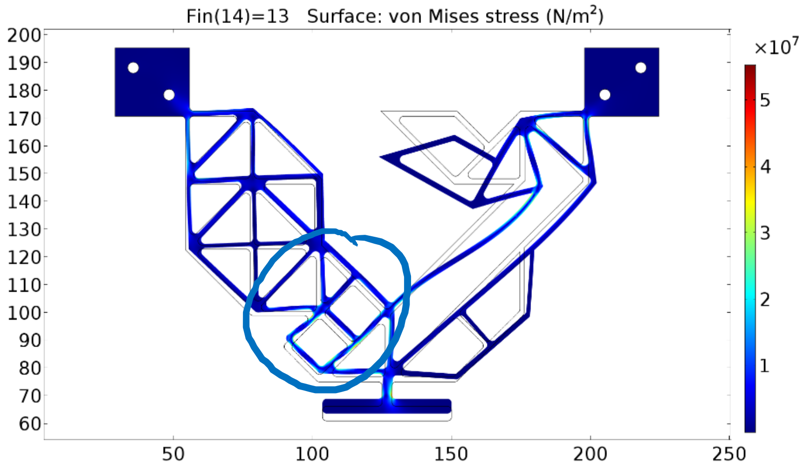


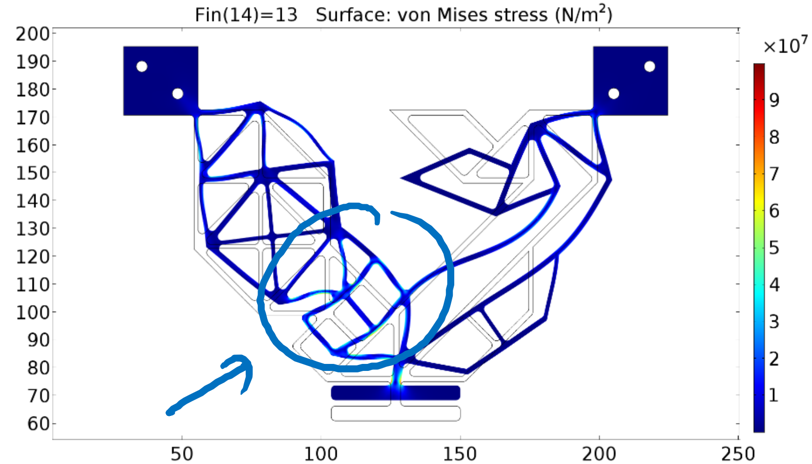
L



NL

$F_{in} = 13$ N

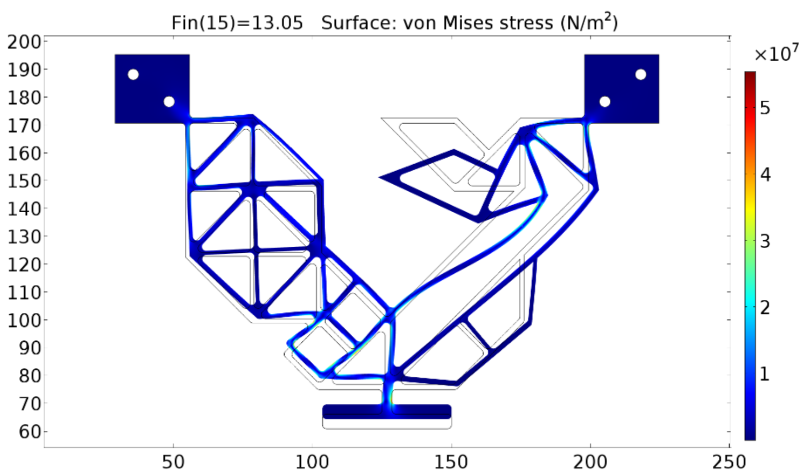


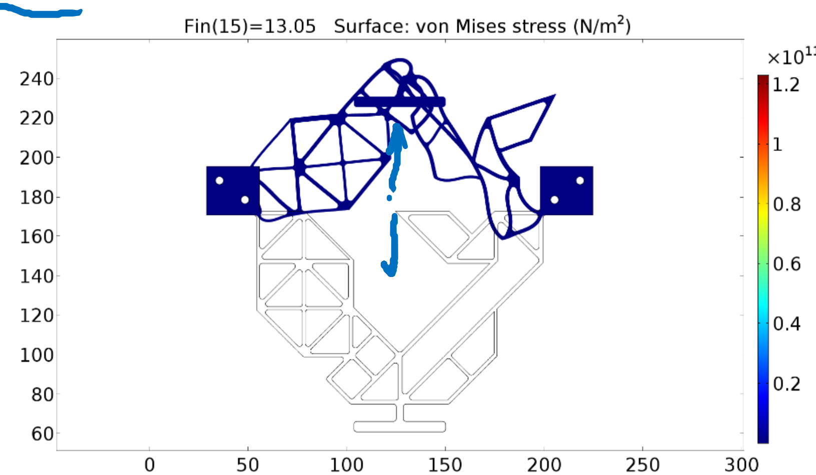


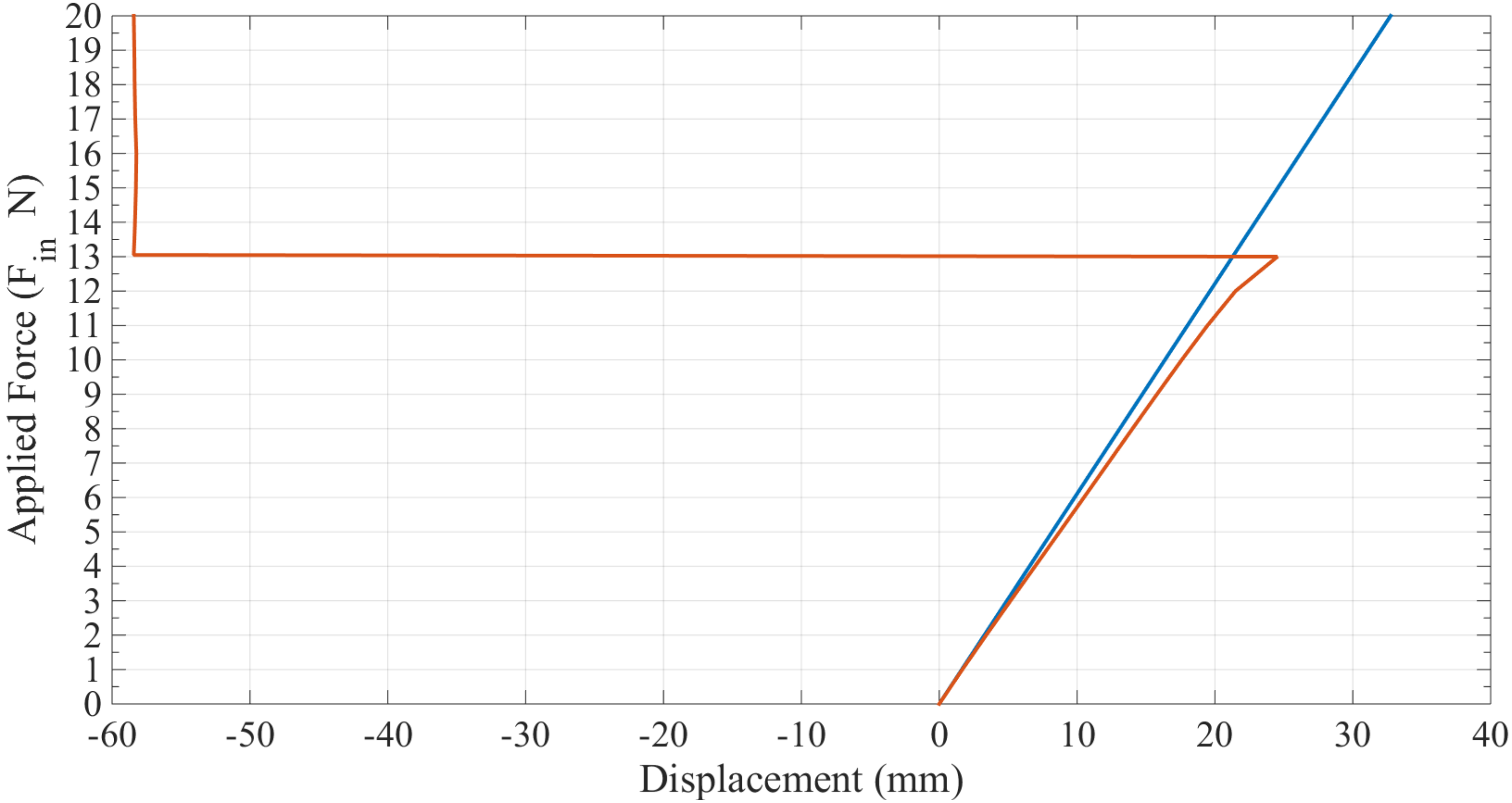
L

NL

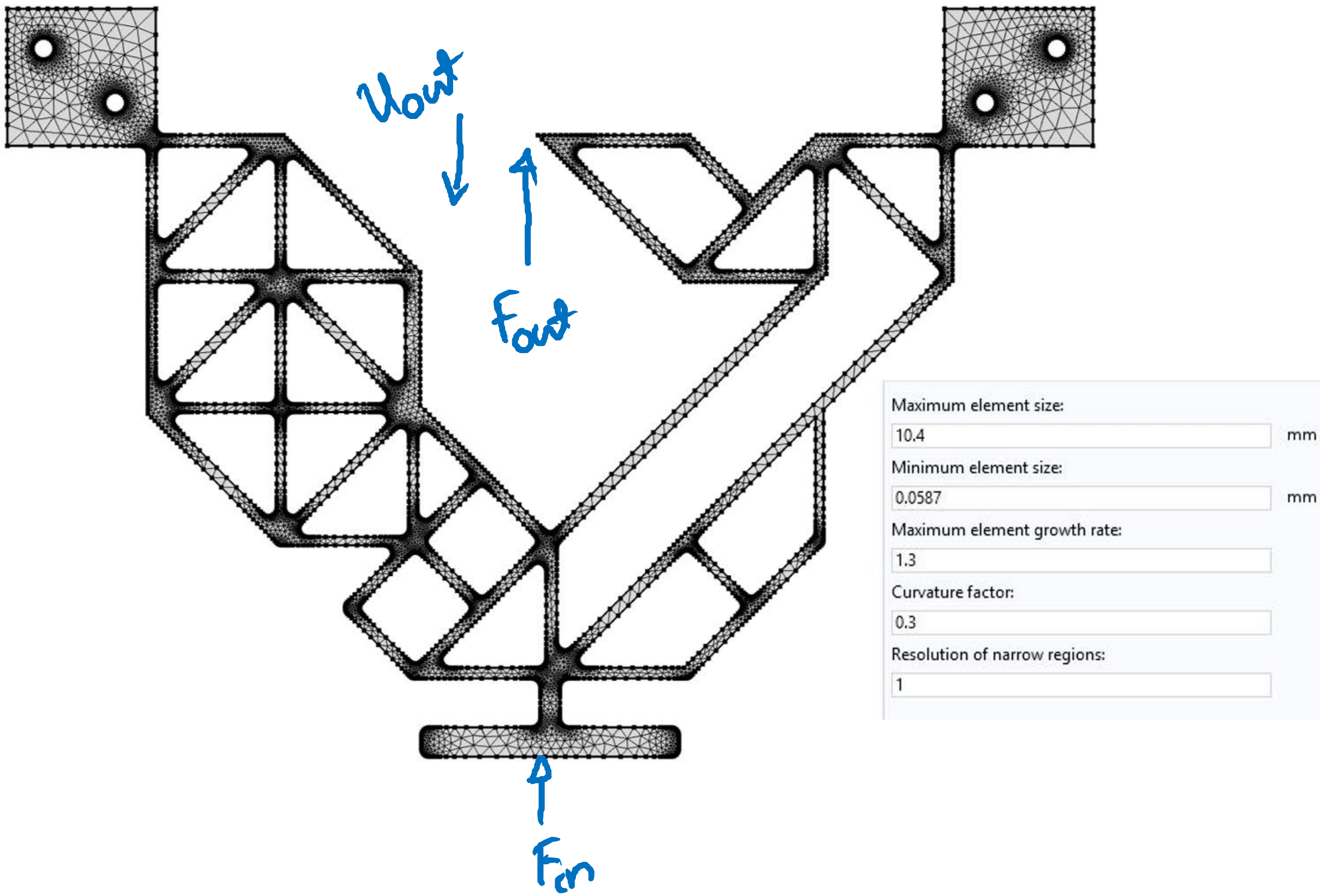
$F_{in} = 13.05$ N



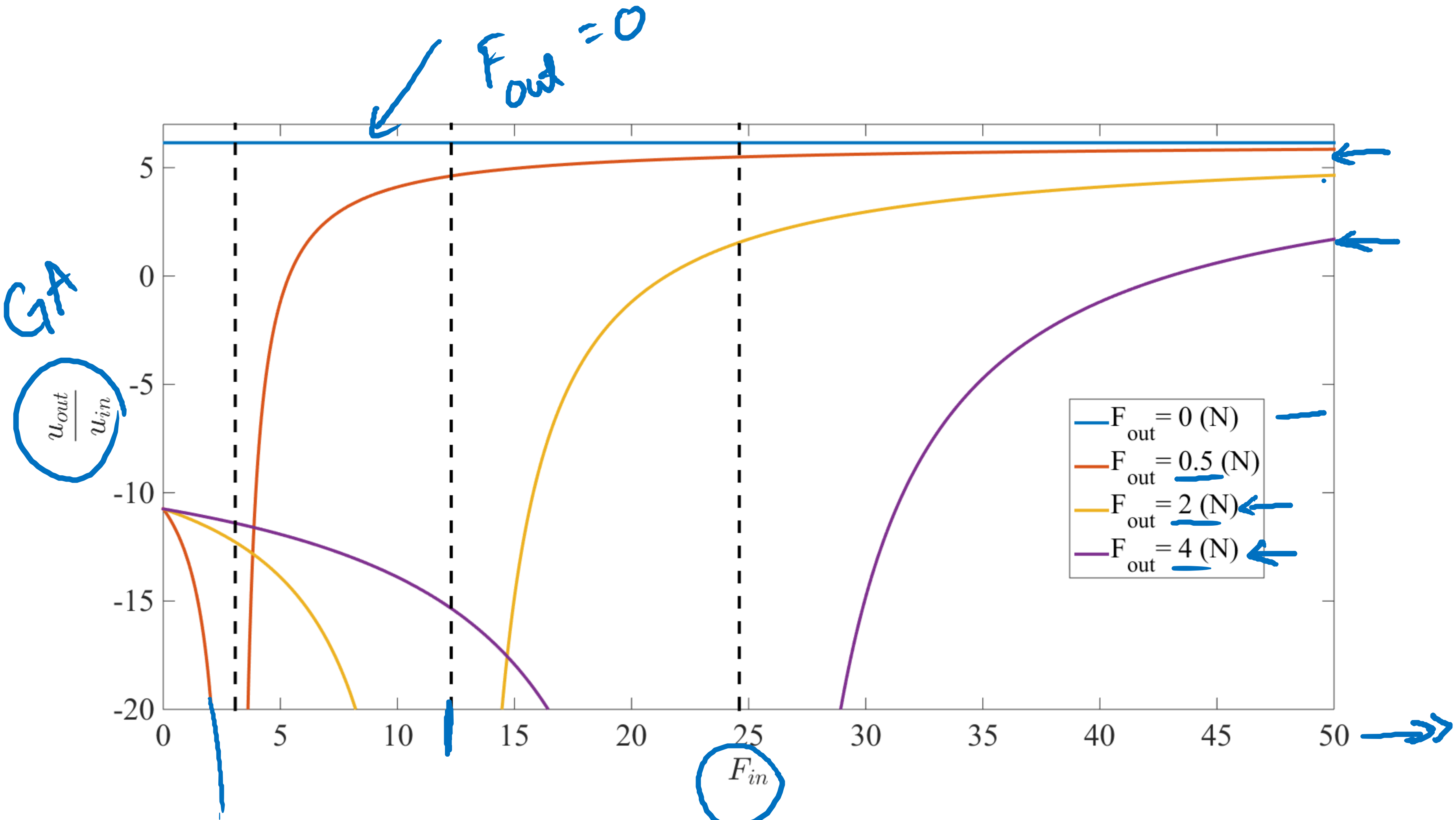



20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-60
-50
-40
-30
-20
-10
0
10
20
30
40
Displacement (mm)
Applied Force (F_{in} N)

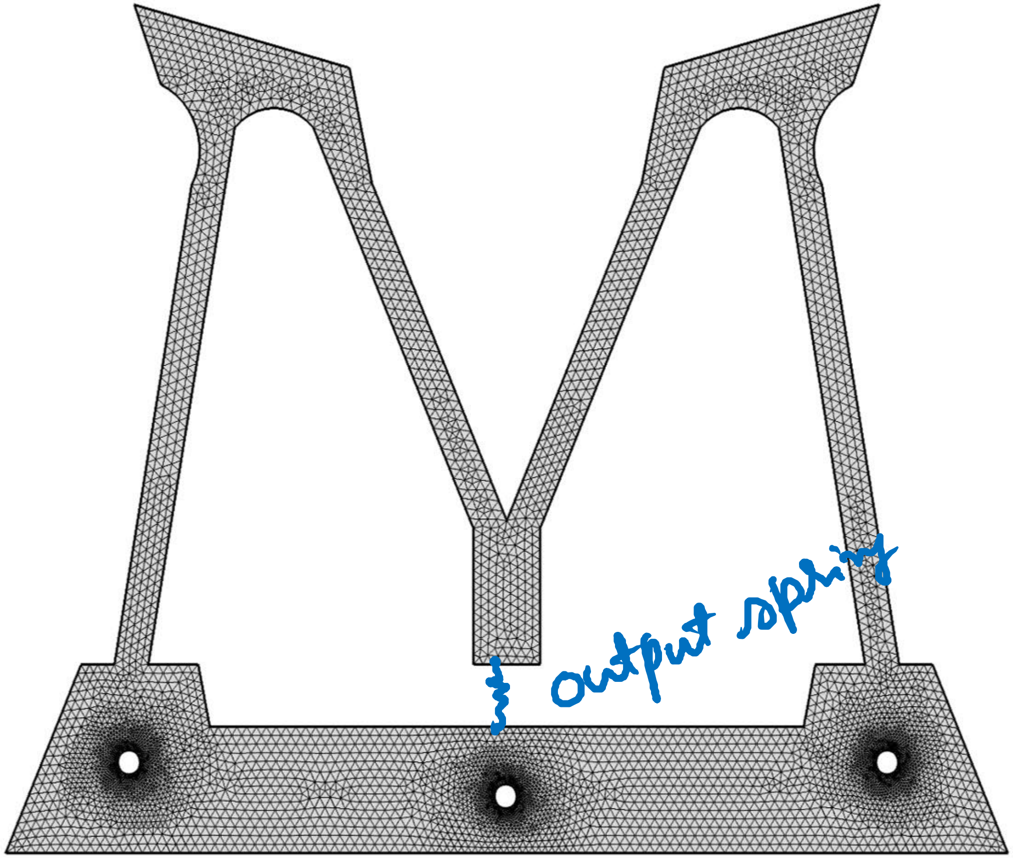
With output load…

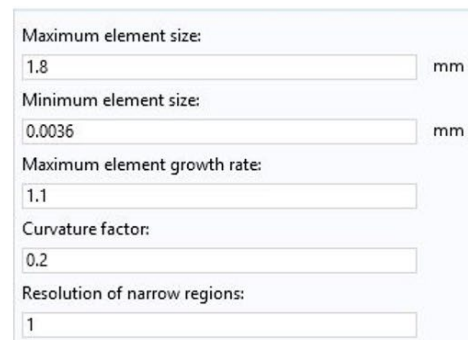


DaCM: parametric sweep with different output loads

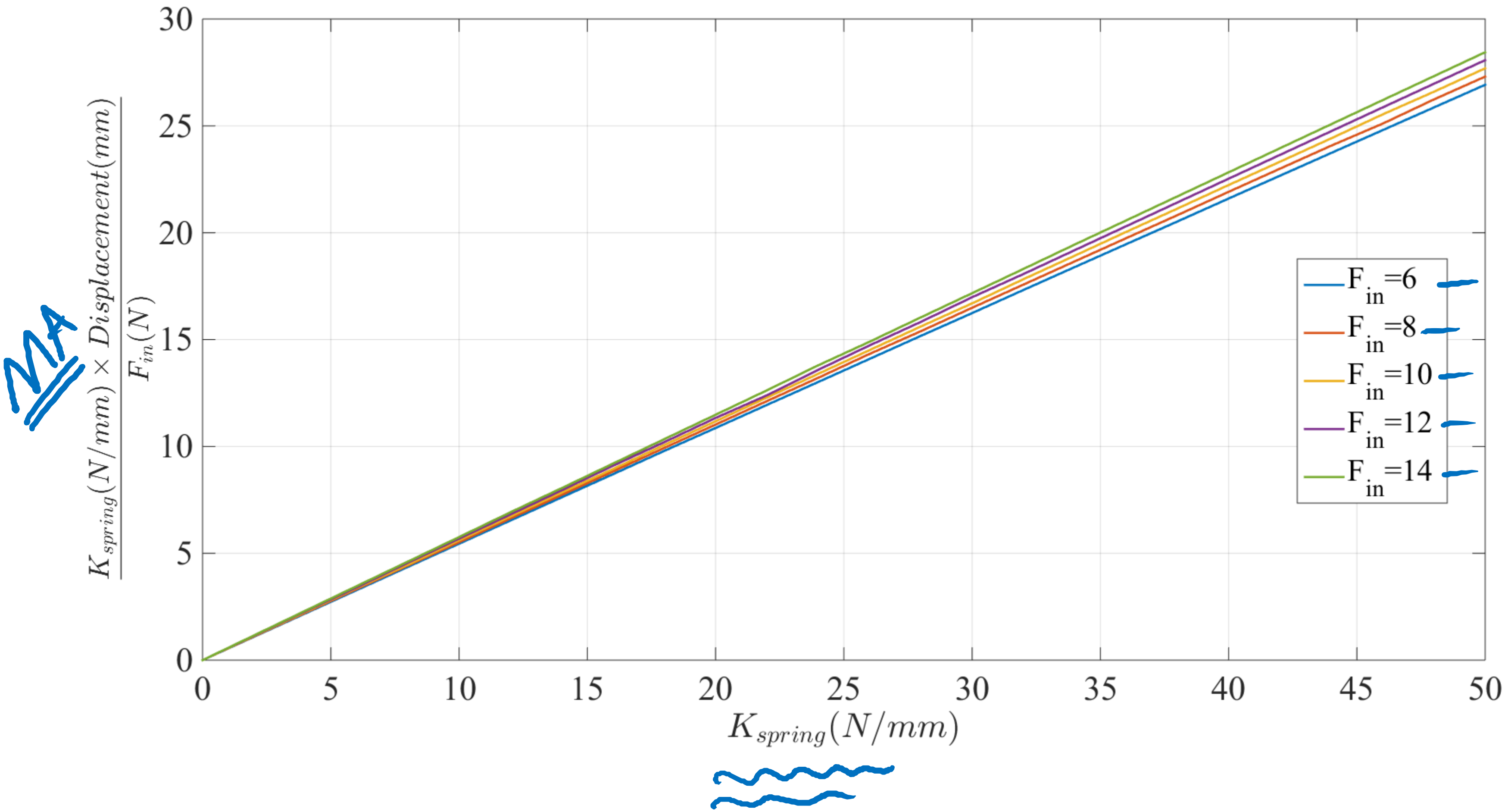


With output spring

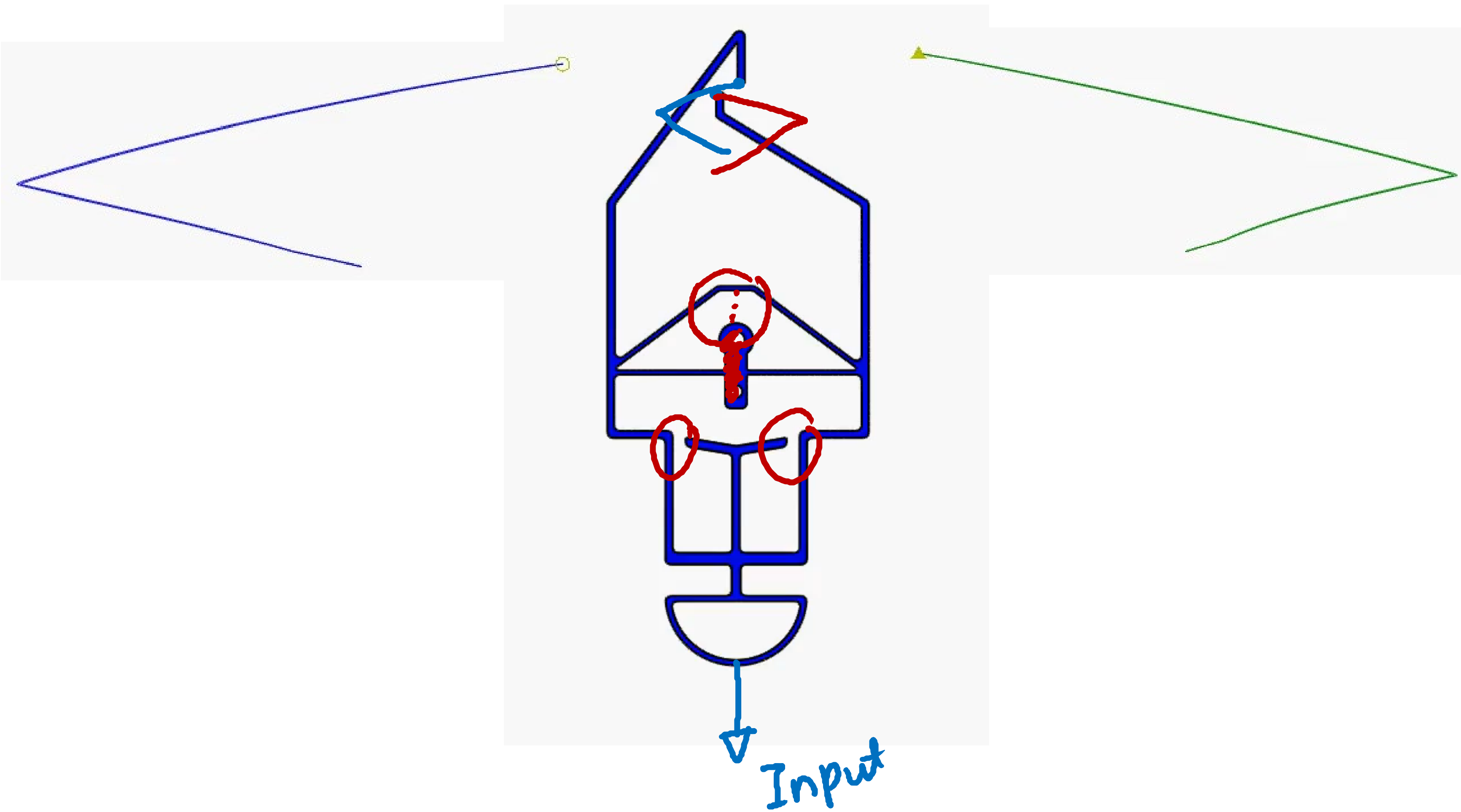


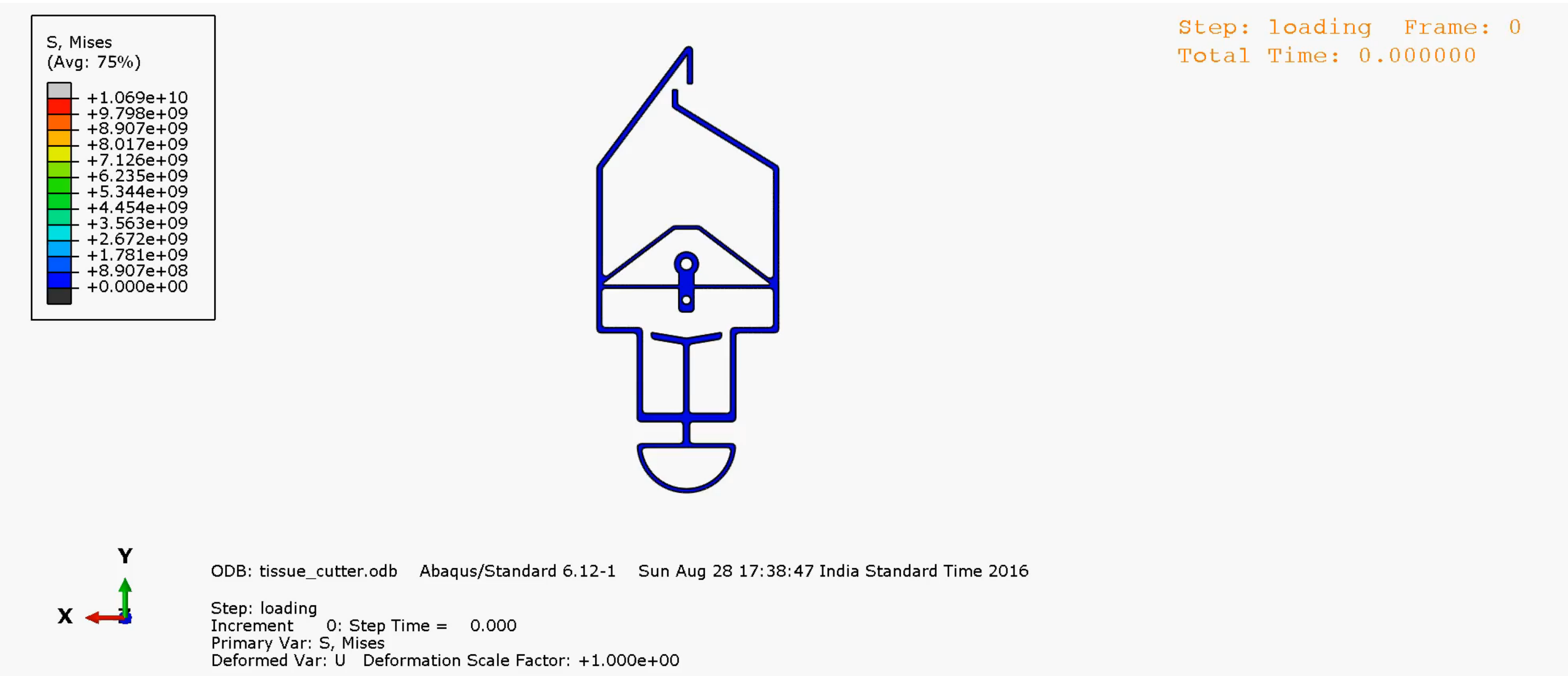


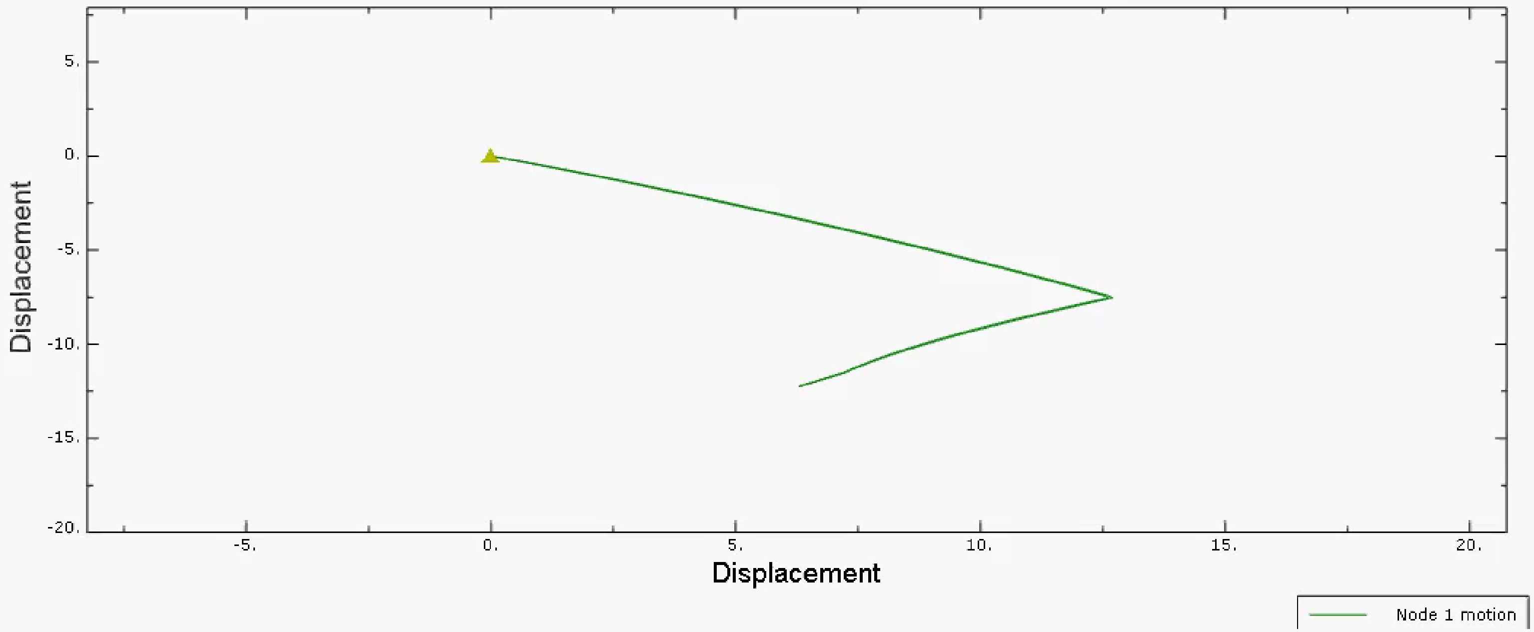
FaCM with different spring loads and different input forces

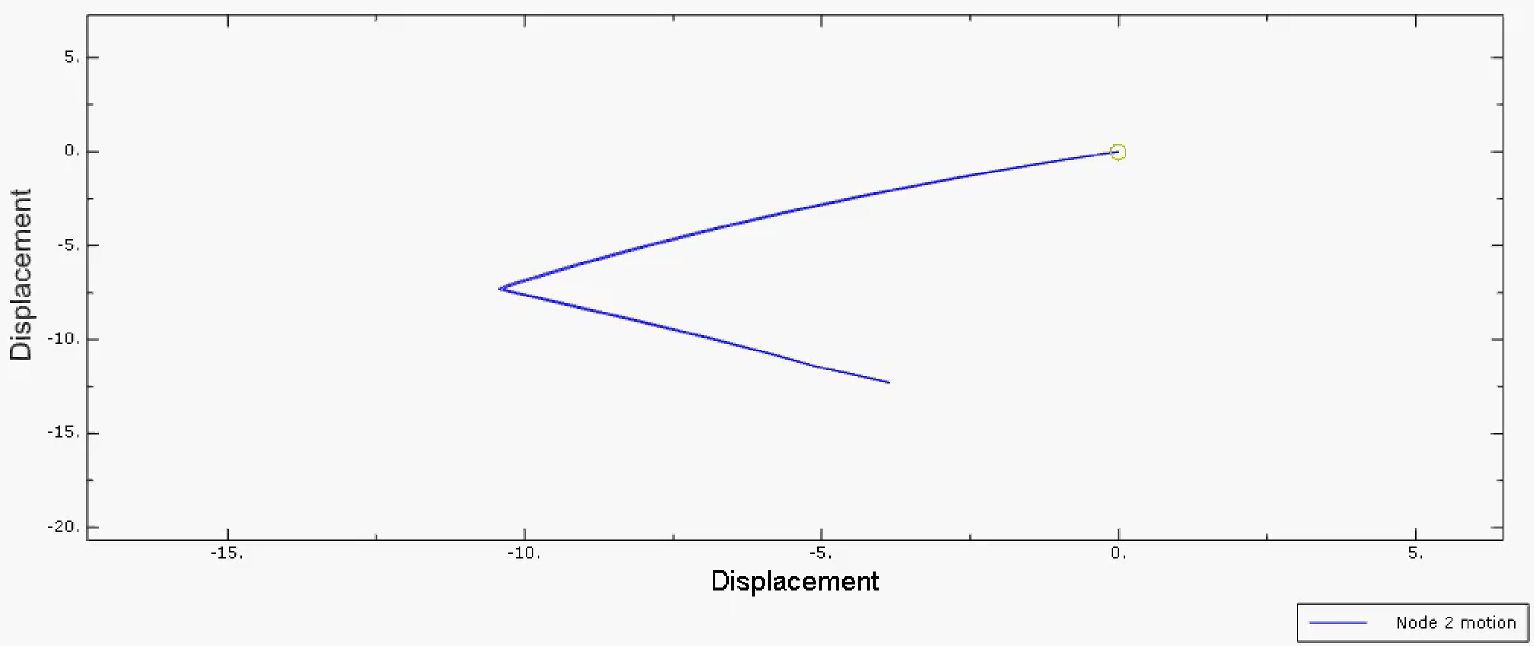


Non-smooth motion in contact-aided compliant mechanisms




S, Mises
(Avg: 75%)
+1.069e+10
+9.798e+09
+8.907e+09
+8.017e+09
+7.126e+09
+6.235e+09
+5.344e+09
+4.454e+09
+3.563e+09
+2.672e+09
+1.781e+09
+8.907e+08
+0.000e+00
Step: loading Frame: 0
Total Time: 0.000000
Y
X
ODB: tissue_cutter.odb Abaqus/Standard 6.12-1 Sun Aug 28 17:38:47 India Standard Time 2016
Step: loading
Increment 0: Step Time = 0.000
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00


5.
0.
-5.
-10.
-15.
-20.
-5.
0.
5.
10.
15.
20.
Displacement
Displacement
Node 1 motion


5.
0.
-5.
-10.
-15.
-20.
-15.
-10.
-5.
0.
5.
Displacement
Displacement
Node 2 motion

Main points

- Abaqus, COMSOL, Creo, ANSYS, NISA, etc.
- Be careful with what elements you use and what we expect to see through modeling.
- Always check mesh-convergence.
- Almost anything can be simulated for compliant mechanisms using FEA.