

Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN) Hinge Joint Structural Performance

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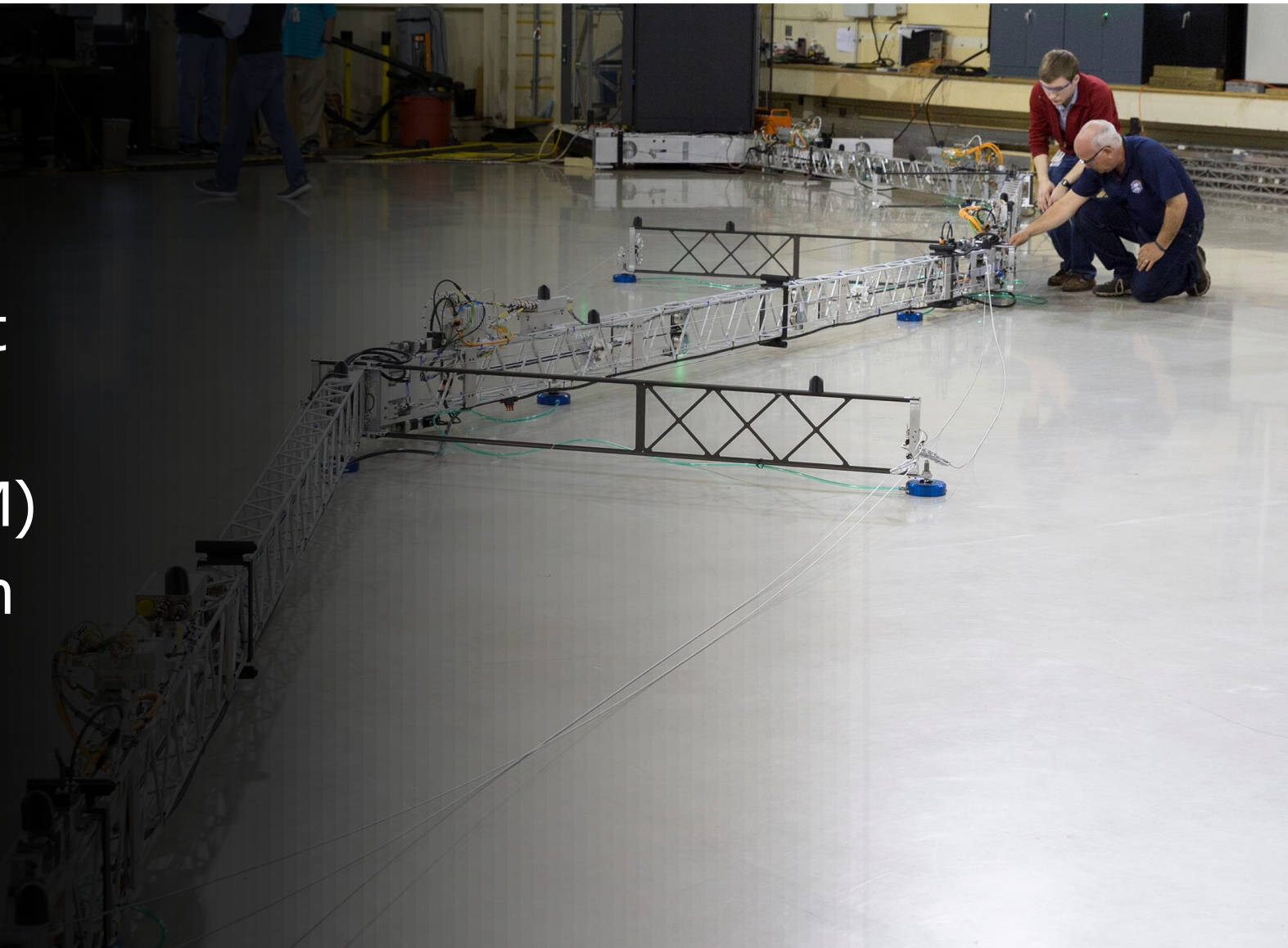
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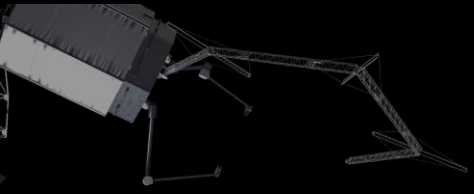
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Outline

- TALISMAN Overview
- Objectives and Approach
- Hinge Joint Description
- Out-of-Plane Stiffness Test
- Test Results
- Finite Element Model (FEM)
- Test and Model Correlation
- Concluding Remarks





TALISMAN Overview



- **Purpose**

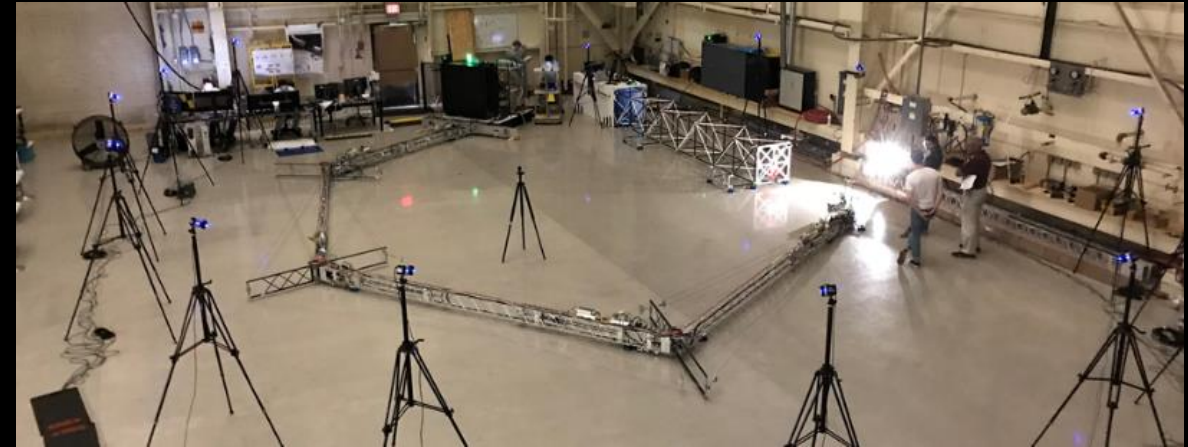
- Long reach manipulator sized (20 meters) for on-orbit assembly operations
- Compact packaging and self deployment

- **Components**

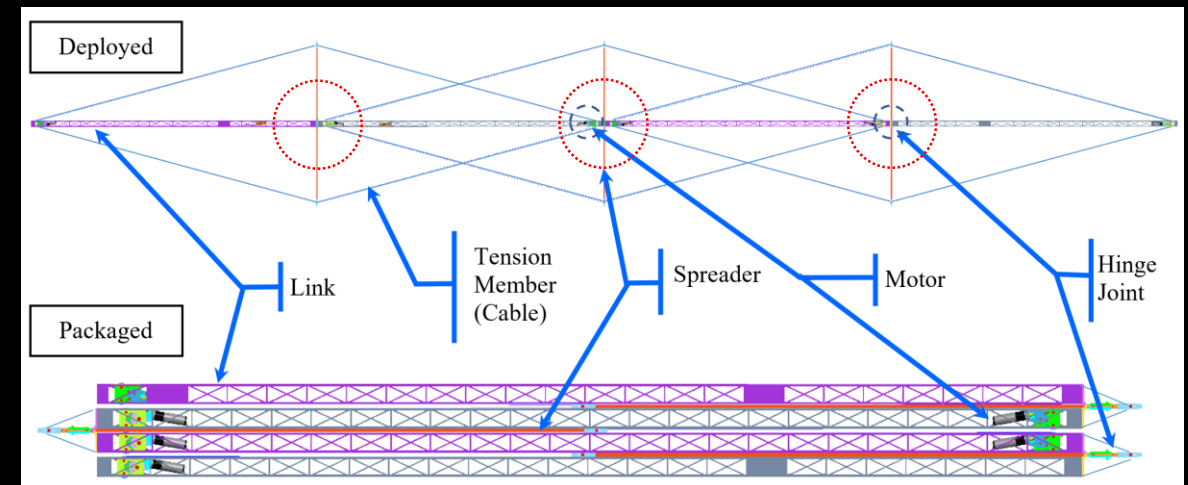
- Compression members (Links)
- Tension members (Cables)
- Spreaders
- Motors
- Hinge joints

- **Operation**

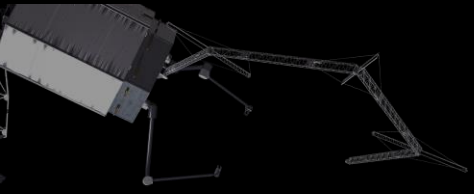
- In-plane rotation at hinge joints actuated by changing cable lengths
- Design currently only considers in-plane loads
- Secondary out-of-plane loads possible



TALISMAN V2.0 operational demonstration.



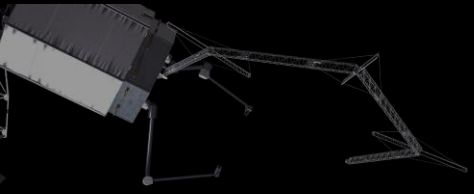
TALISMAN in the deployed and packaged configurations.



Objectives and Approach

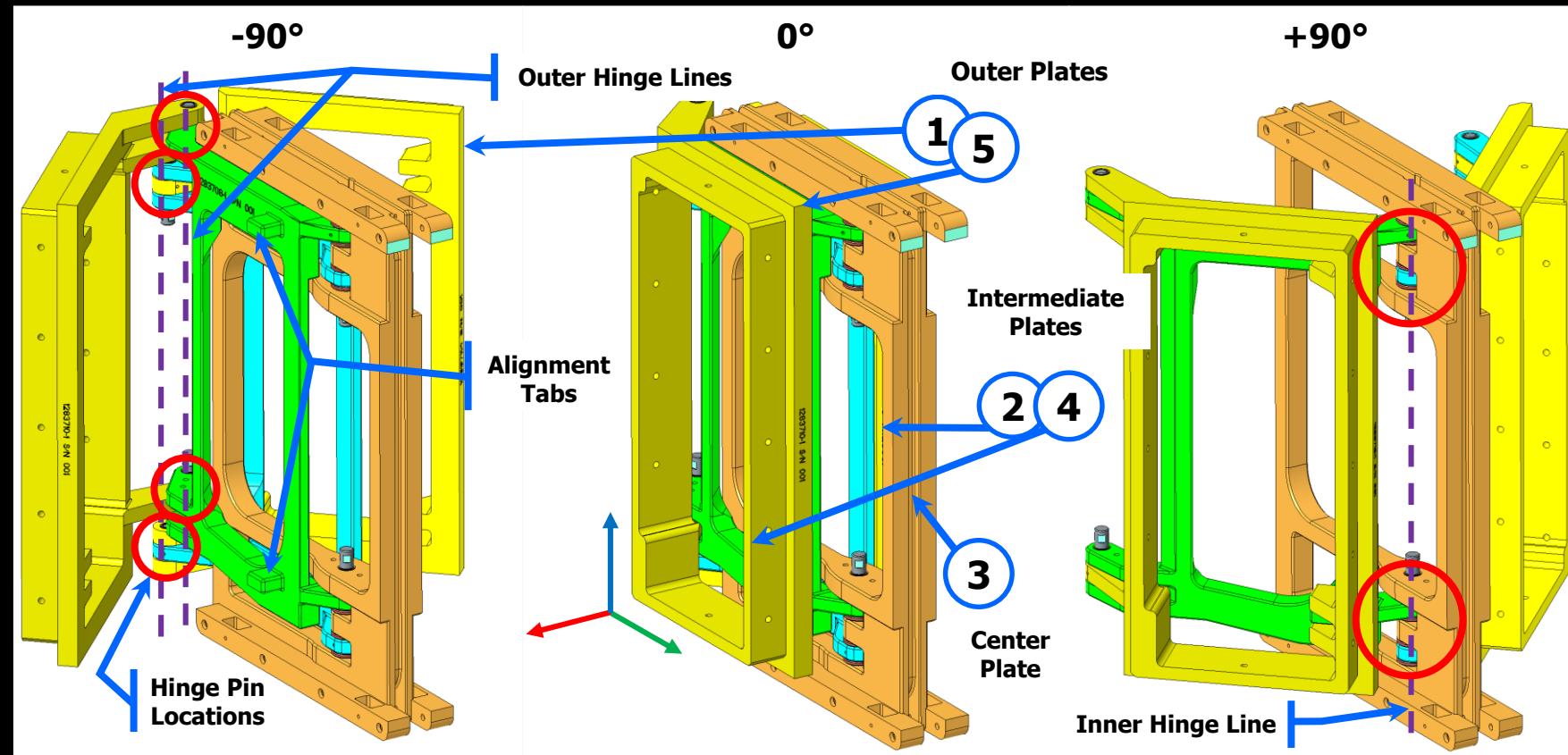


- Objective: Develop and validate an approach for including secondary (out-of-plane) loads in TALISMAN design and sizing process
- Approach
 - Perform hinge joint out-of-plane stiffness tests
 - Determine how to measure out-of-plane behavior through testing
 - Understand out-of-plane behavior of the hinge joint
 - Develop detailed hinge joint FEM
 - Correlate FEM results with test data for several representative joint angles and cable pre-load levels to determine necessary modeling fidelity
 - Use detailed hinge joint model in future design and sizing

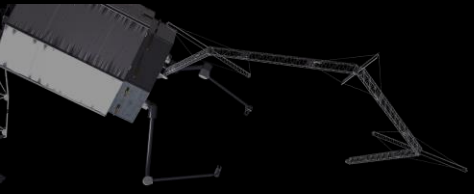


Hinge Joint Description

- Asymmetric design
- Rotation from -180° to +180°
- **5 hinge plates**
- **3 hinge lines**
 - Positive rotation about inner hinge line
 - Negative rotation about outer hinge lines



TALISMAN V2.0 Hinge joint with hinge pins circled, hinge lines highlighted, and hinge plates labeled at the -90°, 0°, +90° joint angles.



Out-of-Plane Stiffness Test



- **Testing:**

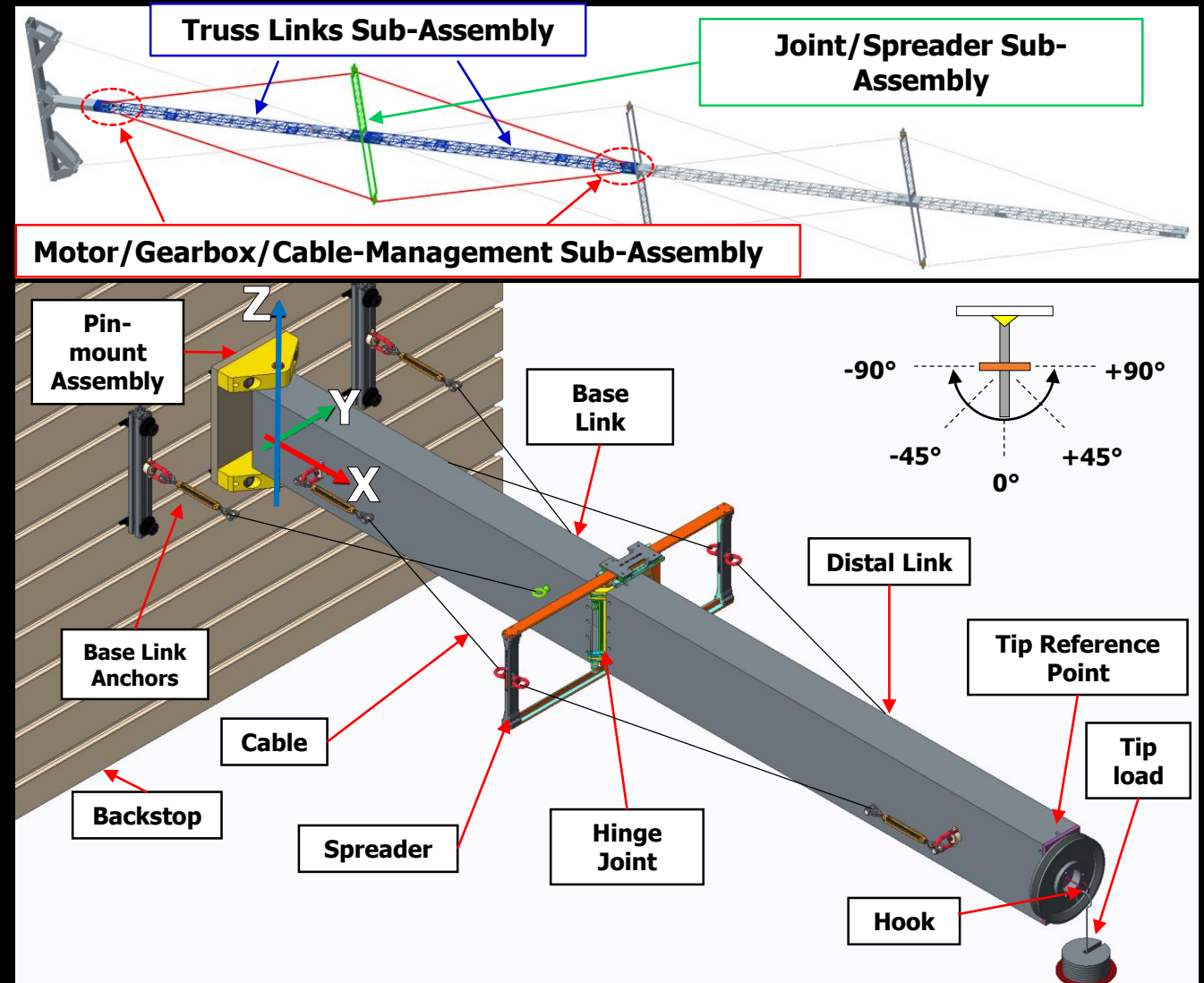
- Measured hinge joint response at 5 joint angles (0° , $\pm 45^\circ$, $\pm 90^\circ$) and 3 cable pre-load levels (25 lbf, 50 lbf, 100 lbf)

- **Sub-scale test specimen**

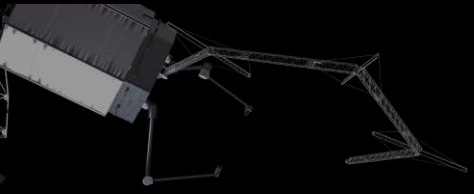
- Full-sized hinge joint
- Quarter-scale link and spreader lengths
- Fixed cable lengths at correct angles

- **Instrumentation**

- Photogrammetry
- Tension sensors
- Strain gages



Sub-scale test specimen schematic.

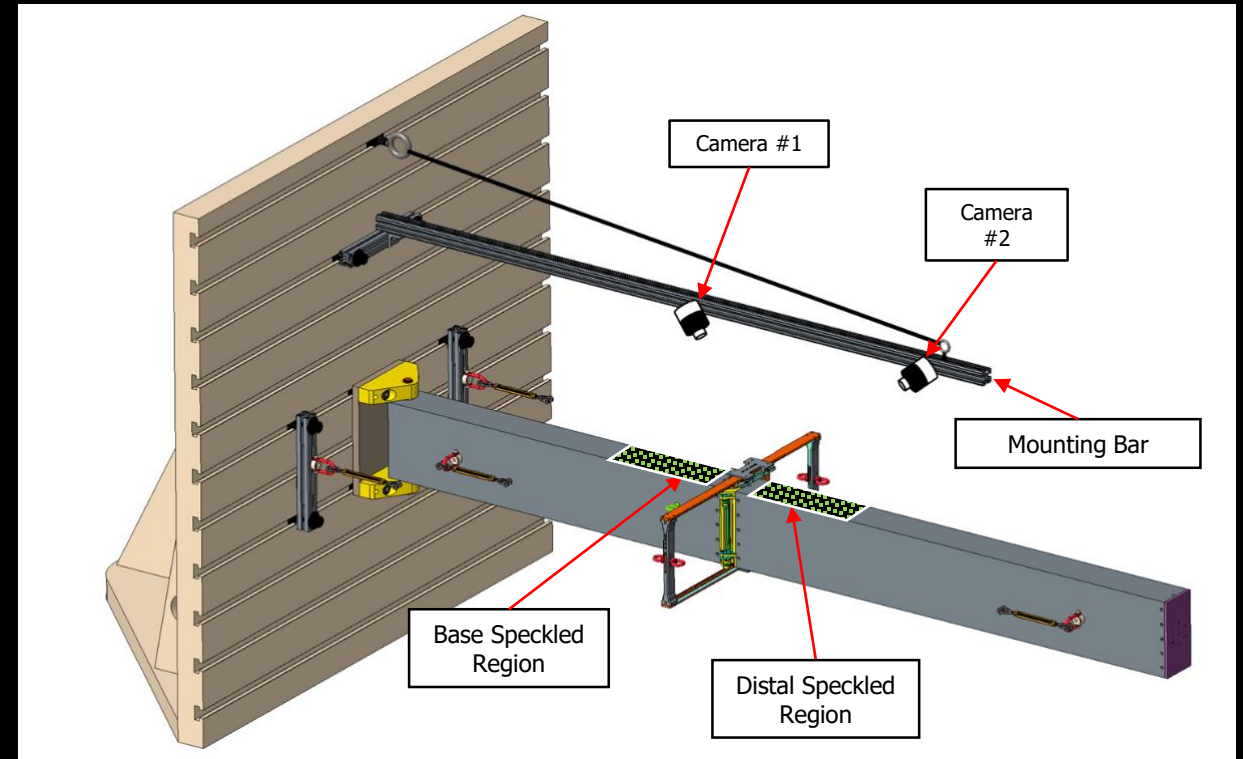


Photogrammetry

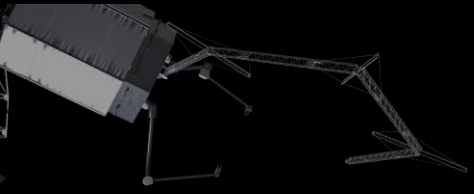


- **Setup:**

- Two 5-MegaPixel photogrammetry cameras
- Speckle pattern on base and distal links
- Calibrated using the appropriate VIC-3D calibration target
- Measured out-of-plane displacements near the hinge joint
- Calculated tip displacements, axial twist, and angle change under applied loads

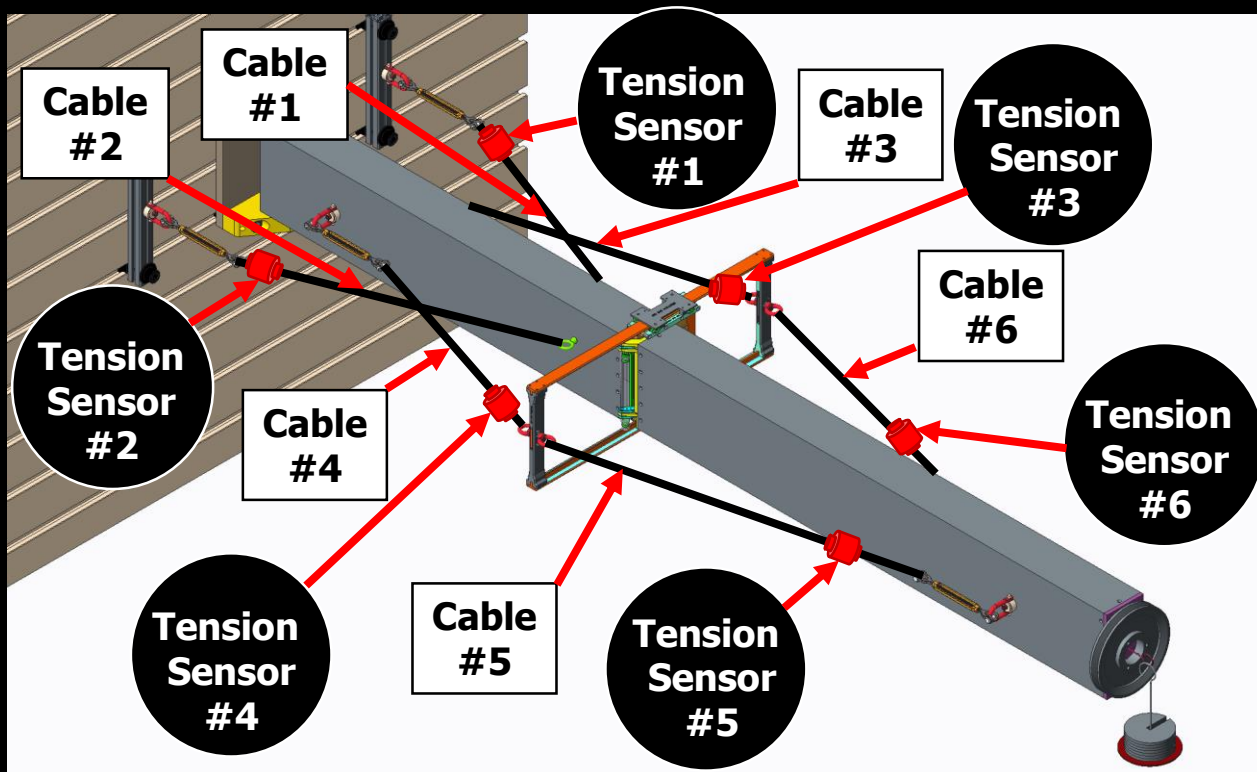


Photogrammetry cameras, speckled regions, and mounting bar.

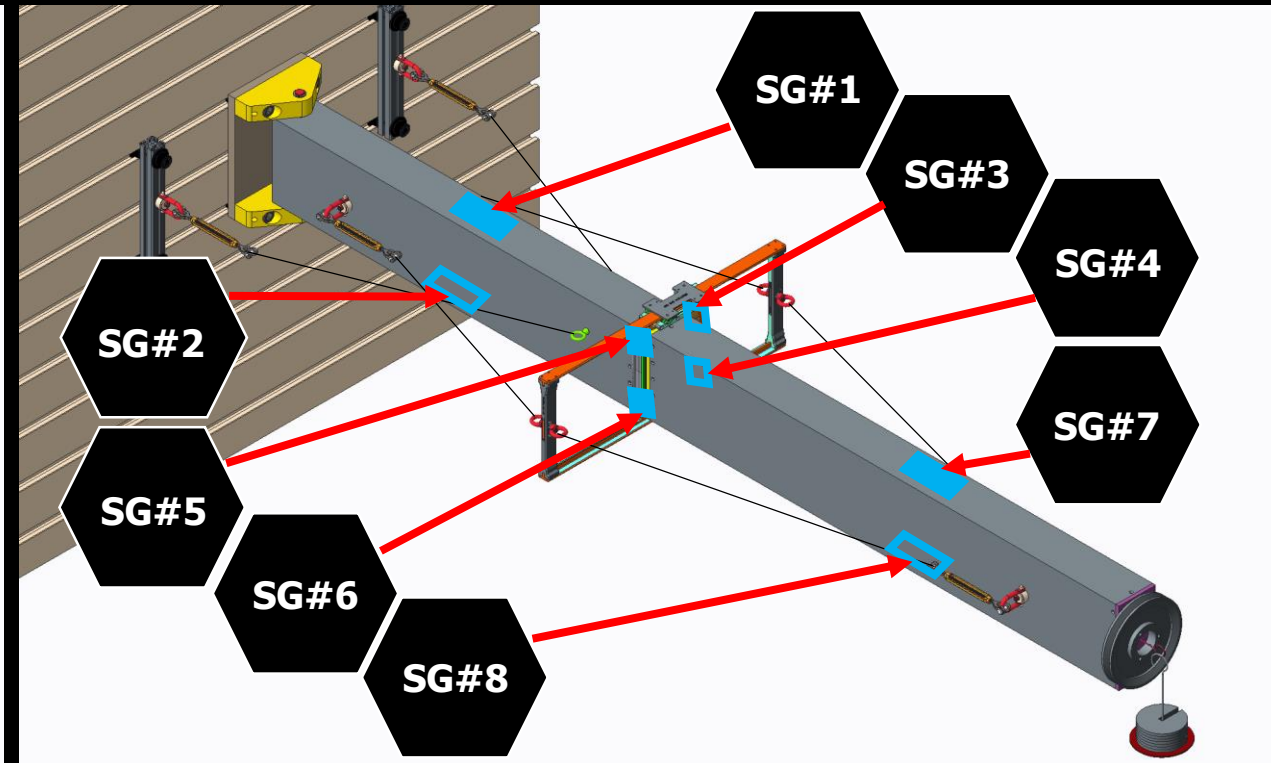


Sensors

- Tension sensors placed in-line with cables, 6 total
- Strain gages placed on links and hinge plates, 8 total



Schematic showing cable identifiers and tension sensor locations.

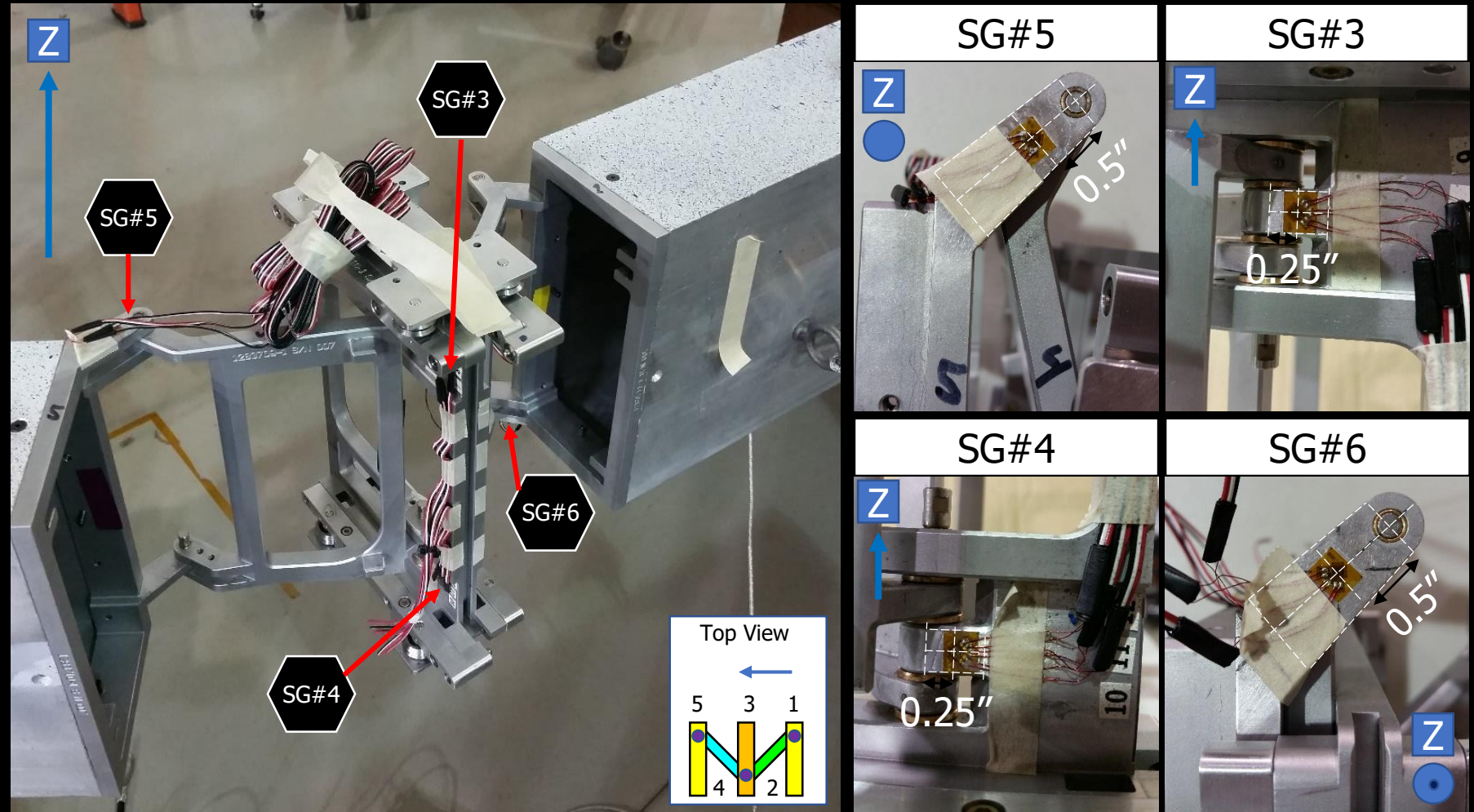


Schematic of strain gage locations with obscured locations shown as unfilled boxes.

Strain Gage Locations on Hinge Joint



- Instrumented hinge pins would be preferred
- Strain gages placed close to hinge pins
- Placement did not interfere with hinge operation



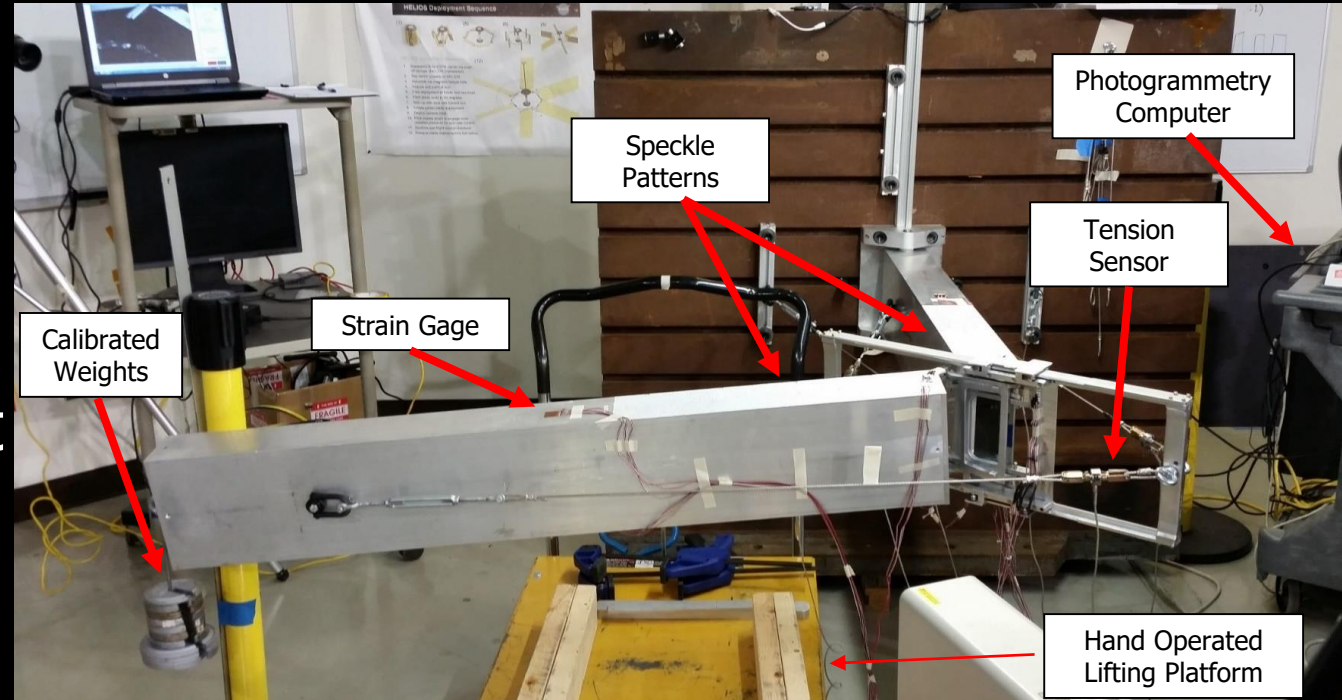
Detailed photographs of strain gage locations on hinge joint.

Test Setup

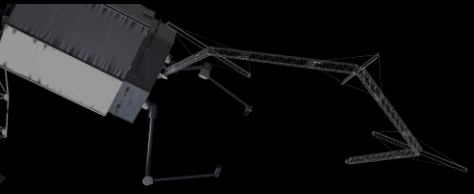


- **The test setup procedure:**

- Support the test specimen by resting it on a hand operated lifting platform
- Manually orient the joint to the desired test angle
- Place tension sensors in-line with fixed length cables
- Pre-load all cables to desired load and verify with tension sensors
- Coupled interactions between joint angles and cable pre-loads require careful adjustment
- The lowest cable pre-load, 25 lbf, corresponds to the maximum cable load used for the TALISMAN V2.0 during operational demonstrations



Test photograph with the hinge joint opened at -90° and loaded with tip mass.

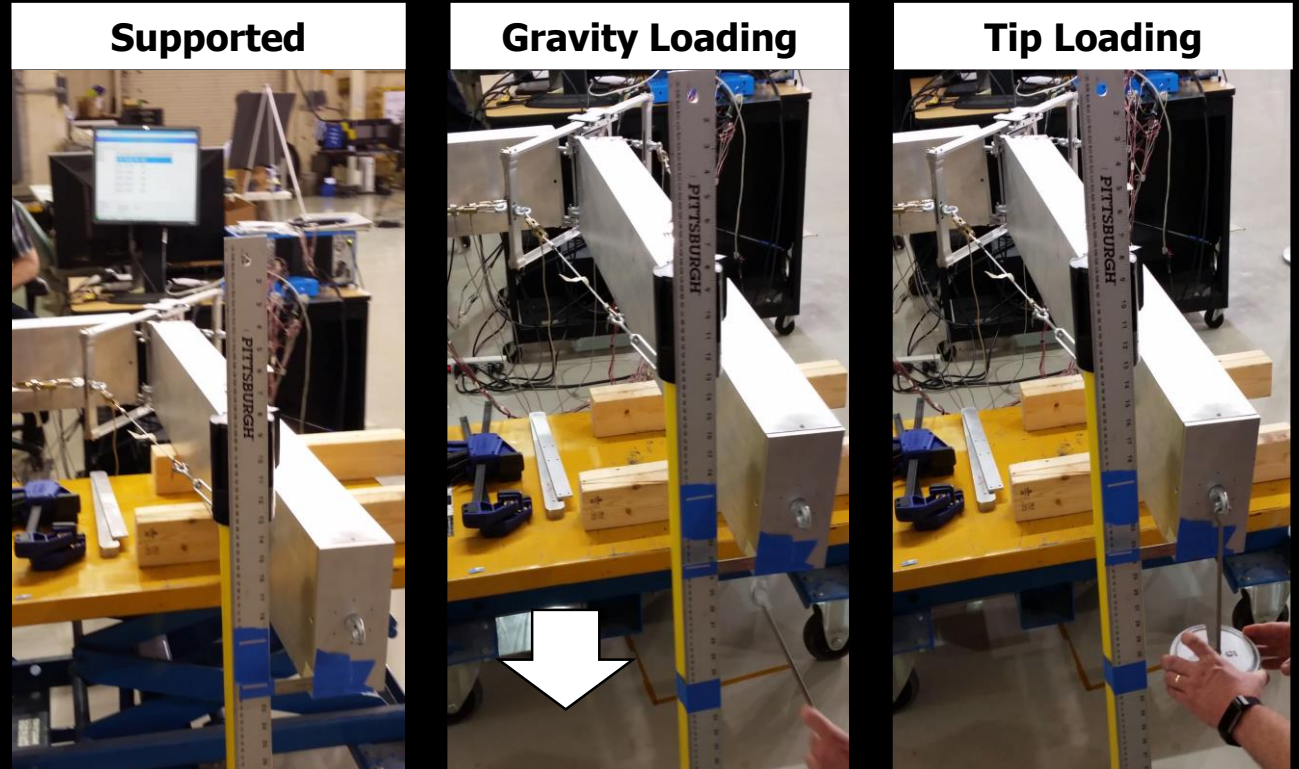


Test Execution

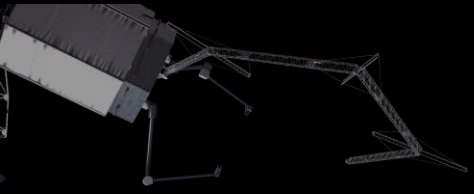


- **Procedure:**

- Initial load and strain measurement taken while the test specimen was still supported by the lifting platform
- Slowly lowered the hand operated lifting platform until the test specimen was self-supported under gravity loading
- Incrementally increased the applied out-of-plane tip load (using calibrated weights)

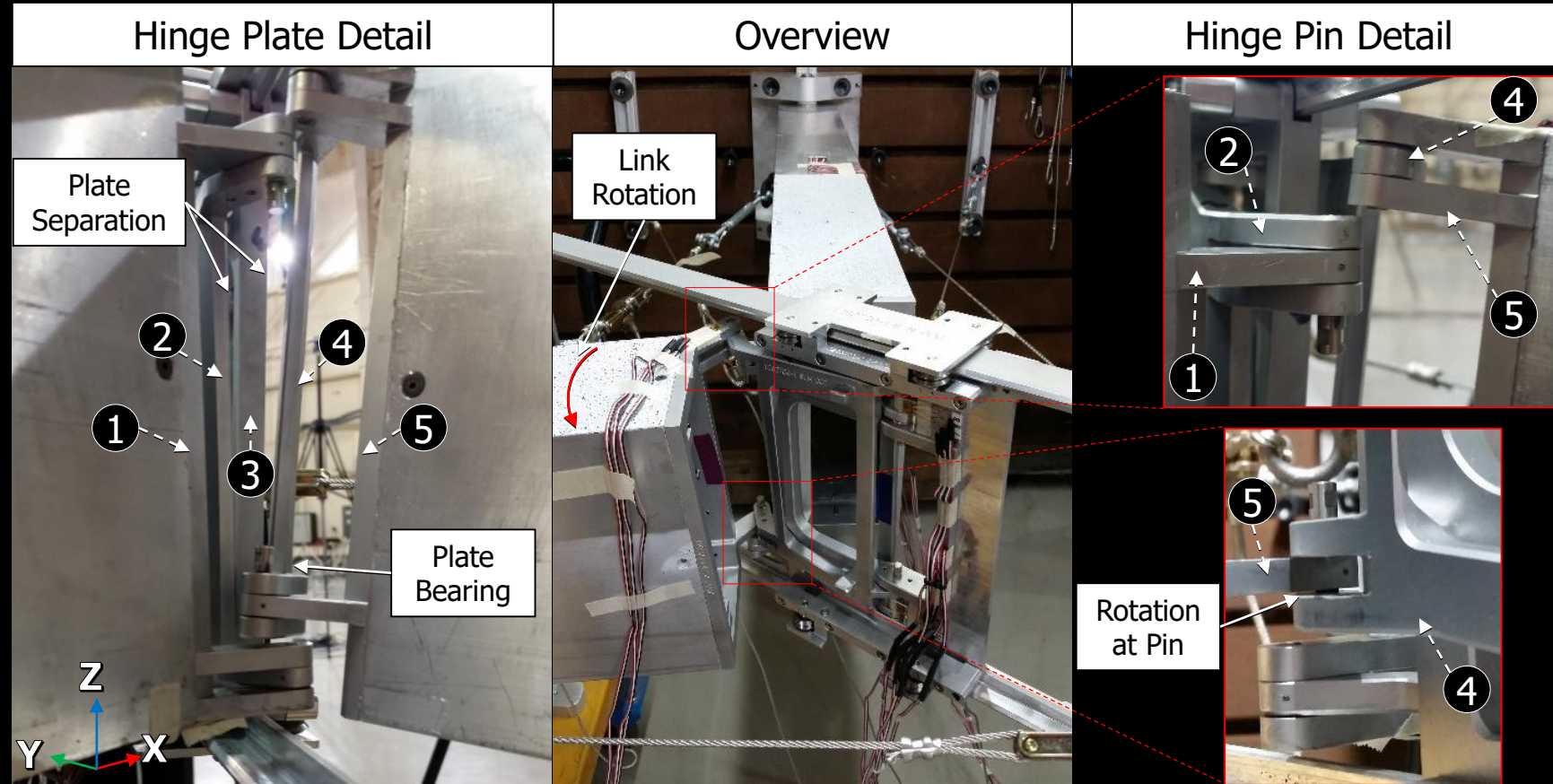


Test execution procedure (photographs are in order).

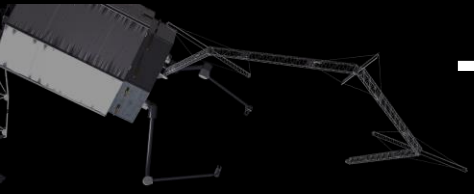


Observations

- Plate separation occurred at top of hinge plates
- Plate bearing occurred at bottom of hinge plates
- Link axial rotation apparent on distal link
- Rotation at hinge pin connections due to connection tolerance



Overview, hinge plate detail, and hinge pin detail photographs of the hinge joint during - 90° joint angle at 100-lbf cable pre-load test at 10.5-lbf of applied tip load.



Test Results – Tip Displacement

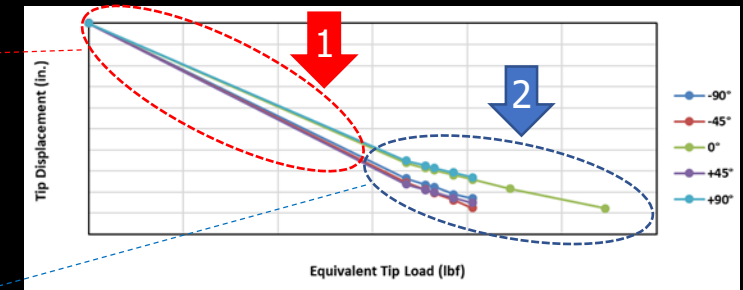


- **1) Cable Dominated Stiffness**

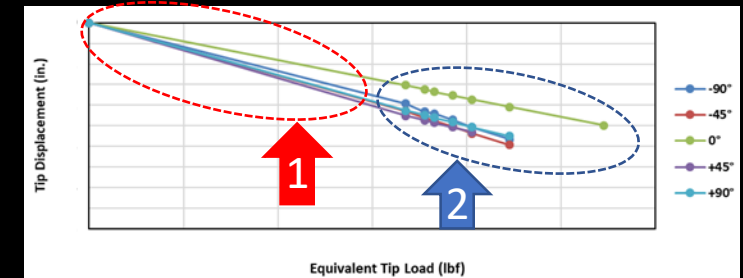
- Present within the initial gravity loading portion of tests
- Hinge joint stiffness **does** change significantly with cable pre-load
- Positive joint angles deflect **more** than negative joint angles

- **2) Hinge Plate Bearing Dominated Stiffness**

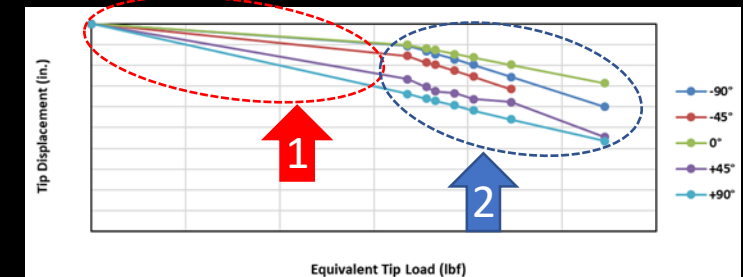
- Present over the applied tip load portion of the tests
 - Hinge joint stiffness **did not** change significantly with cable pre-load
 - Positive joint angles deflect **less** than negative joint angles
- The 0° joint angle may be the stiffest because all hinge plates are able to directly bear on one another with less out-of-plane rotation than the other joint angles



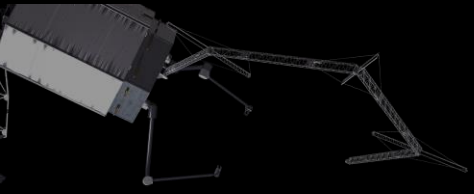
Results for 25-lbf Pre-load - Tip Displacement (in.) versus Equivalent Tip Load (lbf)



Results for 50-lbf Pre-load - Tip Displacement (in.) versus Equivalent Tip Load (lbf)



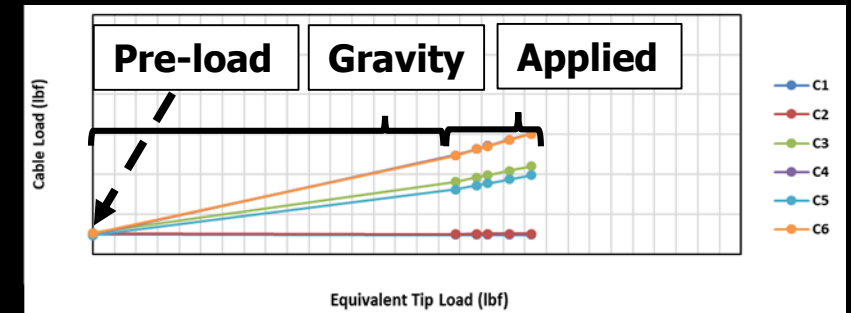
Results for 100-lbf Pre-load - Tip Displacement (in.) versus Equivalent Tip Load (lbf)



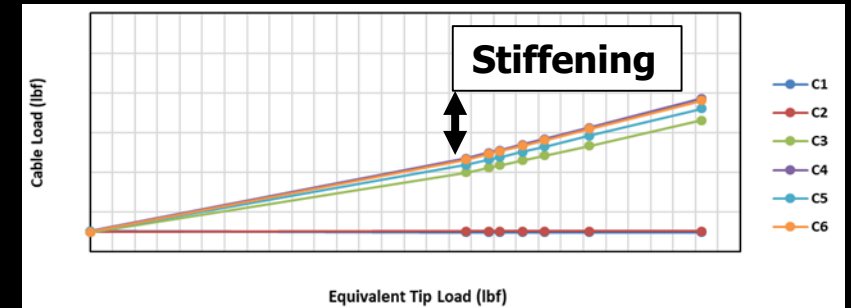
Test Results – Cable Forces



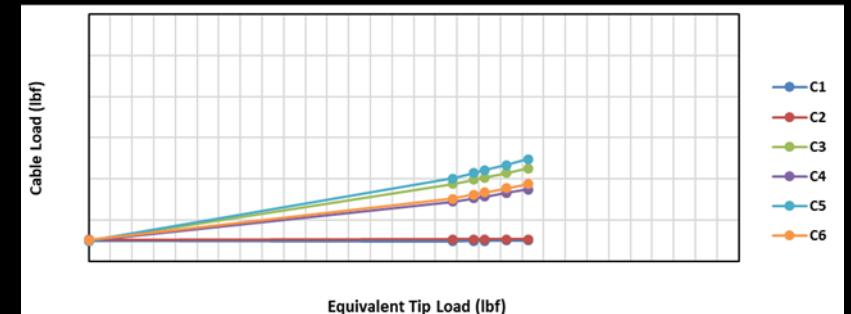
- All cable forces started at the pre-load level
- Base cables (C1 and C2) show no response
- Load increased in C3 through C6 with bi-linear stiffness
 - 0° joint angle – C3 through C6 follow a similar trend
 - Negative joint angles – C6 and C4 carry the highest loads
 - Positive joint angles – C3 and C5 carry the highest loads
- Cable response stiffened after gravity loading (around 100 lbf)



Cable loads for the 25-lbf pre-load at -45° test.



Cable loads for the 25-lbf pre-load at 0° test.

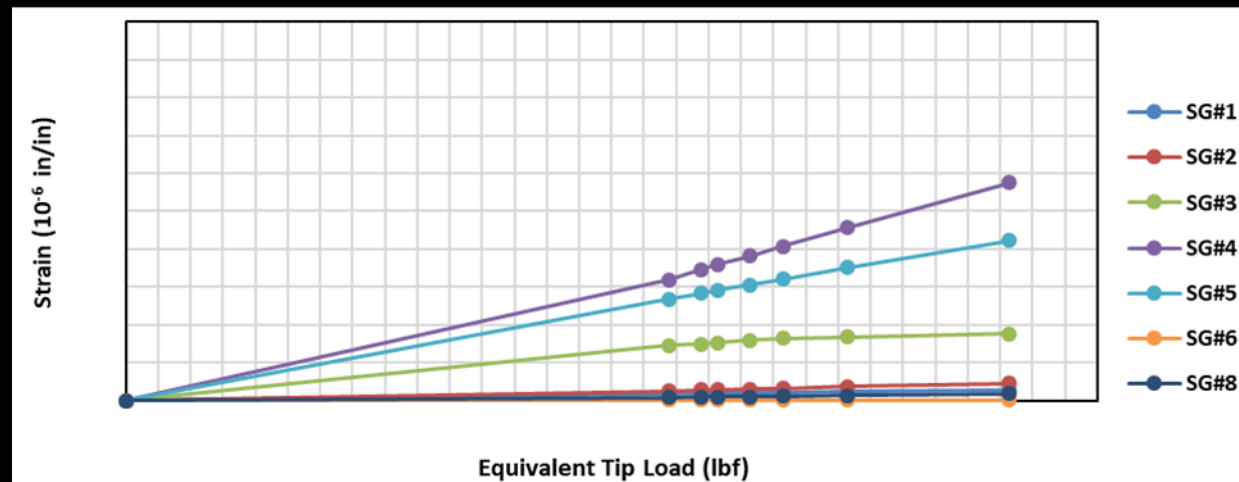


Cable loads for the 25-lbf pre-load at +45° test.

Test Results – Component Strains



- Strain measured on links was negligible for all cases (50 microstrain)
- Strain measured on hinge joint was also very low (500 microstrain and below)
- Bending of hinge plates did not contribute significantly to tip displacement



Strain gage magnitude results for 25-lbf. cable pre-load for 0° joint angle.

Finite Element Model

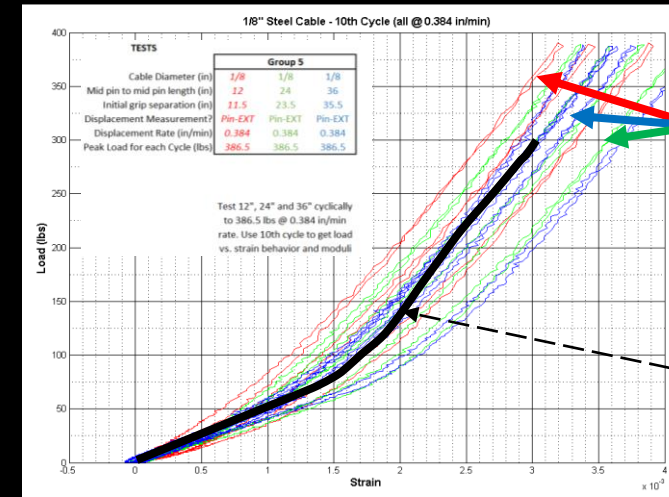


- **Approach**

- A FEM was created in MSC.Patran
- The model correlation used cable forces and the measured tip displacements
- Strain values were not significant enough to incorporate into the model
- 1/8-in. diameter steel cables stiffness derived from tests of 36-in. long cable after 10 load cycles tensioned up to 25% of the rated tensile strength

- **Model Description**

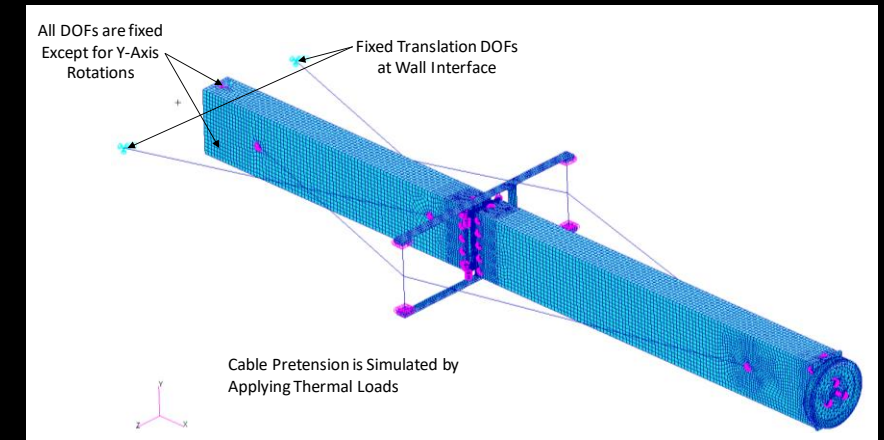
- Translational degrees of freedom (DOFs) are fixed at the base link's pin joint
- The hinge joint model has several contact bodies to capture non-linear behavior
- The 1/8-in. diameter steel cables are pre-loaded by applying thermal loads
- Three CONM2 mass elements represent the addition of suspended mass at the distal link tip



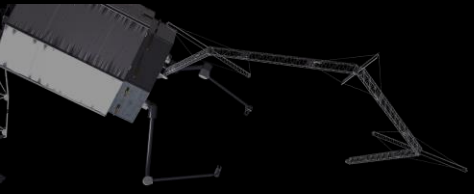
Three cable lengths tested (12 in., 24 in., and 36 in.)

Average 36-in. cable stiffness curve at cycle #10 used for FEM

Graph of 1/8-in steel cable load-strain curves after 10 loading cycles up to 25% of rated load.



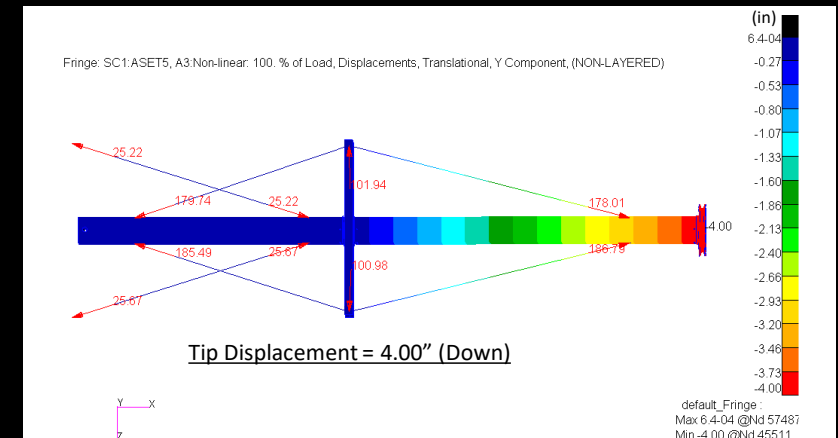
FEM representation of the test assembly (0° joint angle).



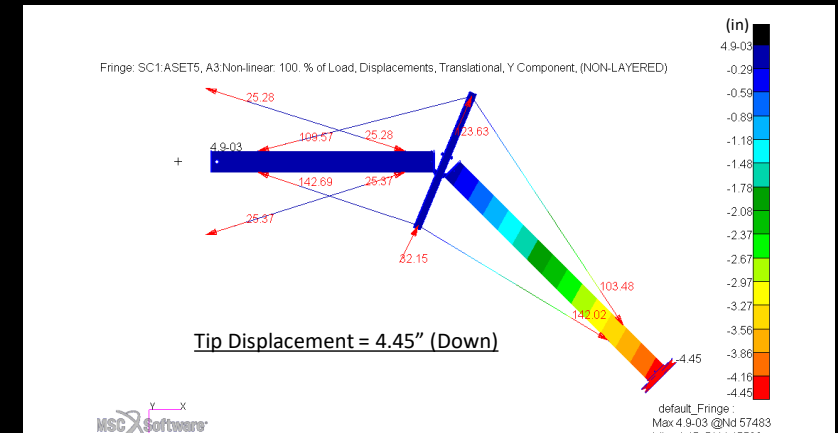
Test and Model Correlation



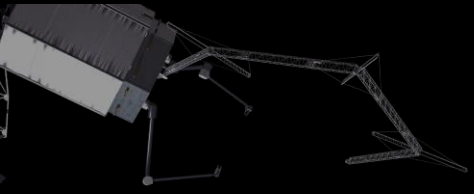
- **Cases modeled:**
 - 25-lbf cable pre-load
 - Three joint angles (0° and $\pm 45^\circ$)
- **Model results:**
 - The tip displacement analysis and testing correlate within 10%
 - Cable force differences were up to 30% for individual cables but summing across the joint resulted in 17% or lower difference
 - Correlation is improved at higher cable loads
- **The differences between the test results and model are likely due to:**
 - Variations in initial cable loads
 - Actual cable stiffnesses
 - Shell model of hinge joint not providing an accurate enough representation of contact



0° Joint Angle with 25-lbf Cable Pre-load FEM versus Test: Comparison of Cable Forces.



-45° Joint Angle with 25-lbf Cable Pre-load FEM versus Test: Comparison of Cable Forces.



Concluding Remarks



- **Out-of-Plane Stiffness Testing:**

- A series of TALISMAN V2.0 hinge joint out-of-plane stiffness tests were conducted at:
 - Five joint angles (0° , $\pm 45^\circ$, and $\pm 90^\circ$)
 - Three cable pre-loads (25 lbf, 50 lbf, and 100 lbf)
 - Up to an equivalent out-of-plane tip load of 27.28-lbf
- Two stiffness regimes were observed for out-of-plane loading
 - **Cable dominated** most affected by cable pre-load
 - **Hinge plate bearing dominated** most affected by joint angle
- Testing provided an initial set of deflection, cable load, and strain data to inform accurate modeling of the hinge joint out-of-plane stiffness

- **Finite Element Model Correlation:**

- Developed an FEM of the hinge joint able to predict tip displacement to within 10% of measured values at various joint angles
- Out-of-plane stiffness from the hinge joint FEM may now be implemented into a full-scale model of the TALISMAN V2.0