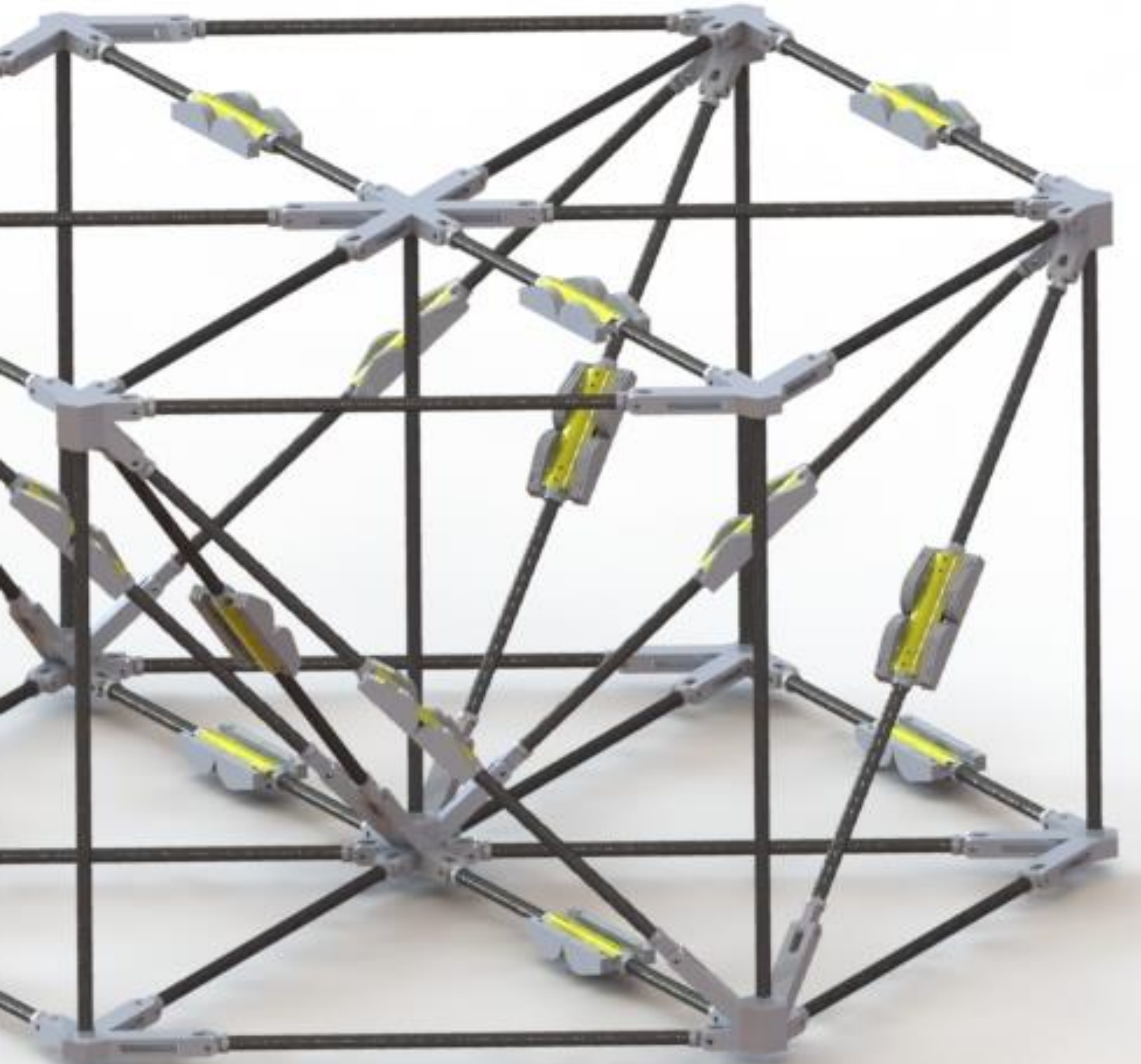


Deployable Modules for Robotically-Assembled Space Structures

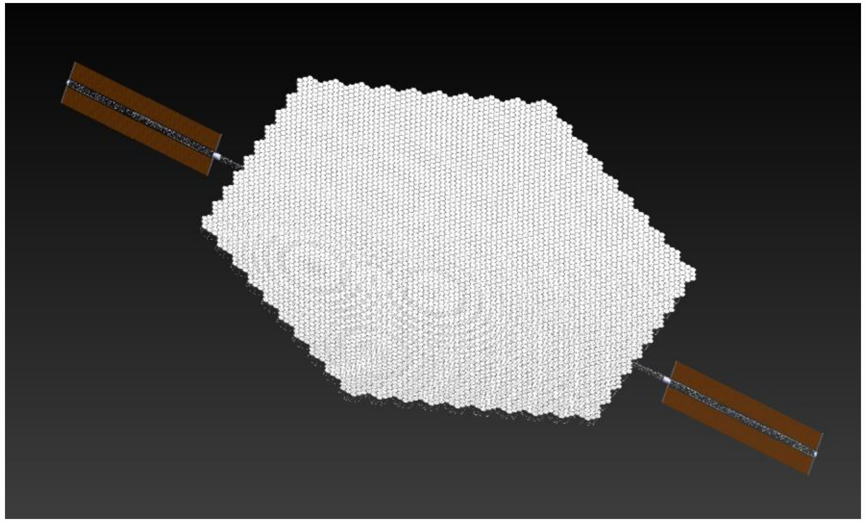
Kristina Hogstrom and Prof. Sergio Pellegrino

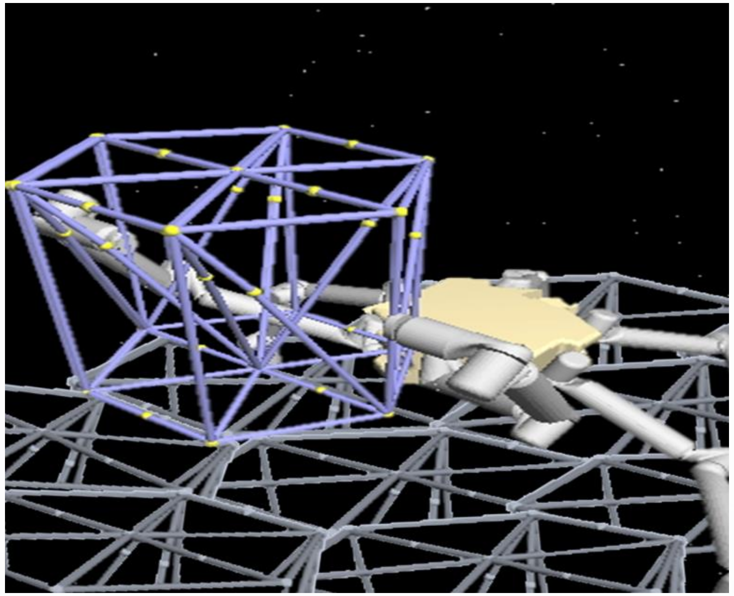
Caltech Solid Mechanics Symposium

February 17th, 2016

Motivation

- Future telescopes may be too large to fit in a single payload fairing
- In-space assembly bypasses fairing limit
- In-Space Telescope Assembly Robotics (ISTAR) project proposed low-cost, lightweight, modular architecture for apertures > 20-30 m

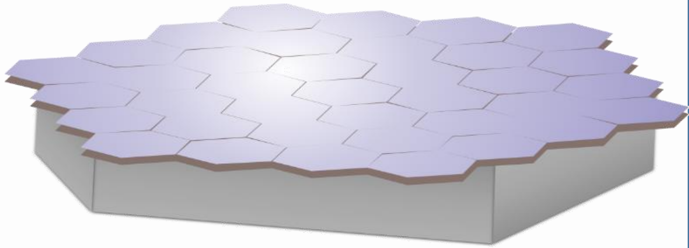




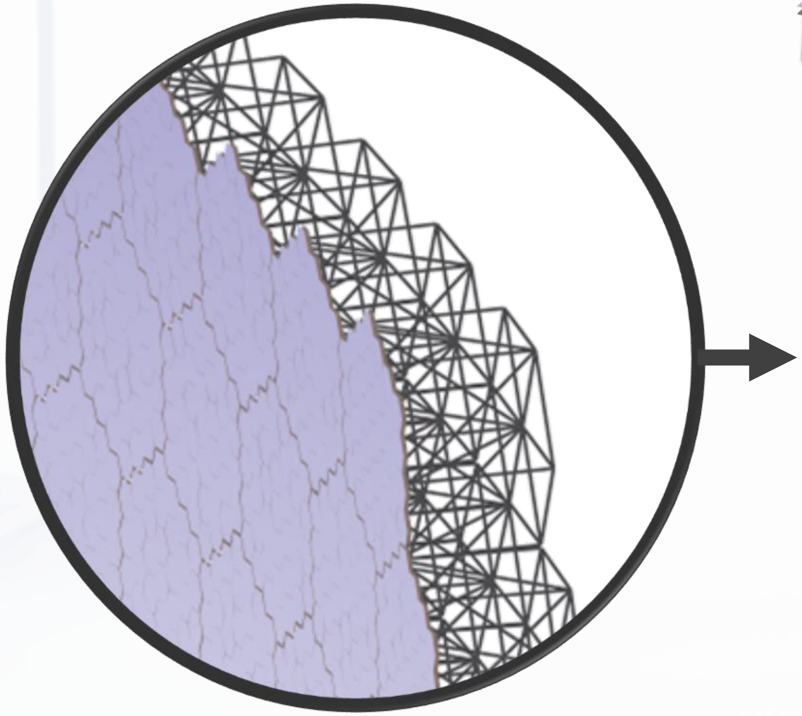
[1]Hogstrom, K., Backes, P., Burdick, J., Kennedy, B., Kim, J., Lee, N., Malakhova, G., Mukherjee, R., Pellegrino, S., and Wu, Y.-H., "A Robotically Assembled 100-meter Space Telescope," *65th International Astronautical Congress*, Toronto, CA: 2014.

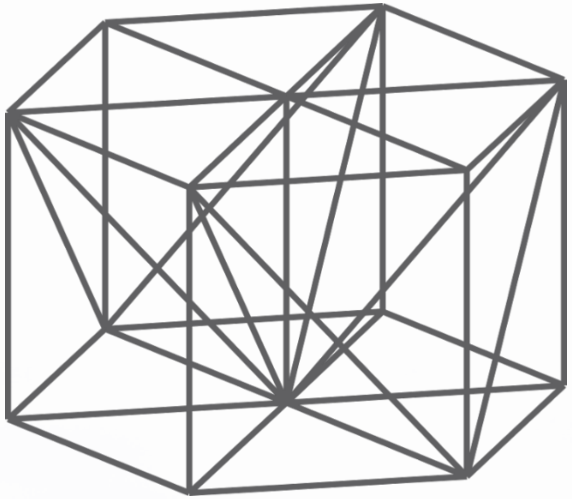
ISTAR Primary Mirror Components

- Mirror modules
  - Groups of off-the-shelf mirror segments
  - Packaged with actuators and electronics
  - Sized to fit in payload fairing
- Truss modules
  - Provide mirror support
  - Fold compactly for launch



Mirror module

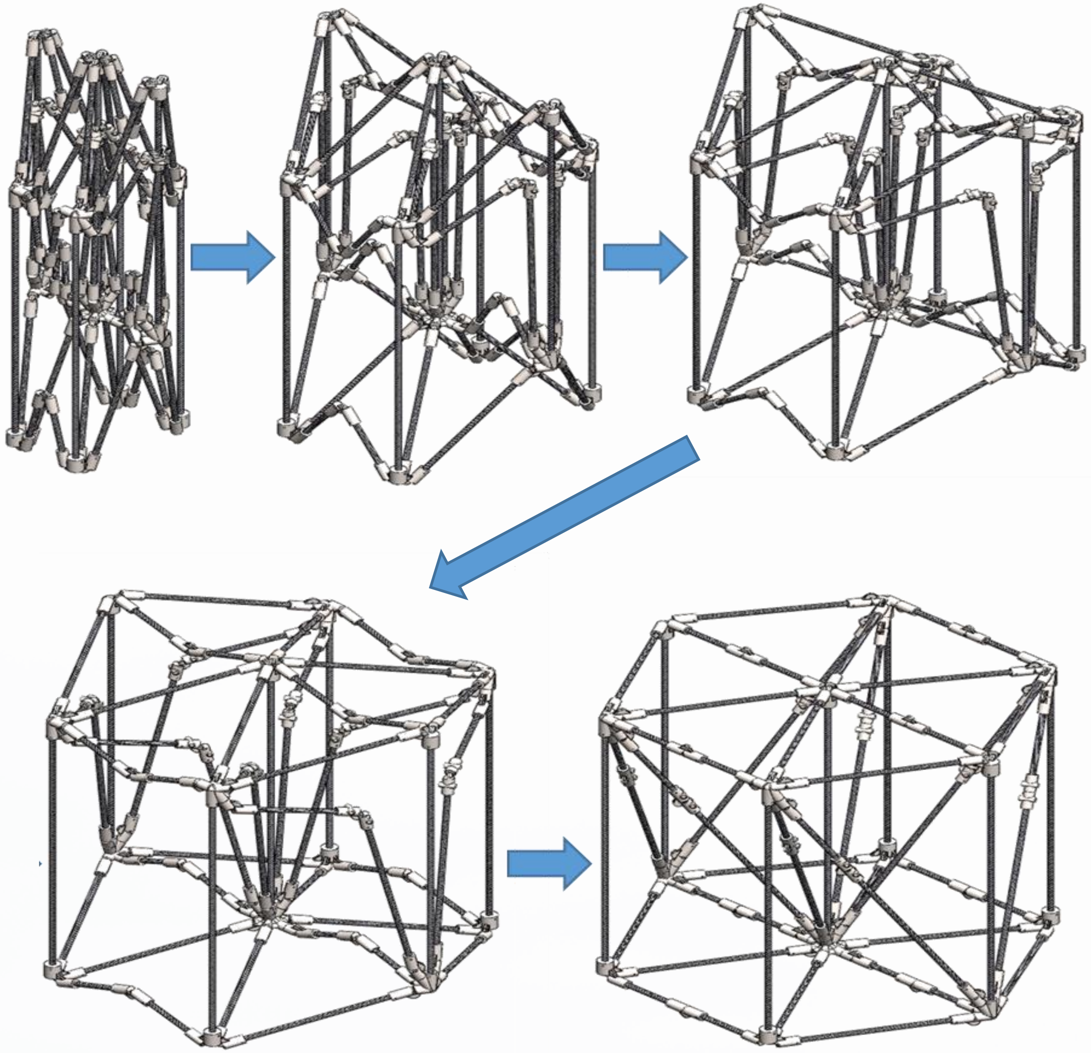




Truss module

ISTAR Truss Module

- Based on Pactruss deployment scheme[1]
- Mid-member Rolamite tape spring hinges
  - Spring forces large enough to self-deploy module
- Deployed by robot controlling displacement of two opposing verticals
  - Work against spring forces for quasistatic deployment
- Bulk manufacturing → fabrication and assembly errors
- Deployment reliability is important mission constraint



[1]Hedgepeth, J. M., *Pactruss support structure for precision segmented reflectors*, Carpinteria, California: Langley Research Center, 1989.

Goals

- Develop simulation toolkit to model deployment behavior of a truss module with errors
  - In context of ISTAR module, but general to any geometry and deployment scheme
  - Geometry easily adjustable to include specified or randomly chosen errors
  - Experimentally validated
- Use toolkit to perform reliability trade studies
  - What kinds of errors are most detrimental?
  - How do module design parameters affect reliability?

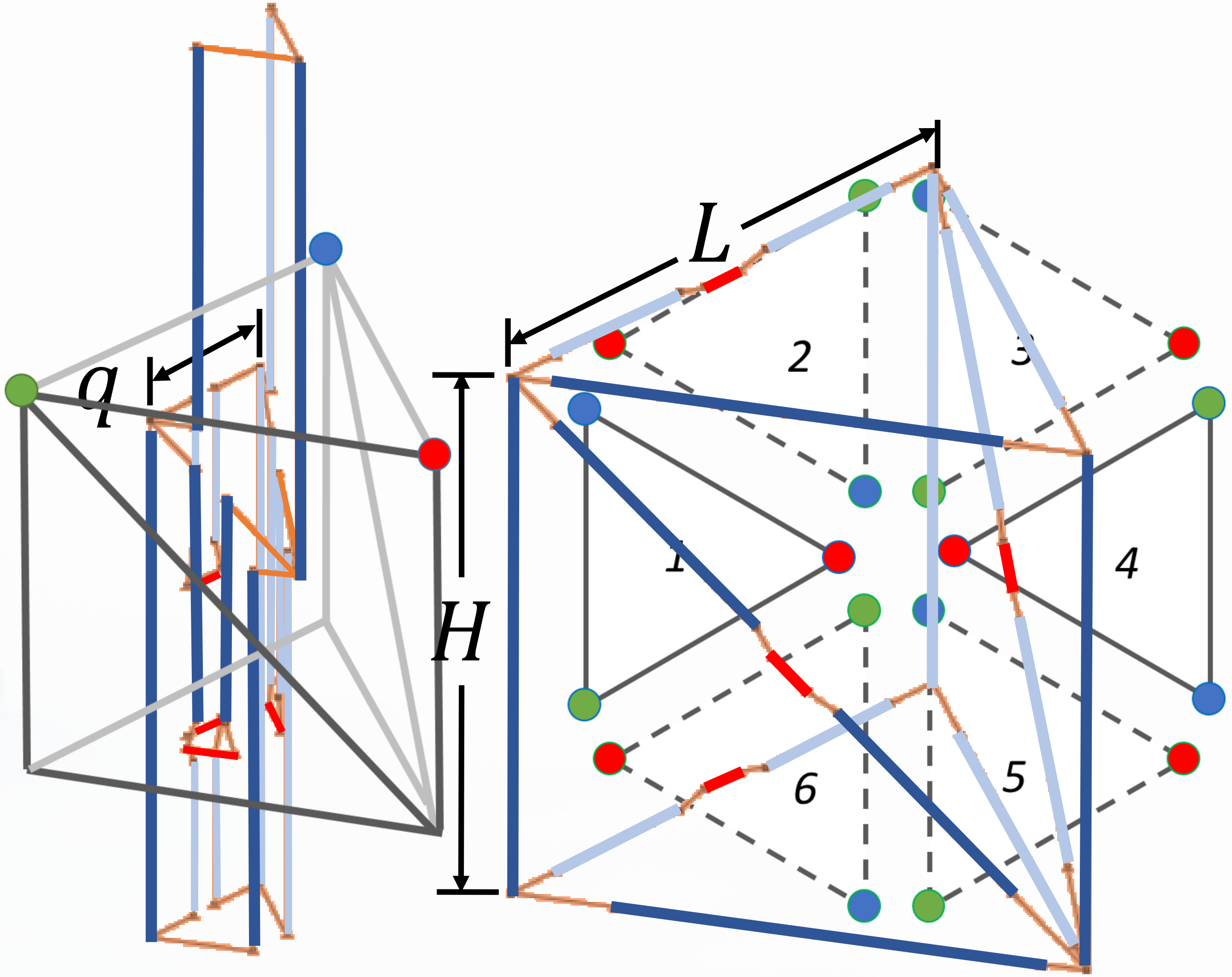
Outline

- Simulation toolkit using Python and Abaqus/Standard
  - Truss model
  - Rolamite tape spring hinge model
  - Methodology
  - Example results
- Experimental validation
  - Construction and measurement of physical modules
  - Experimental methodology
  - Results and comparison to simulations
- Conclusion and ongoing work

[1]SIMULIA Abaqus, Dassault Systemes, Software Package, Ver. 6.13-2, 2013

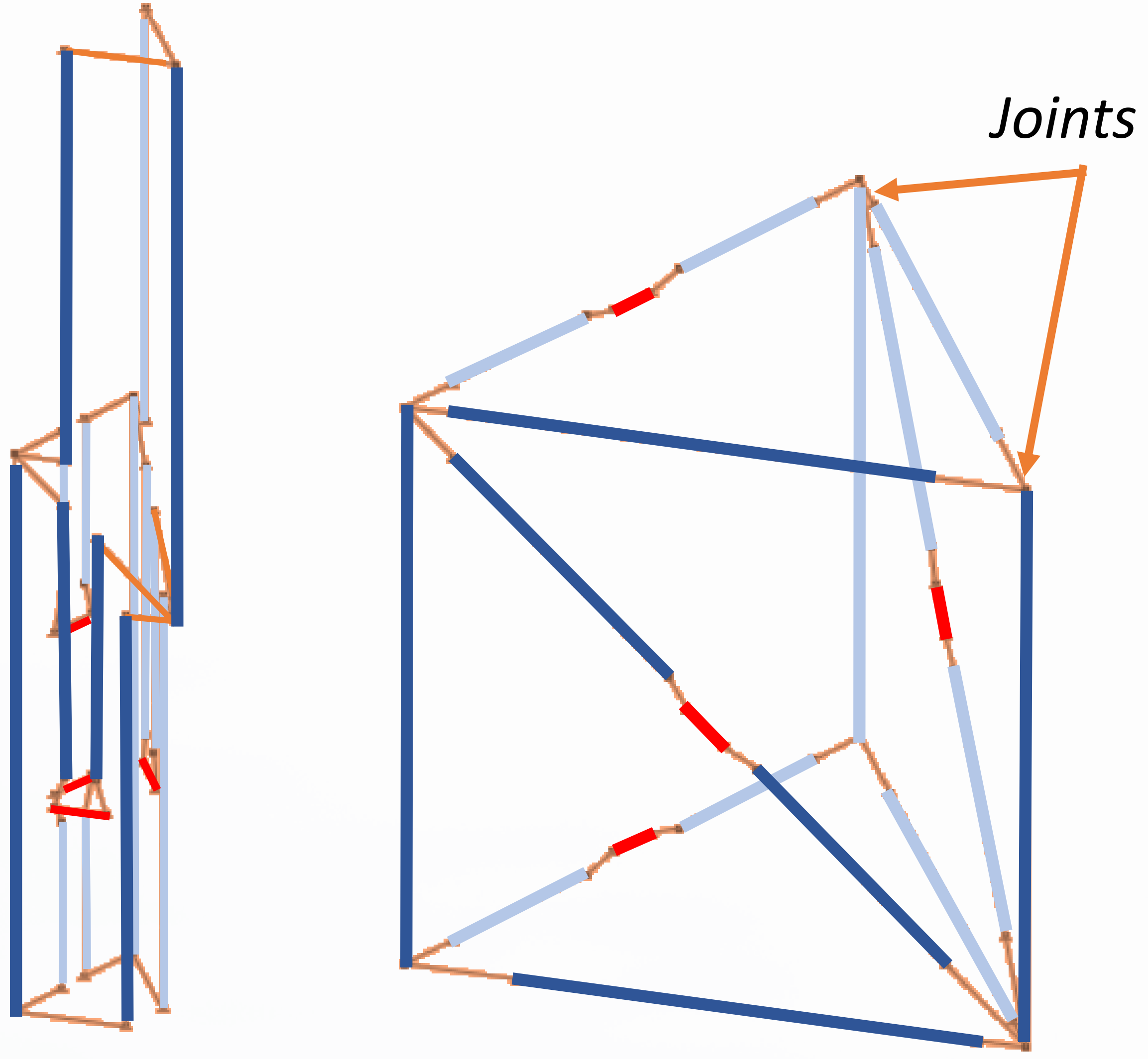
Wedge Model

- Full truss module tessellation of six identical triangular prisms
- Overall dimensions:
  - L: side length of deployed module
  - H: depth of deployed module
  - q: side length of stowed module
- Members modeled as elastic beams



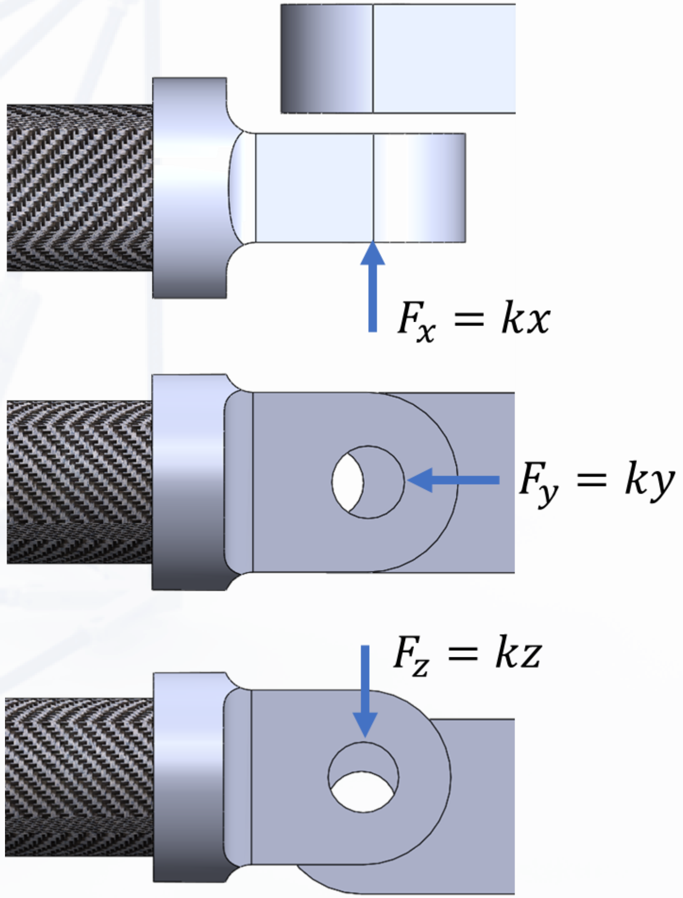
Joint Model

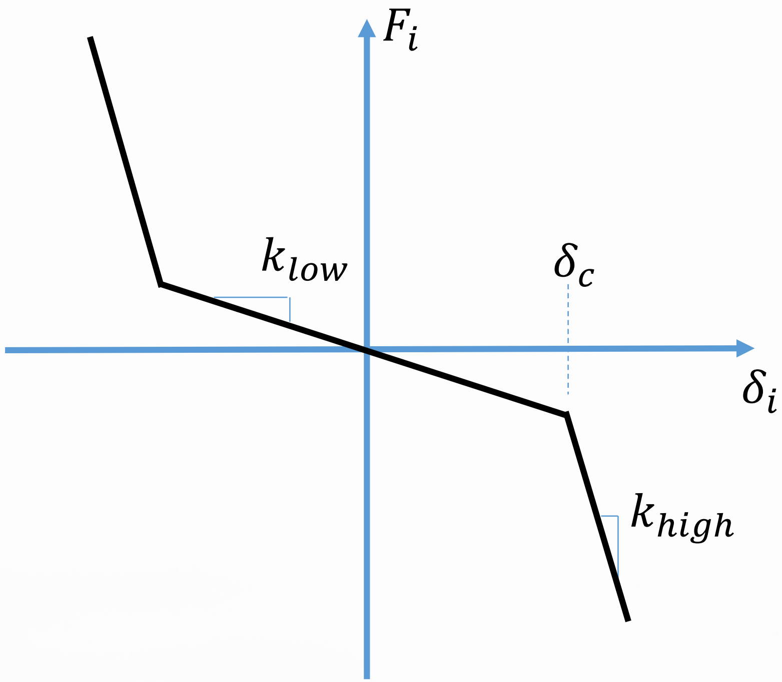
- Joints modeled as massless elastic beam elements fixed to vertical member and hinged to other member
  - Compliance/slack in x, y and z directions
  - Soft stop about rotation axis to prevent overextension
- Joint masses modeled as lumped masses at the top and bottom of each vertical
- Four Rolamite tape spring hinges



Joint Model

- Joints modeled as massless elastic beam elements fixed to vertical member and hinged to other member
  - Compliance/slack in x, y and z directions
  - Soft stop about rotation axis to prevent overextension
- Joint masses modeled as lumped masses at the top and bottom of each vertical
- Four Rolamite tape spring hinges

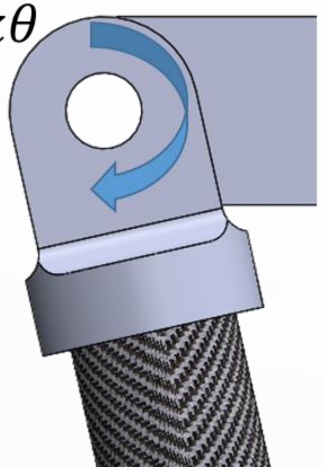


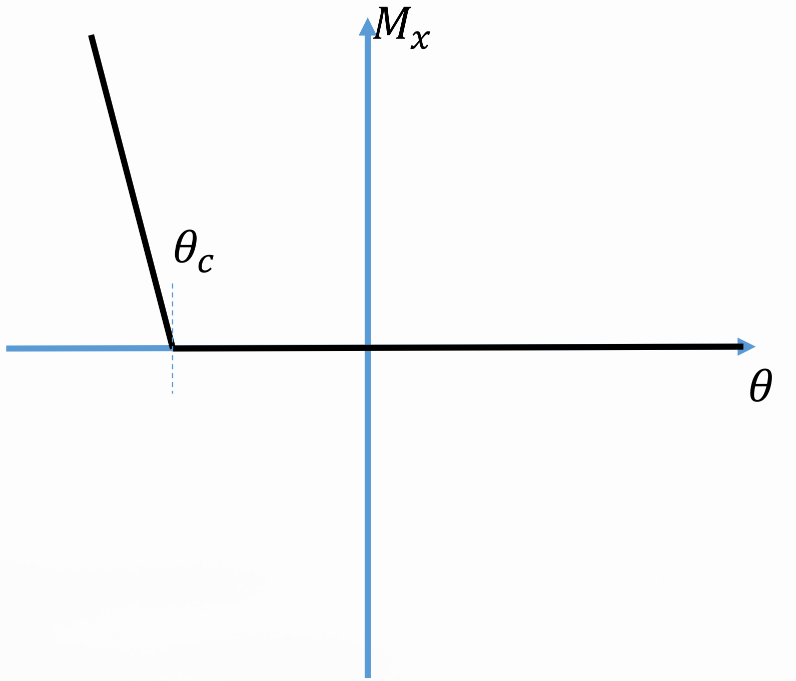


Joint Model

- Joints modeled as massless elastic beam elements fixed to vertical member and hinged to other member
  - Compliance/slack in x, y and z directions
  - Soft stop about rotation axis to prevent overextension
- Joint masses modeled as lumped masses at the top and bottom of each vertical
- Four Rolamite tape spring hinges

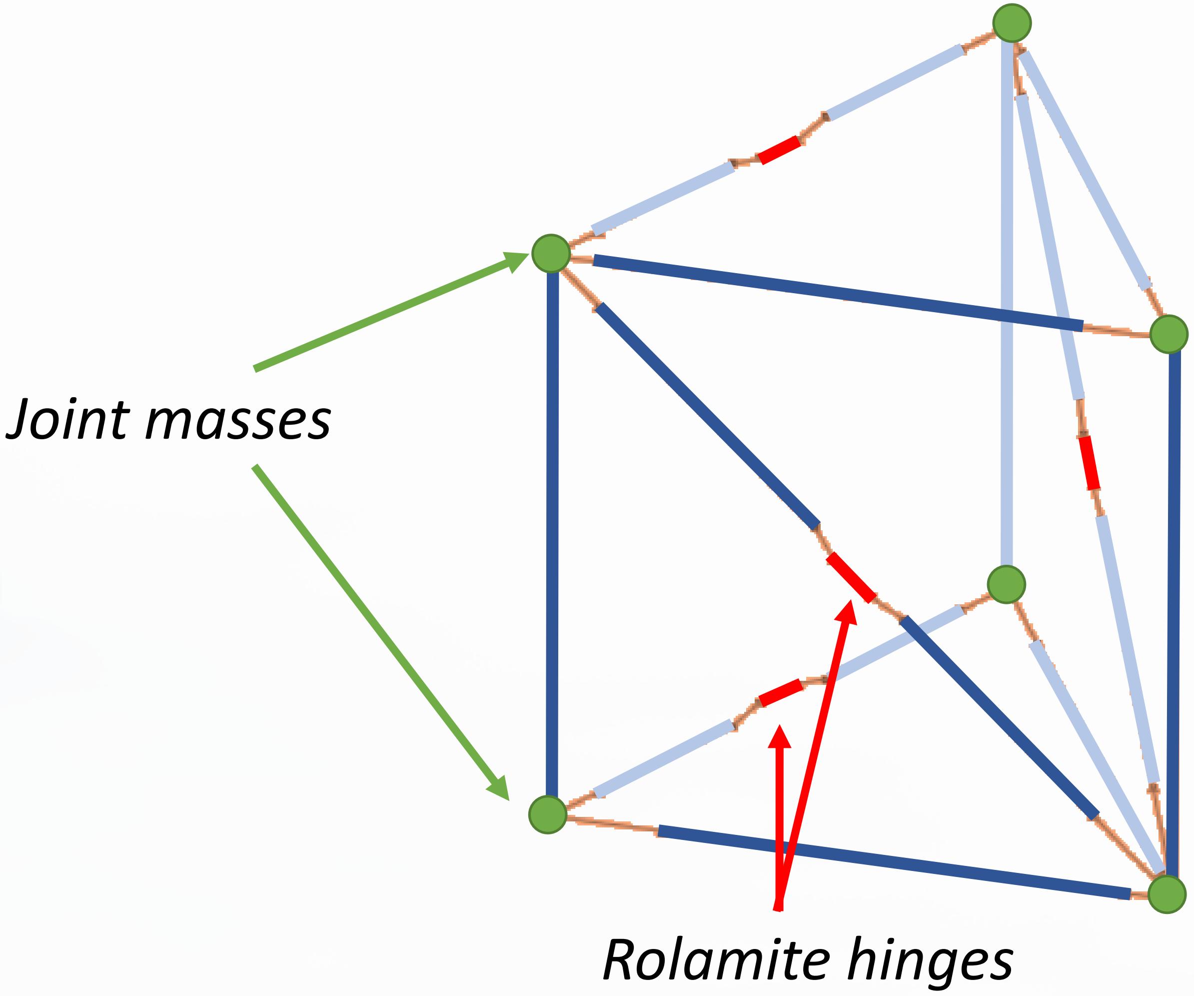
$M_x = k\theta$





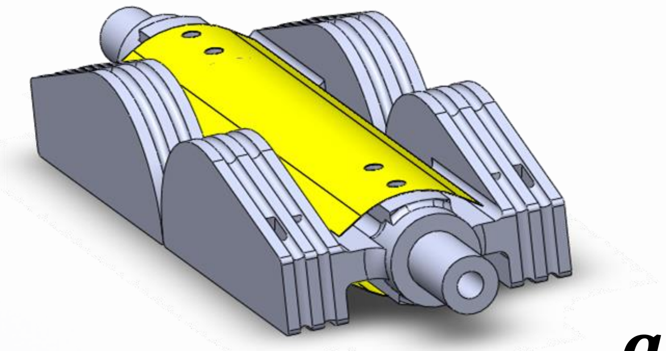
Joint Model

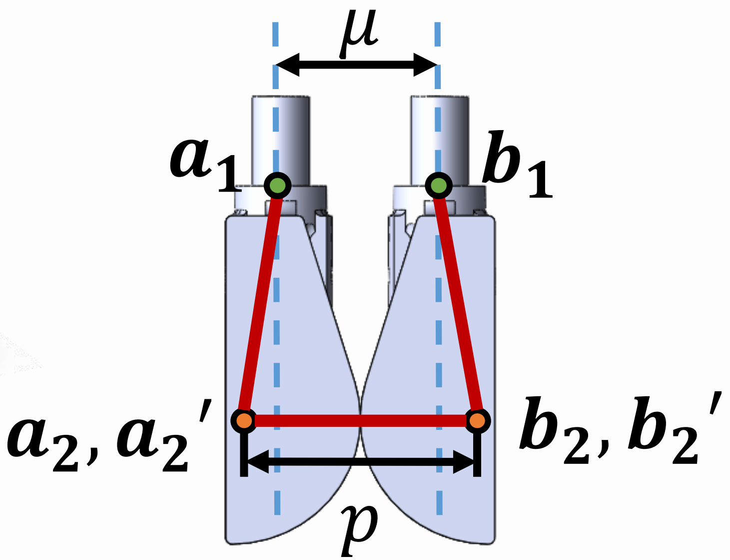
- Joints modeled as massless elastic beam elements fixed to vertical member and hinged to other member
  - Compliance/slack in x, y and z directions
  - Soft stop about rotation axis to prevent overextension
- Joint masses modeled as lumped masses at the top and bottom of each vertical
- Four Rolamite tape spring hinges

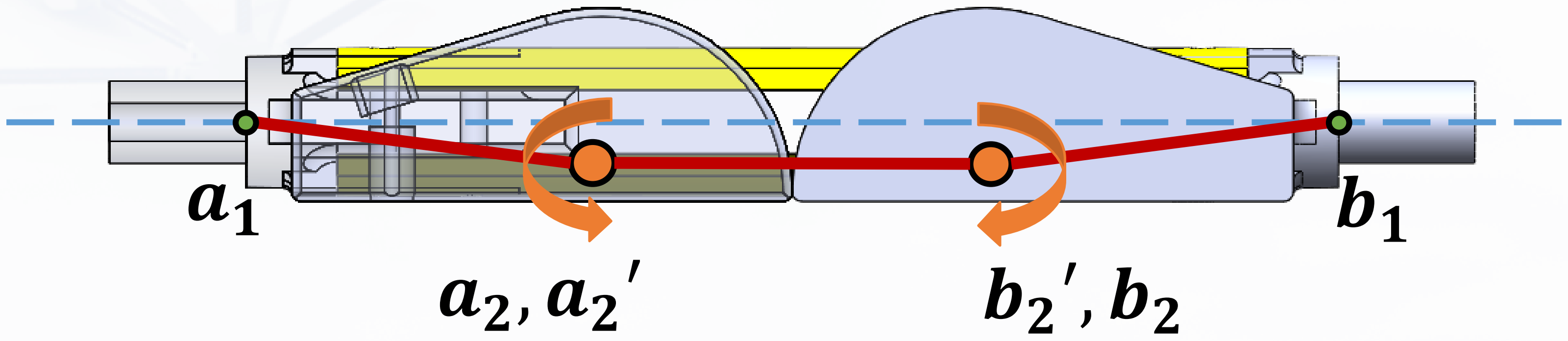


Rolamite Hinge Kinematic Model

- Two pieces of standard tape measure and four circular cams
- p: distance between cam centers
- μ: distance between member centerlines



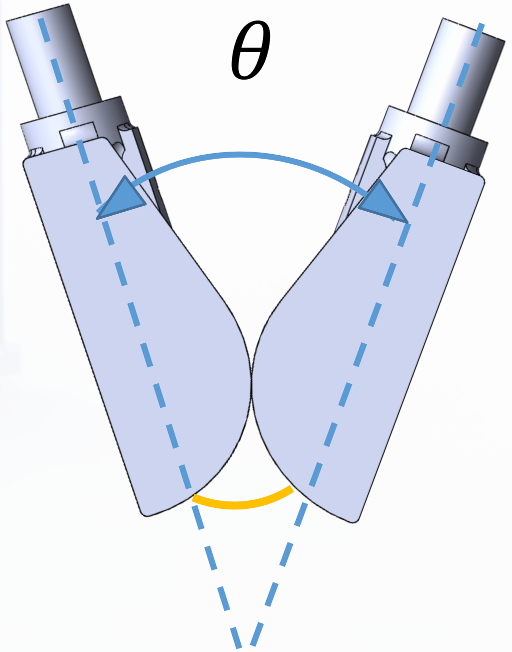


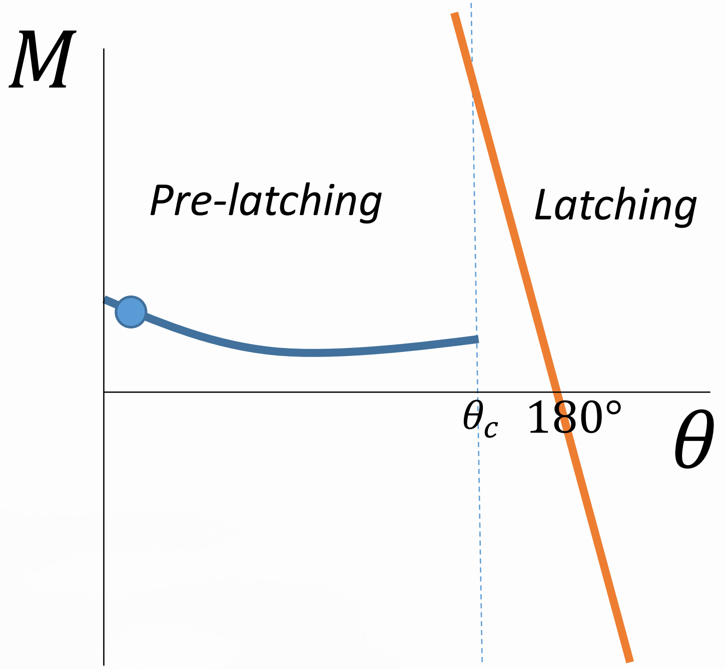


Watt, A. M., “Deployable structures with self-locking hinges,” University of Cambridge, 2003.

Rolamite Hinge Moment-Rotation Profile

- Nonlinear and discontinuous, with pre-latching and latching regions
- Define θ as 0 when fully folded and 180° when deployed
- $M = f(\theta, s_{latch})$
  - $s_{latch} = 0$ if $\theta < \theta_c$ for all history
  - $s_{latch} = 1$ if $\theta \geq \theta_c$ at any point in history
- Apply behavior in Abaqus using user subroutines URDFIL and UFIELD
  - Define $M(\theta, s_{latch})$ with a table
  - URDFIL obtains θ after each increment and sends to UFIELD
  - UFIELD determines and sets new s_{latch} value

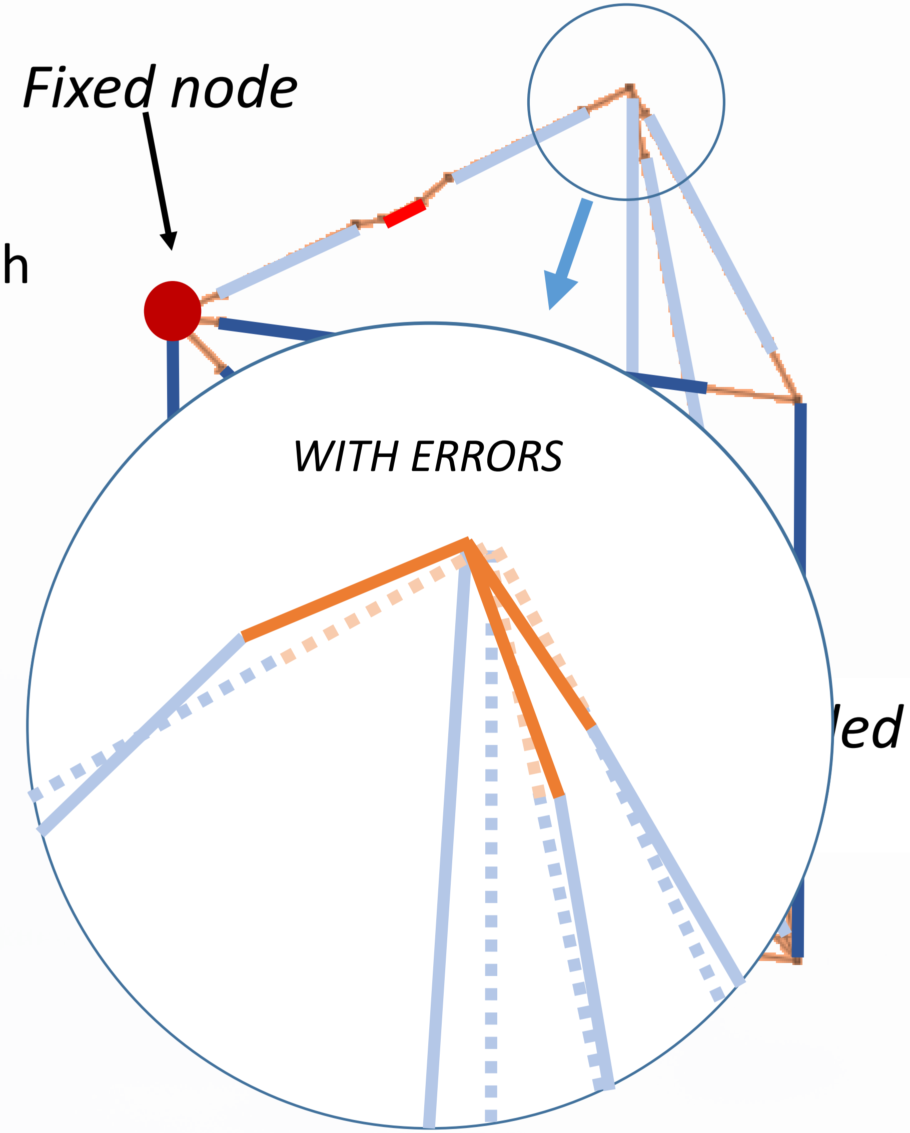




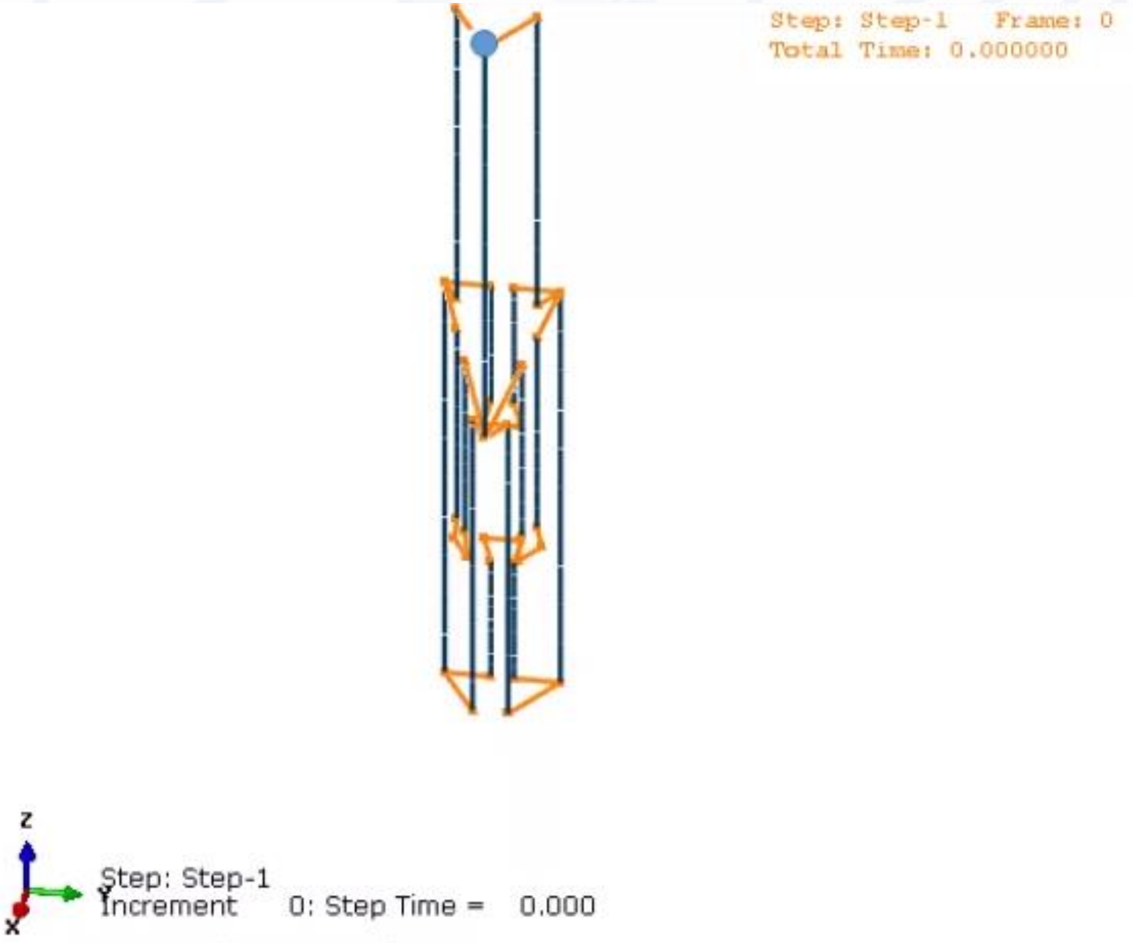
Watt, A. M., "Deployable structures with self-locking hinges," University of Cambridge, 2003.

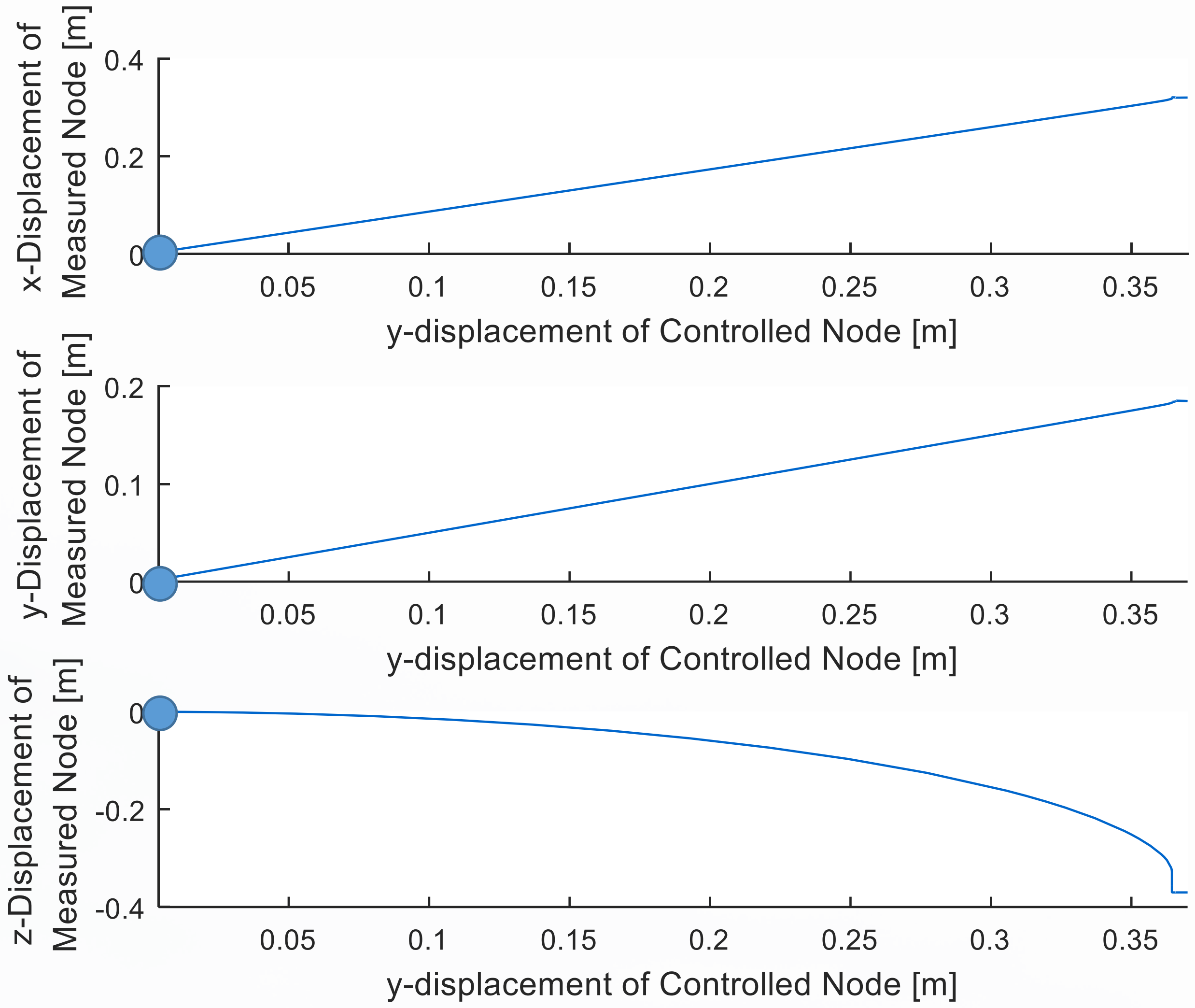
Simulation Methodology

- Create model in stowed position
  - Specify endpoints of members and connectivity with connection behavior
  - No prestress
  - Errors specified or drawn from random distribution
- In static step, apply y-displacement boundary condition to controlled node
  - Assumes quasistatic deployment, independent of rate
- Use automatic stabilization to mitigate instabilities
  - Artificial viscous damping with magnitude proportional to extrapolated strain energy
  - Proportionality constant of 5×10^{-5}

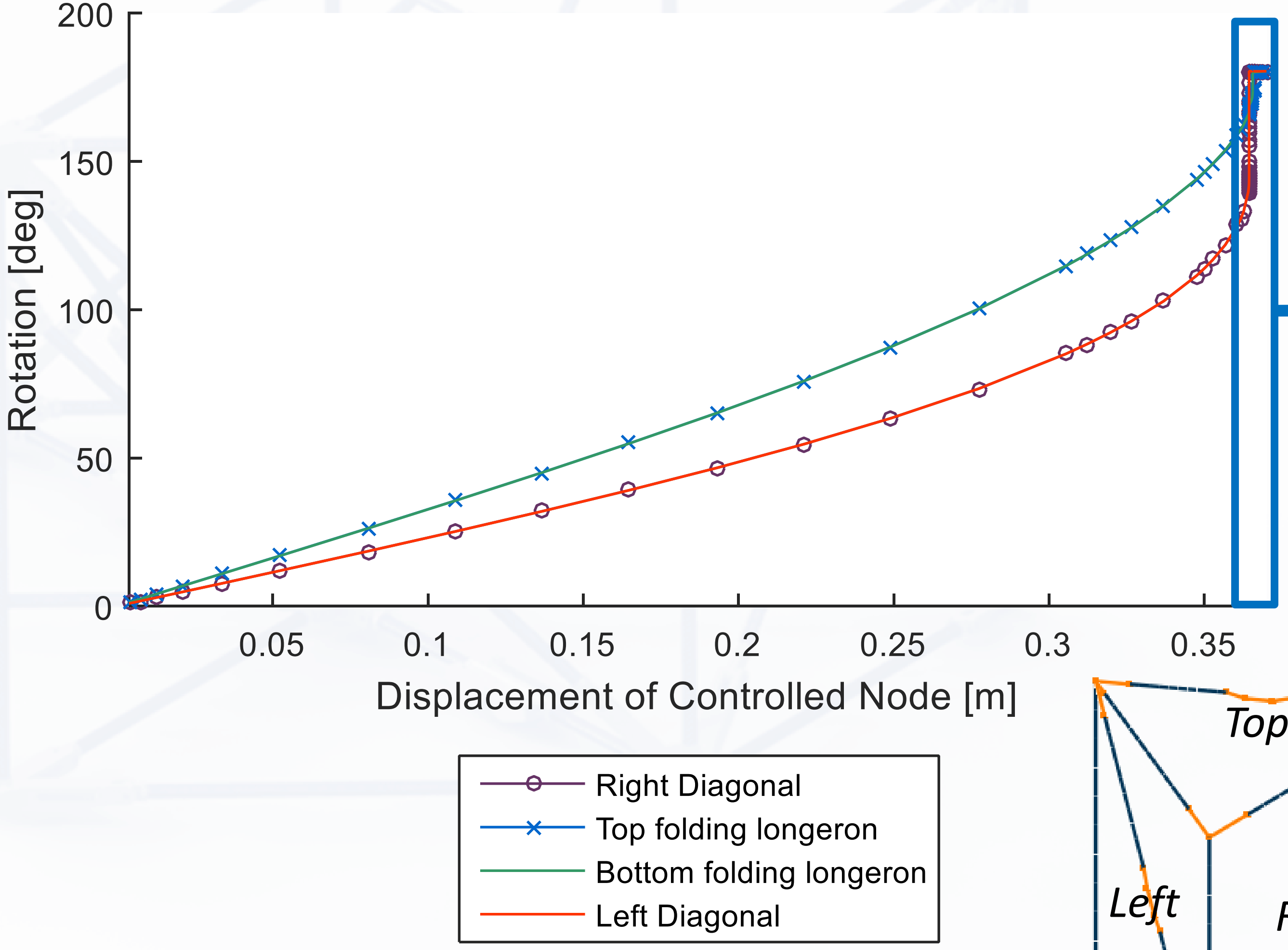


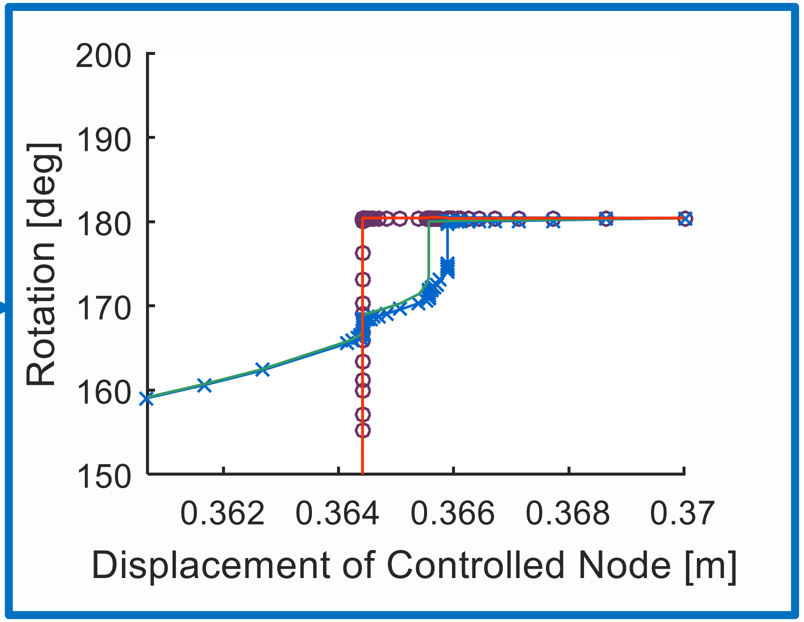
Simulation Results

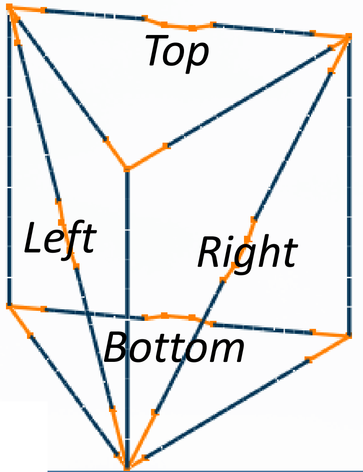




Simulation Results

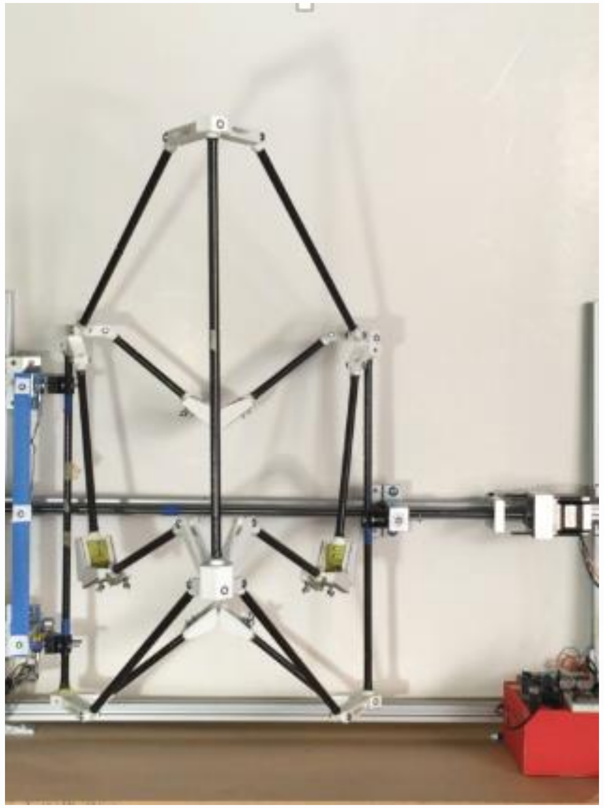


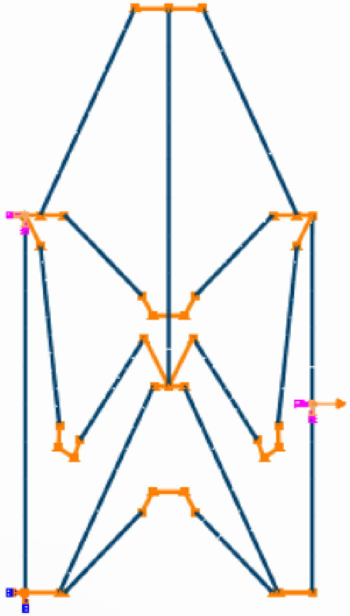




Experimental Validation

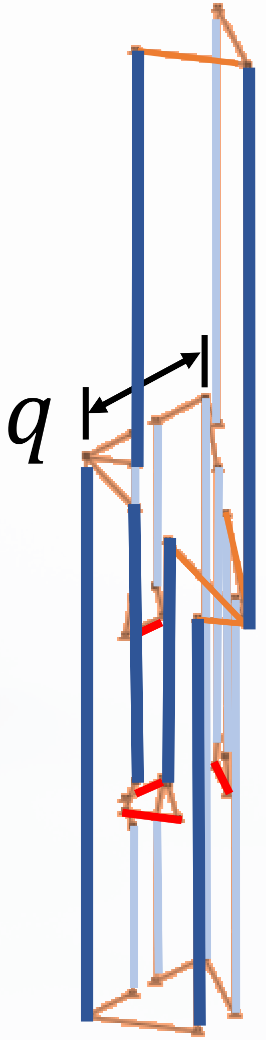
- Need to make sure that simulation toolkit accurately represents deployment behavior
- Quantities to compare:
  - Nodal displacements
  - Rolamite hinge rotations
- Need to recreate geometry of physical module as closely as possible

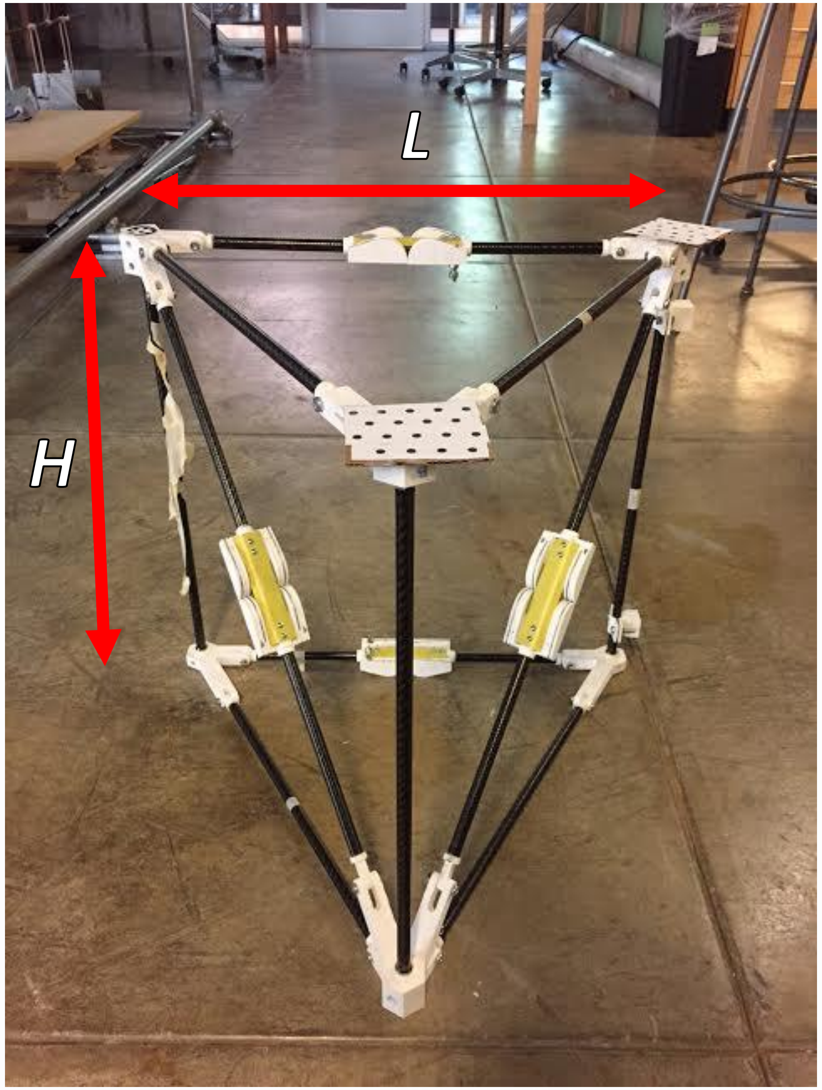




Experimental Model

- Built two modules with same nominal dimensions
- $L = H = 50$ cm
- $q = 13$ cm
- $d_o = 1$ cm
- $t = 0.9$ mm
- Carbon fiber composite rods
- 3D printed ABS plastic joints
- Estimated slack/compliance threshold of 500 μm

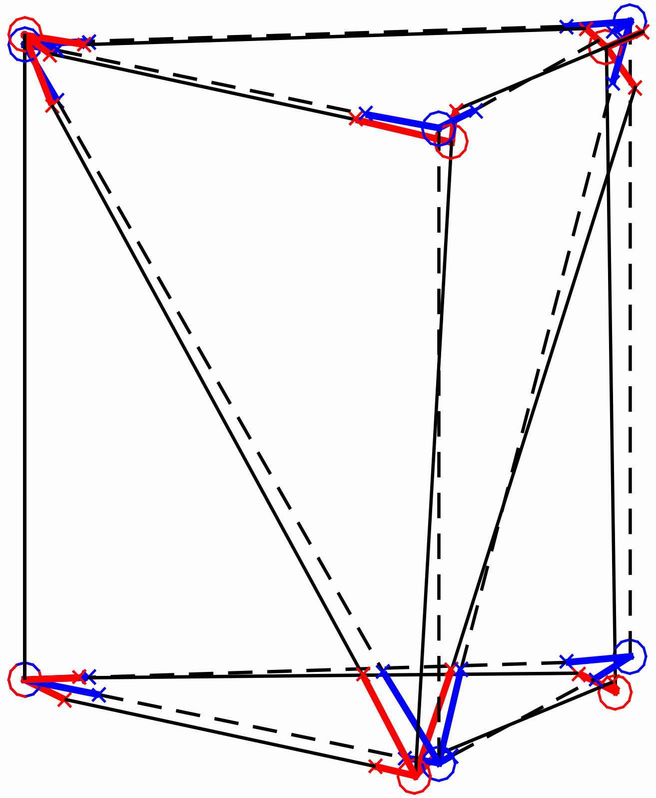




FaroArm Measurements

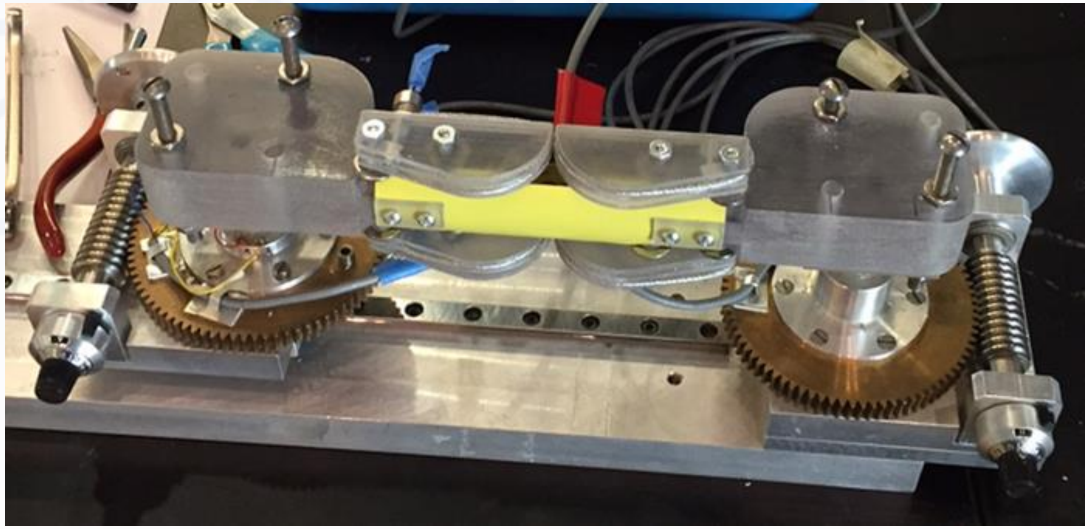
- Coordinate measuring machine built by FARO
- Obtained both stowed and deployed shape
- Touched tip to various locations on modules to obtain member endpoints and hinge axes
- Only second module used in experiments
- Unquantified measurement error due to module moving slightly

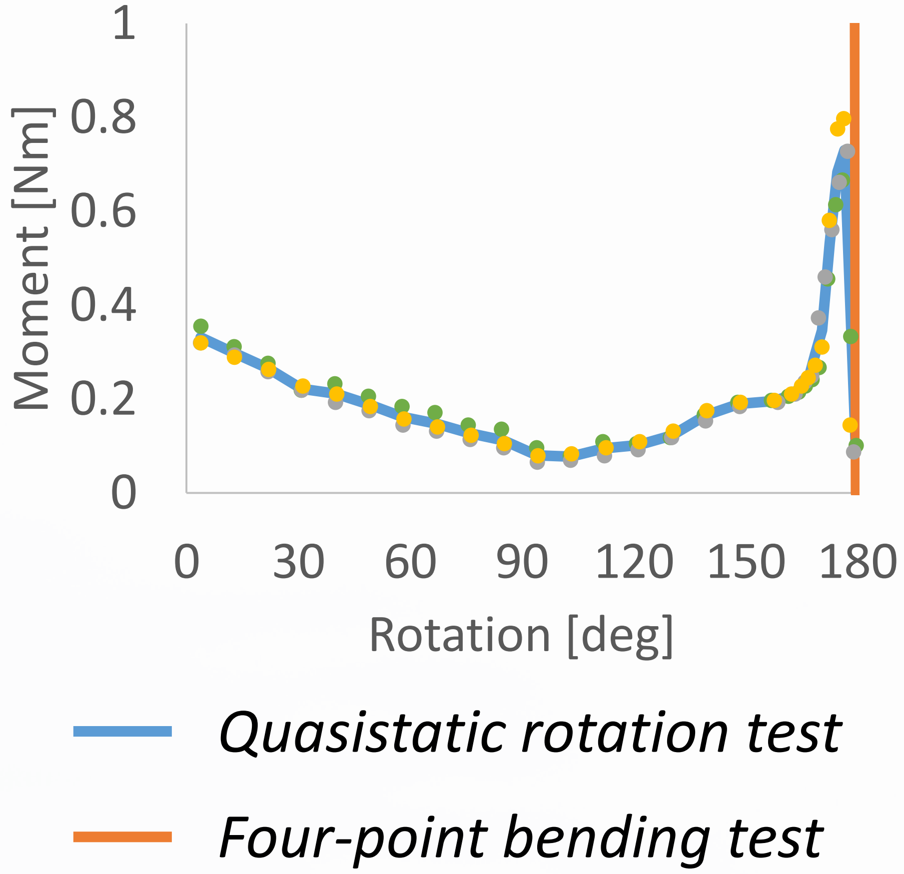
	Average	Maximum
Endpoints	0.91 mm	3.27 mm
Axes	1.23°	3.84°



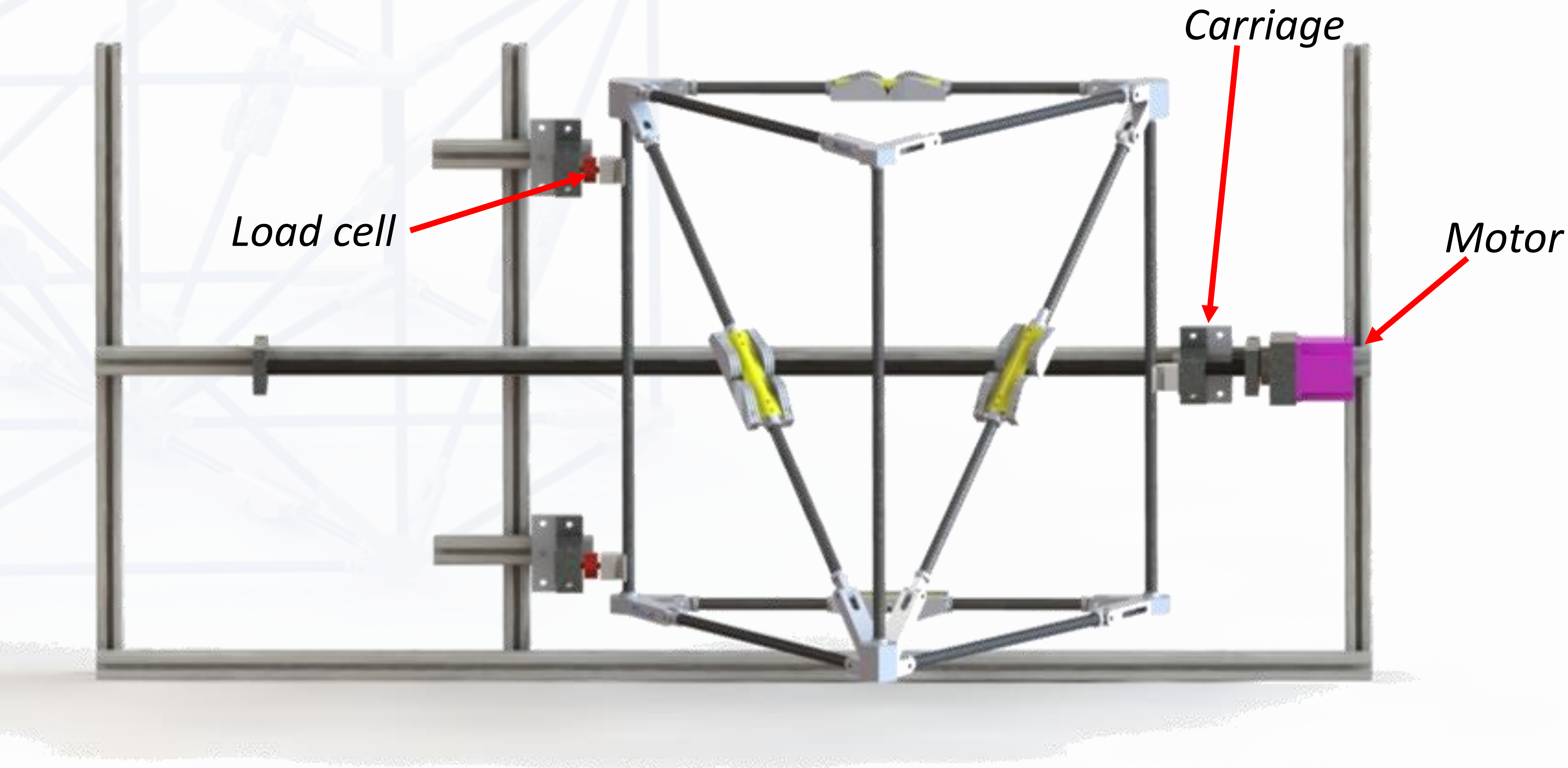
Experimental Rolamite Hinges

- 3D printed cams and commercially obtained tape sections
- Experiments to measure moment-rotation curve
  - Pre-latching: quasistatic rotation test
  - Latching: four-point bending test





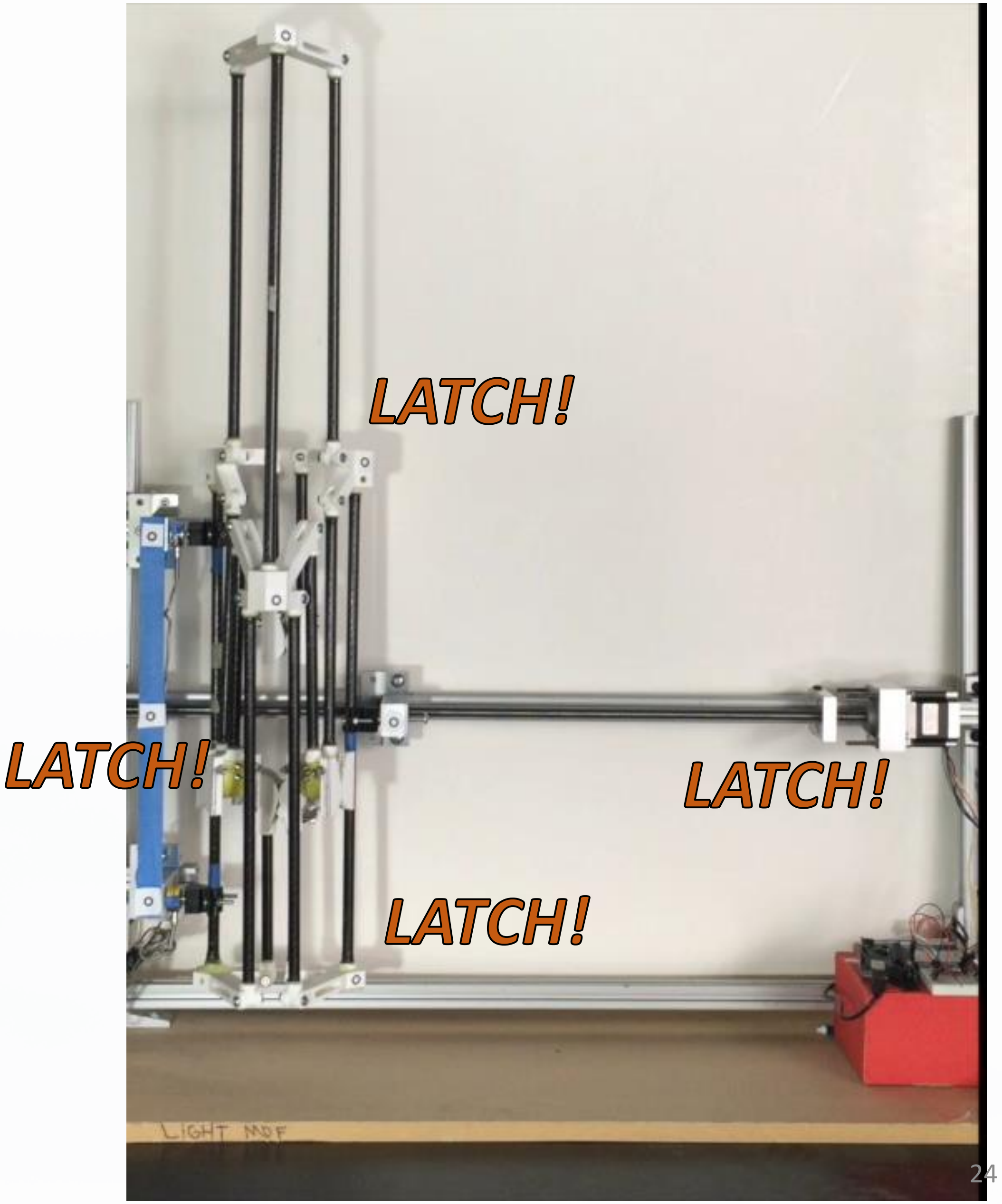
Experimental Setup



Experimental Setup

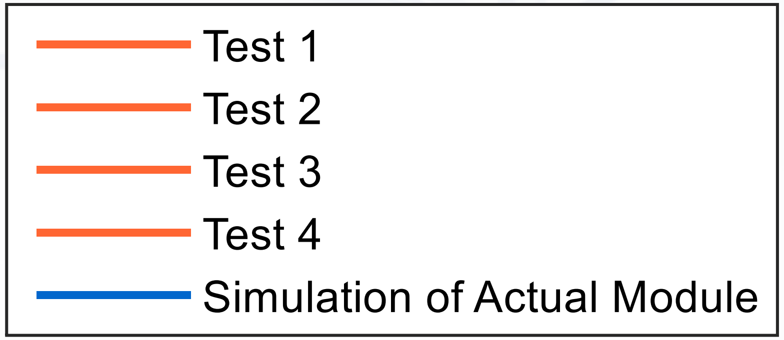
- Stereo camera pair measure nodal displacements in 3D
- iPhone cameras measure Rolamite hinge rotations in 2D
- Full experiment repeated four times

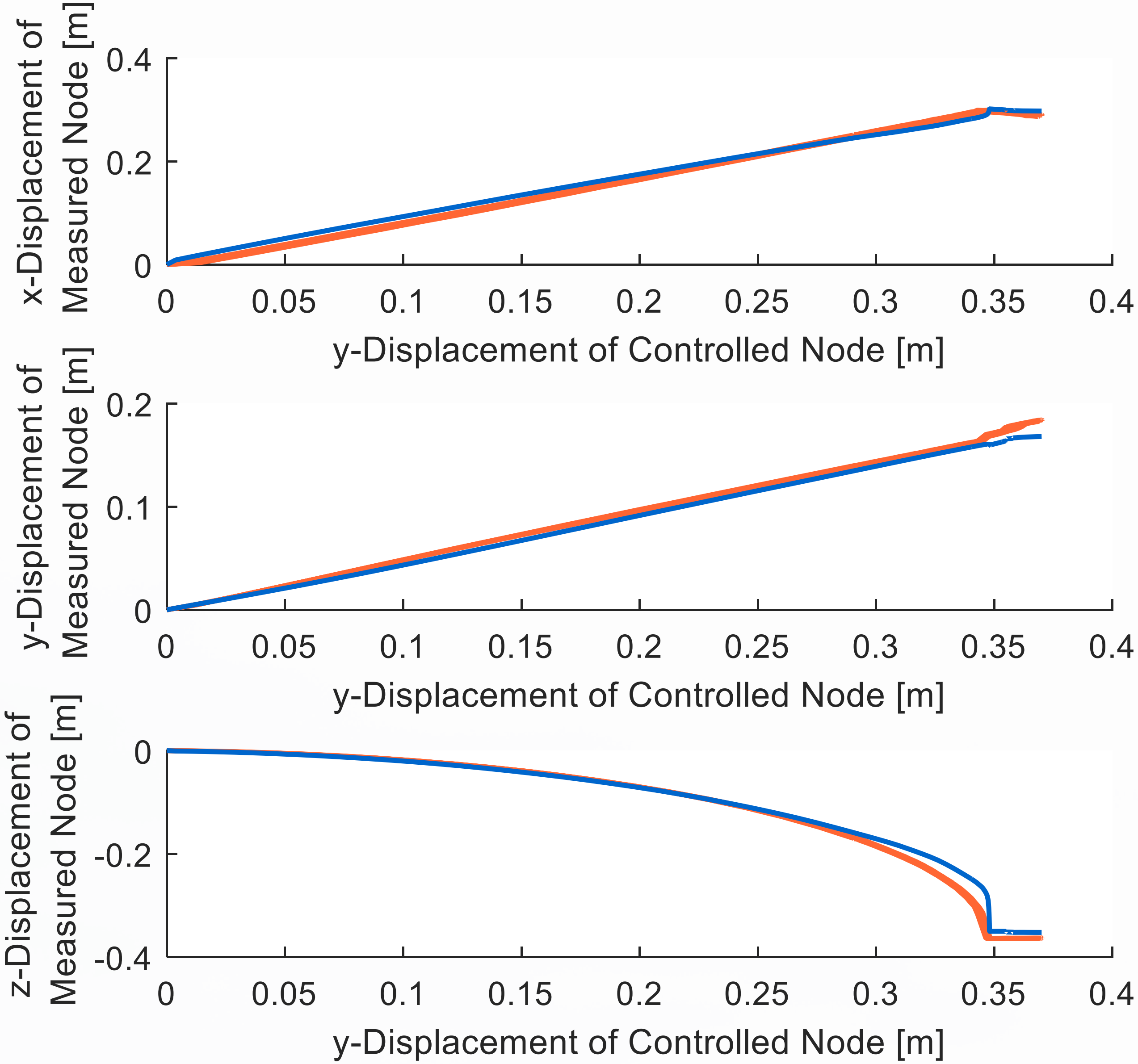
VIDEO SPEED: 8x



Nodal Displacements

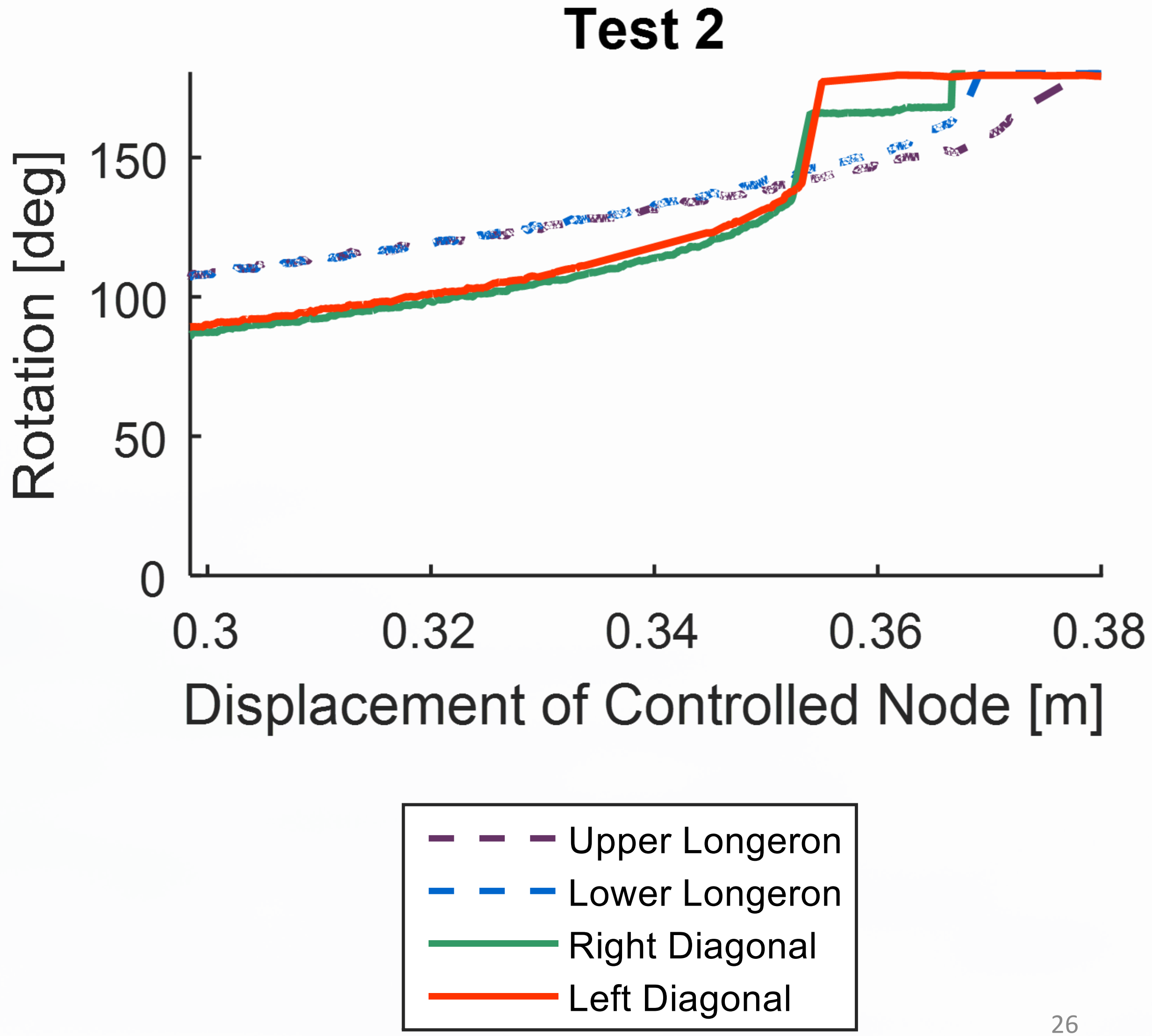
- Simulation matches within 10% of experimental results at end of deployment
- Can see how node becomes fixed in the *x* and *z* directions when diagonal hinges latch





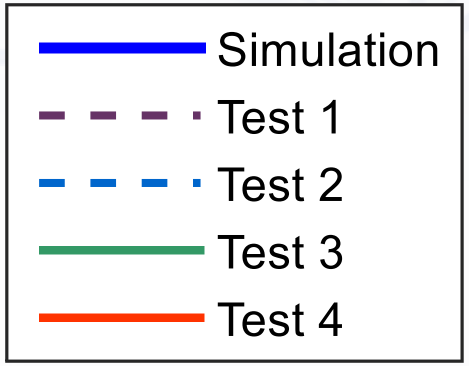
Experimental Hinge Behavior

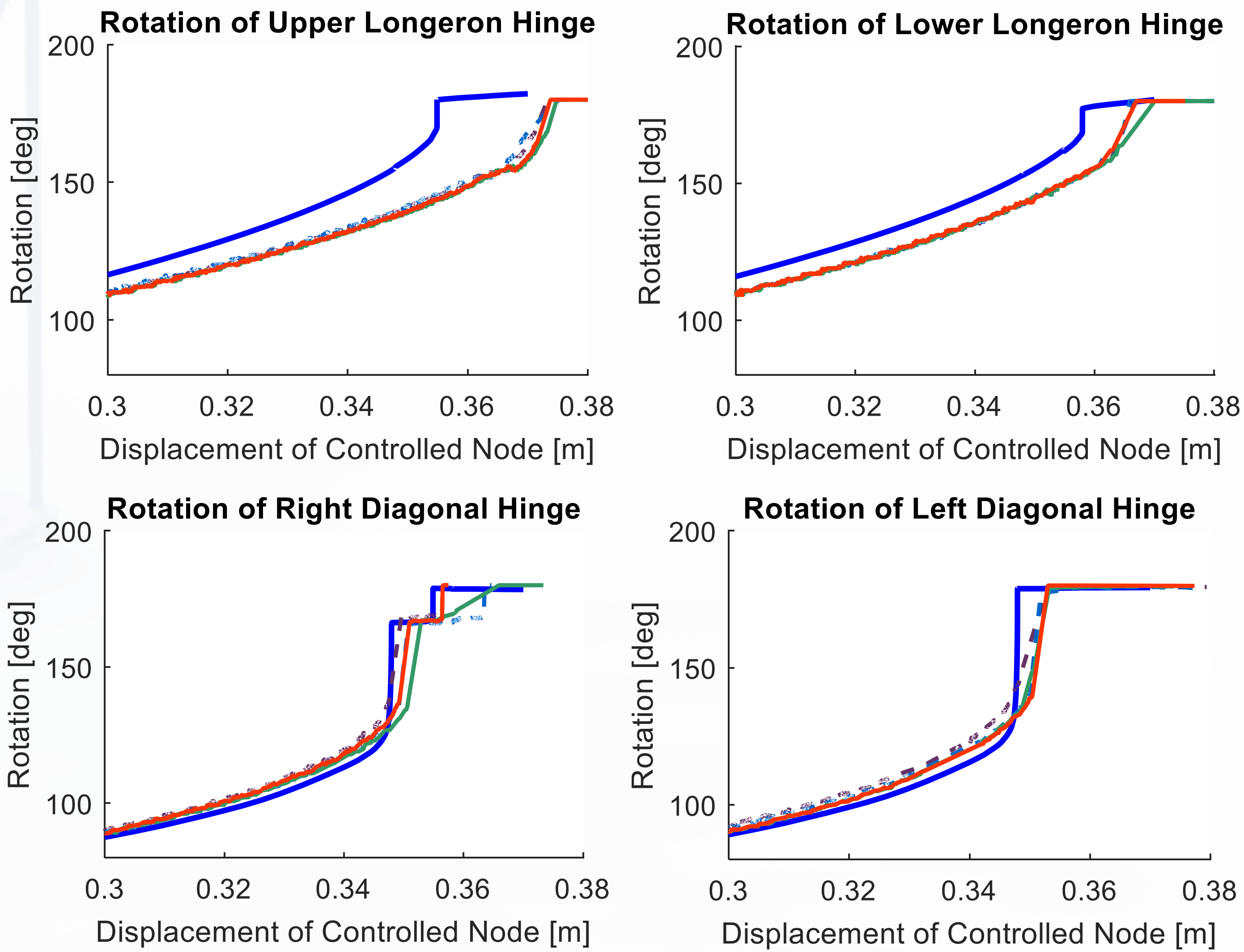
- Left diagonal hinge latches first
- Right hinge forced to suddenly jump to 167.6° ± 1.0° and maintain this value for a short time
- Eventually, right hinge latches, followed by lower longeron hinge and then upper longeron hinge



Hinge Behavior Comparison

- Some discrepancies in timing of longeron hinges, but very good agreement in behavior of diagonal hinges
- Simulation predicts intermediate angle of right diagonal hinge within 2%





Conclusion

- Developed toolkit to simulate the deployment behavior of a truss module
- Achieved good agreement between experiment and simulations
- Possible causes of discrepancies include:
  - Compliance parameters
  - FaroArm measurement errors
- Ongoing work: use toolkit to answer important questions about the reliability of the designed module
  - To estimate reliability:
    - Apply unique random distribution of errors in one simulation, using FaroArm measurements as bounds
    - Determine if simulated deployment is success or failure
    - Repeat many times to obtain percentage of successes
  - Develop suite of reliability trade studies by adjusting module geometry, hinge design, and deployment methods

Acknowledgments

This work was supported by the NASA Space Technology Research Fellowship #NNX13AL67H, with the help and mentorship of Erik Komendera, John Dorsey, and Bill Doggett at NASA Langley Research Center and Stuart Shaklan at the Jet Propulsion Laboratory. Many thanks to Isabelle Phinney for her help with setting up experiments.

Questions?