SAND2011-8566C

Photo-Origami

Photo-Mechanical Bending and Folding of Active Films

ASME IMECE, Soft Materials Symposium November 16, 2011

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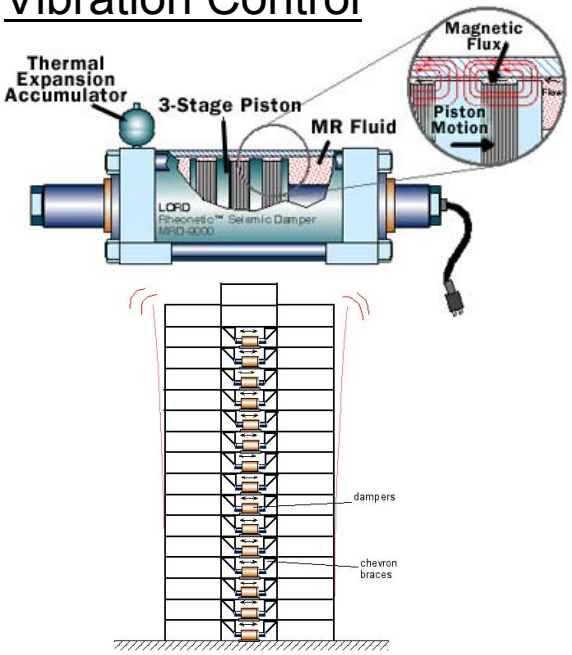
The Need for Smart Materials and Structures

Definition

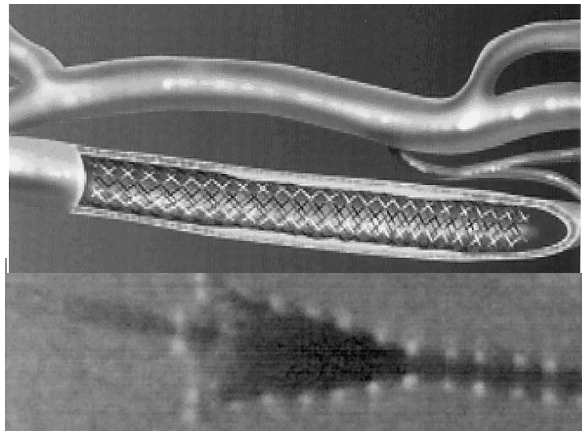
A *Smart Material* exhibits a significant response to a specific stimulus. SAs may be incorporated into a *Smart Structures* which sense changes to the environment and actively respond

Vibration Control



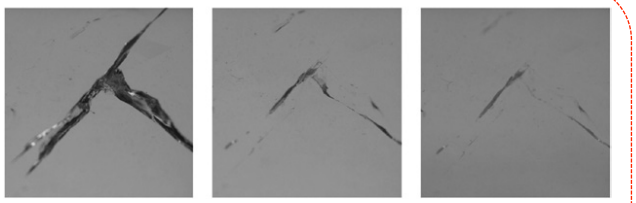
http://science.howstuffworks.com/engineering/structural/smart-structure2.htm

Biomedical Devices

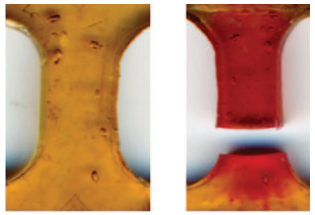


Deurig, *et al.* 1999

Self-Healing and NDE



Tian, *et. al.,* 2009



Caruso, *et al.* 2009

IMECE 2011, Soft Materials Mechanics, Active Polymers I

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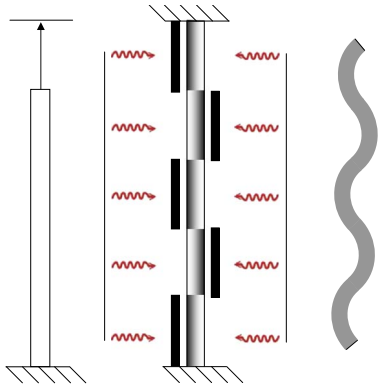
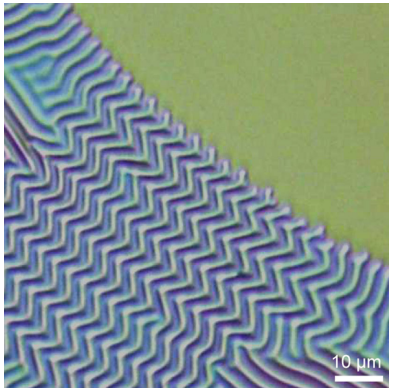
Diverse Mechanically Active Polymers

Photo-Induced Stress Relaxation

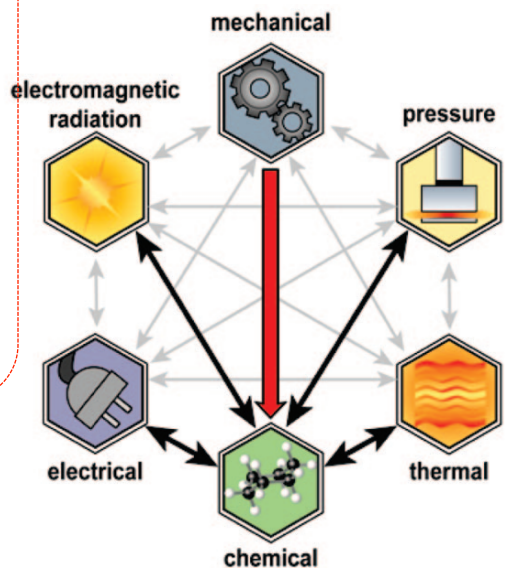


Long, *et al.* 2009

Swelling Induced Wrinkling

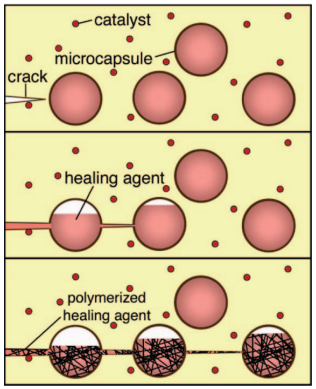


Vanderparre and Damman 2008



Caruso, *et al.* 2009

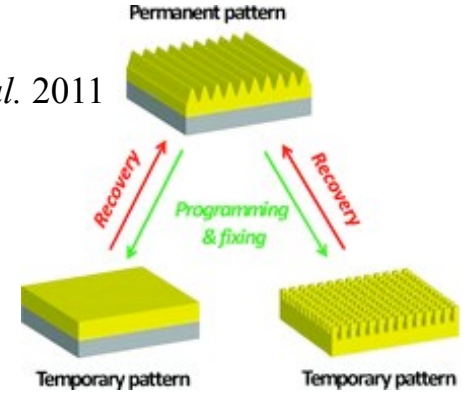
Deformation Induced Crack Healing



White, *et al.* 2001

Thermally Induced Shape Memory

Wang, *et al.* 2011



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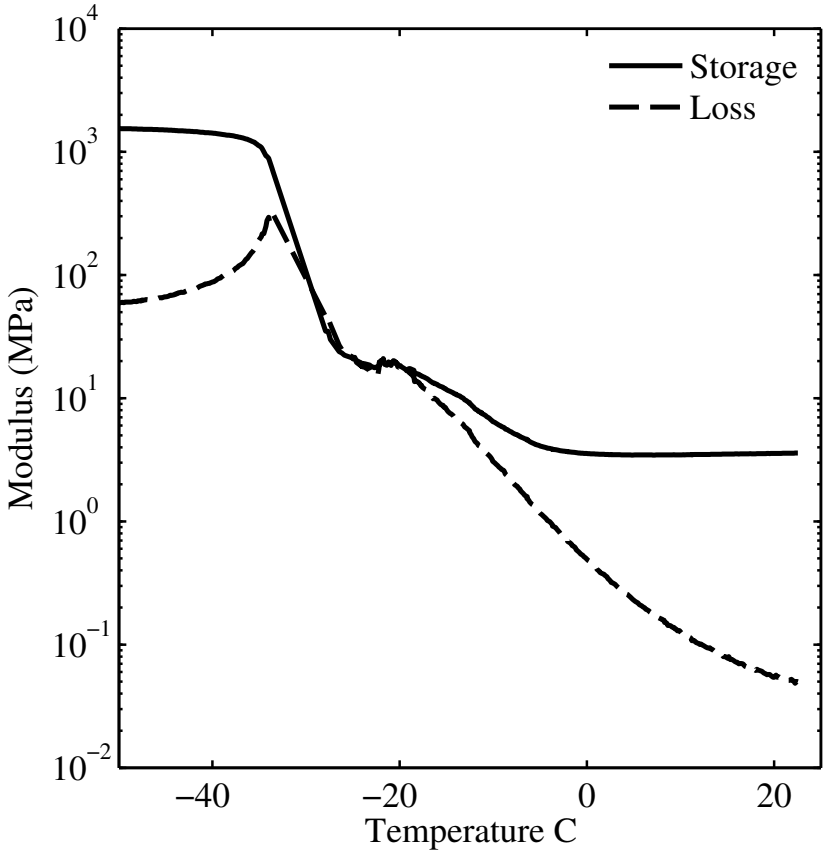
Outline

- **Motivation**
- **A Specific System**
- **Photo-Origami**
- **Summary**

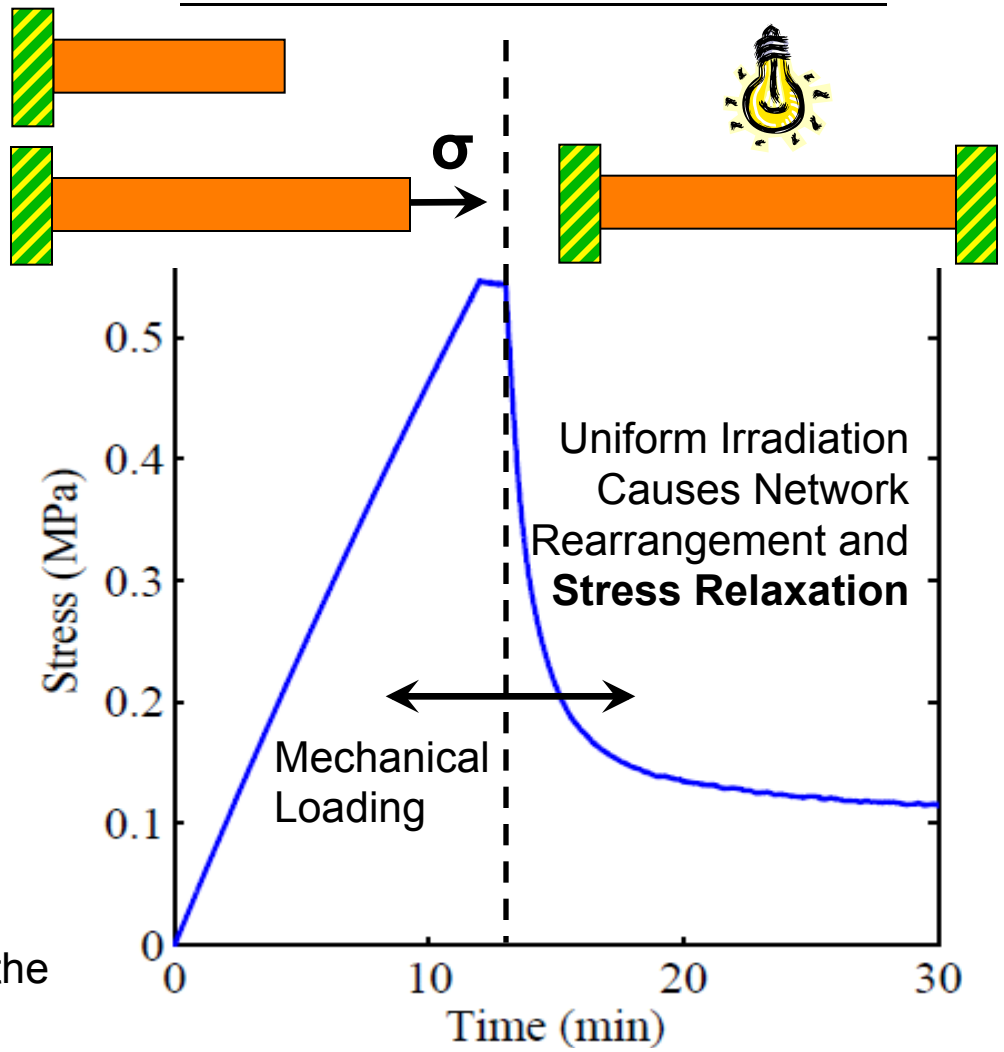
Photo-Induced Network Rearrangement

Network Behavior



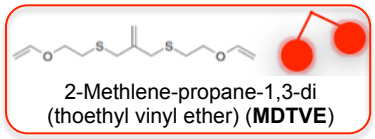
Polymer Dynamics of a lightly cross-linked network. Glass transition as defined by by the peak of the loss tangent is -22 C

UV Induced Stress Relaxation

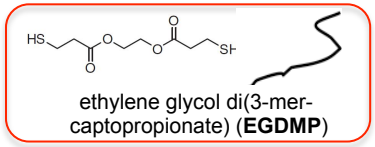


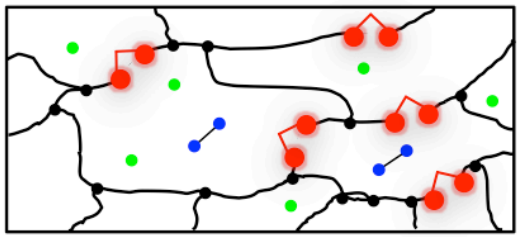
Network Chemistry and Topology

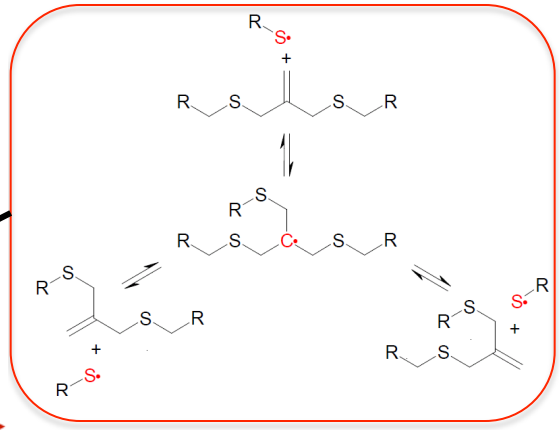
Radical-Rearranging Monomer



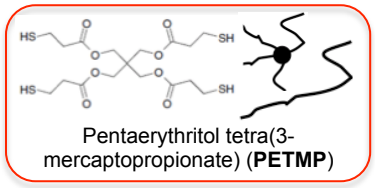
Chain Extending Monomer







Cross-Linker



Secondary Initiator

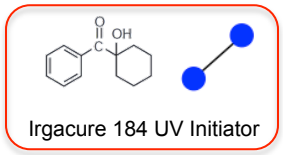
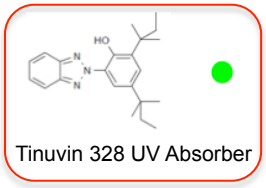


Photo-Absorber



<u>Stress Relaxation Mechanism</u>
Network Connectivity Rearrangement

Radicals undergo addition/ fragmentation chain transfer reactions at C=C sites on the MDTVE

<u>Challenges</u>

- Coupling Radiative Transfer, Photo-Chemistry, Network Rearrangement, and Solid Mechanics
- Utilizing Unique Material Capabilities

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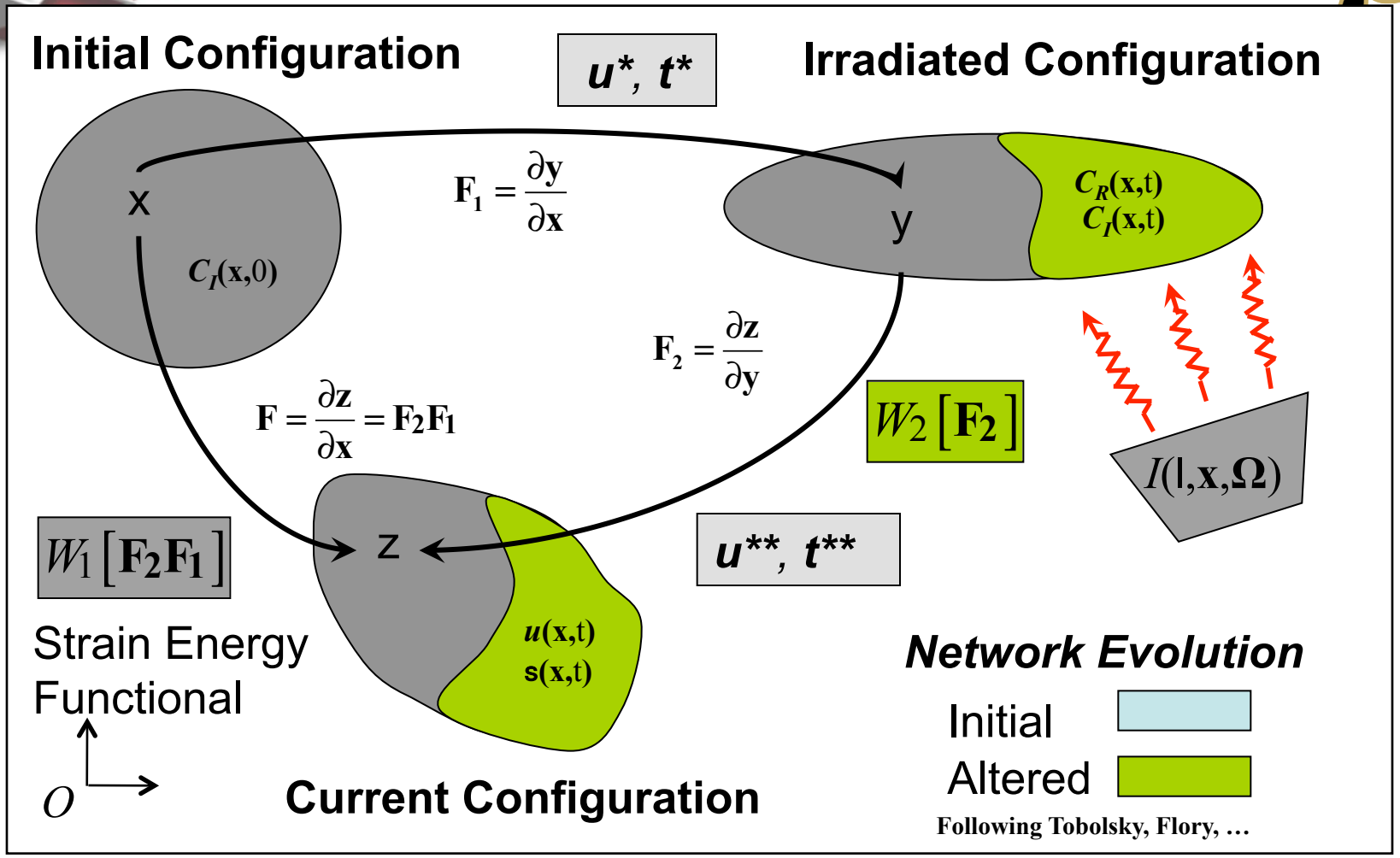
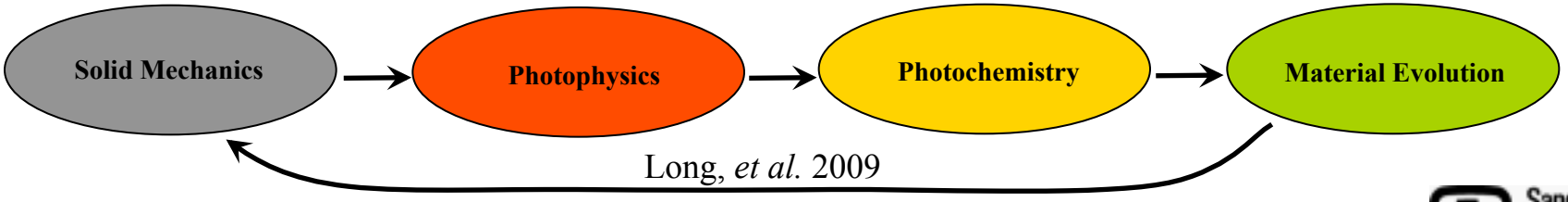
Model Framework





Long, *et al.* 2009

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Multi-Physics Model Summary

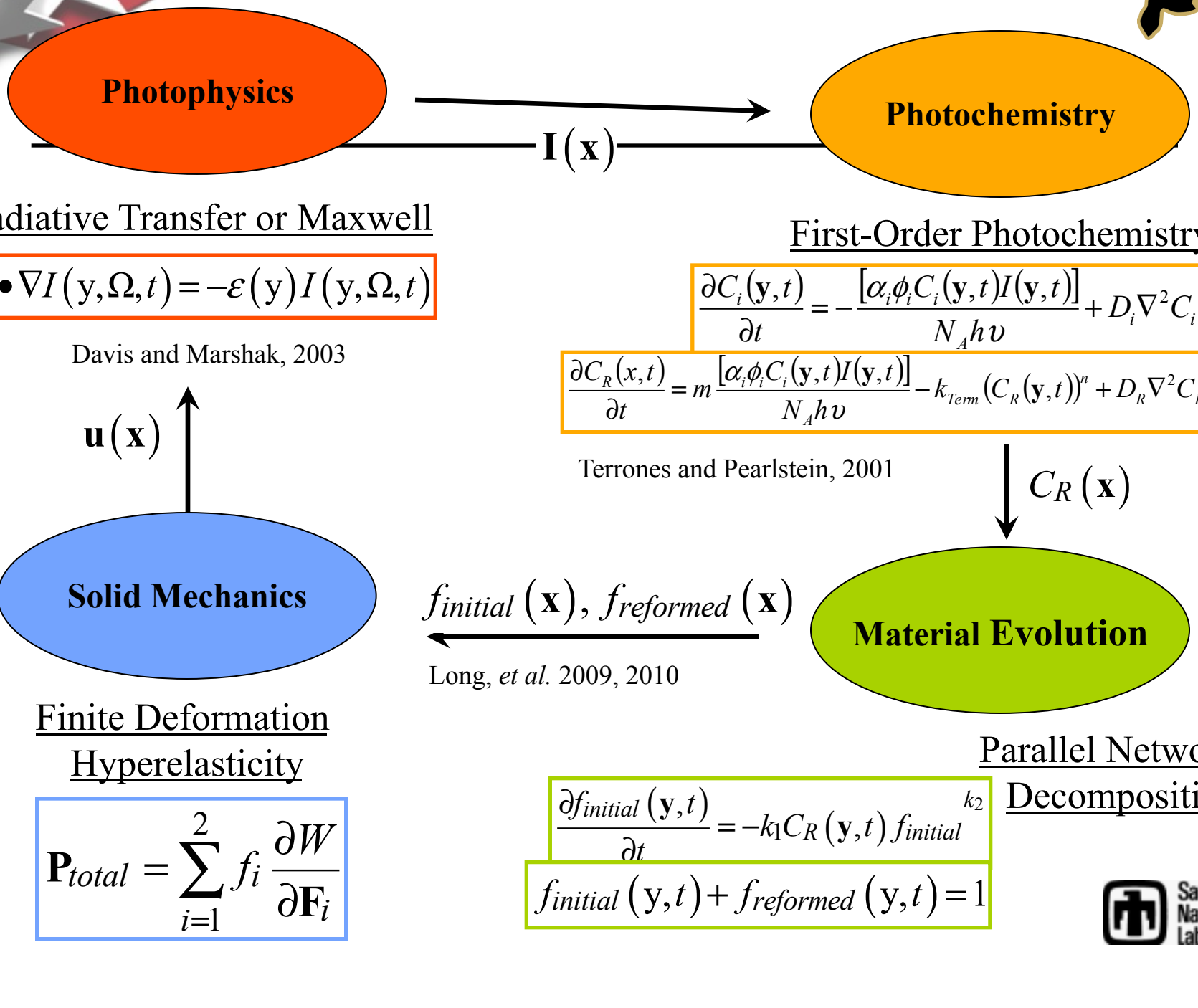

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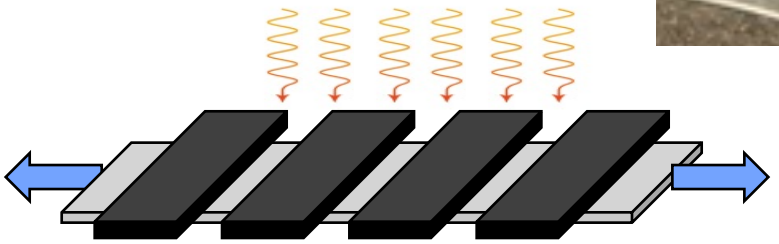
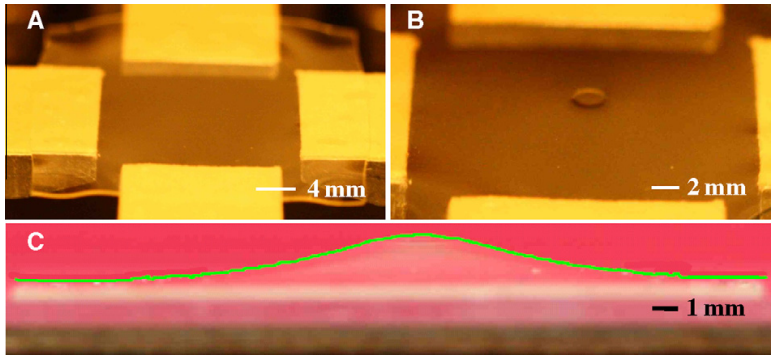
Photo-Mechanical Surface Manipulation

Photo-Origami

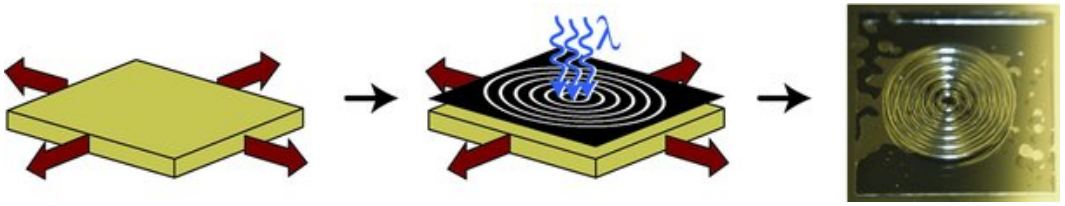


Tunable Buckling



Long, *et al.* IJSS 2011

Localized Photo-Induced Creep



Kloxin, *et al.* Adv. Mat. 2011

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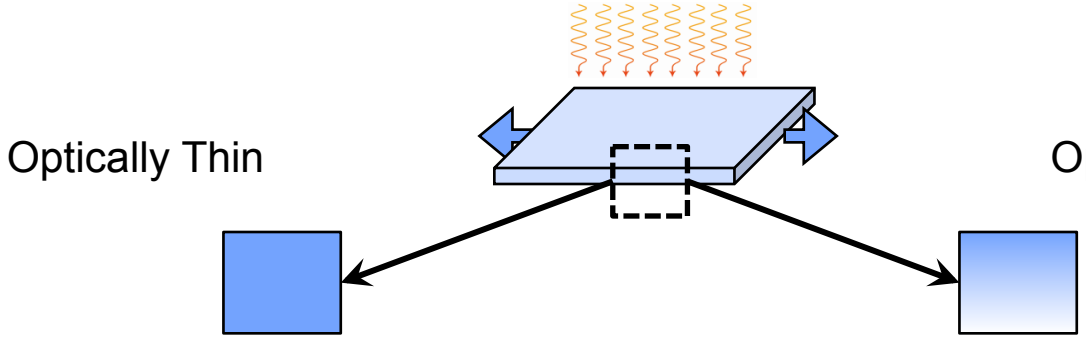
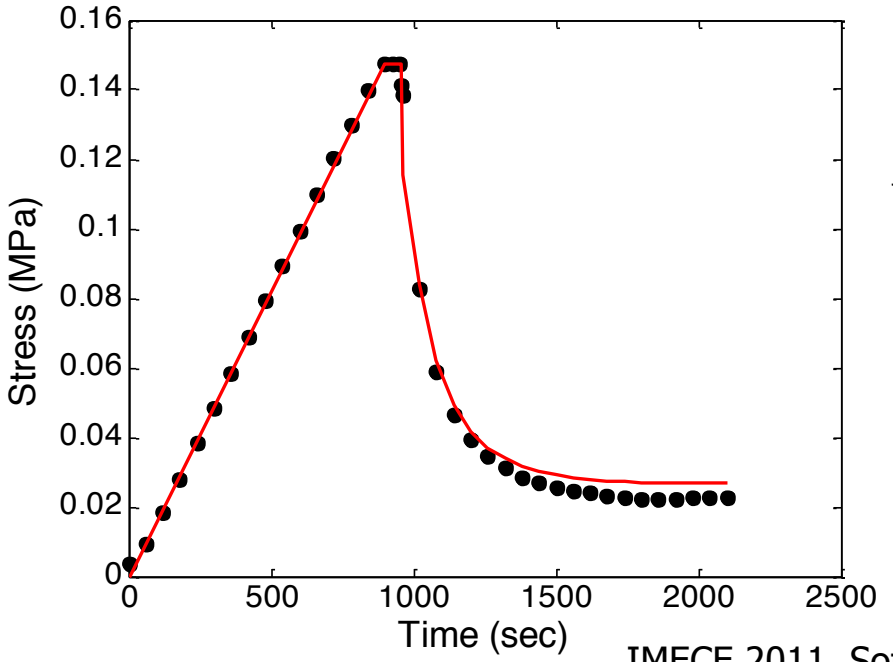
Photo-Origami Basics: Bending





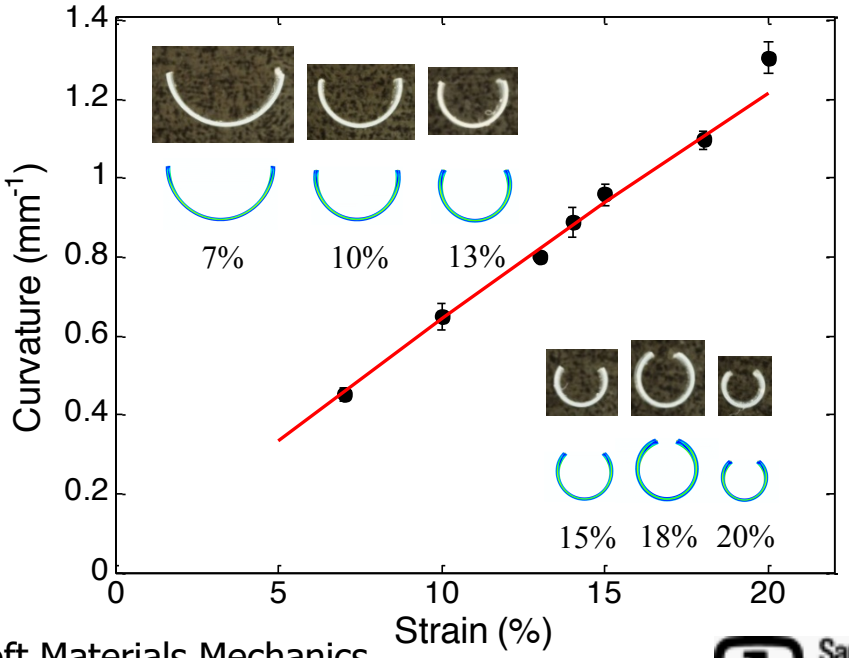


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Photo-Origami Basics: Effects of Initiator Diffusion

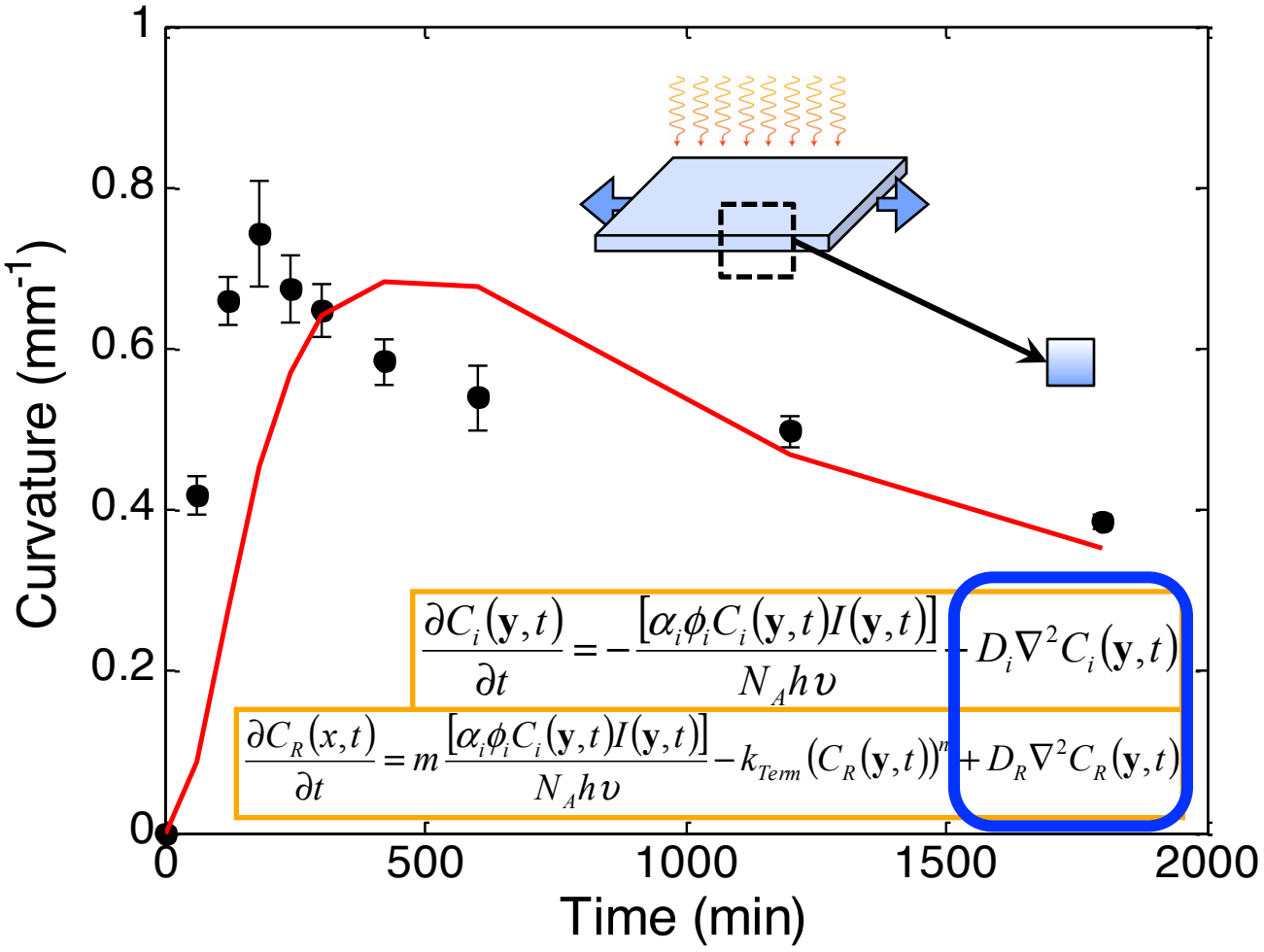

Photo-Origami Basics: Folding of a Hinge

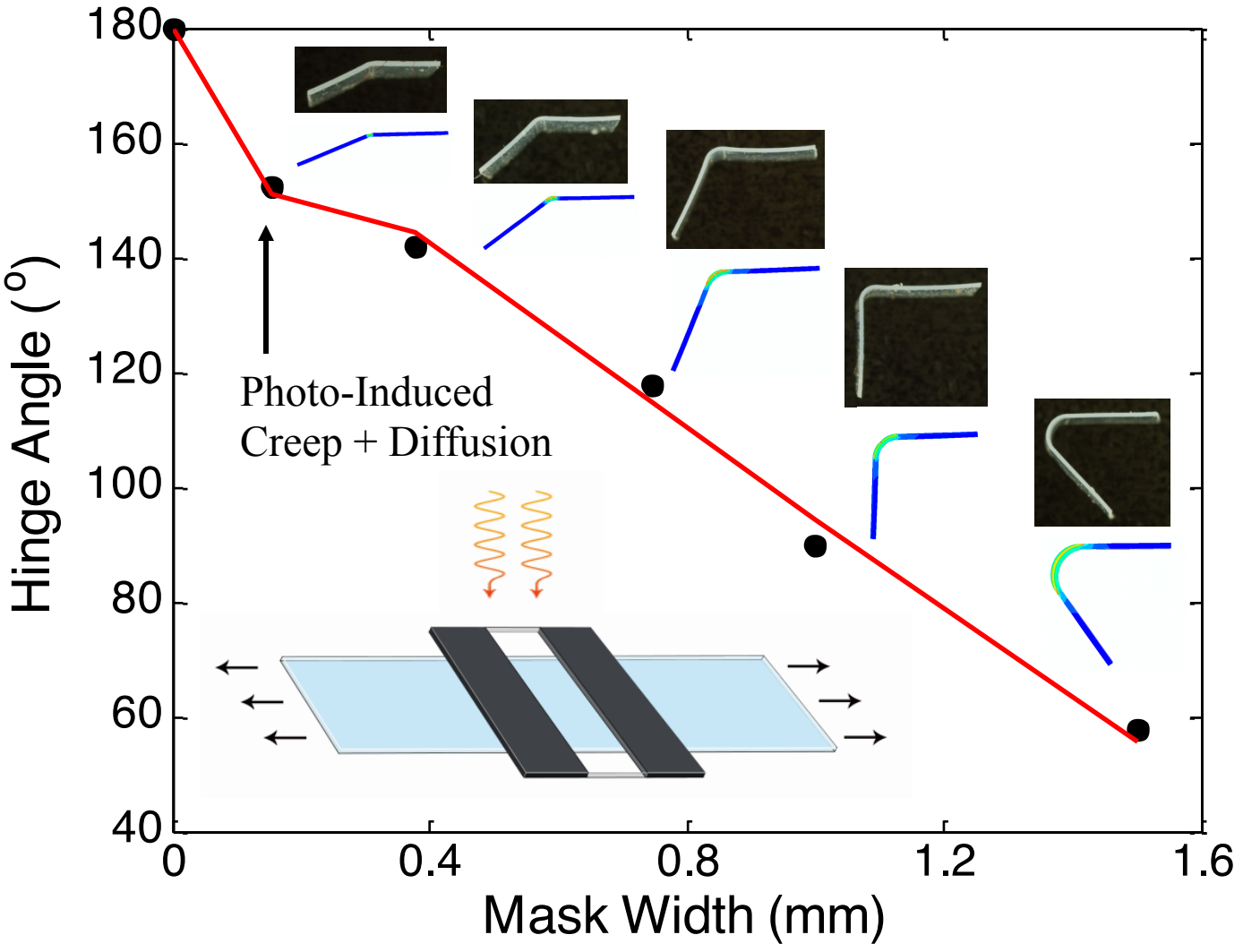

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Photo-Origami in 2D

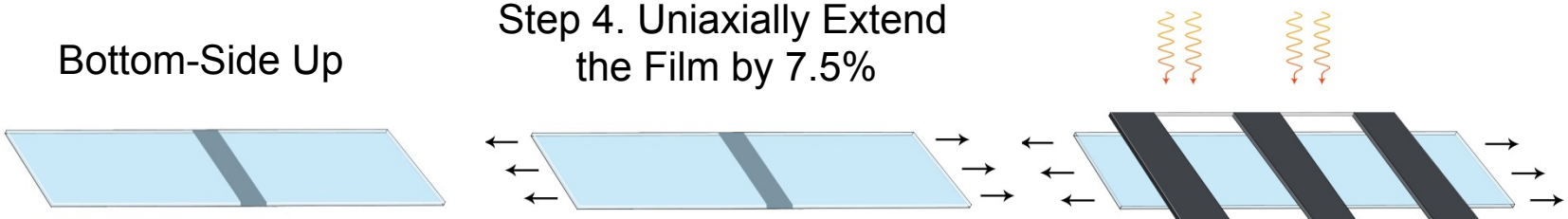
Step 1. 20% Uniaxial Extension of an Optically Thick Film

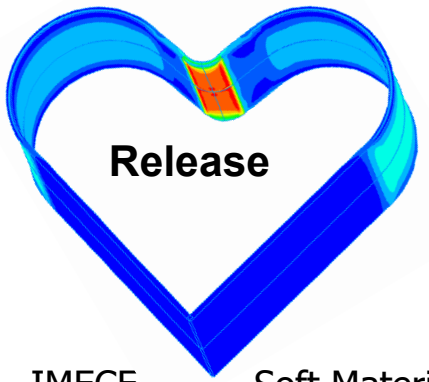
Step 2. Irradiation Through 0.75 mm Mask

Step 3. Flip the Film. The Stress Relaxation Varies with Depth

Bottom-Side Up

Step 4. Uniaxially Extend the Film by 7.5%





Step 5. Irradiate 6.3 mm Zones Spaced 1.5 mm from the Center

IMECE ..., Soft Materials Mechanics, Active Polymers I

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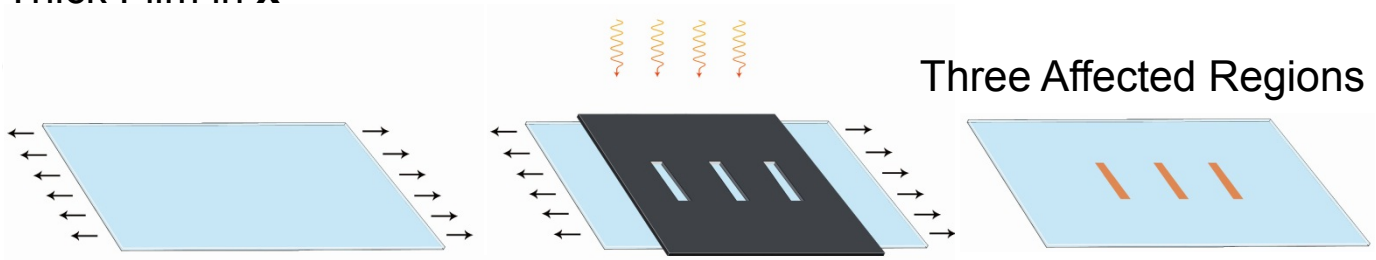
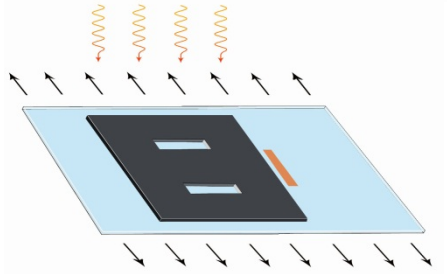
Photo-Origami in 3D: Programming a Box

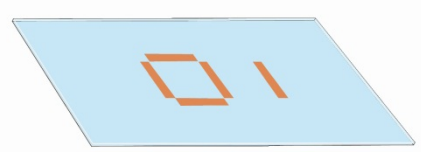
Step 1. 20% Uniaxial Extension of an Optically Thick Film in **x**

Step 2. Irradiation Through 0.75x5 mm Slits Spaced 6 mm

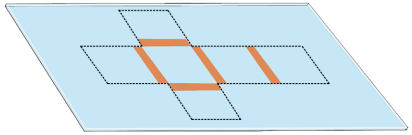




Step 5. Release



Step 6. *Cut Out* "Cross"



Step 3-4. Uniaxially Extend the Film by 20% in the **y** direction. Irradiate through 0.75x4 mm Slits Space 6 mm Apart.

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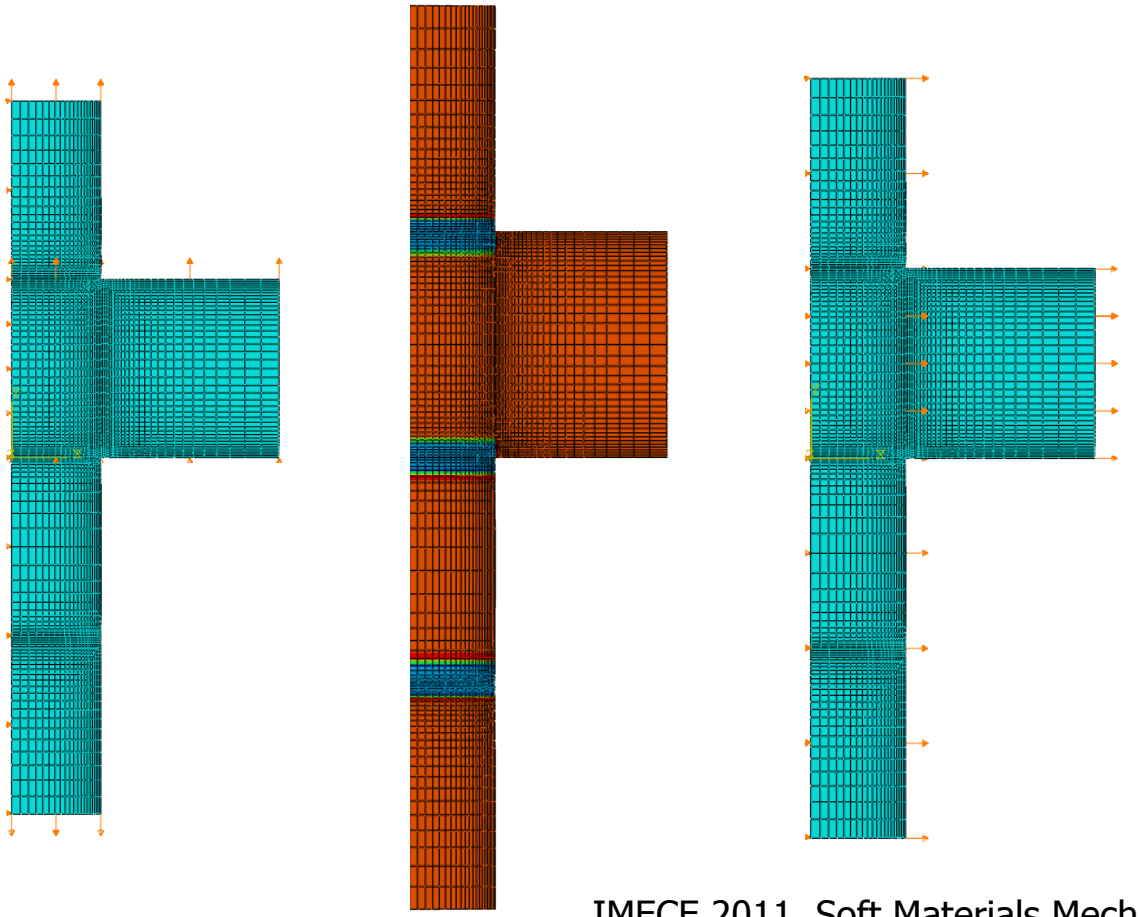
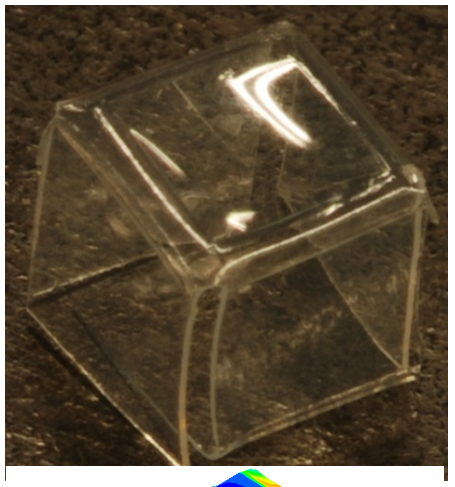
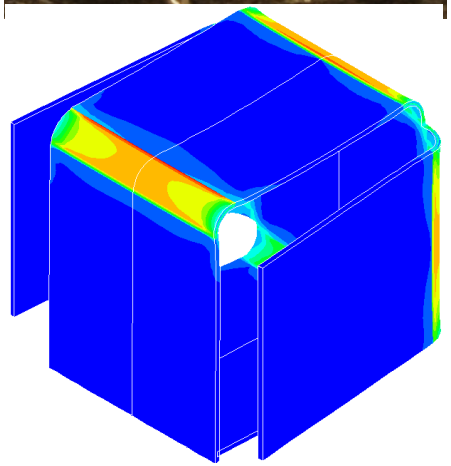
Photo-Origami in 3D: Programming a Box

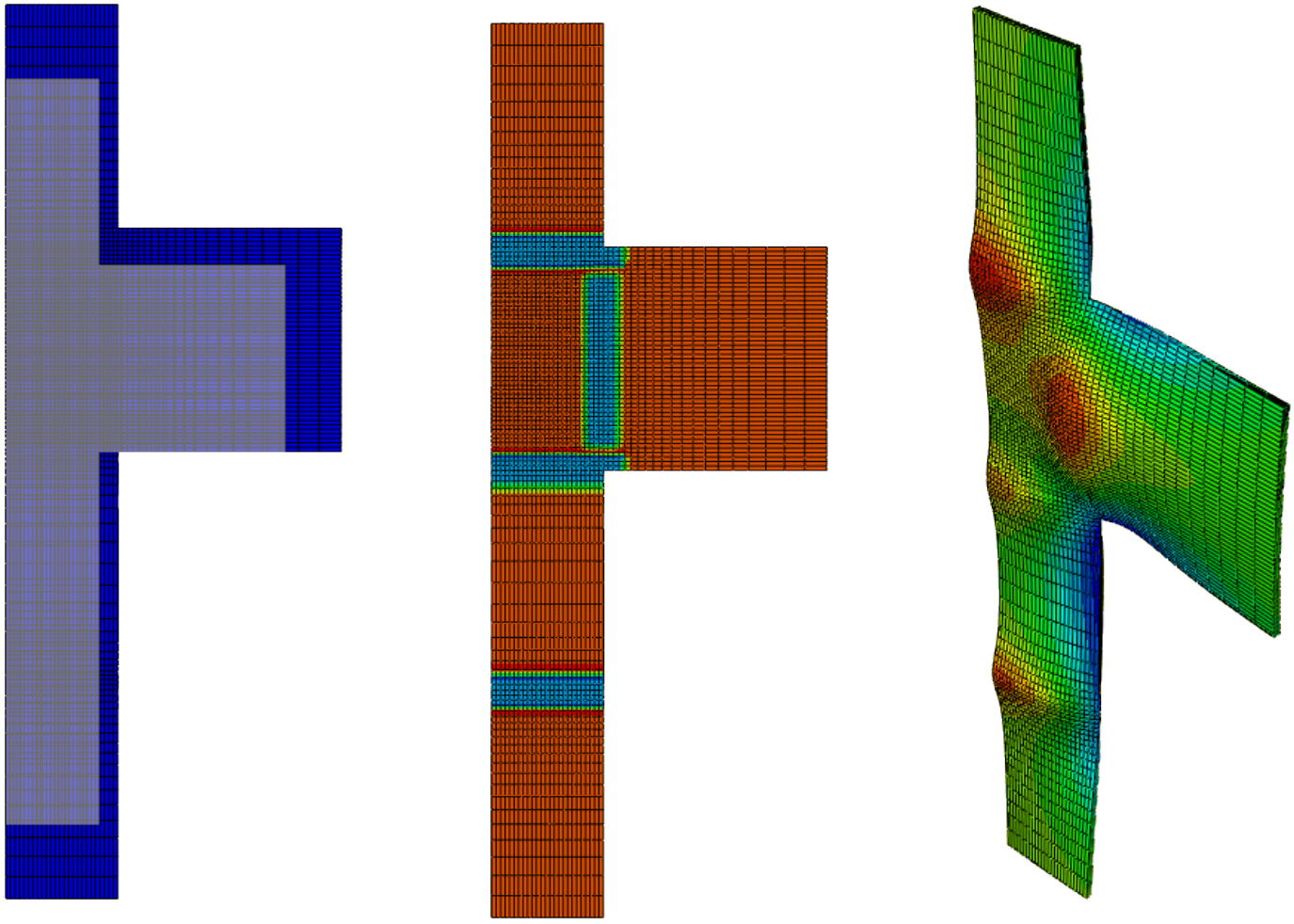
Finite Element Modeling







Consequences of Different Protocols



Summary and Future Work

- The *intelligent* combination of photo, chemical and mechanical treatments results in an enormous design space to shape active films
- The use of high fidelity simulations is essential to the development of complex, 3D photo-origami structures
- Future work involves:
  - The combination of photo-induced origami and elastic instabilities
  - The integration of photo-active films to smart composite structures for sensing applications

Thank You! Questions?

Relevant Literature Contributions

- Ryu, J., et al. Photo-Origami. Submitted to Nature Materials
- Long, K.N., et al. 2011. Photo-induced deformation of active polymer films: Single spot irradiation. International Journal of Solids and Structures
- Long, K.N., et al. 2010. Light-Induced Stress Relief to Improve Flaw Tolerance in Network Polymers. Journal of Applied Physics
- Long, K.N., et al. 2009. Photomechanics of Light-Activated Polymers. Journal of the Mechanics and Physics of Solids

Contact

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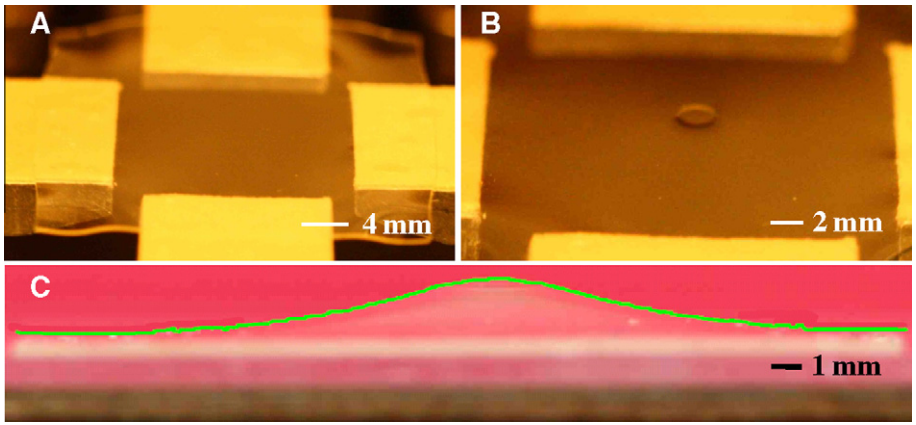
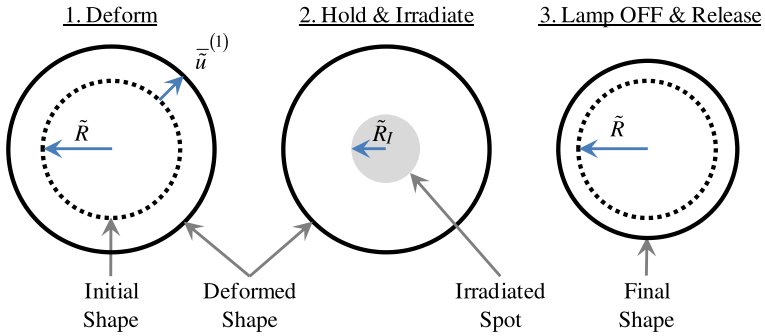
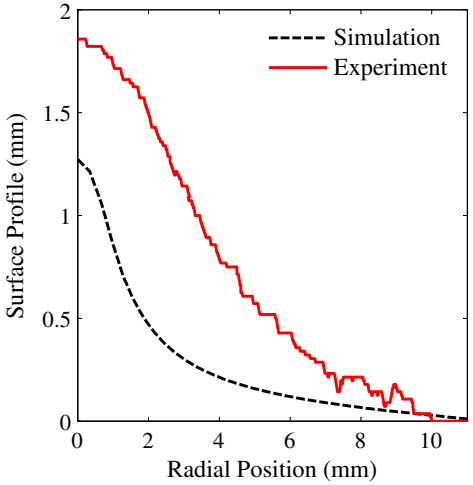
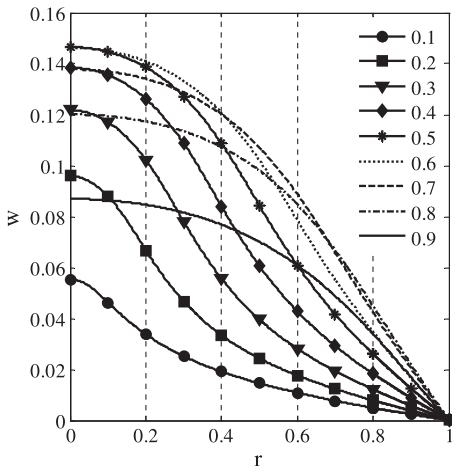
Using Elastic Instabilities in Stress Relaxing Films to Control Surface Profiles









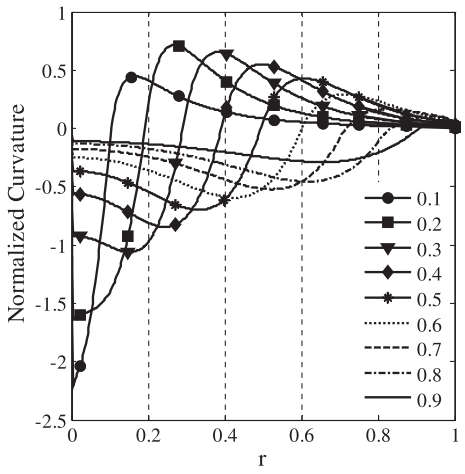


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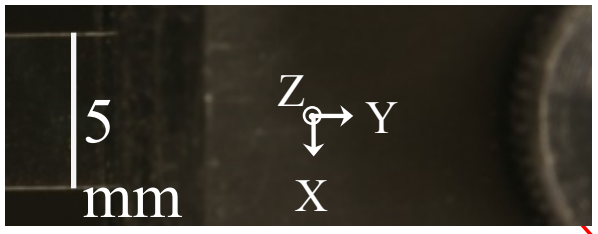
Photo-Induced Stress Relaxation to Improve Flaw Tolerance



Approximate Dimensions (mm)

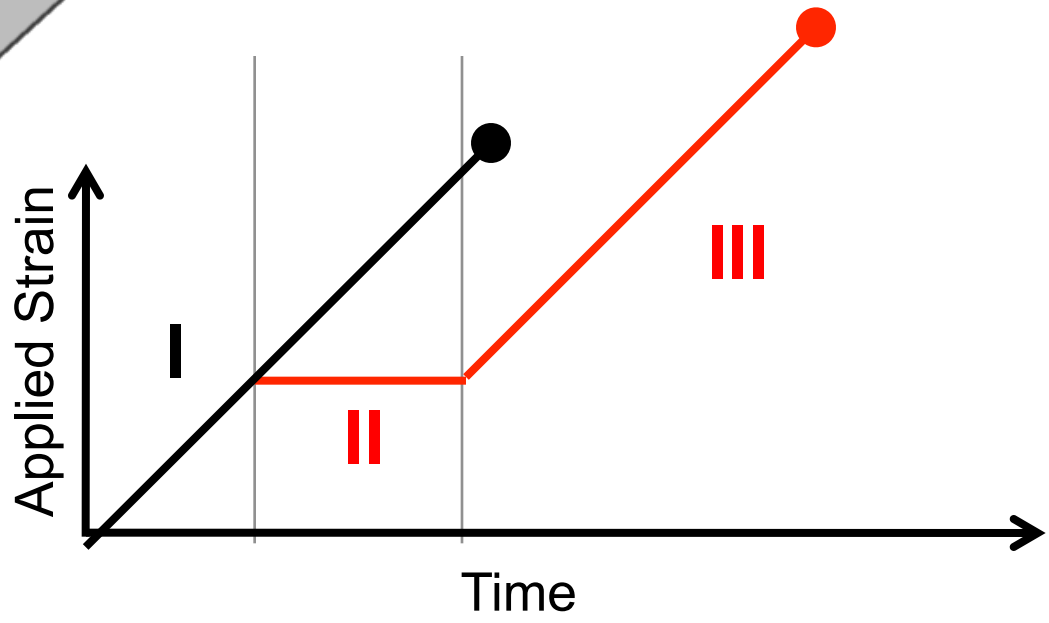
15 (L) x 5 (W) x 0.19 (T), 1.5 (D)

Photomechanical Protocols

I Stretch 1%/min

II Hold and Irradiate

III Stretch 1%/min (no light)



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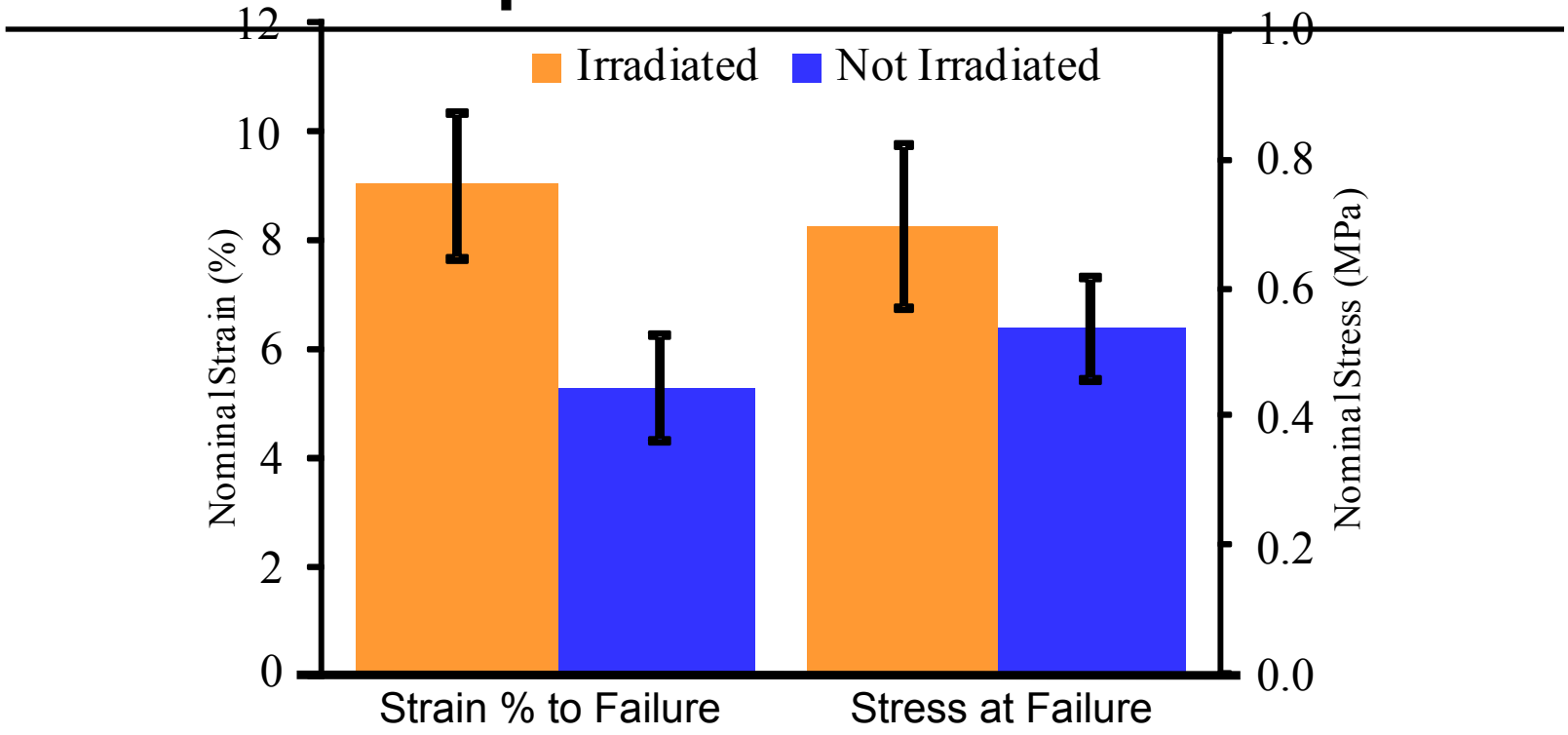
Experimental Results



- Mean and Standard of Deviation of 12 specimens is shown
- Strain-to-Failure Increased by ~70% ($p \sim 10^{-8}$, n = 12)
- Nominal Stress-at-Failure Increased by ~30% (p=0.0013, n = 12)

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Representative Experiments and Simulations Under Each Protocol