Stiffness Control of Polymer Flexure Joints for Microrobotic Applications

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ES 240

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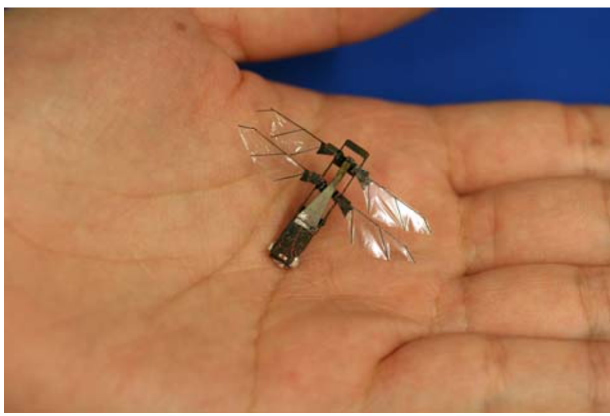
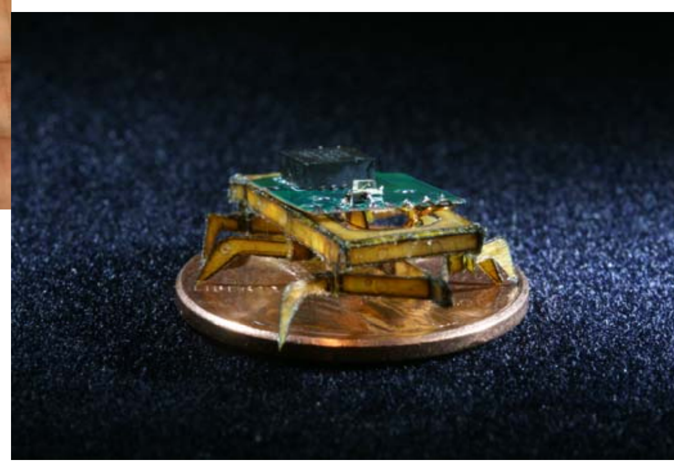
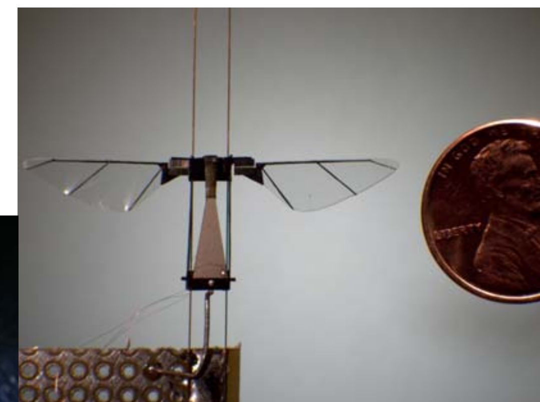
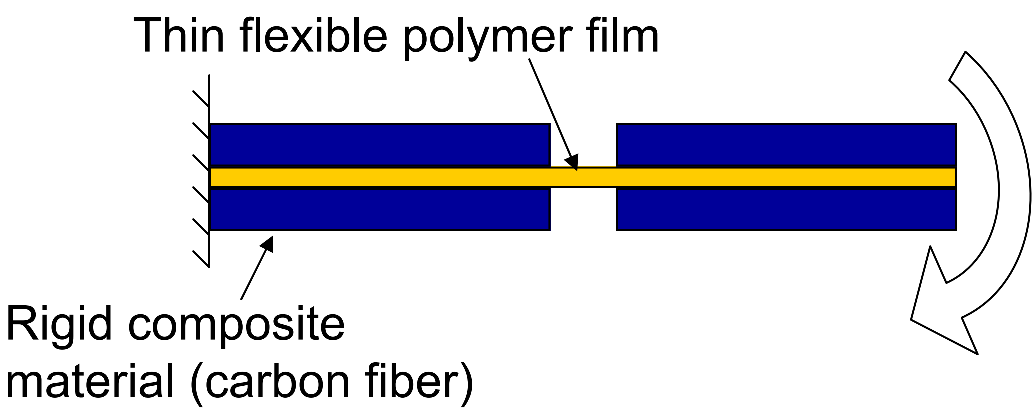


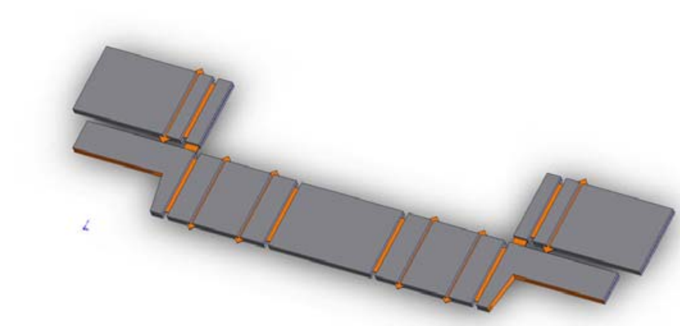




Compliant Flexure Joints

- Problem: Large-scale “pint joints” don’t work with insect-scale robots
- Surface forces (friction) dominate inertial forces at small scale
- Traditional manufacturing techniques insufficient for such tiny robots
- Solution: Use flexible polymer hinges that act as revolute joints



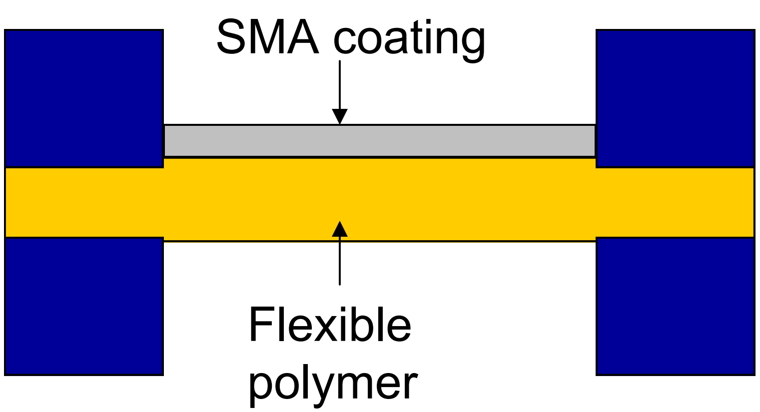


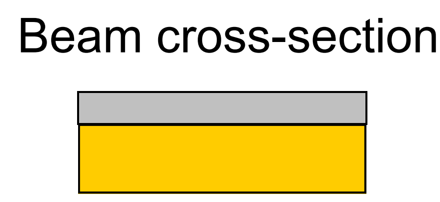
Flexure Joint Stiffness

- Carbon fiber can be assumed to be rigid
- Each joint can be modeled as a cantilever beam with bending stiffness k = E*I/L where E = elastic modulus, I = cross-sectional moment of inertia and L = flexure length
- Stiffness is thus a constant for a given flexure geometry and material
- Desirable to actively modulate the stiffness of the flexure joints – this can affect robot dynamics for control purposes
- To change stiffness, need to either vary flexure geometry or material properties

Modulating Flexure Stiffness

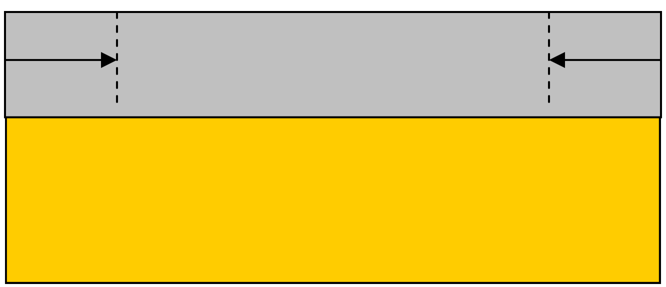
- Idea: add material with variable elastic properties to flexure joint
- This allows change in the equivalent bending stiffness of the entire flexure
- Two-layer flexure can be modeled as a composite beam
- This can be accomplished with shape-memory alloy (SMA) materials, which have a very temperature-dependent elastic modulus



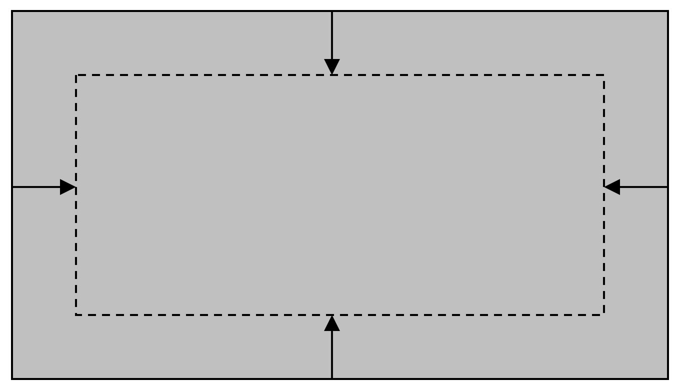


But it's not that simple…

- Shape memory alloys also undergo a large strain when they are heated (~7%)
- Problem: thin film bonded to rigid substrate, film wants to contract
- Similar to plate theory homework problem
- Will result in deformation of the film and substrate, possible delamination or failure of the flexure



Side View



Top View

Finite Element Analysis with COMSOL

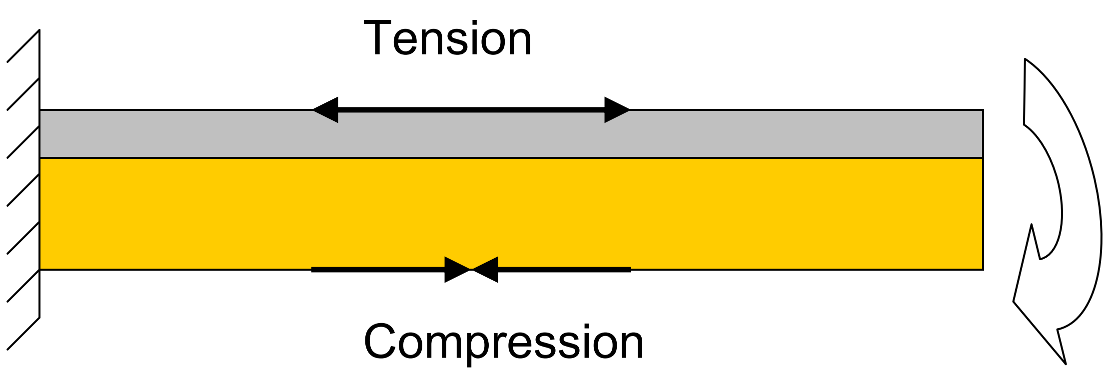
- Create two 3D plates rigidly fixed to each other on one side
- First model
  - Boundary conditions: one edge fixed, opposite edge has applied distributed moment, other edges free
  - Calculate moment with $M = k_{eq}*\theta$ (analagous to $F = k*x$), where θ is desired angle of rotation of flexure joint
  - Does not account for large induced strain (~7%) when SMA is heated
- Second Model
  - Keep flexure flat, not concerned with rotation
  - Want to model contraction of SMA when heated and resulting stresses
- Third Model: Combination of loads from models 1 and 2

Failure Criteria

- Criteria for delamination of film involves fracture mechanics and the amount of energy available to drive a crack – beyond scope of this project
- Instead interested in possible plastic deformation of either polymer layer or SMA
- This could occur due to either large-angle deformation of flexure or large strain induced in SMA when heated – will analyze both cases

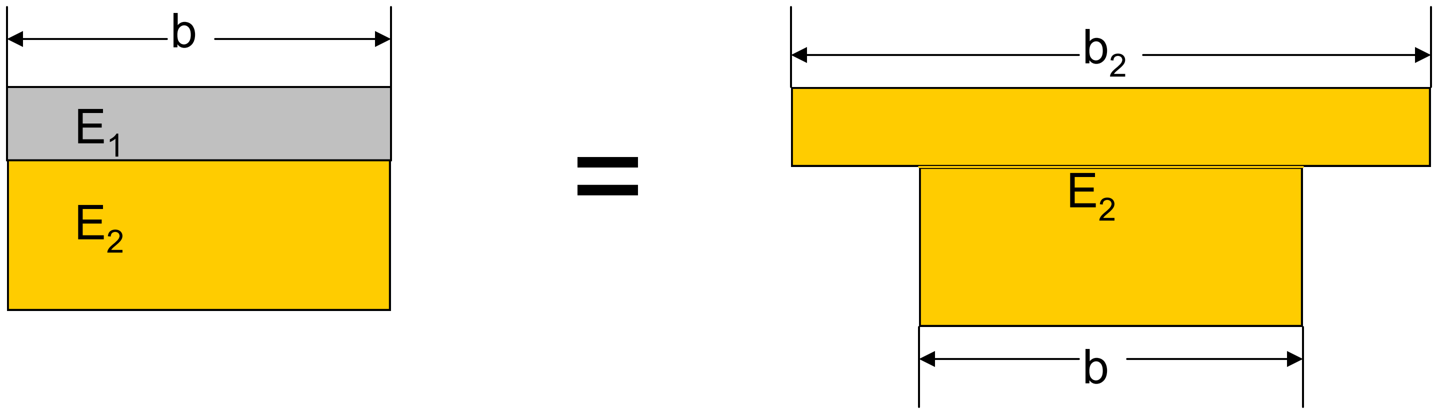
First FEA Model – Beam Bending

- BCs – one edge fixed, distributed moment on opposite edge, all other faces free. Run twice with moment in opposite directions, putting each side alternately in compression or tension



Equivalent Modulus of a Composite Beam

- From undergraduate solids course



Where b_2=nb, n = E_1/E_2

Therefore, if you can actively control E_1, you can change the equivalent stiffness and moment of inertia, and thus the entire bending stiffness k = E*I/L.

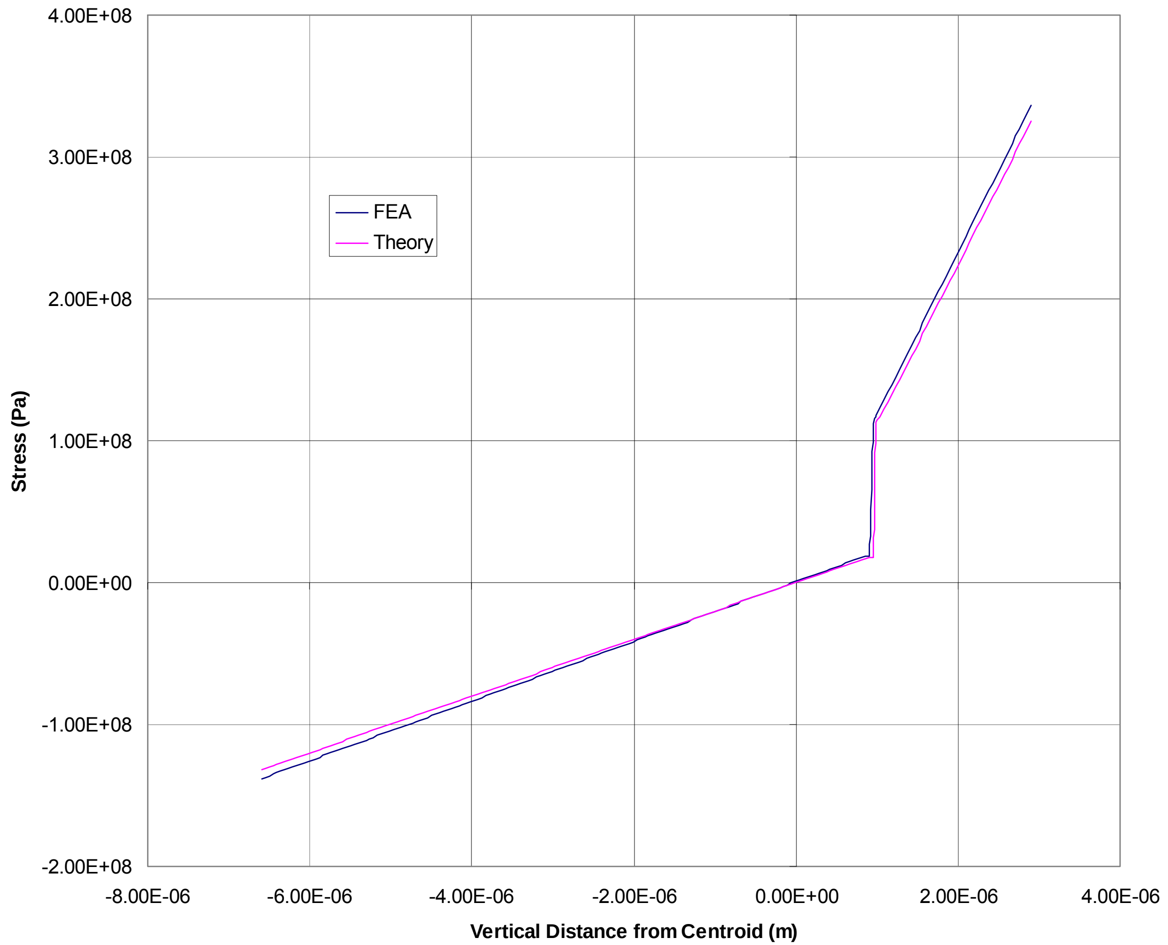
2-D Sanity Check

Beam Theory:

$$\sigma = \frac{My}{I}$$

Must be adjusted slightly for composite beam, then compared with FEA results

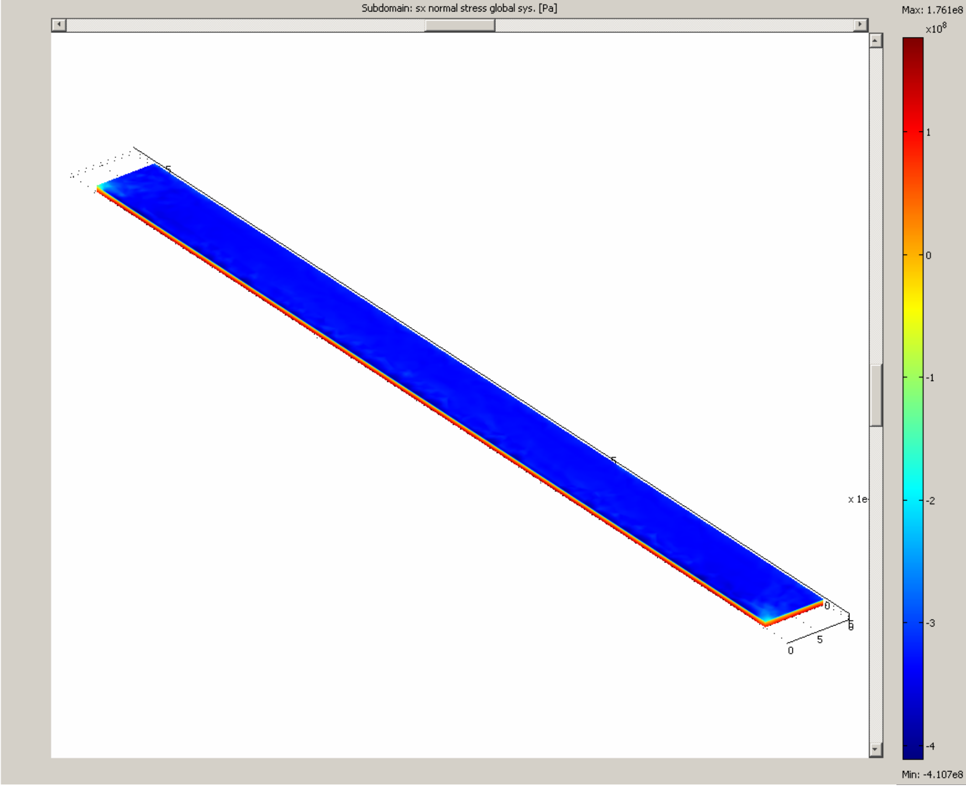
Theoretical and Finite Element Bending Stresses Due to Applied Moment

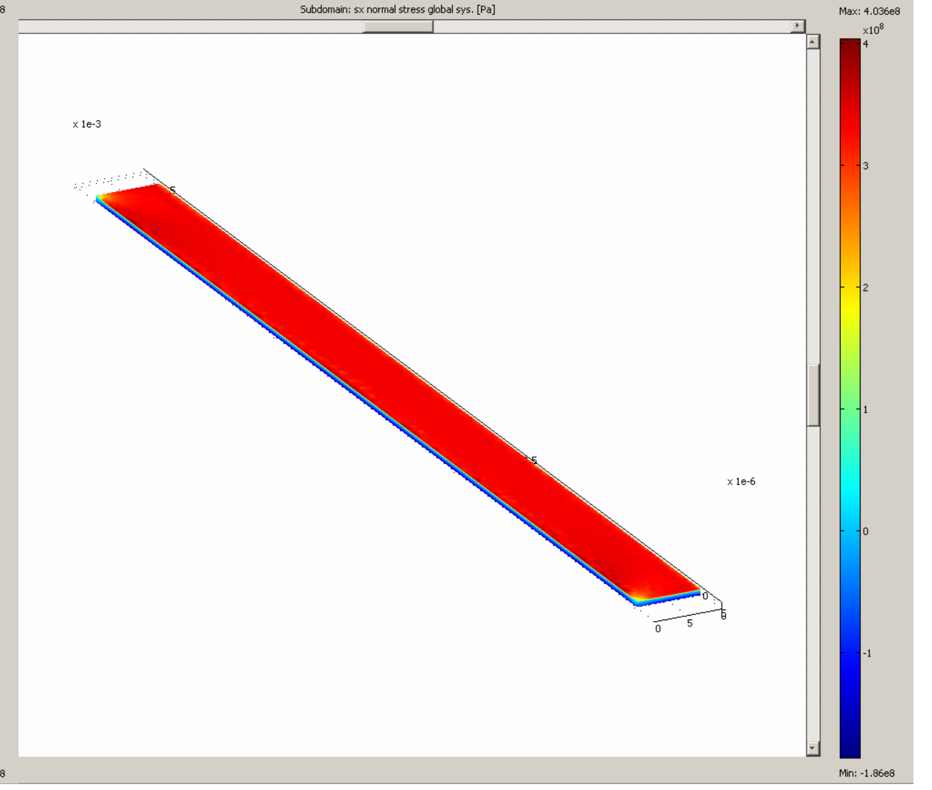


Results of first model – low temp SMA phase

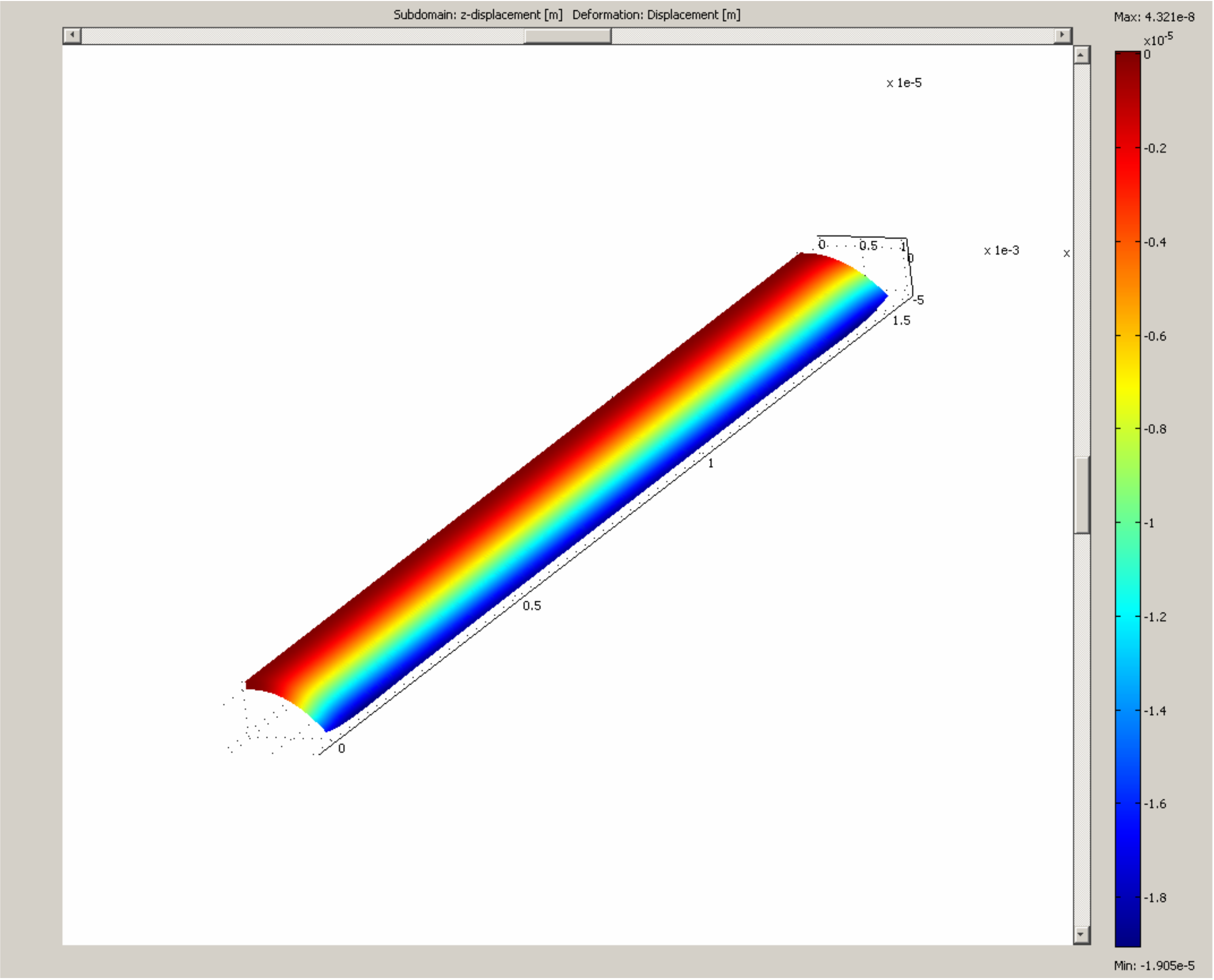
•Max tensile stress in Kapton ~176 MPa, just over yield strength of 172 MPa

•Max tensile stress in SMA ~400 MPa, well over low-temp phase yield strength of 100 MPa – <u>SMA will plastically deform</u>





Deformed Shape Plot

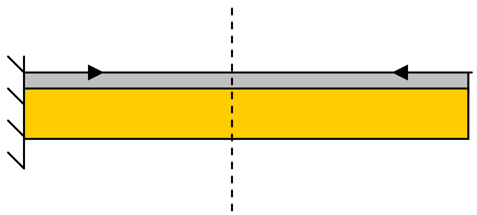


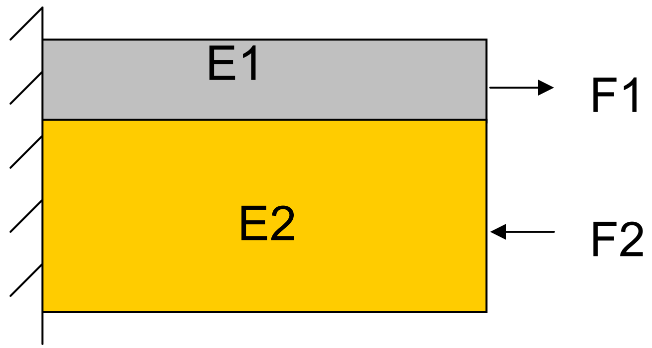
Second FEA Model – SMA Contraction

- Previous models did not take into account large strain SMA undergoes when heated
- SMAs have a *negative* coefficient of thermal expansion – they contract with increasing temperature
- This can be modeled with FEA program, assuming thermal expansion coefficient of kapton is ~0 compared to the SMA
- Fixed-fixed boundary conditions at the beam edge – not worried about rotation yet, just effects of contracting SMA

Reality Check: 1D Thermal Strain Analysis

1) Force Balance:





$$\sigma_1 A_1 = \sigma_2 A_2$$

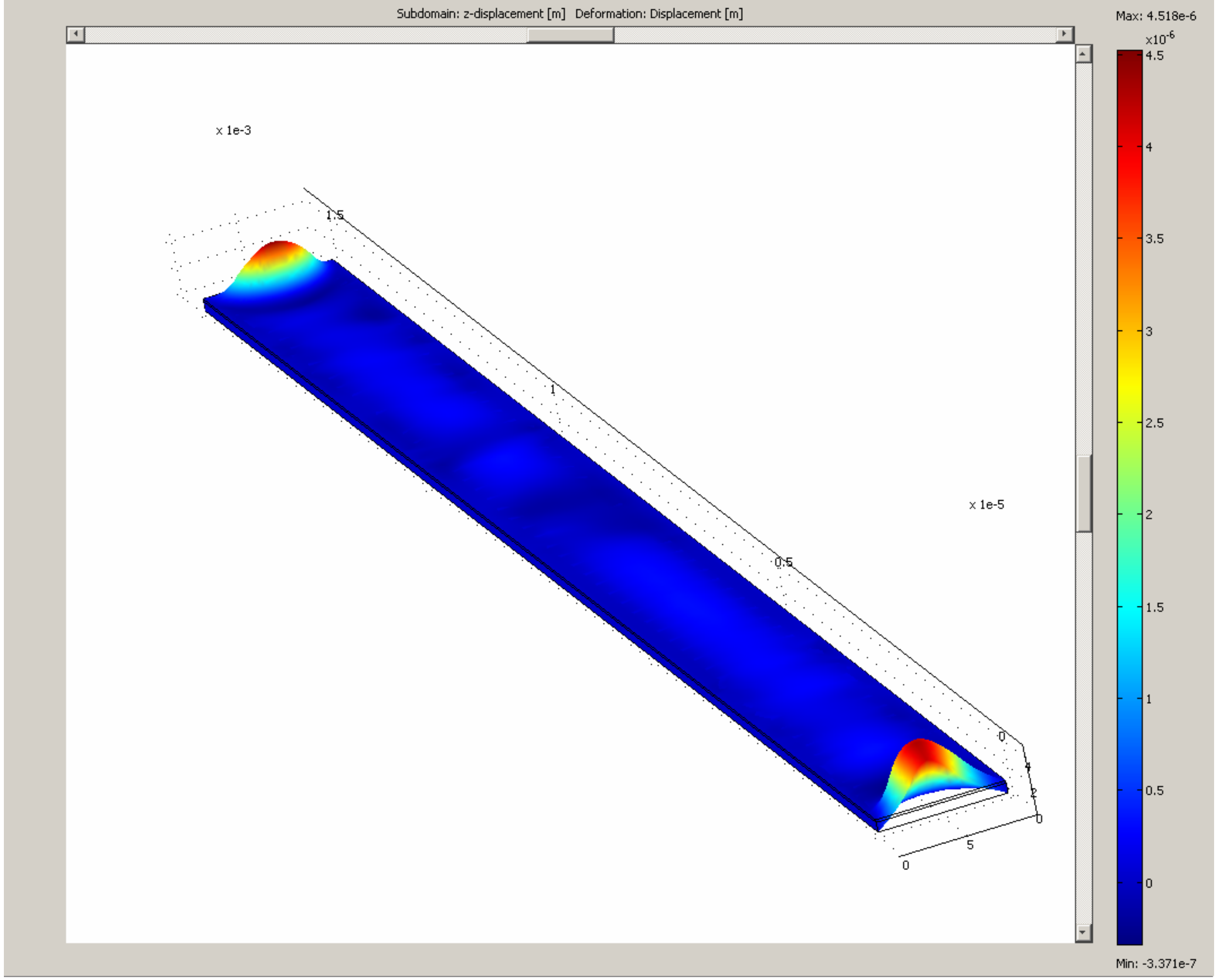
2) Set strains equal

$$\frac{\sigma_1}{E_1} + \alpha_1 \Delta T = \frac{\sigma_2}{E_2} + \alpha_2 \Delta T$$

- Two equations, two unknowns σ_1 and σ_2
- Thermal expansion coefficient for kapton negligibly small compared to SMA
- Analytical results:
  - σ_{kapton}= -.393 GPa, σ_{SMA} = 1.47 GPa
- FEA Results:
  - σ_{kapton}= -.35 GPa, σ_{SMA} = 1.2 GPa

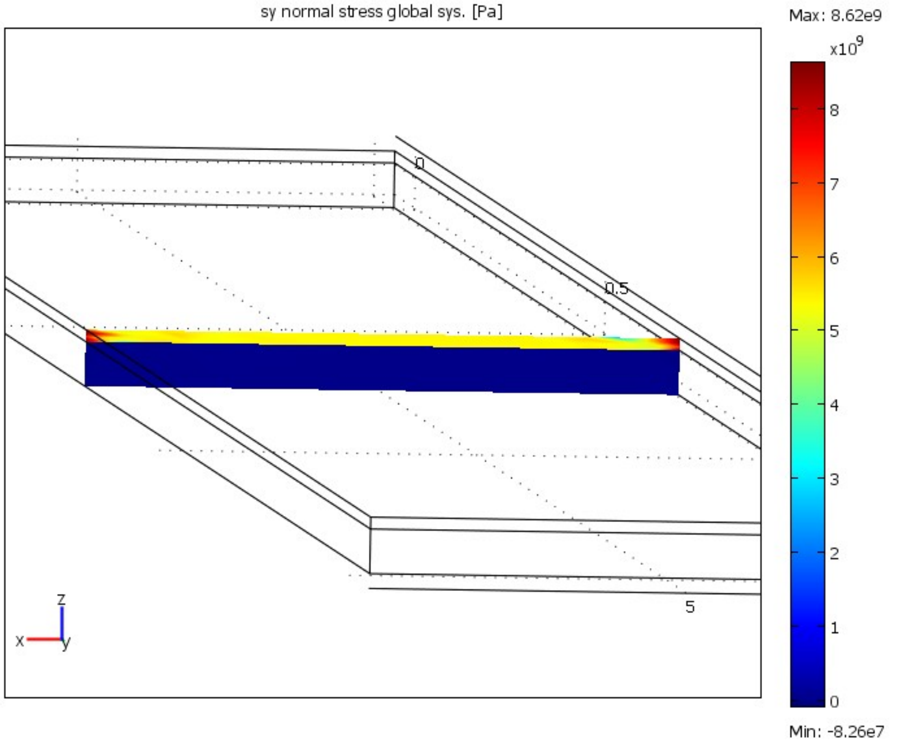
Results of Second Model – Deformed Shape

- Largest deformation occurs at free edges of flexure



Second Model - Stresses

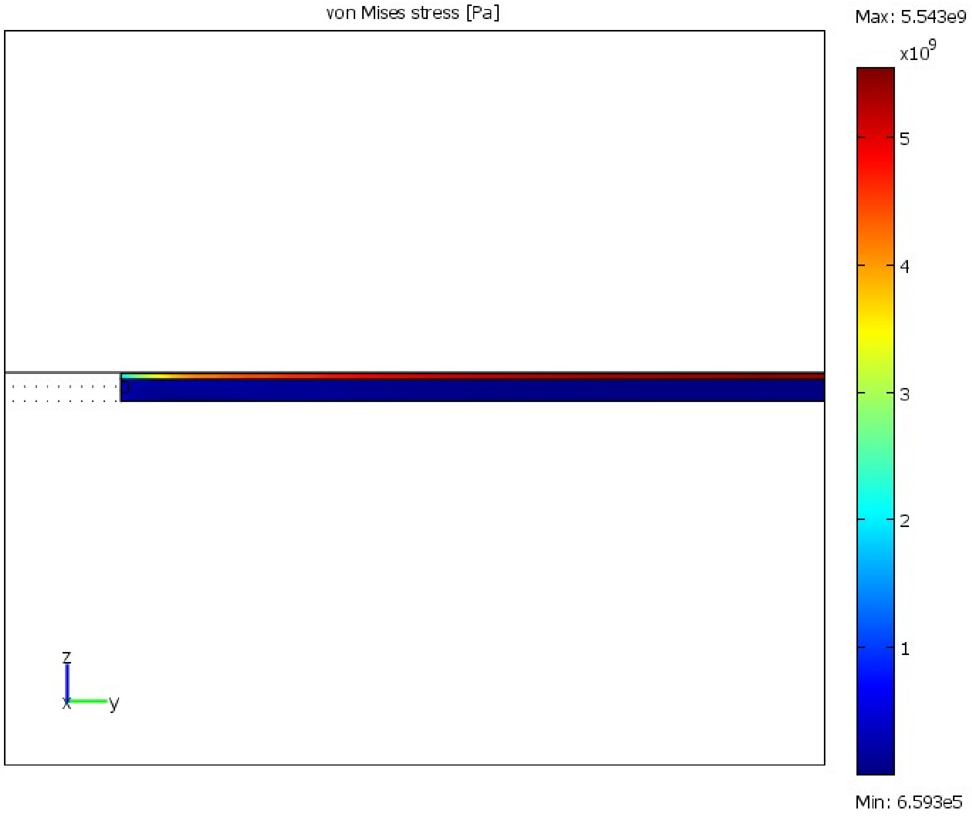
- Stresses are rather high due to the large strain of the SMA, especially at the edges (roughly 2x stress concentration)
- This will likely result in failure of the SMA
- SMA may fracture since stress is above the ultimate tensile strength (960 MPa), not just the yield strength



Second model – stress (continued)

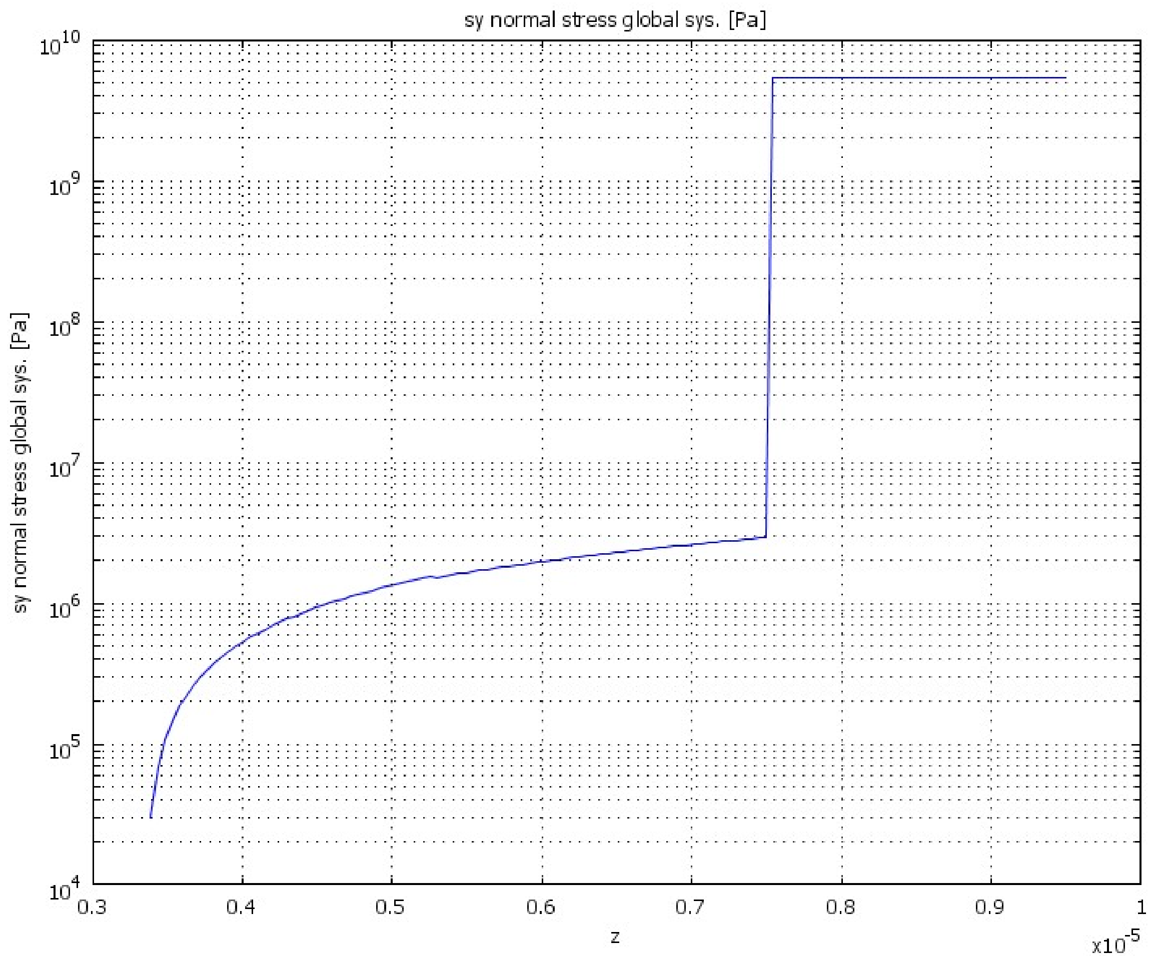
- Despite large deformations at edges, highest von Mises stresses actually occur in the center of the flexure

Side view of long side of flexure – note lower stress at the edge of SMA layer



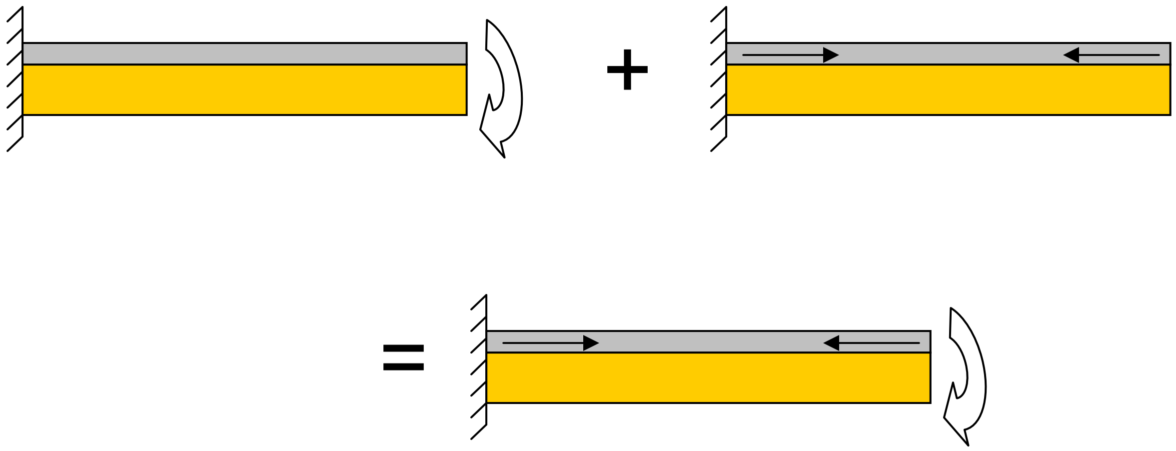
Line plot of normal stress at center plane

•log plot shows that stress in kapton layer is not constant, as it appears in contour plot on previous slide



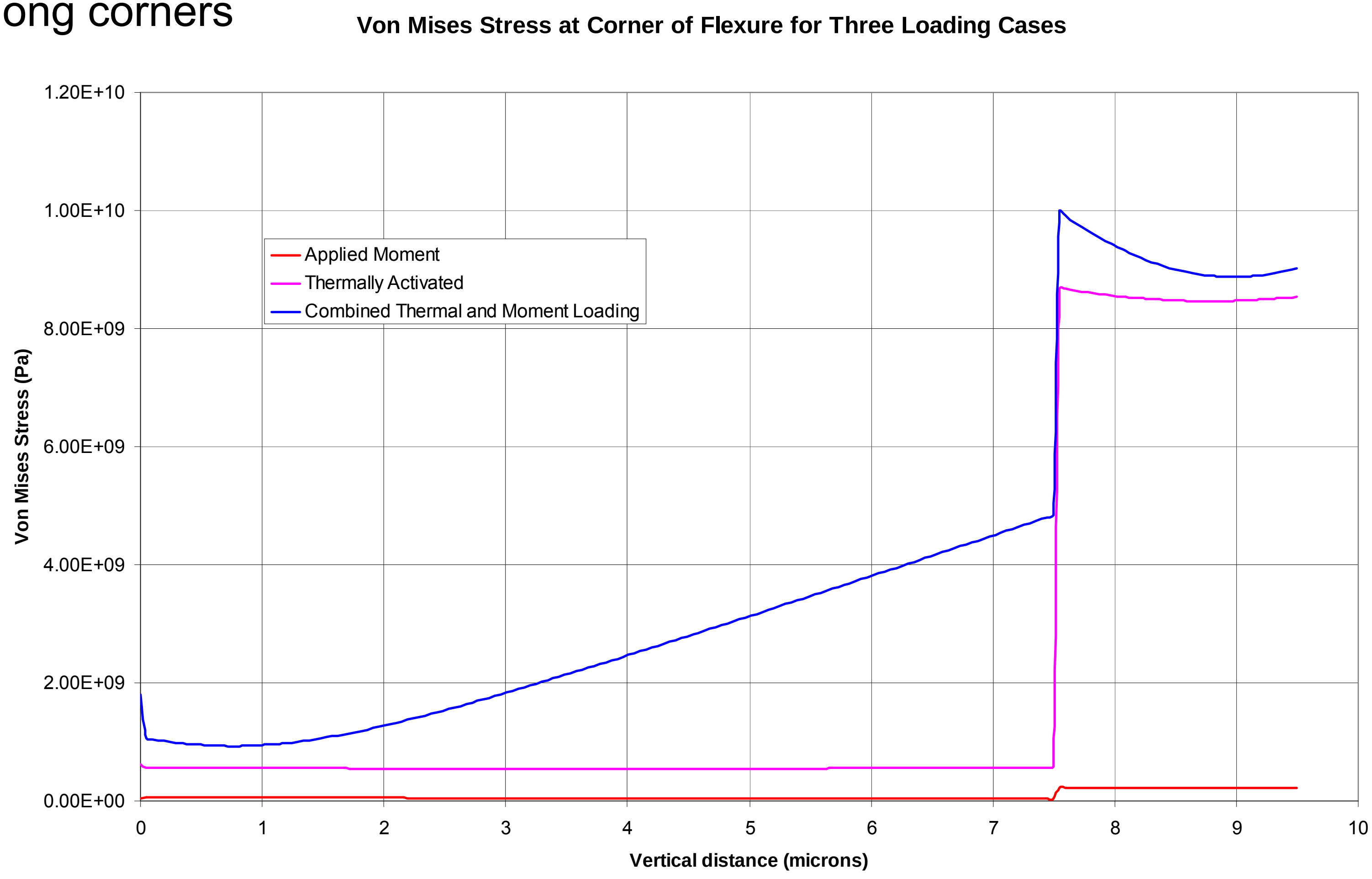
Third Model: Combination of Loading Cases

- Account for both applied moment and contraction of SMA due to thermal actuation
- Resulting stresses are higher
- Stress concentrations occur at corners in all three models



Combination Loading: Corner Stresses

Stress concentration about
2x along corners



Conclusion

- This flexure design will fail under the imposed loading
- Shape memory alloy may be too stiff for this purpose
- Possible solution: use of shape-memory polymer, which is more flexible
- Questions?

Appendix: References

- For details on composite beam calculations, see R.C. Hibbeler, "Mechanics of Materials"
- For more information on the Harvard Microrobotics Lab, visit the group's website: http://www.micro.seas.harvard.edu/
- Material properties were taken from www.matweb.com – searchable online database that includes brand-name materials (Such as Kapton and Nitanol)

Appendix: Physical Parameters

- Geometry:
  - Flexure length = 100 μm, width = 1500 μm, thickness = 7.5 μm
  - SMA coating thickness = 2 μm
- Material Properties
  - Kapton ® Polymer Film from Dupont Corporation:
    - E = 5 GPa
    - *v* = .34
    - Tensile strength = 172 MPa
  - Nitinol Shape Memory Alloy (Low Temp/High Temp phases)
    - E = 28 GPa / 75 GPa
    - *v* = .3 / .3
    - Tensile strength = 100 MPa / 560 MPa
    - undergoes ~5% linear strain (contraction) when heated