UNIVERSITY OF MARYLAND

Light-activated Shape Memory Polymers (SMPs): Muscle actuation for prosthetics

ENMA490

Final Report Presentation:

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Outline

- Justification
- Light Actuation Mechanism
- Design Goals
- Modeling and Results
  - Von Mises Stress Simulation
  - Fatigue Life Simulation
  - SMP Thickness Optimization
  - Light Actuation Calculations
- Testing and Results
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  - Actuation Testing
- Prototyping
- Conclusions
- Acknowledgements

Justification

Motivation

- **Shape memory** for muscle replacement
- **Polymer** for flexibility, light-activation
  - no contamination, no thermal radiation, lightweight

Intellectual Merit

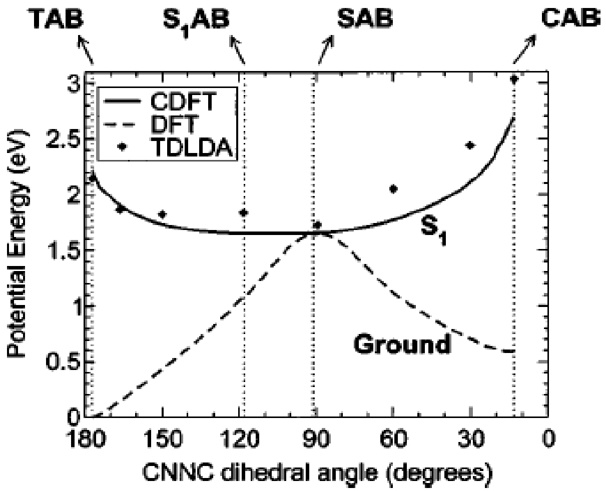
- **Material properties**: modeling and characterization
- **Design process**: precursor selection, modeling, specs

Impact

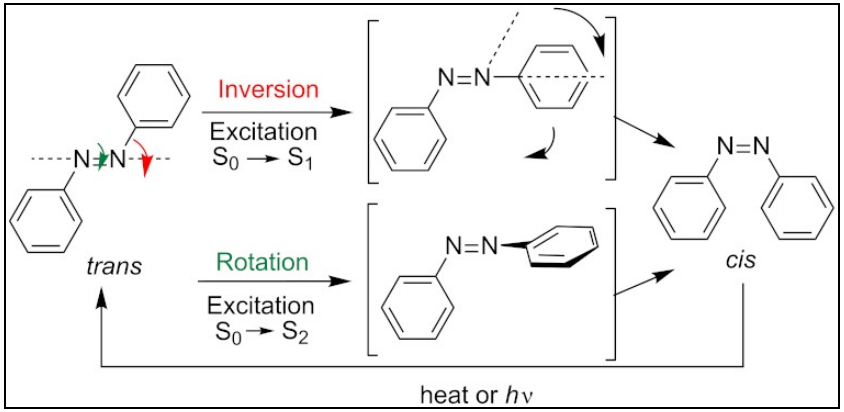
- **Medical applications**
  - researchers and patients
  - muscles and other applications
- **Robotics**

Light Activation Mechanism

- Azobenzene



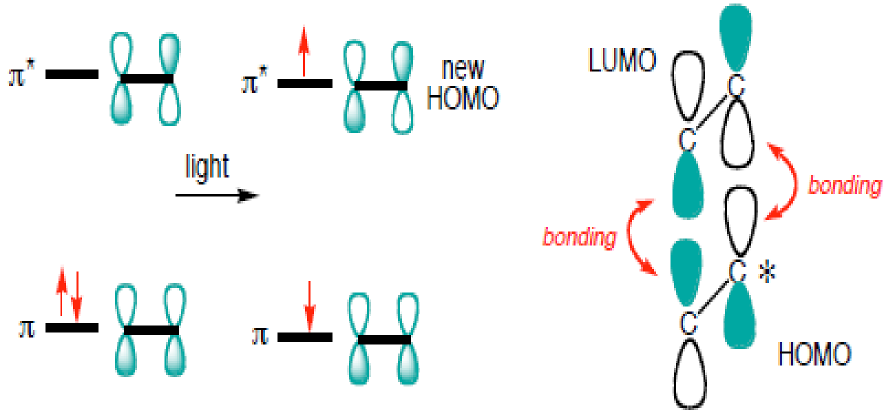
Potential energy vs. dihedral angle (Tiago et al.)



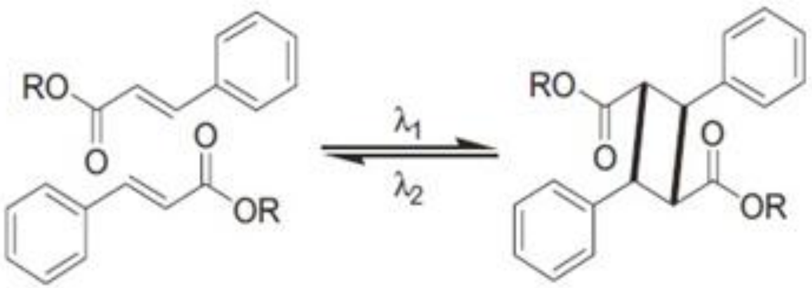
Reversible photo-isomerization of azobenzene (Marino et al.)

Light Activation Mechanism

- Cinnamic Acid (CA)



[2+2]cycloaddition of cinnamate group SMPs under UV light λ > 260 nm (Evans. D.A.)

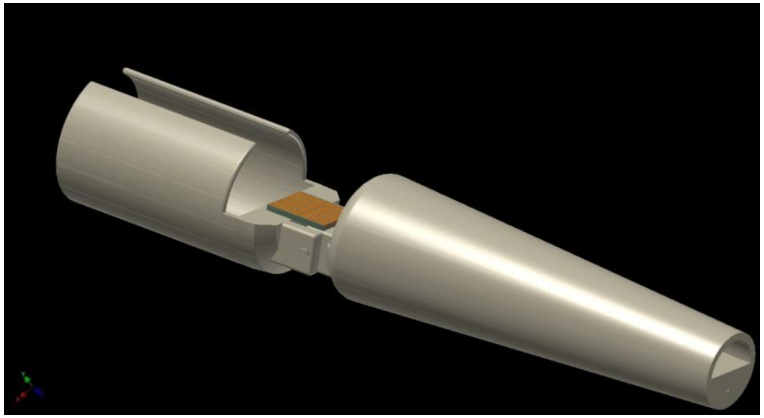


λ_1 > 260 nm; λ_2 < 260 nm

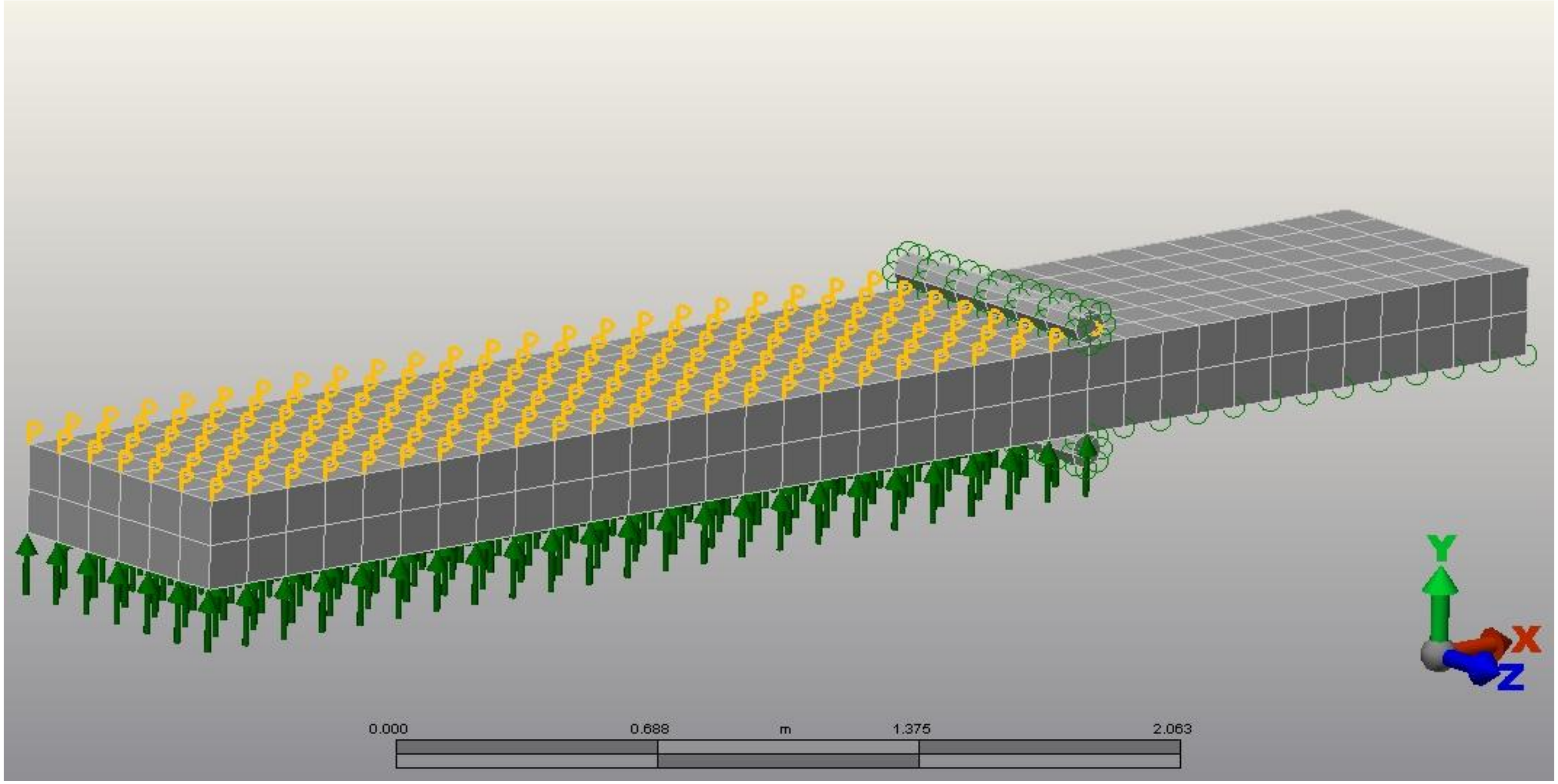
Reversible photo-crosslinking of cinnamic acid (Jiang et al.)

Design Goals

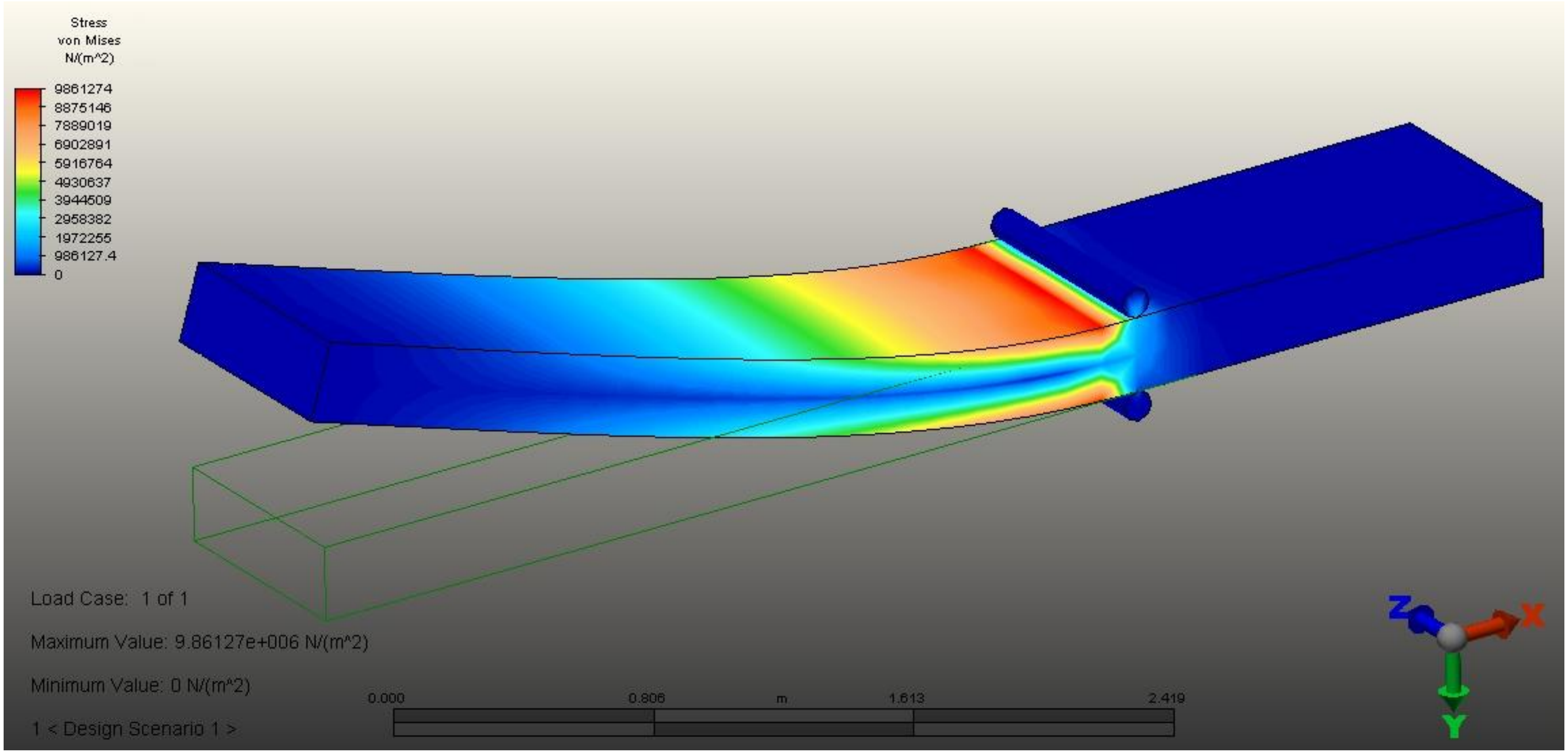
- Azobenzene SMP to be used as an artificial muscle
- Light source remotely located on the prosthetic arm
  - Polarization controlled bending motion at $\lambda < 514$ nm
- Prosthesis pin segment can accommodate 4 strips
  - 4.5 cm x 0.75 cm
- Azobenzene strips modeled to simulate:
  - Von Mises stress
  - Fatigue life
  - Optimal thickness



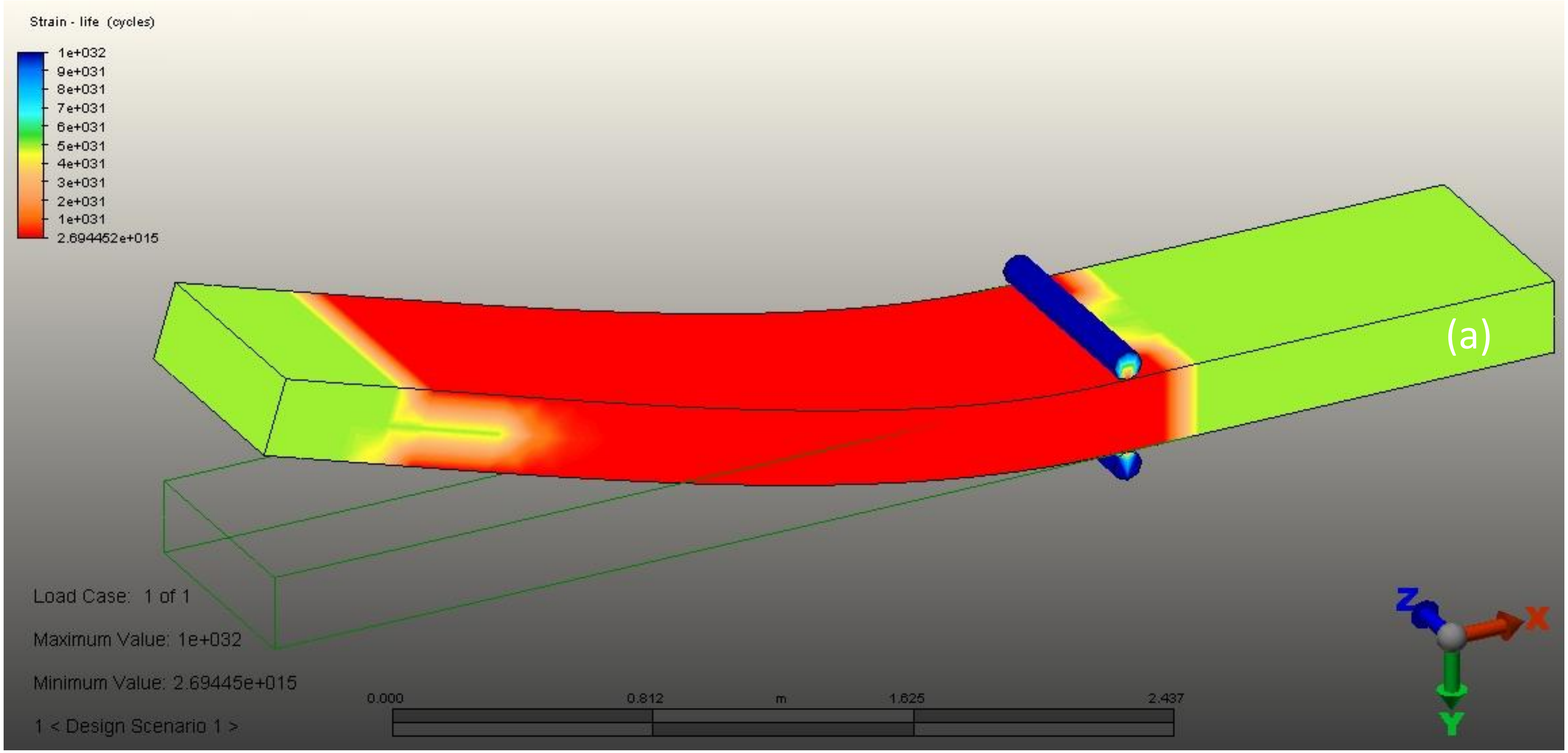
Meshed SMP Model



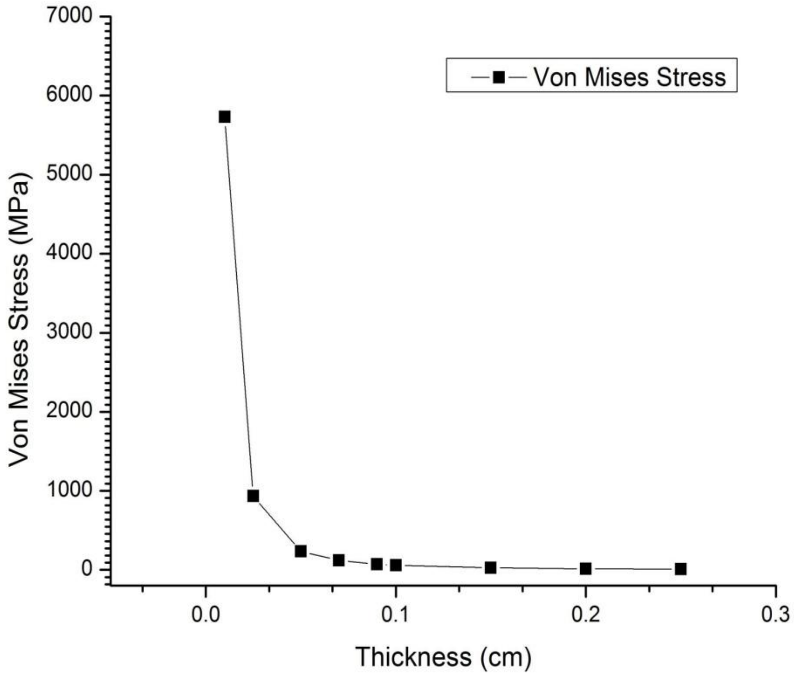
von Mises Stress Simulation



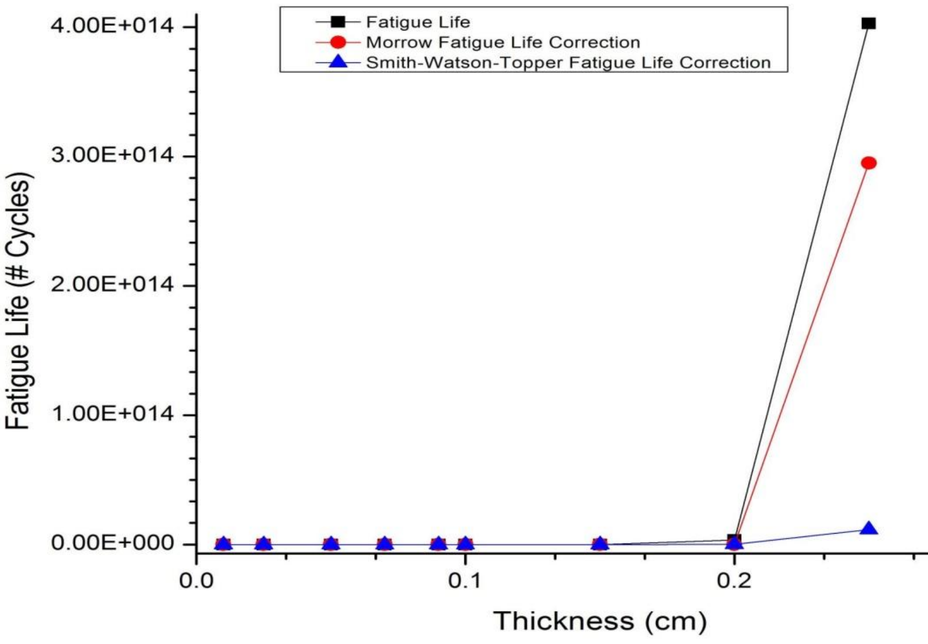
Fatigue Simulation



Effects of SMP Thickness



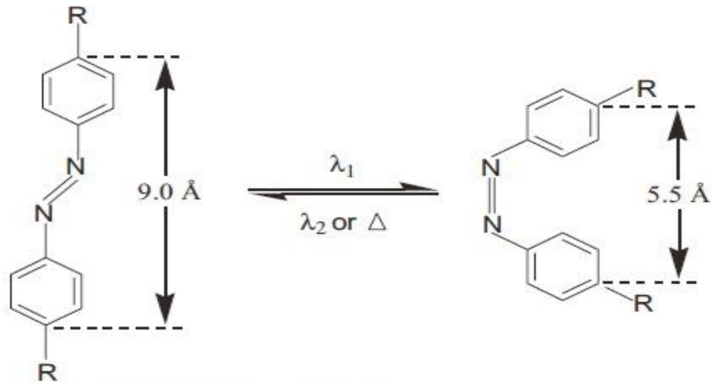
von Mises stress vs. SMP thickness



Fatigue life vs. SMP thickness

Light Activation Calculations

- von Mises Strain ($\varepsilon_{v.M.s}$) = 0.01345 m/m
- $\Delta l = \varepsilon_{v.M.s} l_0$
- Quantum Yield
  - 0.25 (E → Z)
  - 0.53 (Z → E)
- Beer-Lambert law
  - $\varepsilon C l = -log\left(\frac{P}{P_0}\right)$
- Extinction coefficient
  - ~ 2-3e+004 M-1·cm-1 (E)
  - ~ 1.5e+003 M-1·cm-1 (Z)
- P_0 = 2.05e+006 photons·cm^{-2} (E)
- P_0 = 9.67e+005 photons·cm^{-2} (Z)



λ_1 = 330-380 nm; λ_2 > 420 nm

3.5 x 10^{-8} cm / Azo molecule

Azobenzene chemical properties

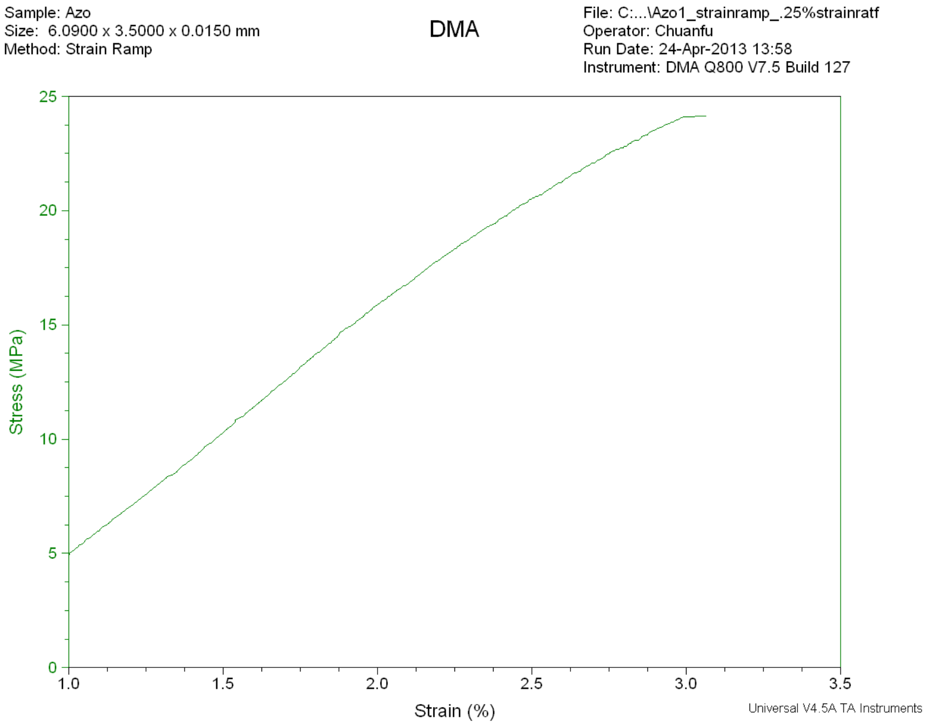
- MM = 1822.22 g/mol
- ρ = 1.09 g/cm^3

Testing: DMA

- Strain Ramp Test
  - Temperature: 24˚C
  - 0.25% strain/min

- Exp. σ_y = 24 MPa
  - Theoretical = 54 MPa

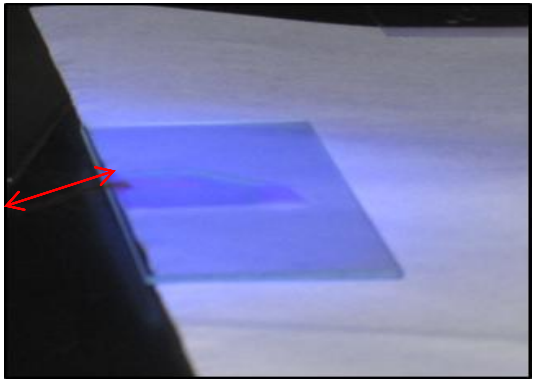
- Exp. E = 763.6 MPa
  - Theoretical = 990 MPa



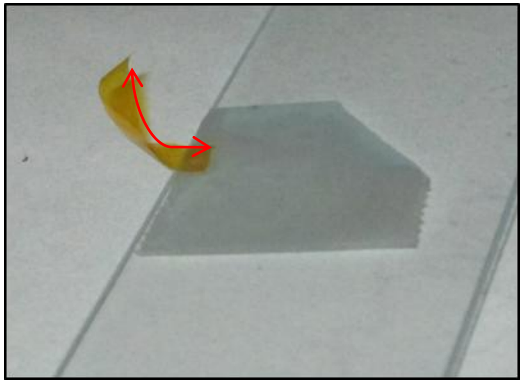
Strain Ramp Test for Azobenzene SMP sample.

Testing: Light Actuation

- 473 nm Laser – 20 mW/cm^2
  - No response from Azo strip
- Hg Lamp (with 418 nm filter) – 82 W
  - No response from Azo strip
- 365 nm UV lamp – 150 W
  - Reversible actuation possible
  - At distance ~10 cm, 3 minutes for full bending motion



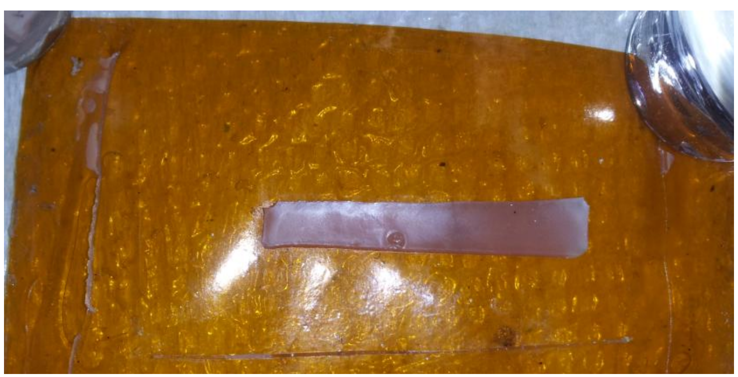
Relaxed Azobenzene SMP strip.



Activated Azobenzene SMP strip.

Prototyping

- Due to expense of Azobenzene, we prototyped using CA
- Based off of Lendlein, et al.
- Synthesized monomer HEA-CA
  - Involved performing a reflux and distillation
- Grafted our polymer using HEA-CA, BA, PPG, and HEMA
- Performed grafting at 80° C for 18 hours
  - Rinsed with hexane and chloroform



Conclusions

- Goals – model and prototype with azobenzene
- Accomplished/Results
  - Modeled azobenzene - stress, strain, fatigue, and CAD of prosthesis
  - Tested azobenzene
  - Prototyped using cinnamic acid-based polymers
- Comparison with other designs
  - Similarities - other research concerns similar applications - McKibben, etc.
  - Novelty - different material and mechanism for elbow bending
- Future research
  - Testing - more actuation with azobenzene
  - If more money, prototype azobenzene SMPs
  - Test within actual application, prototype entire arm mechanism
  - Redesign for inclusion in robotic systems

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Xin Zhang

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Information:
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Dr. Anderson
Dr. Lloyd
Dr. Martinez-Miranda
Dr. Nie
Dr. Salamanca-Riba
Dr. Seog
Dr. Steffek
Dr. Wuttig

Questions?

EXTRA SLIDES

Technical Approach

- Background:
  - Photoisomerization of Azobenzene
  - Reversible photo crosslinking of cinnamate-groups (cinnamic acid and cinnamylidene AcOH)
- Relevant Equations:
  - High-cycle fatigue & Low-cycle fatigue (Coffin-Manson relation) => Morrow's Design rule

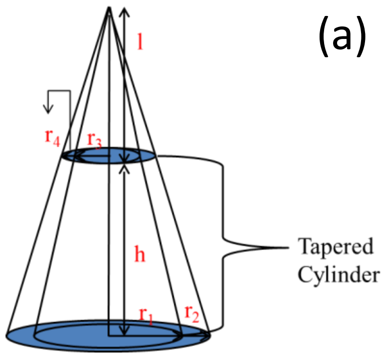
$$\frac{\Delta\varepsilon_{el}}{2} = \frac{\sigma_f'}{E}(2N_f)^{-b} \qquad \frac{\Delta\varepsilon_{pl}}{2} = \varepsilon_f'(2N_f)^{-c} \qquad \Delta\varepsilon = \Delta\varepsilon_{pl} + \Delta\varepsilon_{el}$$

- Empirical data:
  - Average dimensions of a human arm
- Mechanical and physical properties of azobenzene and Cinnamate group SMPs
  - Glass transition temperature and photo-induced stress
- Numerical analysis:
  - Structural and fatigue analysis via Autodesk Simulation Multiphysics

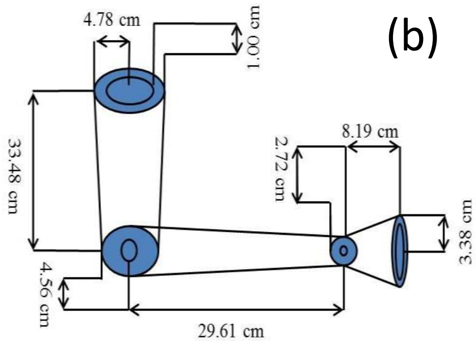
Arm Prosthesis Model/Design

- Dimensions of an average human arm (R.F. Chandler)
- Use HDPP as the base material for the prostheses
  - Density of HDPP = 0.902 g/cc (MatWeb)
- Each component of the arm is estimated as a hollow tapered cylinder with a 1 cm thickness
- Use the difference of cone volumes

$$V = \frac{1}{3}\pi\left((r_1)^2 - (r_2)^2\right)(h+l) - \frac{1}{3}\pi\left((r_3)^2 - (r_4)^2\right)(l)$$



(a)



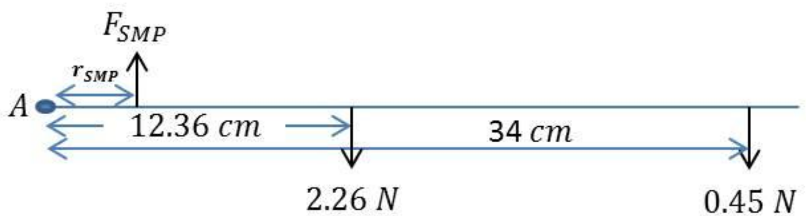
(b)

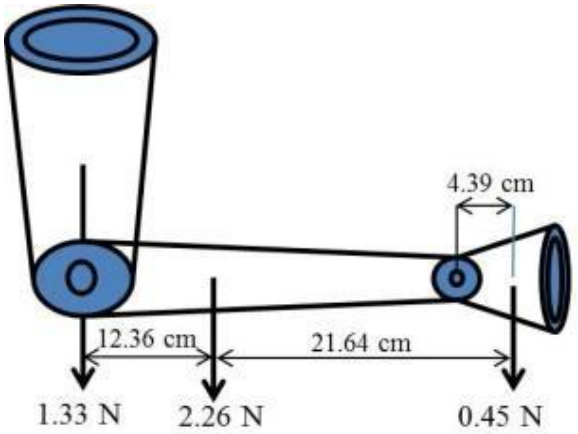
Arm Prosthesis Model/Design

- Center of mass of the tapered cylinder segments

$$\bar{x} = \frac{\int \tilde{x}\, dm}{\int dm} \qquad \bar{y} = \frac{\int \tilde{y}\, dm}{\int dm} \qquad \bar{z} = \frac{\int \tilde{z}\, dm}{\int dm}$$

- Free body diagram of the prosthetic arm (c)





$$+\rightarrow \sum F_X = 0,$$

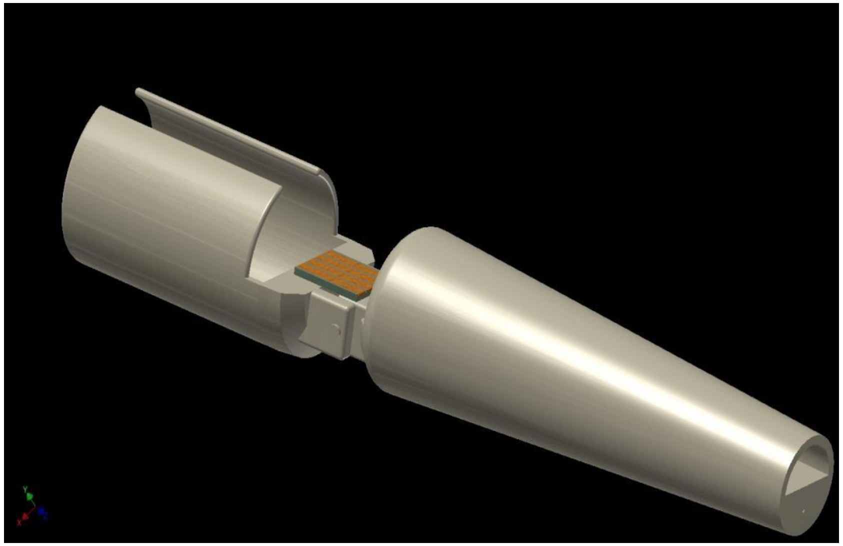
$$+\downarrow \ \sum F_y = 2.26\ N + 0.45\ N - F_{SMP} = 0$$

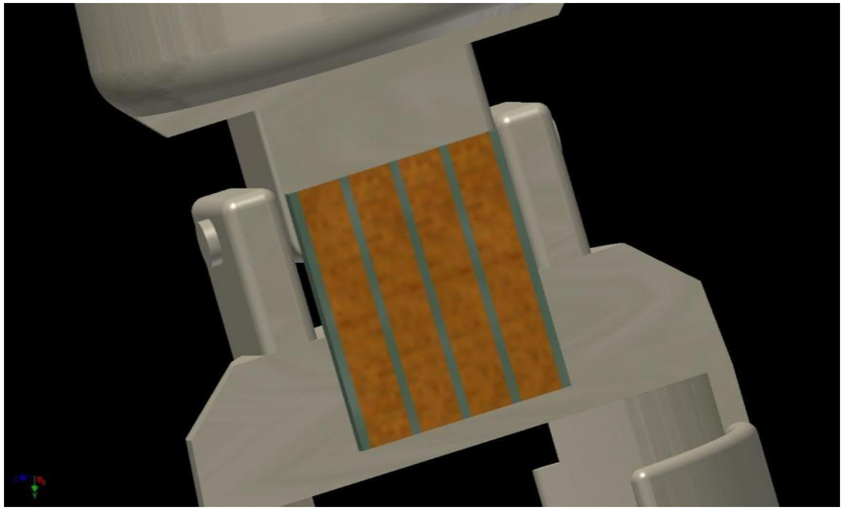
$$\circlearrowright + \sum M_A = (2.26\ N)(12.36x10^{-2}\ m) + (0.45\ N)(34.0x10^{-2}\ m) - F_{SMP} r_{SMP} = 0$$

- The bending moment exerted by the forearm and hand in static equilibrium is 0.432 Nm and the load on a single SMP strip that is 4.5 cm and balances the bending moment is approximately 7.025 N

Arm Prosthesis Model/Design

- Autodesk: 3D model with a pin segment
- Cross-section of forearm and upper arm cut in half
  - Flat surface to mount the SMP
- Maximum rectangle within the forearm base to extrude the pin segment
  - Maximal area for mounting SMP
- SMP strip volume
  4.5 x 0.75 x 0.25 cm3





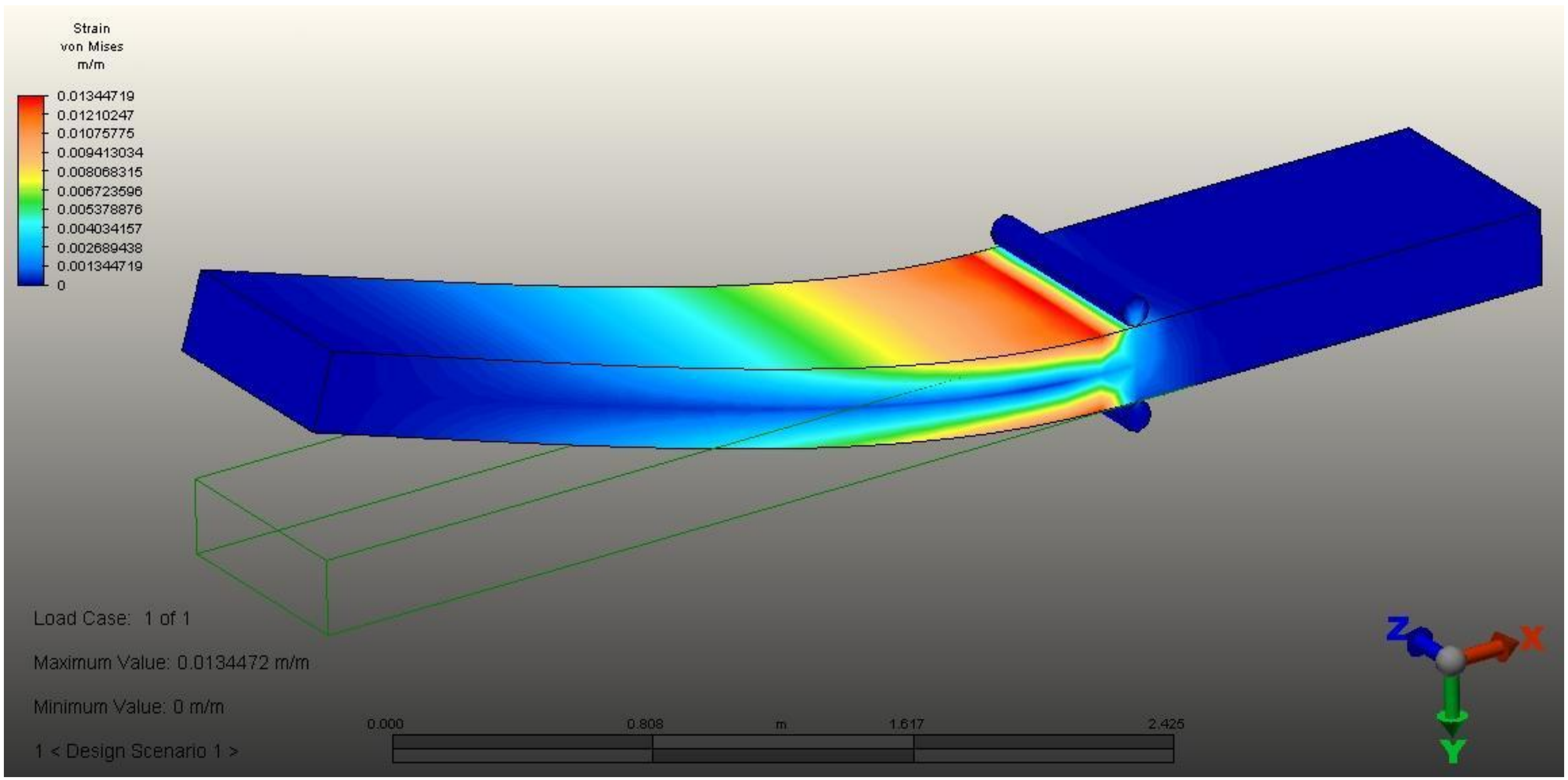
von Mises Stress Simulation

- Parameters used for structural modeling/simulation (Cheng et al.)
  - Poisson's ratio - 0.35
  - Young’s modulus - 0.99 GPa
  - Photo stress - 25 kPa
- Other inputs
  - Weight loading - 3.4 N (5x weight load of 2.71 N over 4 uniformly loaded strips)
- Autodesk Multiphysics Settings
  - Static/linear/isotropic
  - 1.5x0.75 cm^2 area of the SMP sheet fixed (3 d.o.f)
  - Cylinder hinges fixed (3 d.o.f)
  - Brick element
  - Auto mesh (692 elements)
- Von Mises Stress
  - Maximum value - 9.86 MPa (predicted yield stress is 54 MPa)

von Mises Strain Simulation

- Performed using von Mises simulation parameters (Cheng et al.) and inputs/constraints
- Autodesk Multiphysics Settings
  - Static/linear/isotropic
  - Uniform loading
- Strain response
  - Highest strain levels develop on the bottom and top of the surface
- von Mises Strain - 0.0135 (m/m)
  - Predicted yield strain is 0.0545 m/m

von Mises Strain Simulation



Fatigue Simulation

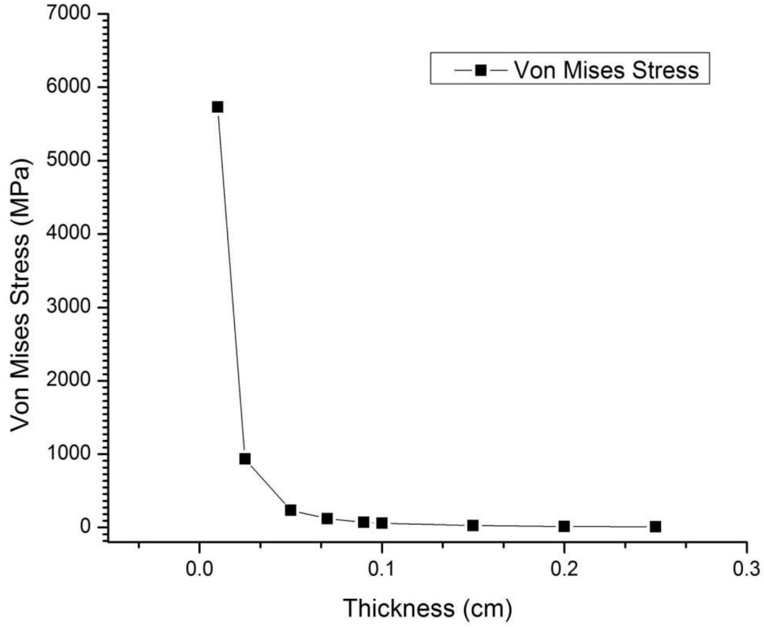
- Autodesk fatigue analysis
  - T.S.: 80 MPa (Nylon 6 approximation)
  - Constant amplitude
  - Half cycle of a sine wave used to model the load curve (load vs. time)
  - Desired cycles to failure: 10^5 cycles
- Fatigue response
  - Normal: 4.027×10^{14} cycles
  - Morrow correction: $\left[\frac{\Delta\varepsilon}{2} = \frac{(\sigma_f' - \sigma_m)}{E(2N_f)^b} + \varepsilon_f'(2N_f)^c\right]$, 2.951×10^{14} cycles
  - Smith-watson-Topper correction: $\left[\frac{\Delta\varepsilon * \sigma_{max}}{2} = \frac{\sigma_f' * \sigma_f'}{E(2N_f)^b} + \varepsilon_f' {}_* \sigma_f'(2N_f)^{b+c}\right]$, 1.16×10^{13} cycles

	Young's Modulus (GPa)	Poisons ratio	Density (g/cc)	Glass transition temperature (˚C)
Azobenzene	0.99	0.35	1	56
Nylon 6 (film grade)	0.1-3.30	0.39-0.4	1.04-1.38	50

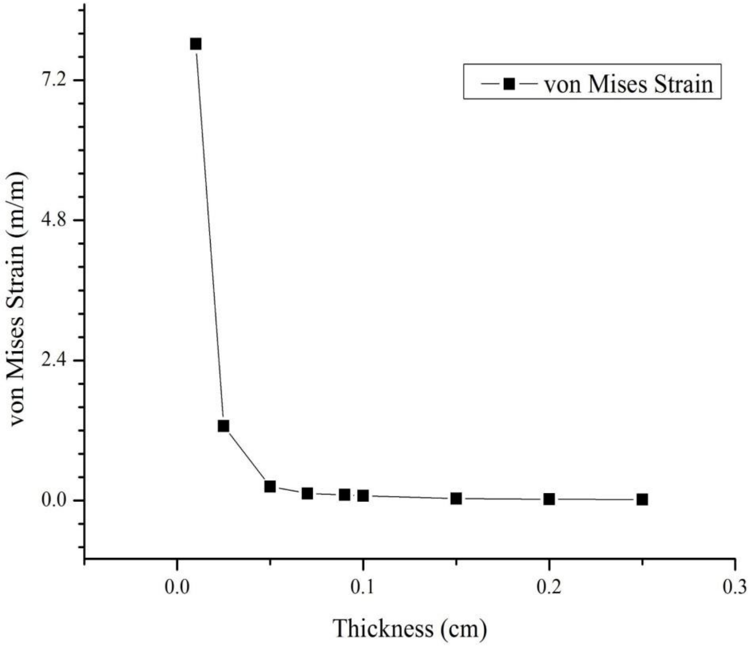
Material properties for Nylon 6 obtained (matweb.com)

Effects of SMP Thickness

- Fatigue life vs. azobenzene SMP thickness



von Mises stress vs. azobenzene SMP thickness



von Mises strain vs. azobenzene SMP thickness

Absorption of Azo by Conformation