Three Dimensional Cellular Structures Enhanced By Shape Memory Alloys

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NASA GRC

Three Dimensional Cellular Structures Enhanced By Shape Memory Alloys

Objective: Explore and develop lightweight structural concepts married with advanced "smart" materials to achieve a wide variety of benefits in airframe and engine components

Three concepts are being married:

1. Cellular (lattice) structures
2. Auxetic structural concepts
3. Shape memory alloys

Innovative aspects:

- First ever study of lattice structures made from an SMA
- First ever auxetic structures made from an aerospace structural alloy, and from an SMA
- First ever superelastic cellular structure.
- SMA actuation technology will be extended from one- to three-dimensional actuation.

Cellular Structures

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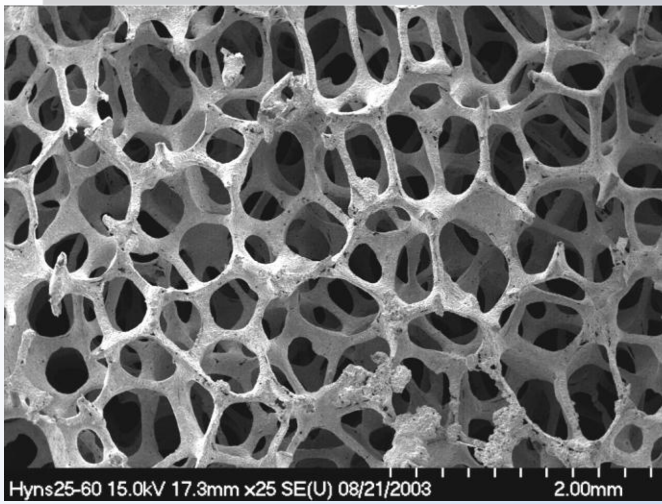
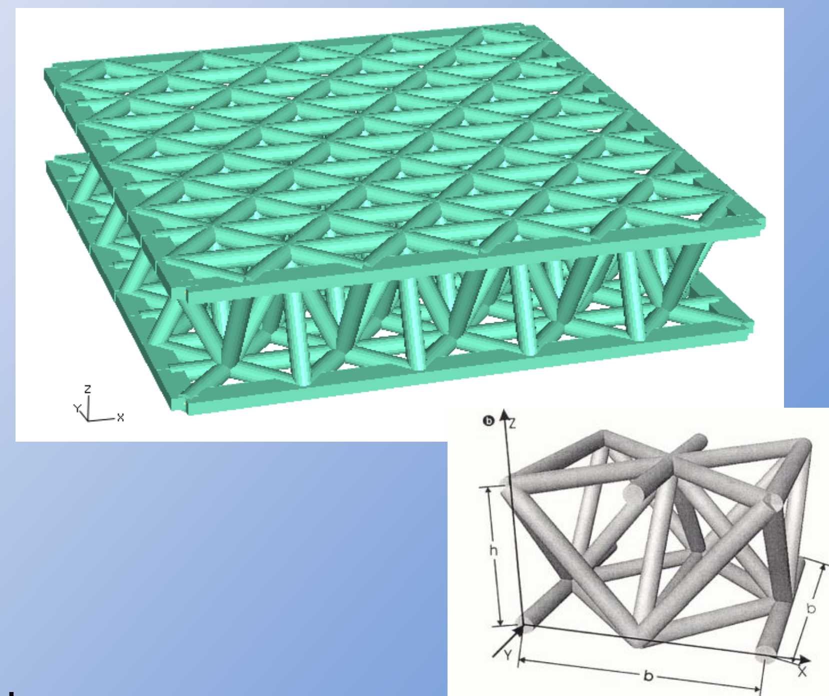


Foam

Lattice Block

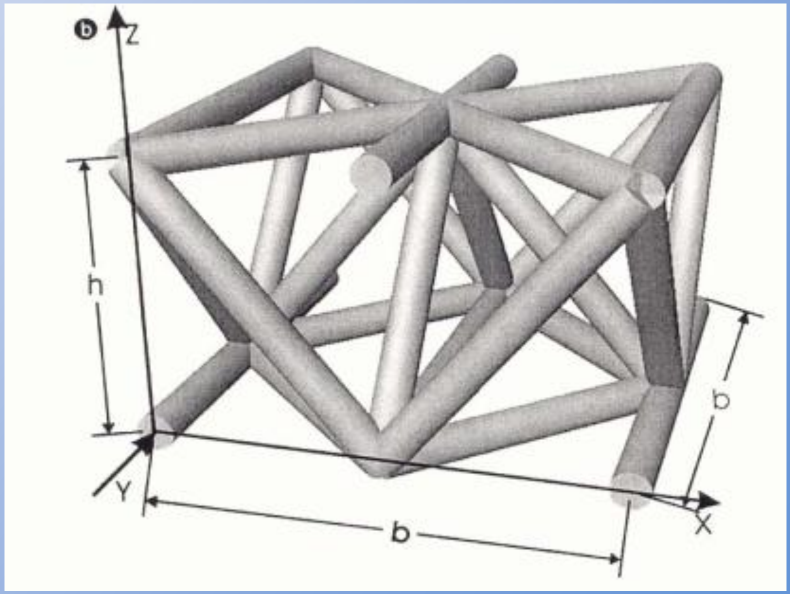


Honeycomb

Lattice Blocks

Lattice blocks refer to materials manufactured into a light weight truss structure, similar to the trusses on a highway bridge, but on a centimeter scale.

- Specific stiffness nearly equivalent to honeycomb.
- More isotropic than honeycomb
- Not as restrictive as honeycomb:
    - Can be applied to most alloys; aluminum, steel, nickel superalloys, titanium, fiber composites;
    - Adaptable to many shapes
- Does not sacrifice damage tolerance



Reduces weight while maintaining stiffness, damage tolerance and strength, all at a reasonable cost.

Auxetic Structures

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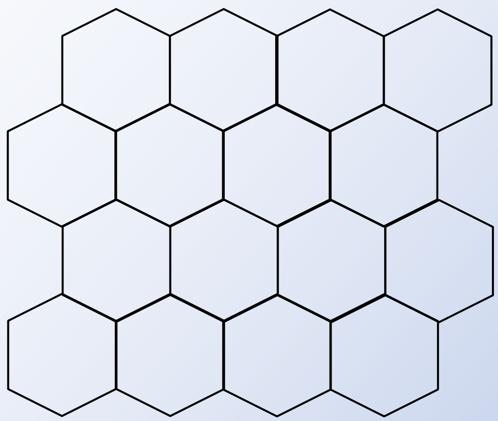
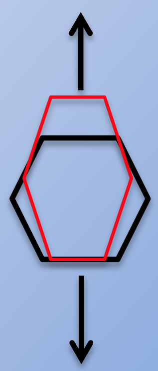
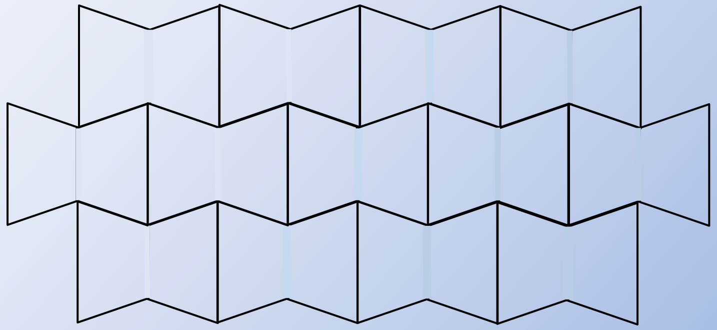
Characterized by negative Poisson's ratio: the structure gets thicker in tension, the opposite of normal behavior

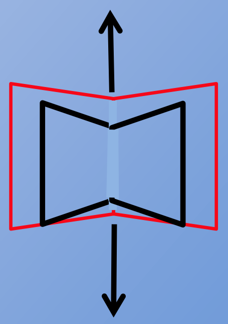


Conventional structure





Auxetic structure



Examples of Auxetic-Enabled Concepts

from the literature

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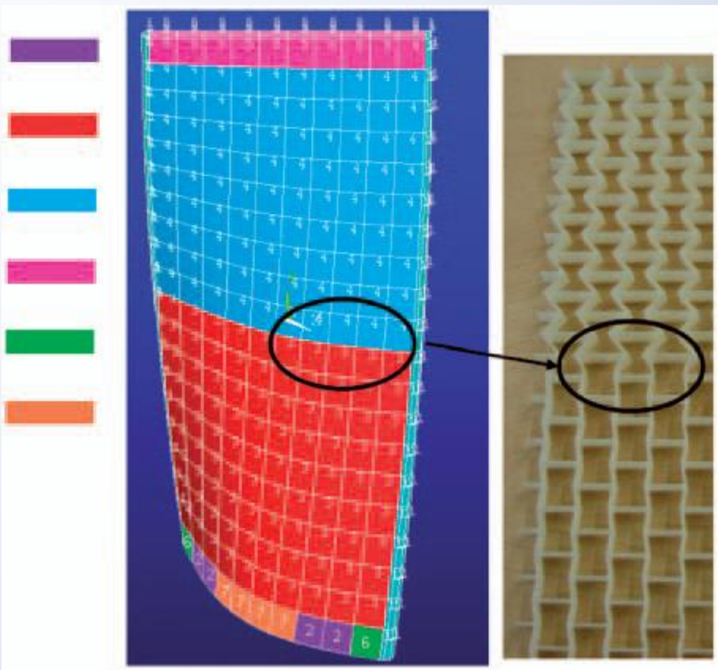
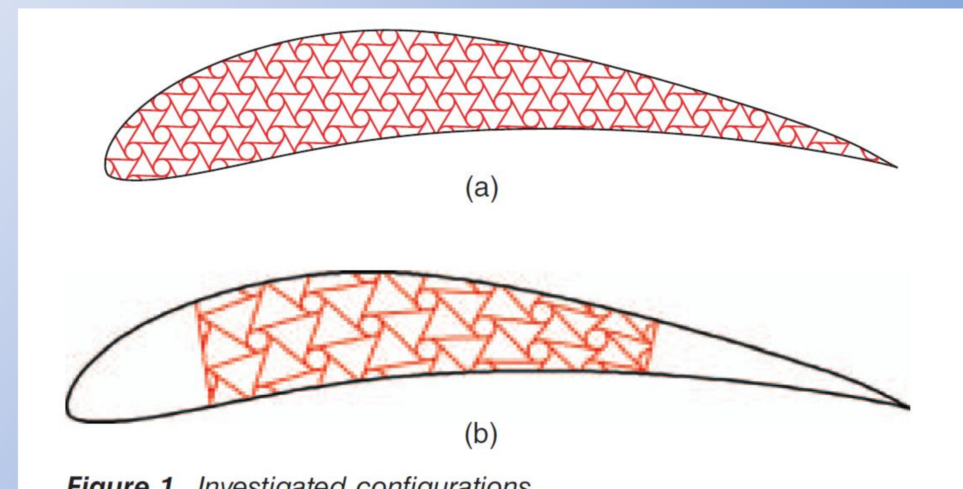
Light Weight, Flutter Resistant Fan Blade



Lira et al, 2012

Morphing Airfoil



Spadoni and Ruzzene, 2005

Shape Memory Alloys

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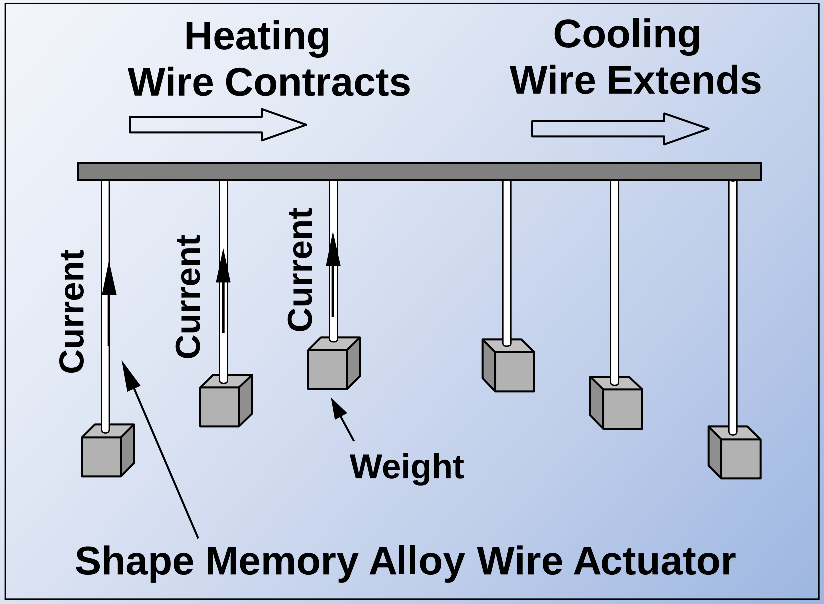
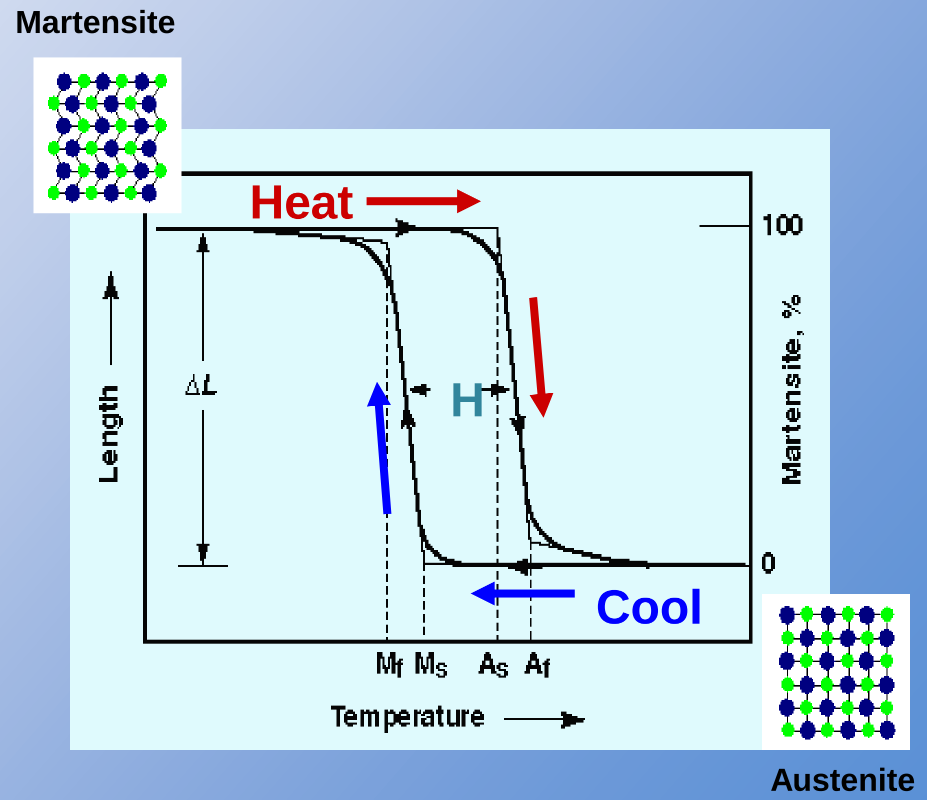
SMA's: can be deformed at low temperature and recover their original shape upon heating; some SMA's can perform <u>*work*</u> by accomplishing this recovery against a significant bias force

Example of SMA performing work





SMA's can be used in multiple designs.

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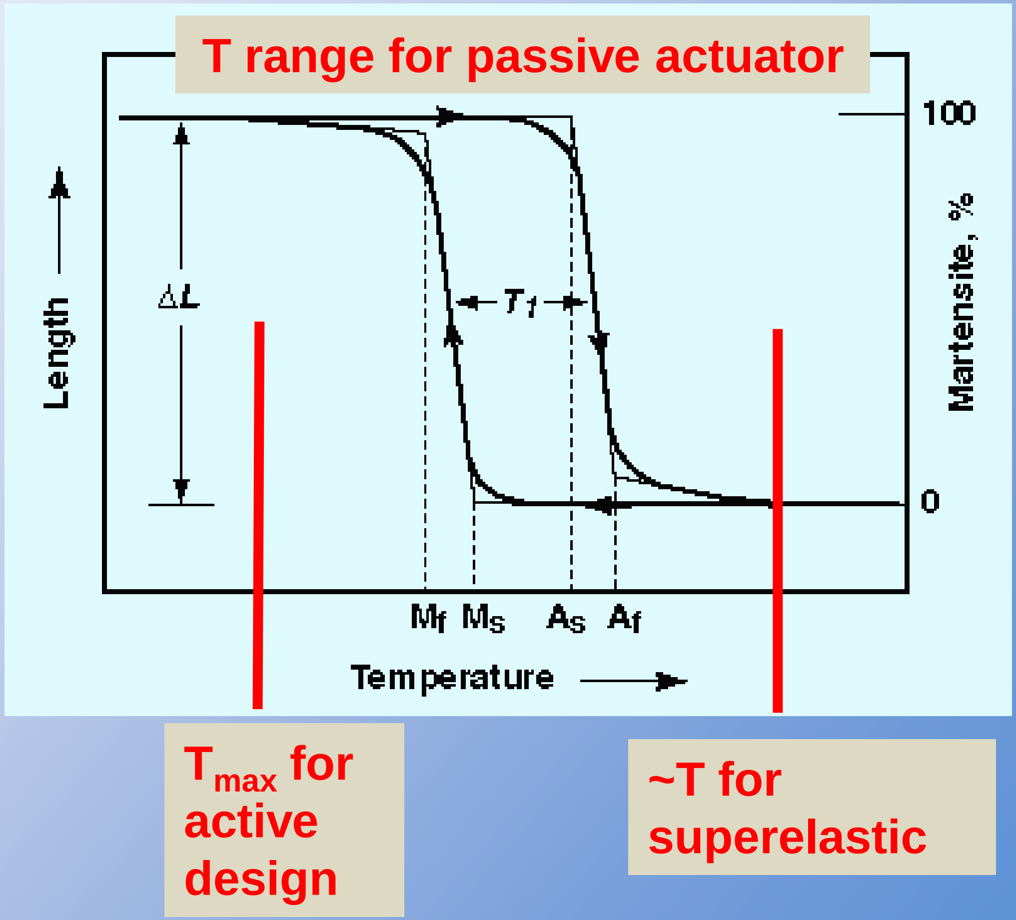
Passive: The material heats up during normal engine operation and actuates automatically

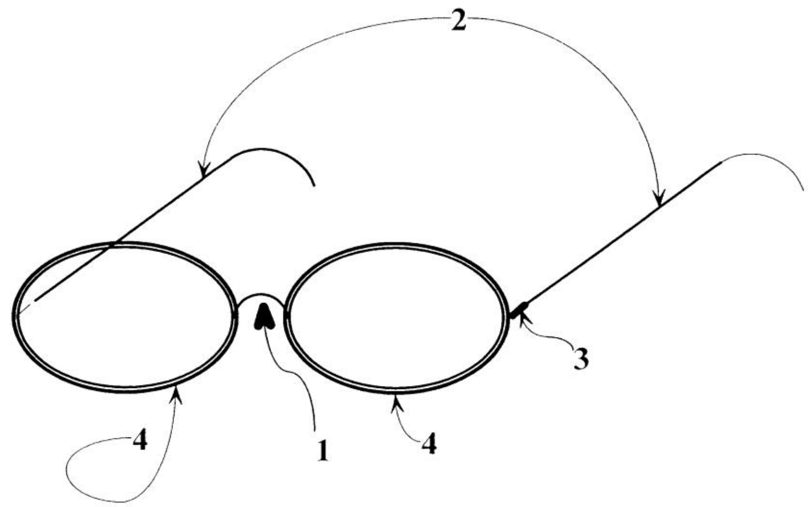
Active: The material is used below it's transformation temperature and supplemental heat (eg., electrical resistance heating) is used to actuate "on demand."

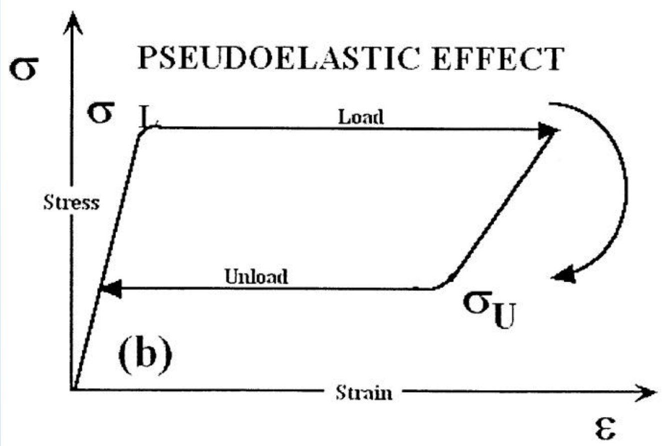
Self-healing: Simple thermal treatments can recover deformation.

Superelastic: The material is used above its transformation temperature and transforms due to stress



Superelastic Behavior





Examples of Superelastic Behavior Measured in Our Labs

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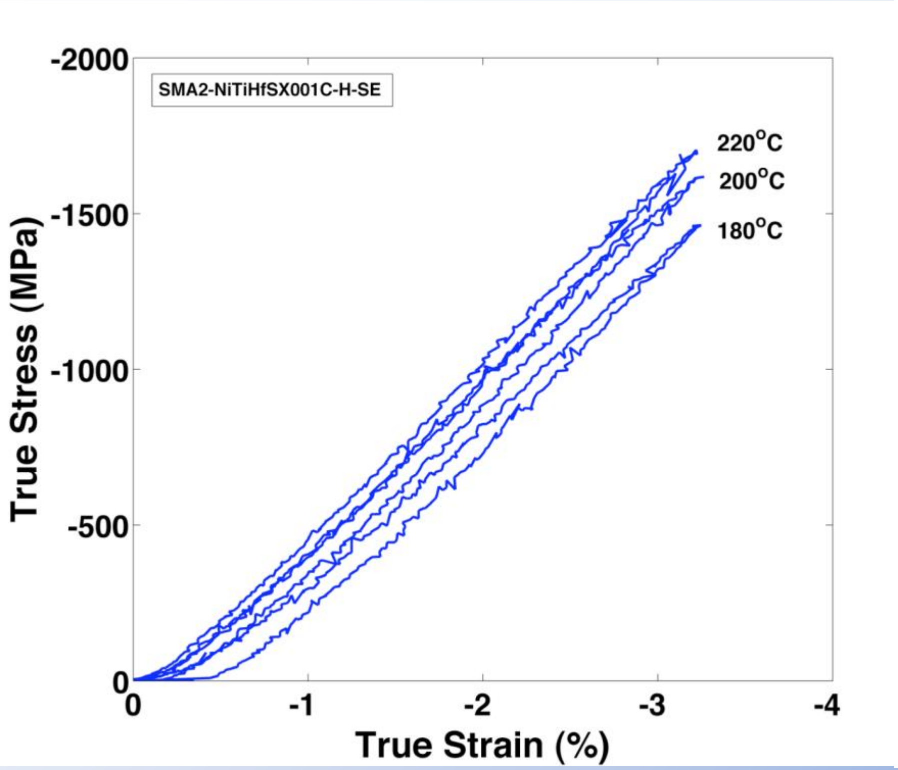
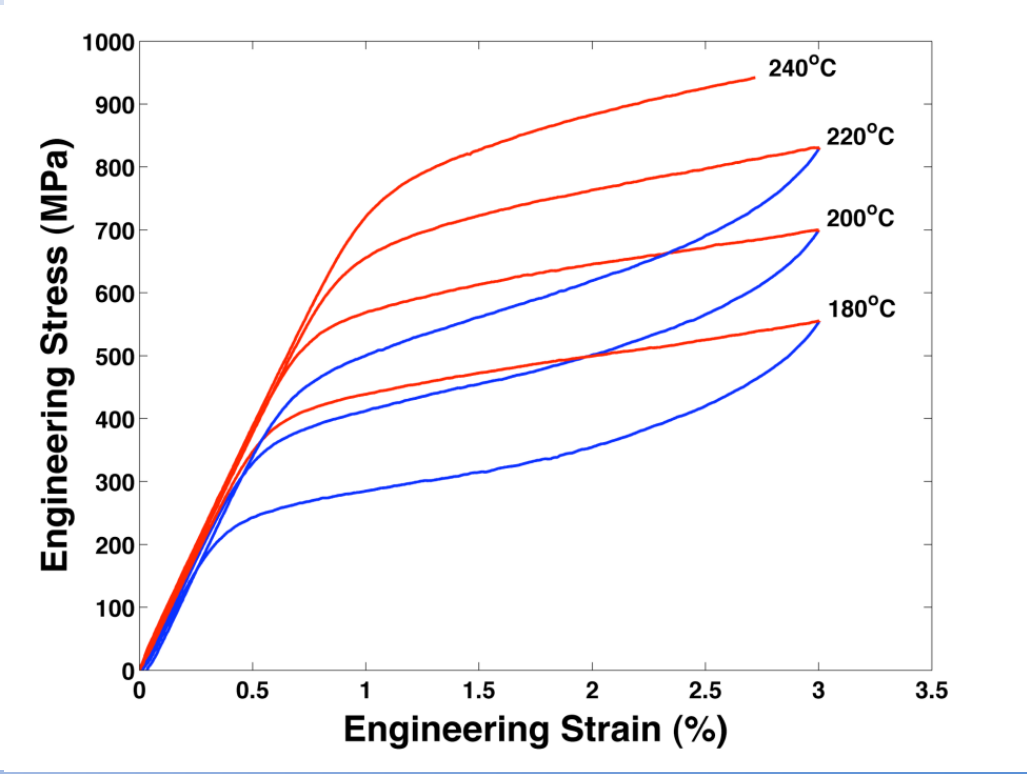
NiTi + Hf, single crystal, compression



NiTi + Hf, polycrystal, tension



Benefits: Light Weight, Aerodynamic Efficiency

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Lattice Block **plus** Auxetic structure **plus** Shape Memory Alloys

Lattice Block
- Light weight
- Damage tolerance

Auxetic structure
- Higher strength
- Higher strain capability (for morphing)
- Impact energy absorption

Shape Memory Alloys

Shape Memory
- In-situ actuation
- 3D actuation
- Self healing
- Damping, energy absorbing

Superelastic
- Exceptional strength and recoverable strain
- Impact resistance
- Gust load alleviation

- Airframe & Engine Structures: *morphing, self healing, impact resistant*
  - Cases
  - Inlets/nozzles
  - Fan blades
  - Morphing wings
  - Flaps, control surfaces

Approach

Examine all structural concepts with both an aerospace structural alloy (Ti-6-4) and an SMA

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Castings delivered from SBIR Phase II with T45 Inc.

Testing of ligaments machined from lattice (tension, compression)

a. *Confirms expected material properties*
b. *Input for Finite Element Model*

Finite element modeling: Pre-test predictions of lattice structural benchmark tests.

Structural benchmark tests (bending, compression)

a. *Confirm expected structural properties in important loading modes*
b. *Validation test for model*

Finite element modeling: Post test validation.

a. *Identify features for improved accuracy*

Expected Results:

1. *Experimental confirmation of benefits: weight, strength, flexibility, SMA actuation*
2. *Validated model that can be extrapolated to provide structural optimization for a given application*

Lattice Castings from T45 Inc.

Casting Defects

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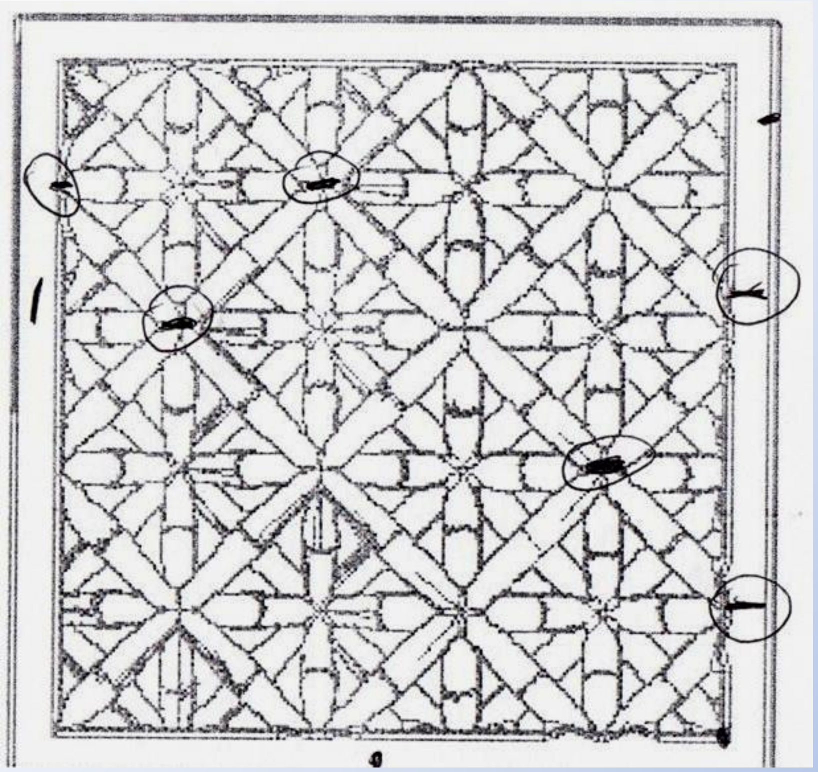
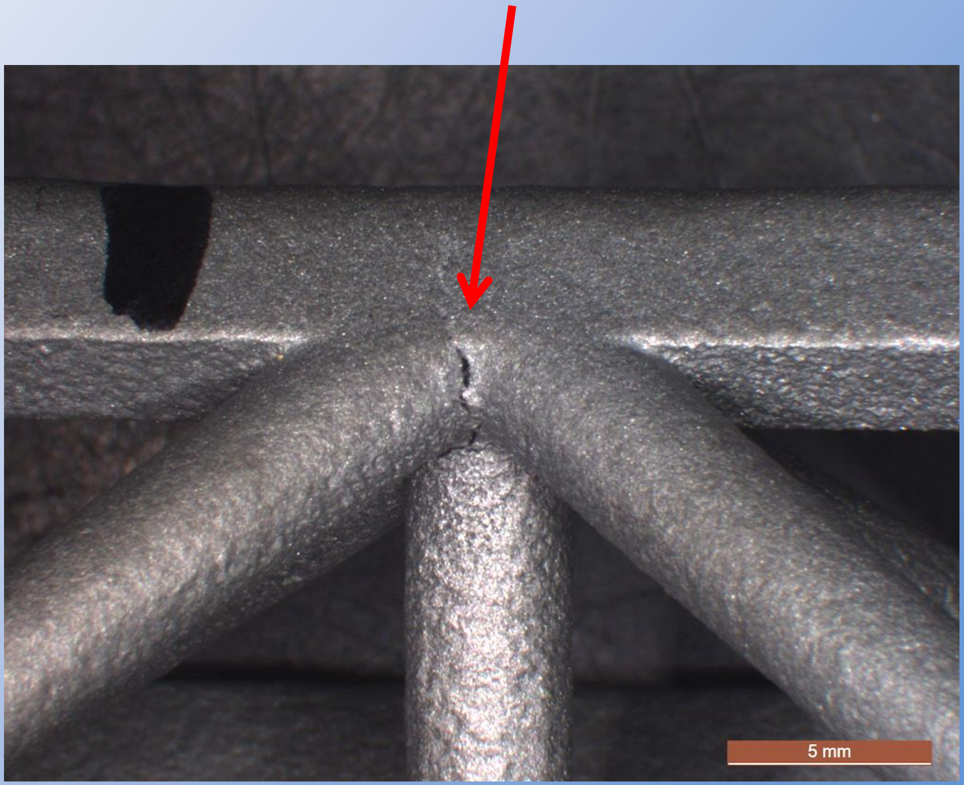


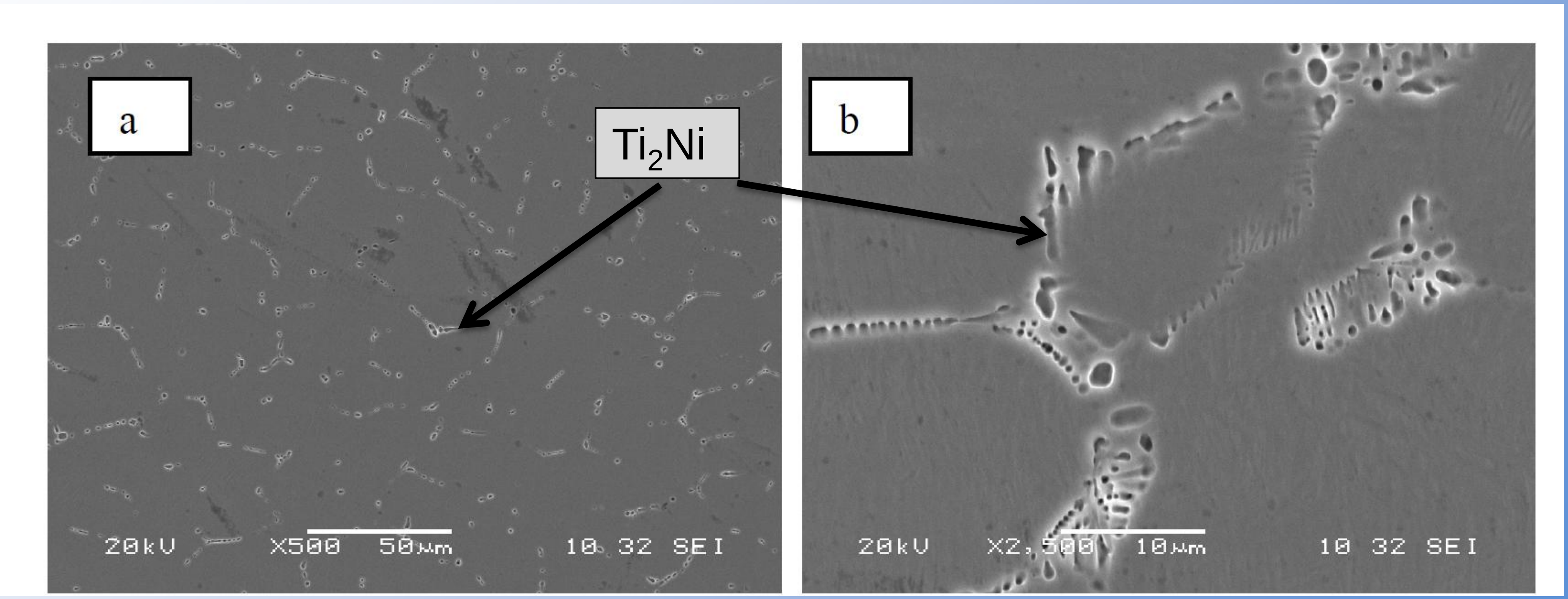
Inspection Map Supplied by Transition45

Crack



SMA Microstructure

- Ni-50 at% Ti chosen: very high actuation capability, but not as compatible to processing via casting
- Deleterious Ni_2Ti formation limits ductility, castability



Auxetic Lattice From T45

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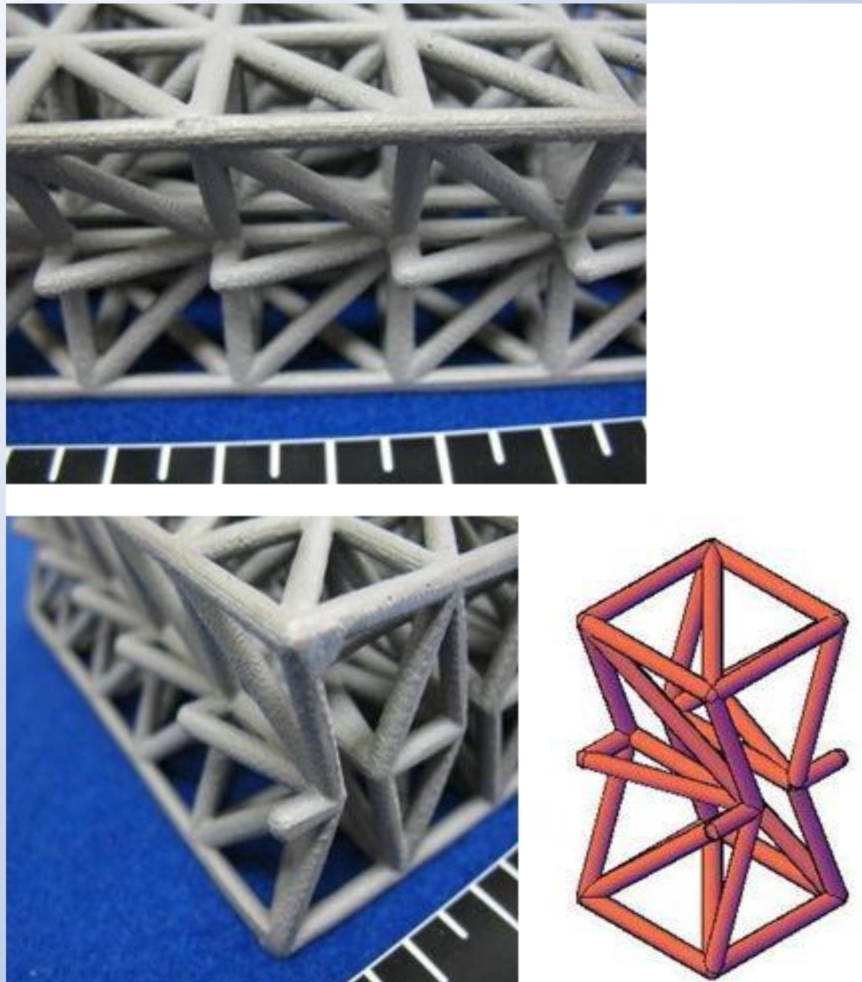


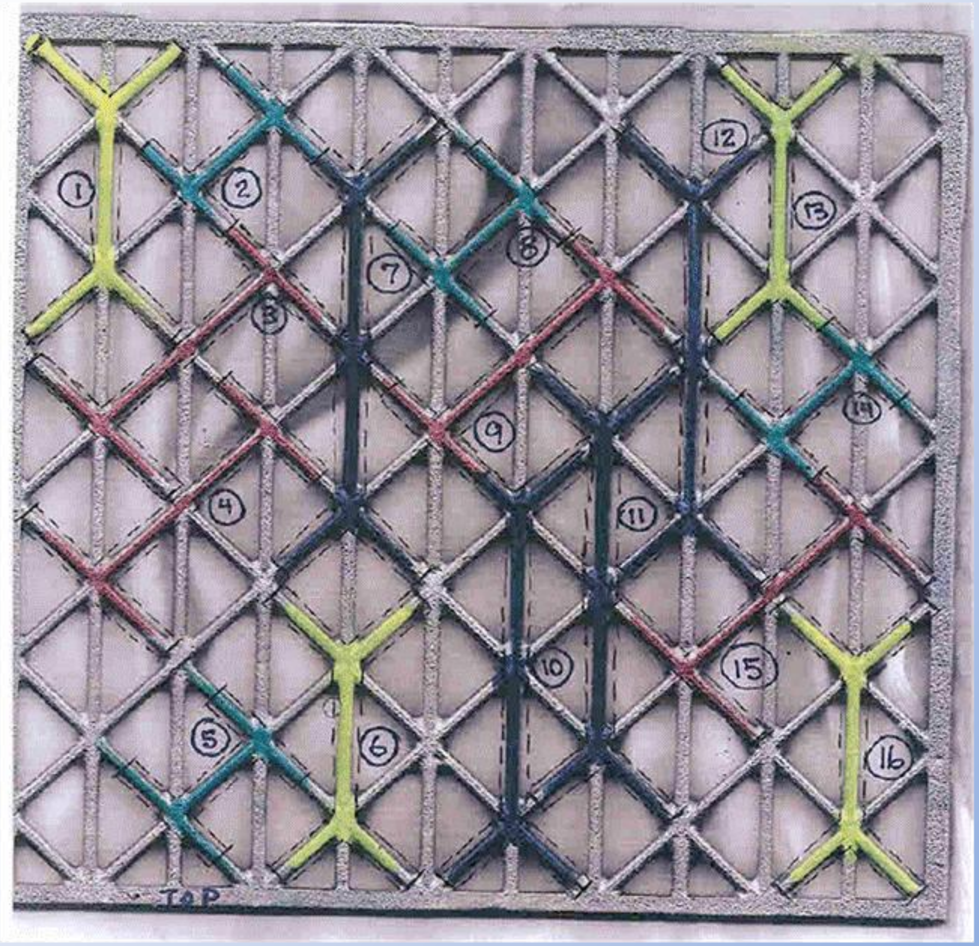
Mechanical Testing of Ligaments

Nathan Wilmoth

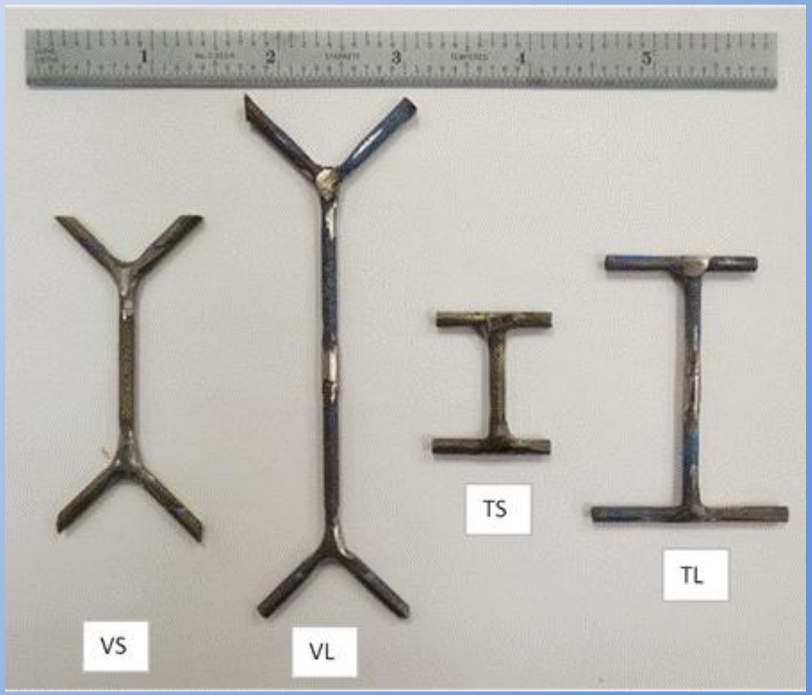
Ti-6-4 Tensile Test Specimens

NARI

8x8 Ti-6-4 Panel Layout



- Specimens removed from panel
- All specimens cut via EDM



Ti-6-4 Tensile Test Data

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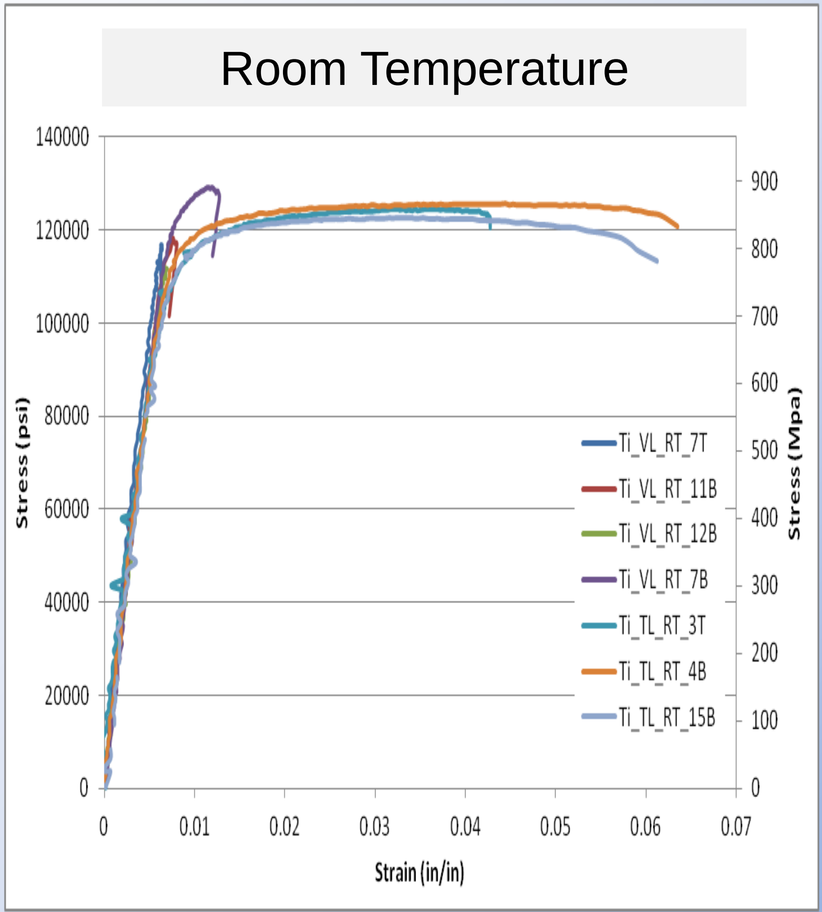
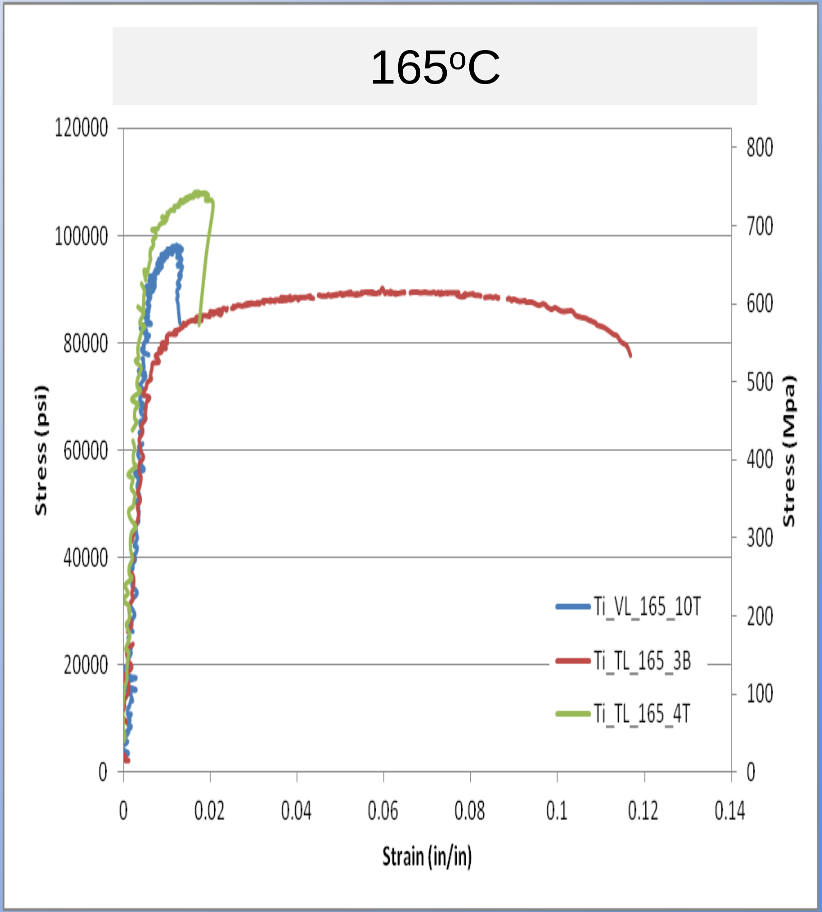
- No scatter in elastic modulus but scatter in strength and ductility is under investigation (expect casting defects as main source)
- Reasonable agreement with literature data





Ti-6-4 Compression Test Data

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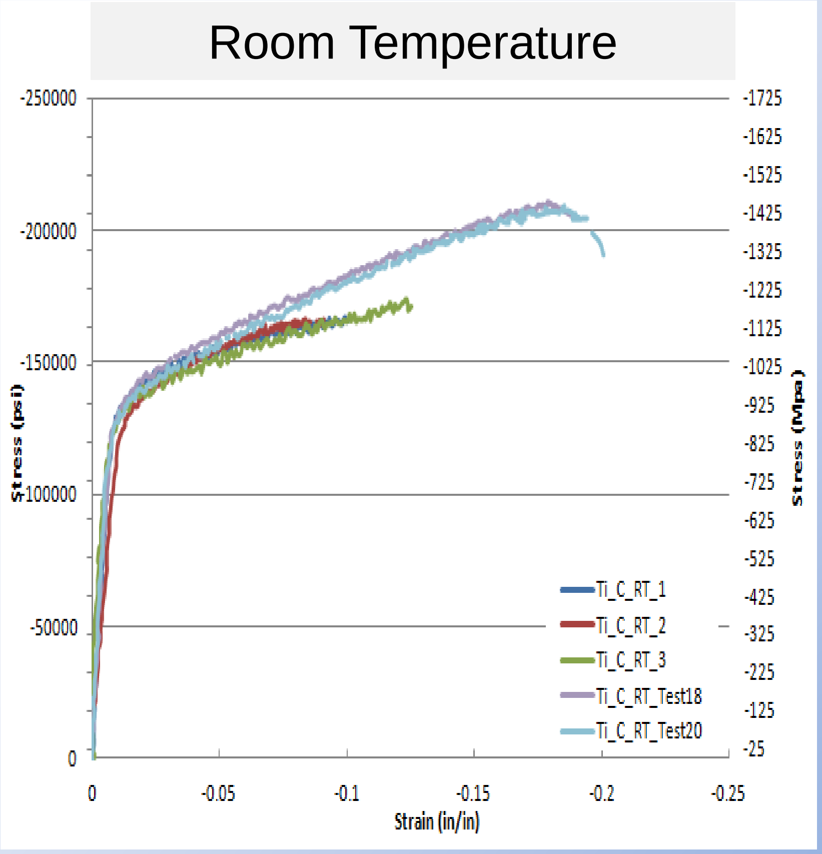
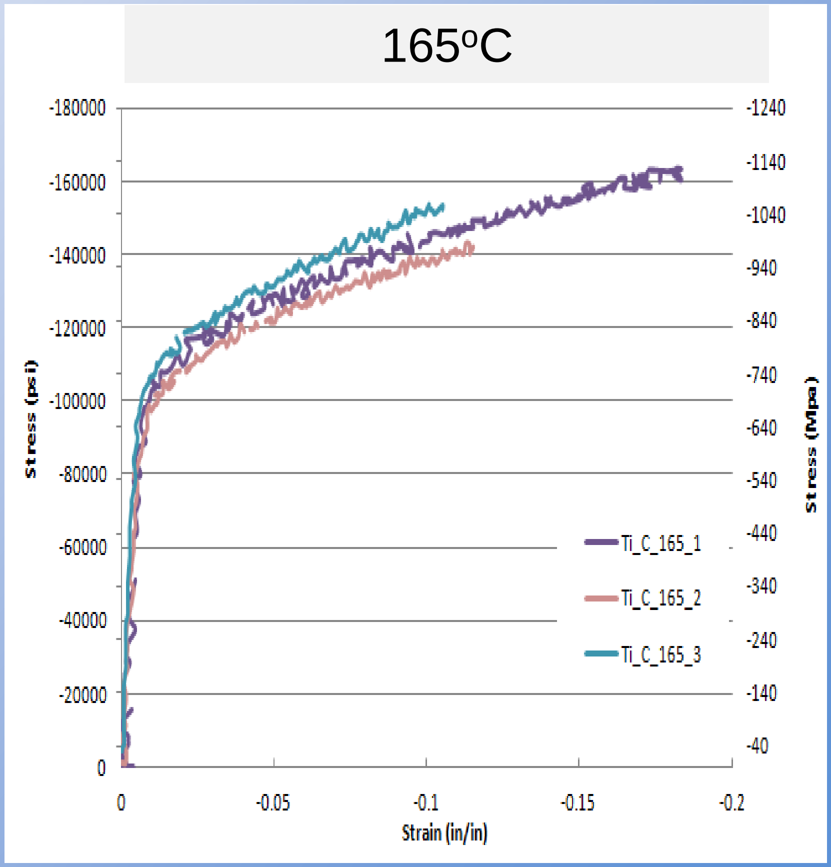
- Very little scatter among specimens
- Compares well with literature data
- Shows much more hardening than tensile data





SMA Ligaments

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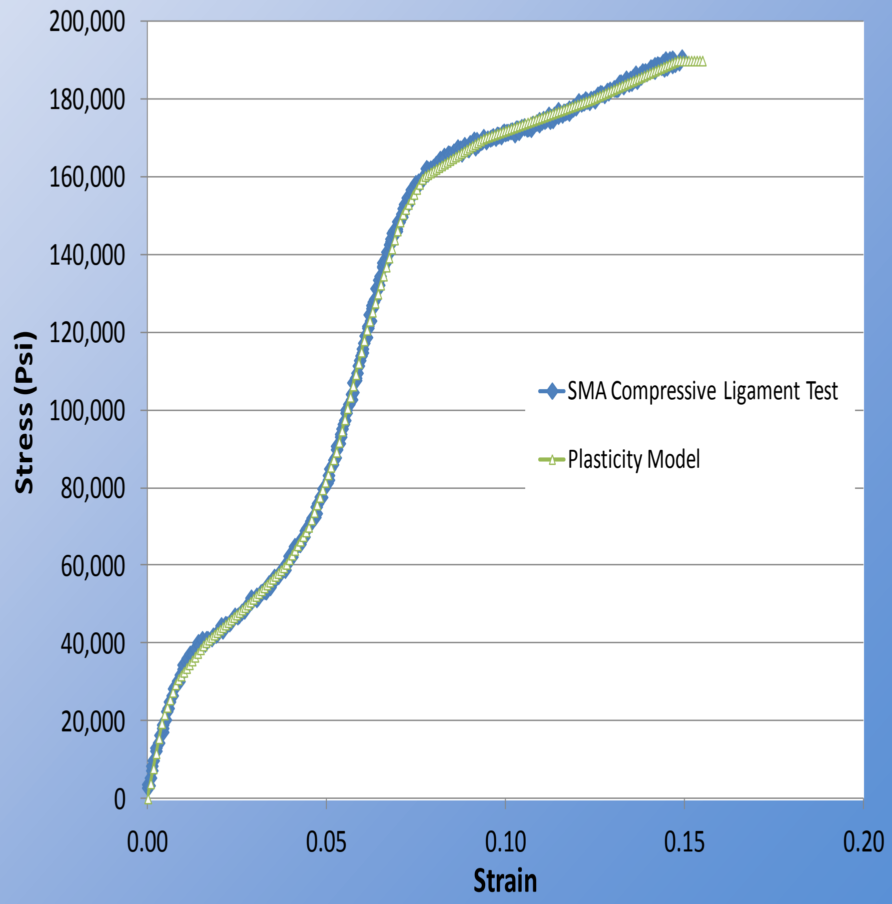
Tension

Testing
awaits new
crack-free
castings

Compression



Pre-Test Predictions

Brett Bednarcyk
Eric Baker

Abaqus Finite Element Model

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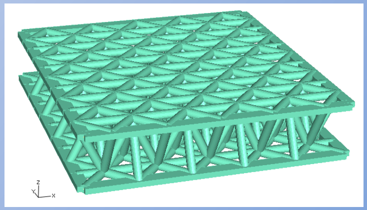
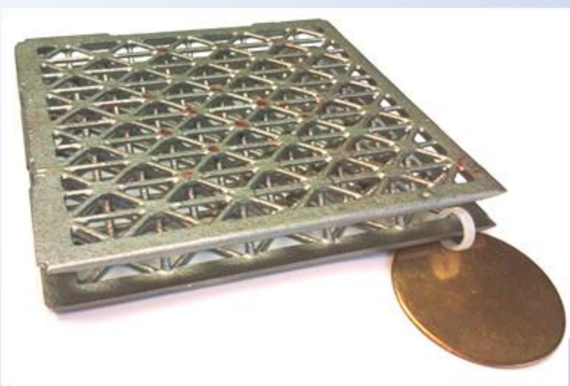
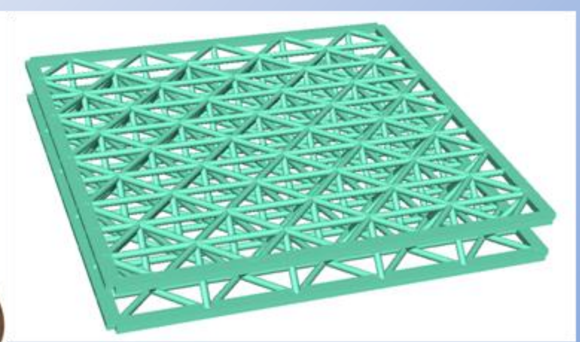
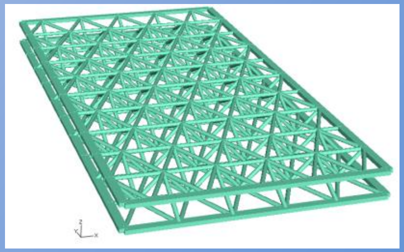
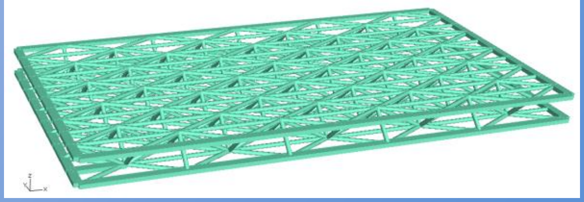
- Python script constructed to automatically generate Abaqus finite element model of lattice geometry
- Python script is parametric, so easy to generate and execute many configurations
- Lattice struts are modeled as beams











Material Behavior

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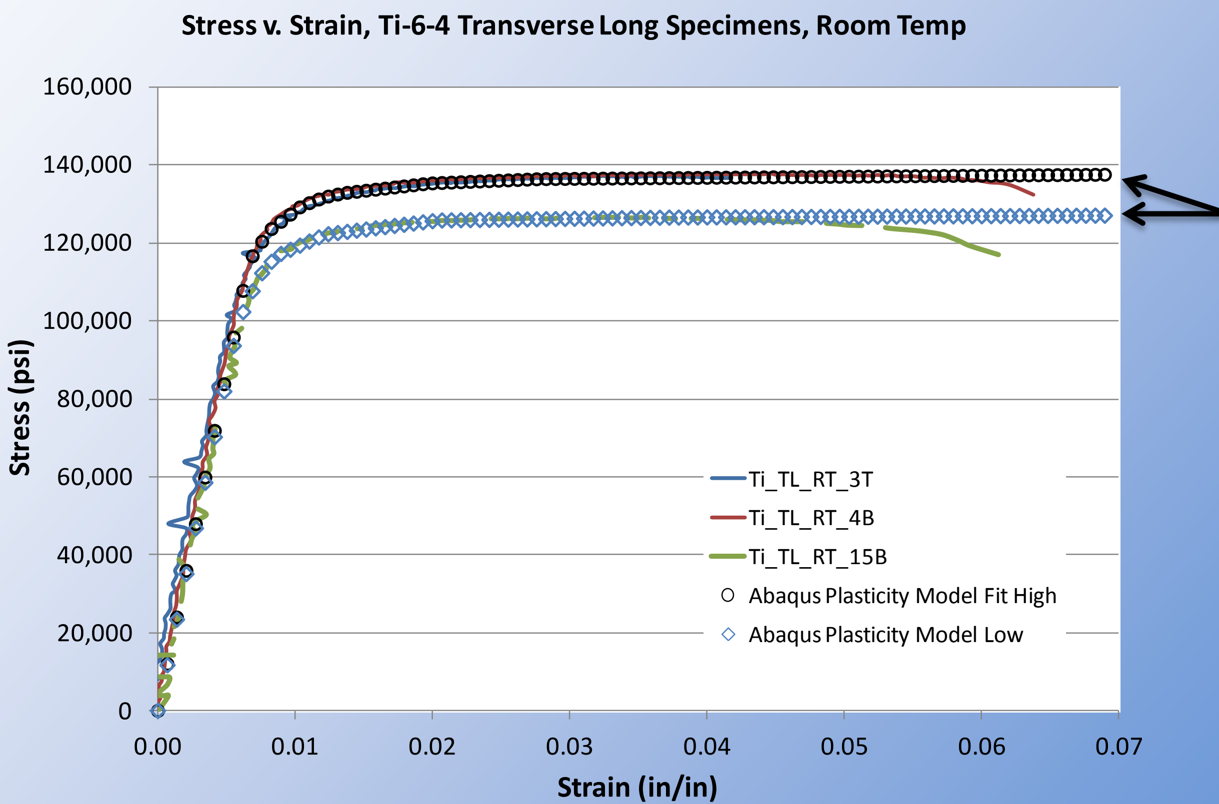
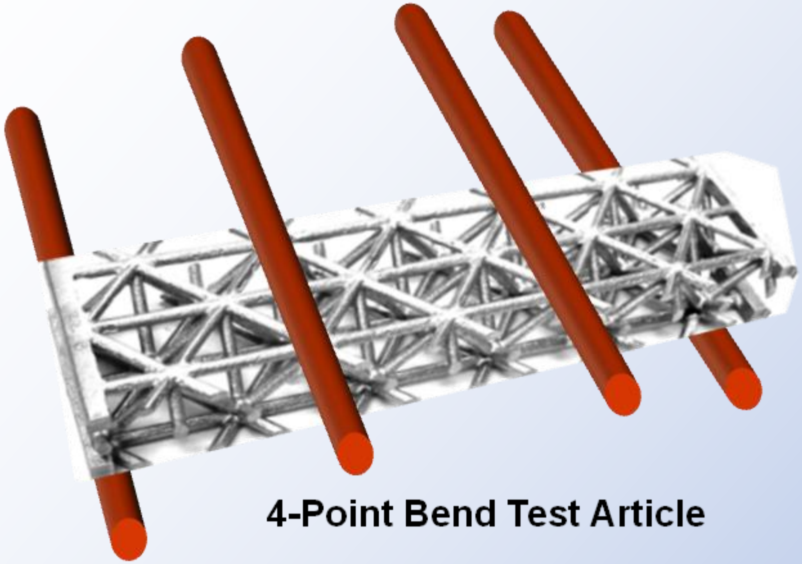
- Nonlinear Ti-6-4 material response modeled using von Mises plasticity
- Fit to ligament tests performed at NASA GRC



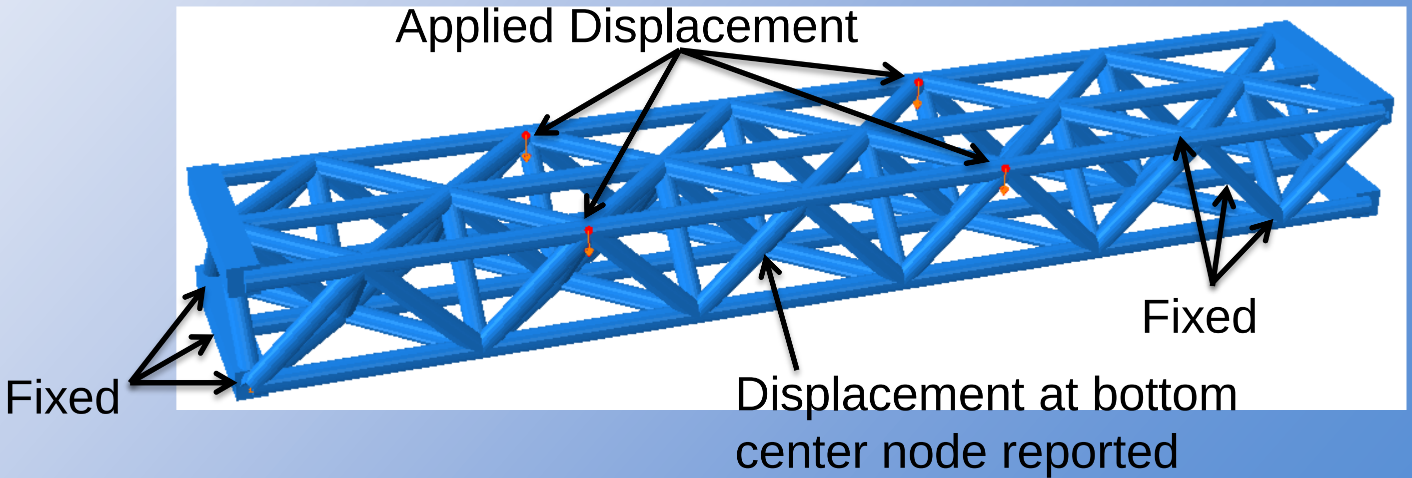
Two fits to examine sensitivity to material behavior

4-Point Bend Test Article and Model



4-Point Bend Test Article

- Struts modeled as beams with circular cross-section
- Second-order beam elements
- Nonlinear geometric analysis
- No failure, just plastic flow
- Displacement control



Parametric Study Conducted

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- Material response: stiffer and more compliant
- Strut diameter (3.25 mm, 3.5 mm, 3.75 mm)
- Panel height (18 mm, 21.5 mm)
  - 18 mm corresponds to all nodes centered on strut centroids
  - 21.5 mm used as way to approximate off-set nodes
  - Working on including true off-sets in Python script
- Also performed mesh convergence study

Full Factorial Simulations

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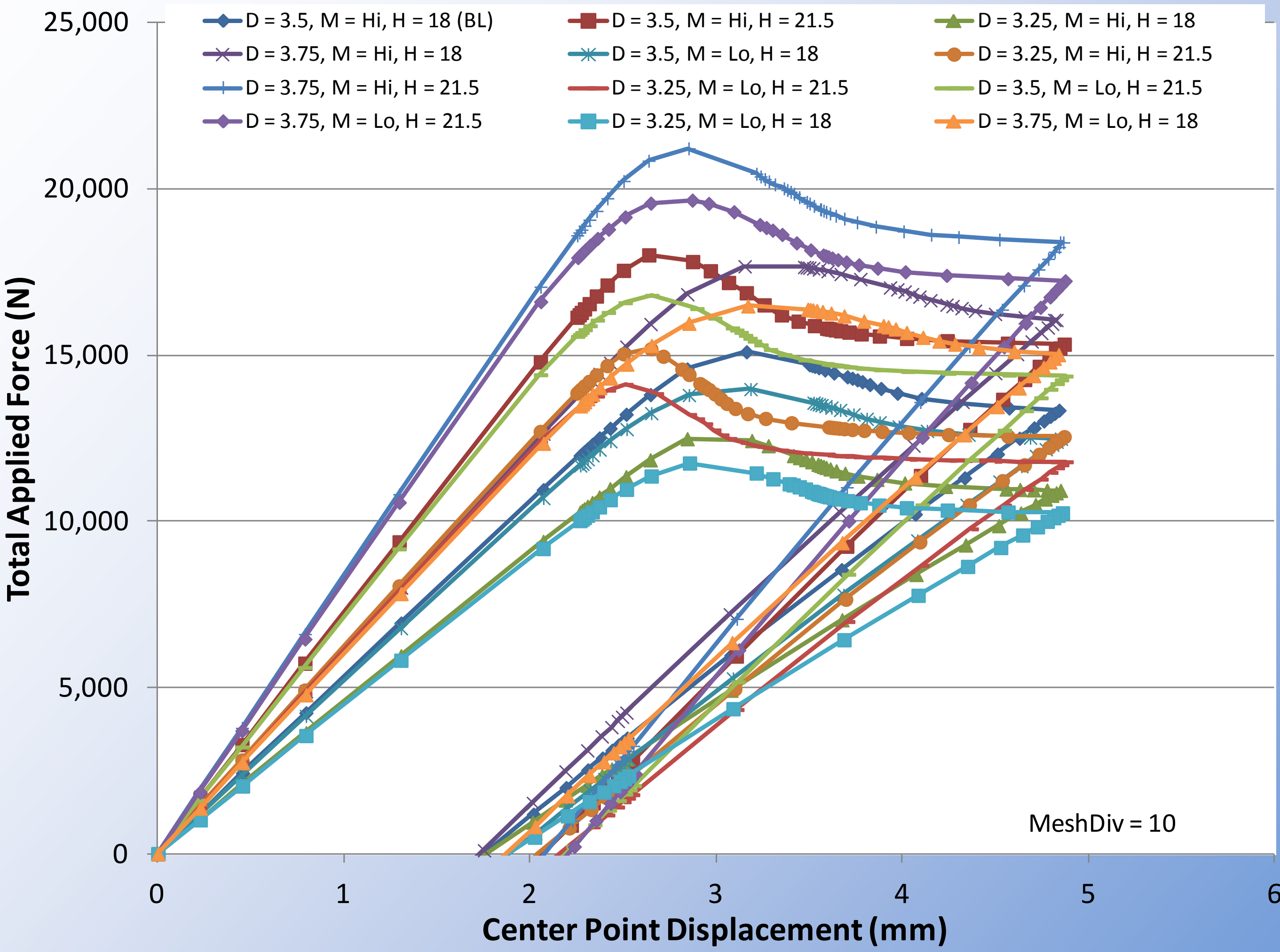

- Peak variation: 11,760 N (2643 lb) to 21,230 N (4772 lb)
- Slope variation: 4489 N/mm to 8400 N/mm

Model prediction using best estimates for geometric features

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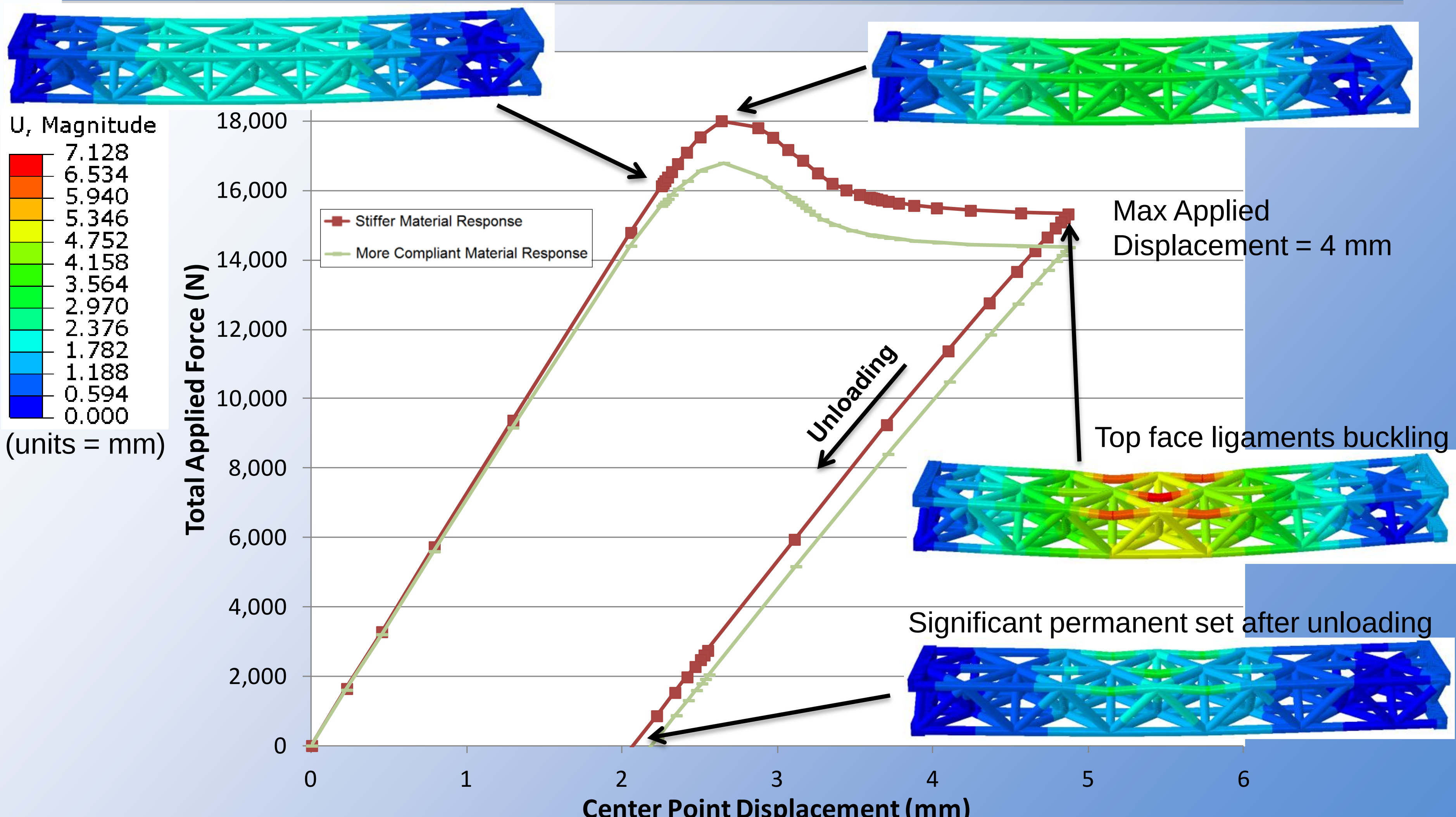


Strut Diameter = 3.5 mm, Height = 21.5 mm, Mesh Level = 10

Structural Benchmark tests

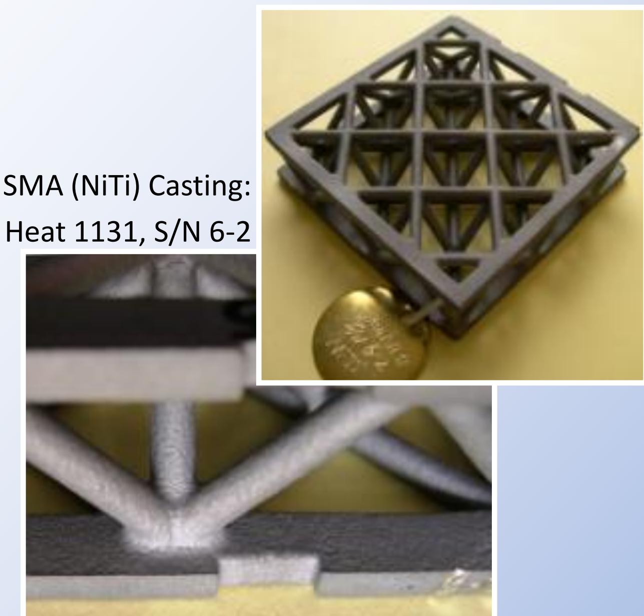
Dave Krause

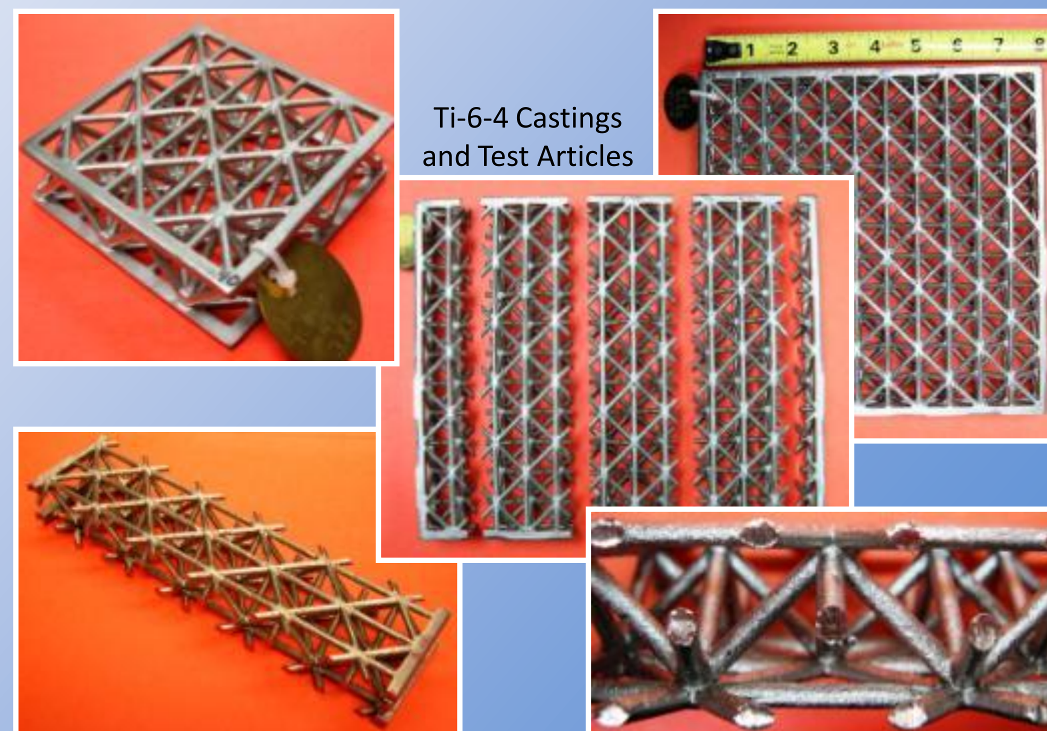
Structural Benchmark Testing of 3-D Cellular Structures

NARI

- Received initial conventional lattice castings of both SMA & Ti-6-4
- “Flat-wise compression” tested as-received
- “4-point beam bending” test articles machined from larger castings

SMA (NiTi) Casting:
Heat 1131, S/N 6-2





Ti-6-4 Castings
and Test Articles

Structural Benchmark Testing of Lattice Blocks

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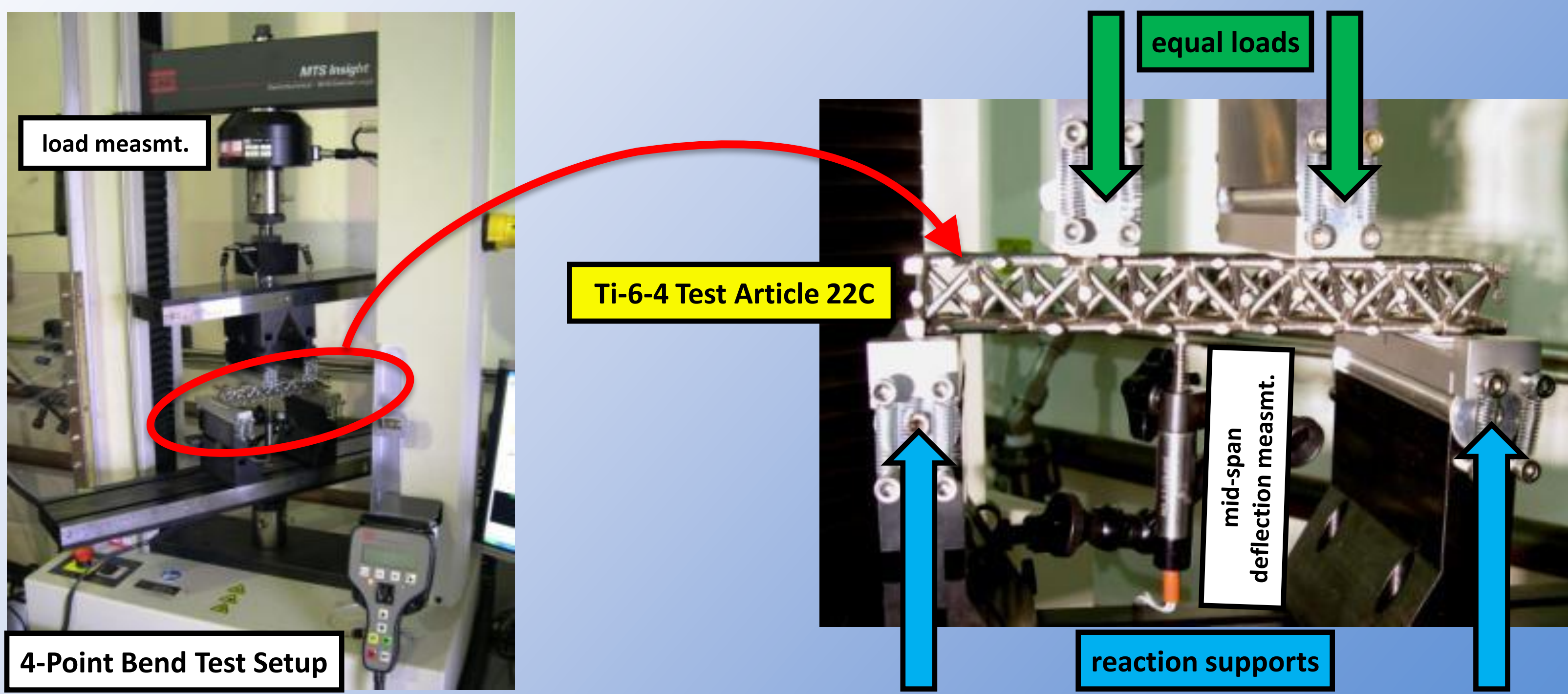
- Completed first structural benchmark tests of a Ti-6-4 lattice test article
  - room temperature testing
  - 4-point beam bend testing used standard articulated fixture



Structural Benchmark Testing of Lattice Blocks

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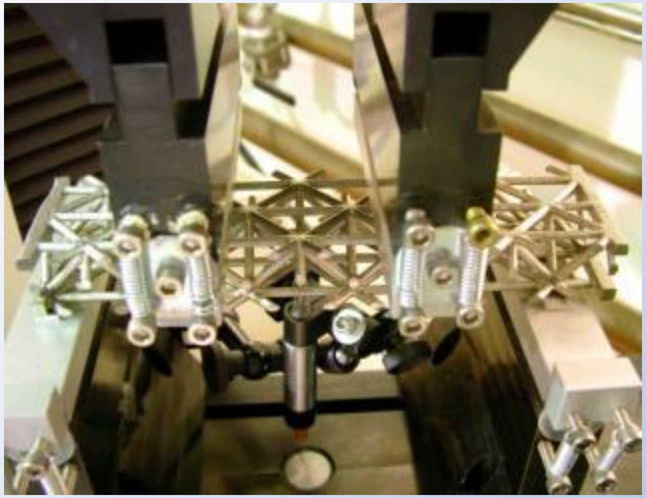
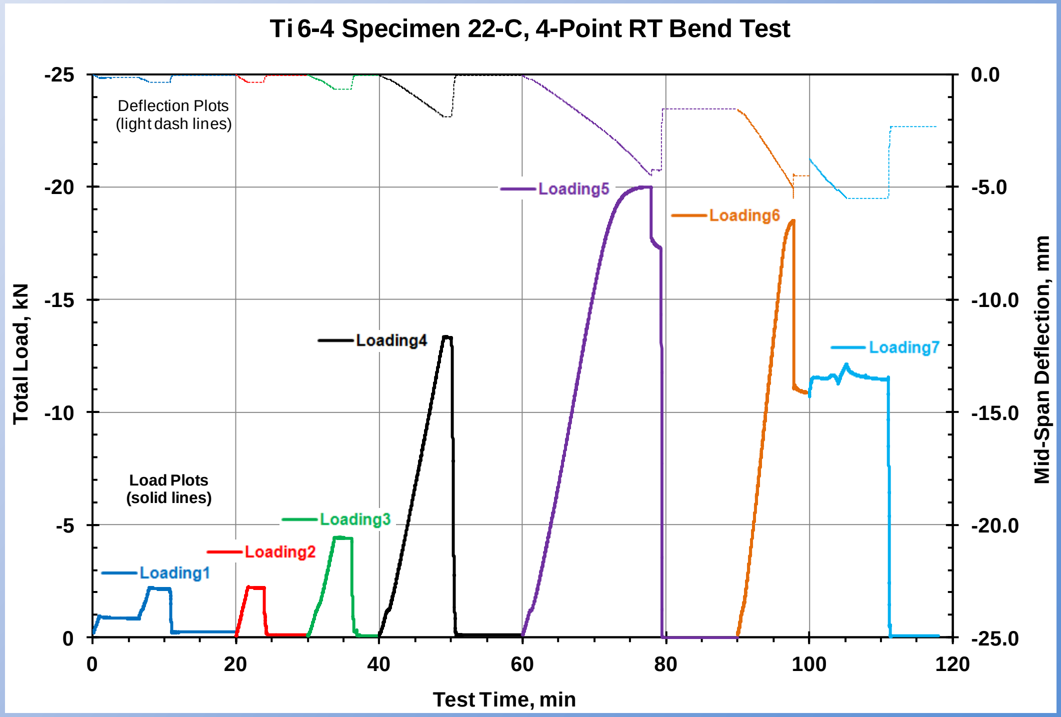
Benchmark Bend Test Description (continued)--

- conducted the following loadings
  - "elastic" loadings to 2.224 kN total under stroke control, then load control
  - "elastic" loadings to 4.448 and 13.34 kN total under stroke control
  - loading to failure, followed by residual strength testing, under stroke control



Ti-6-4 Test Article 22C top view



Structural Benchmark Testing of Lattice Blocks

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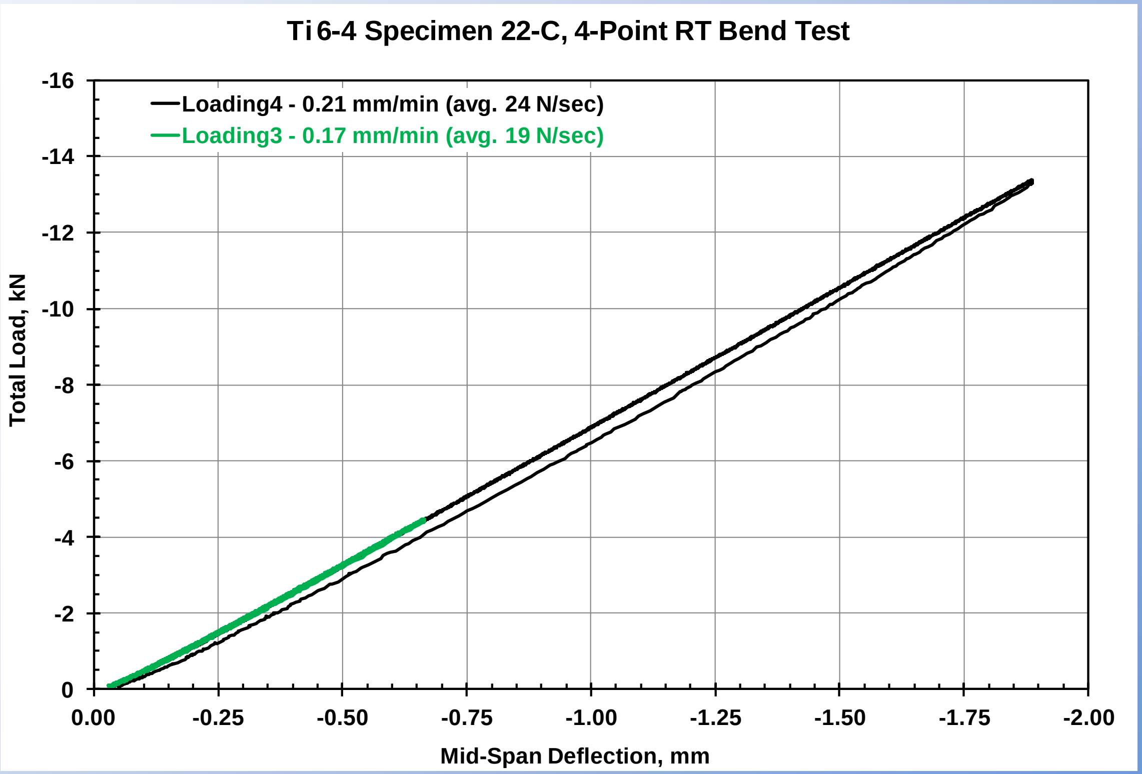
Benchmark Bend Test Results (continued)--

- Elastic load ramp cycles to 4.448 and then 13.34 kN total produced very linear deflection, with repeatable response



Structural Benchmark Testing of 3-D Cellular Structures

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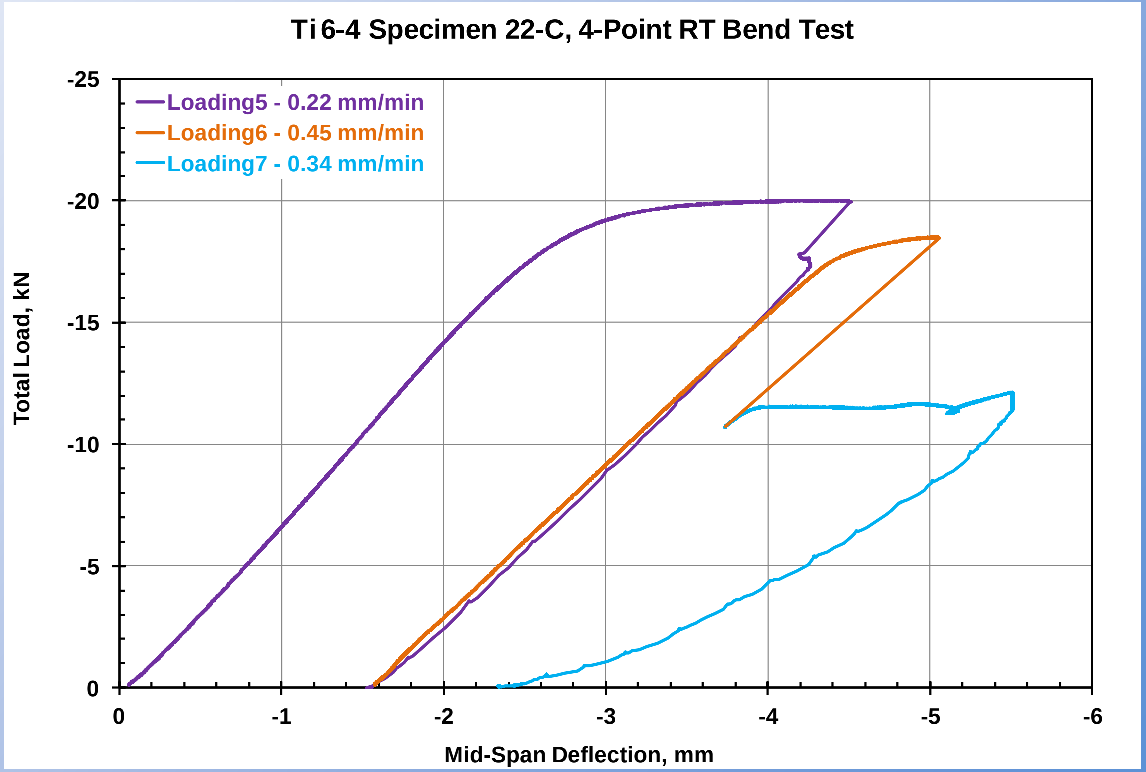
Benchmark Bend Test Results (continued)--

- continued loading produced first observed failure at a maximum load of 20.01 kN
- after unloading, additional strength was observed until second failure at 18.49 kN
- extra deformation at constant 12 kN load was available until test limits reached

Ti-6-4 Test Article 22C at end of testing



Structural Benchmark Testing of Lattice Blocks

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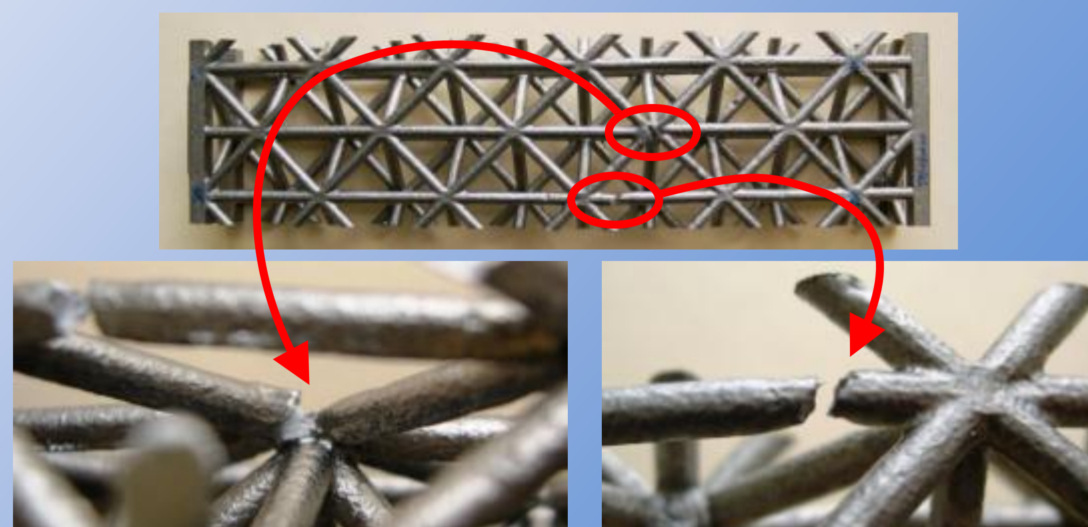
Benchmark Bend Test Results (continued)--

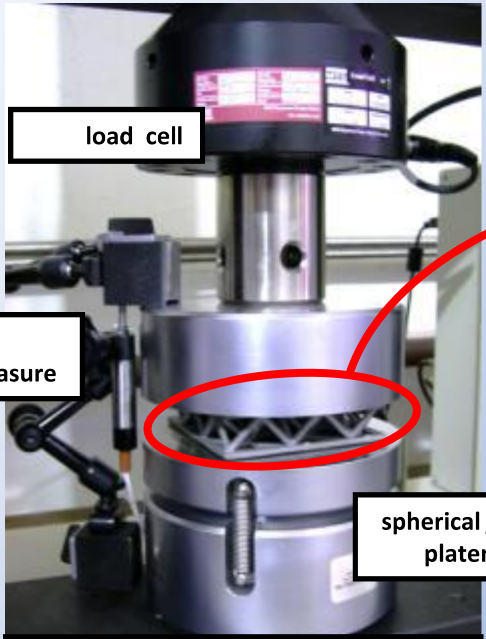
- structural response stayed linear until approximately 18 kN total load
- after the first failure, the test article held a constant load of 17.17 kN (vs. the peak load of 20.01 kN)
- following final testing, 2 fractures were discovered on the bottom (tensile) surface of the test article: one at a node and one through a strut, both under the right-hand side load roller



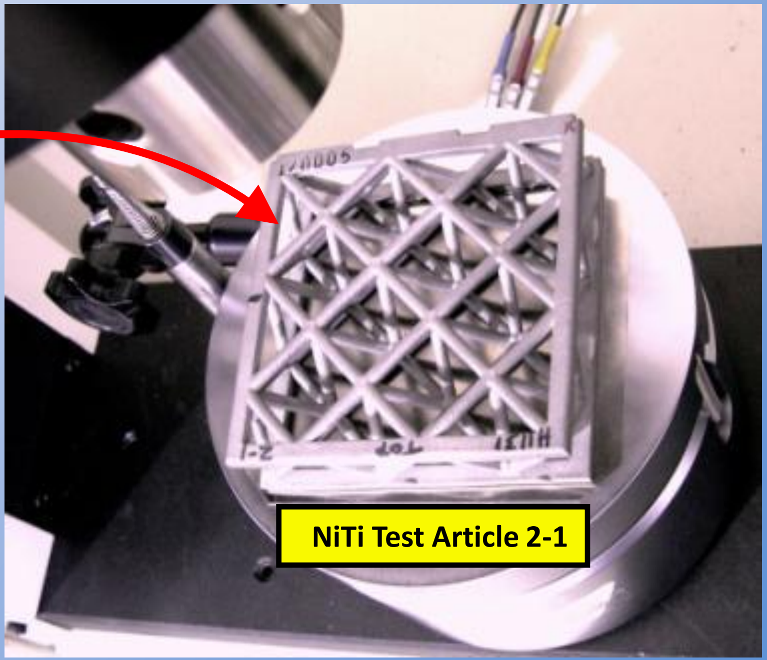
Structural Benchmark Testing of SMA Lattice Blocks

Benchmark Compression Test Status--

- completed structural benchmark testing of SMA (NiTi) test article
  - room temperature testing
  - flat-wise compression testing used standard spherical joint fixture



Flat-Wise Compression Test Setup



Structural Benchmark Testing of SMA Lattice Blocks

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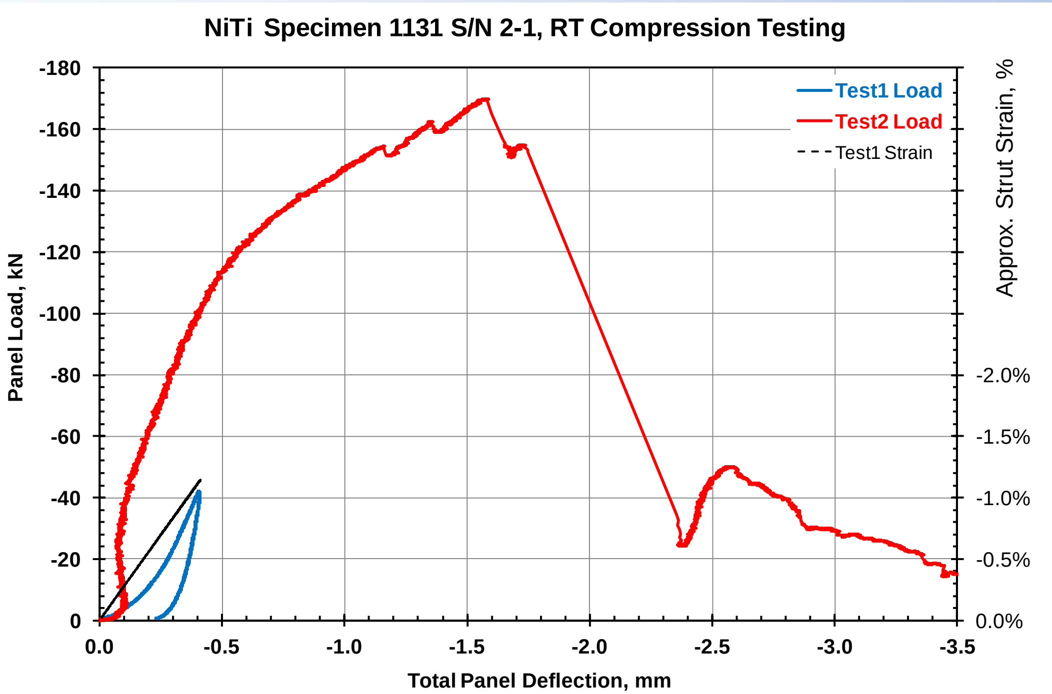
- First load/unload showed non-linearity : both specimen micro-yielding at geometric non-uniformities and SMA material response could contribute.
- Second loading curvature shows evidence of SMA material response.
- First failure at 155 kN total panel loading, continued loading produced peak resistance of 170 kN at approx. 6% structural compliance



Structural Benchmark Testing of SMA Lattice Blocks

- Test article failure description
  - initial tensile crack in integral cast perimeter frame at 155 kN, probably at pre-existing flaw
  - loads redistribution within lattice structure provided additional strength to peak load (170 kN)
  - additional crack(s) in perimeter frame changed stress distribution, placing struts in bending
  - progressively, most nodes separated and many struts had mid-length cracks also
  - specimen condition did not warrant post-test thermal treatment for strain recovery (healing)

Post Test Model Validation

Comparison to Test Data

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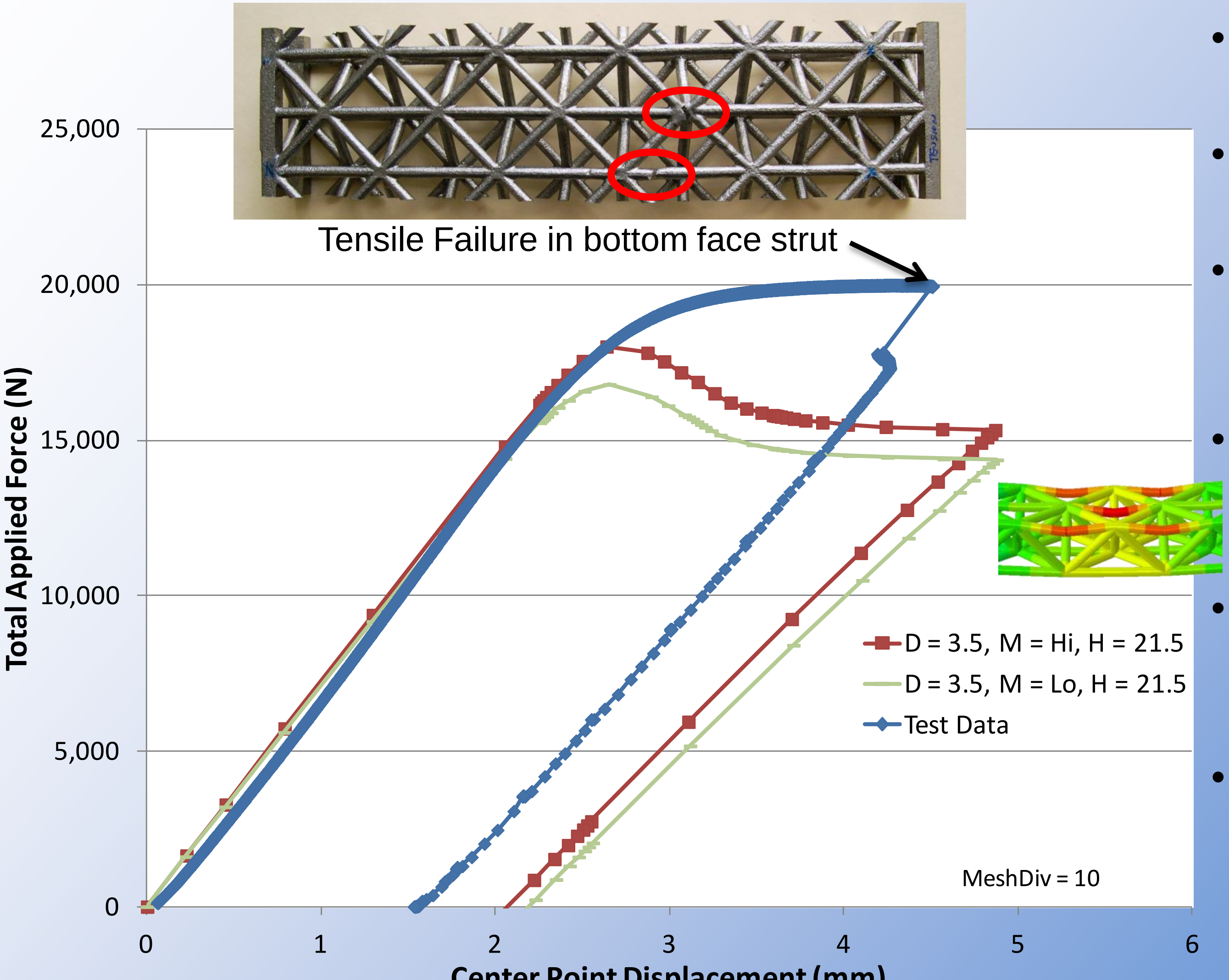

- Initial slope predicted well
- Onset of nonlinearity predicted well
- Predictions exhibit softening not seen in experiment
- Softening in model caused by buckling of top face axial struts
- Lack of softening in test data suggests limited buckling
- Failure not included in model, but great deal of plasticity predicted in bottom face axial struts

Possible Causes of Discrepancy

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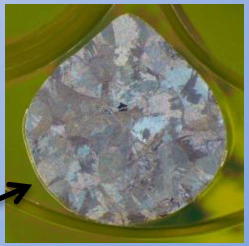
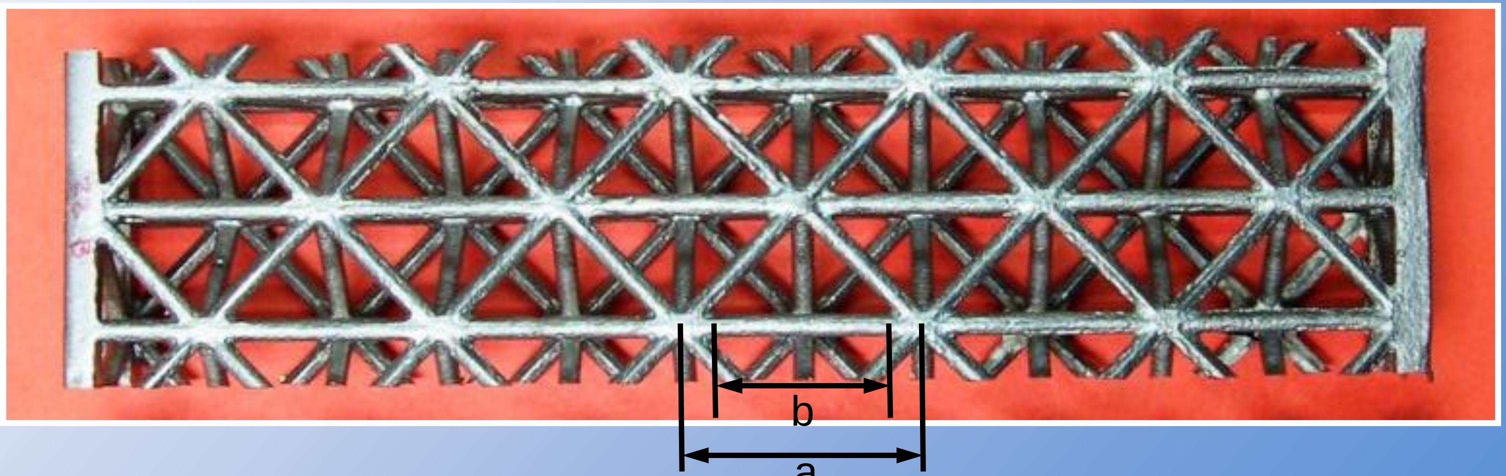
- Difference in material behavior in compression
  - Did not have strut compression test data before 4pt bend tests
- Factors delaying the onset of buckling in top face struts
  - Tear drop shape of face struts – increases moment of inertia
  - Defects in bottom face struts – will cause increase in plasticity resulting in lower compression in top face struts
  - Lower effective face strut length caused by excess material at LBS nodes
    - Node to node length, a = 36 mm; free span length, b ≈ 27 mm

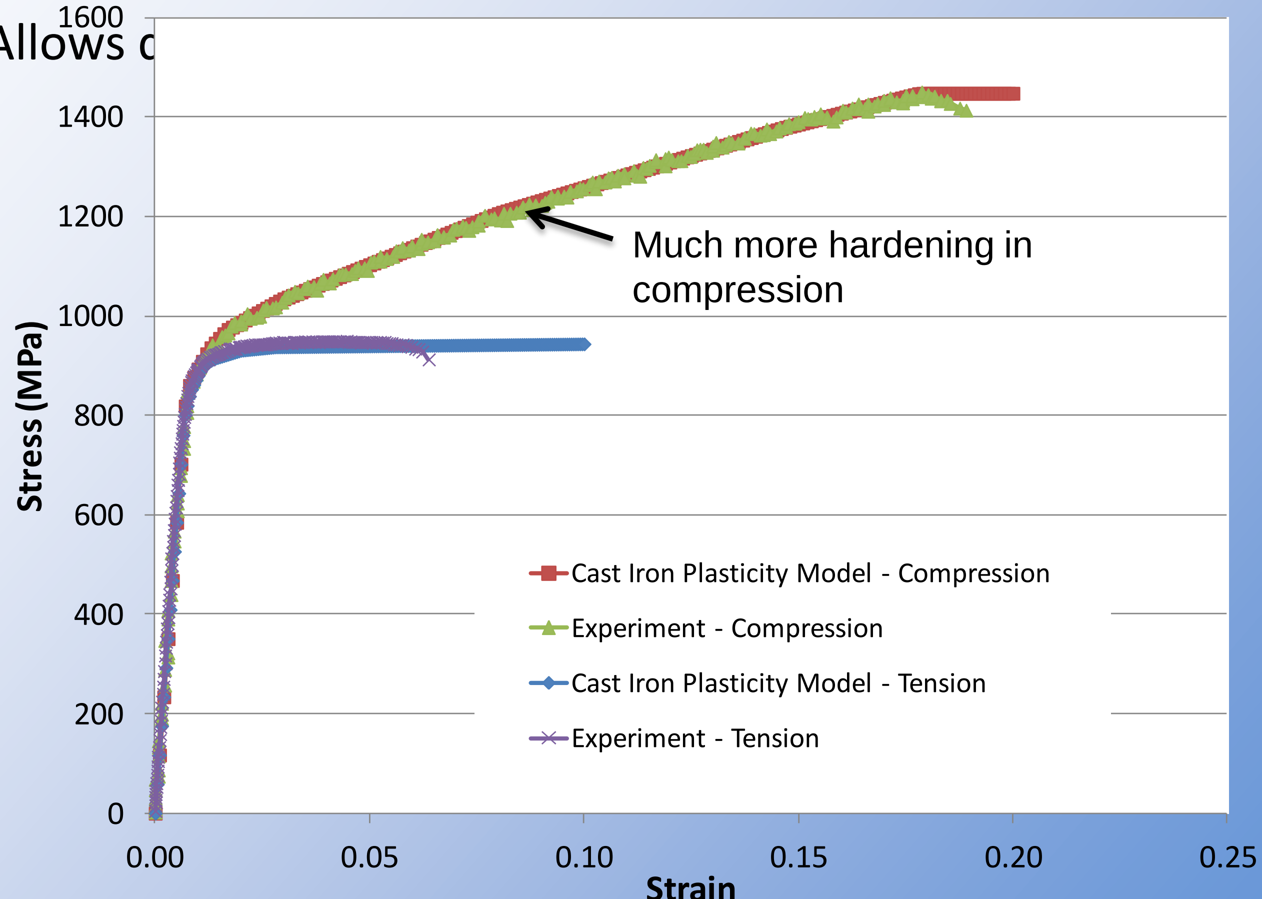




Different Tension-Compression Material Behavior

NARI

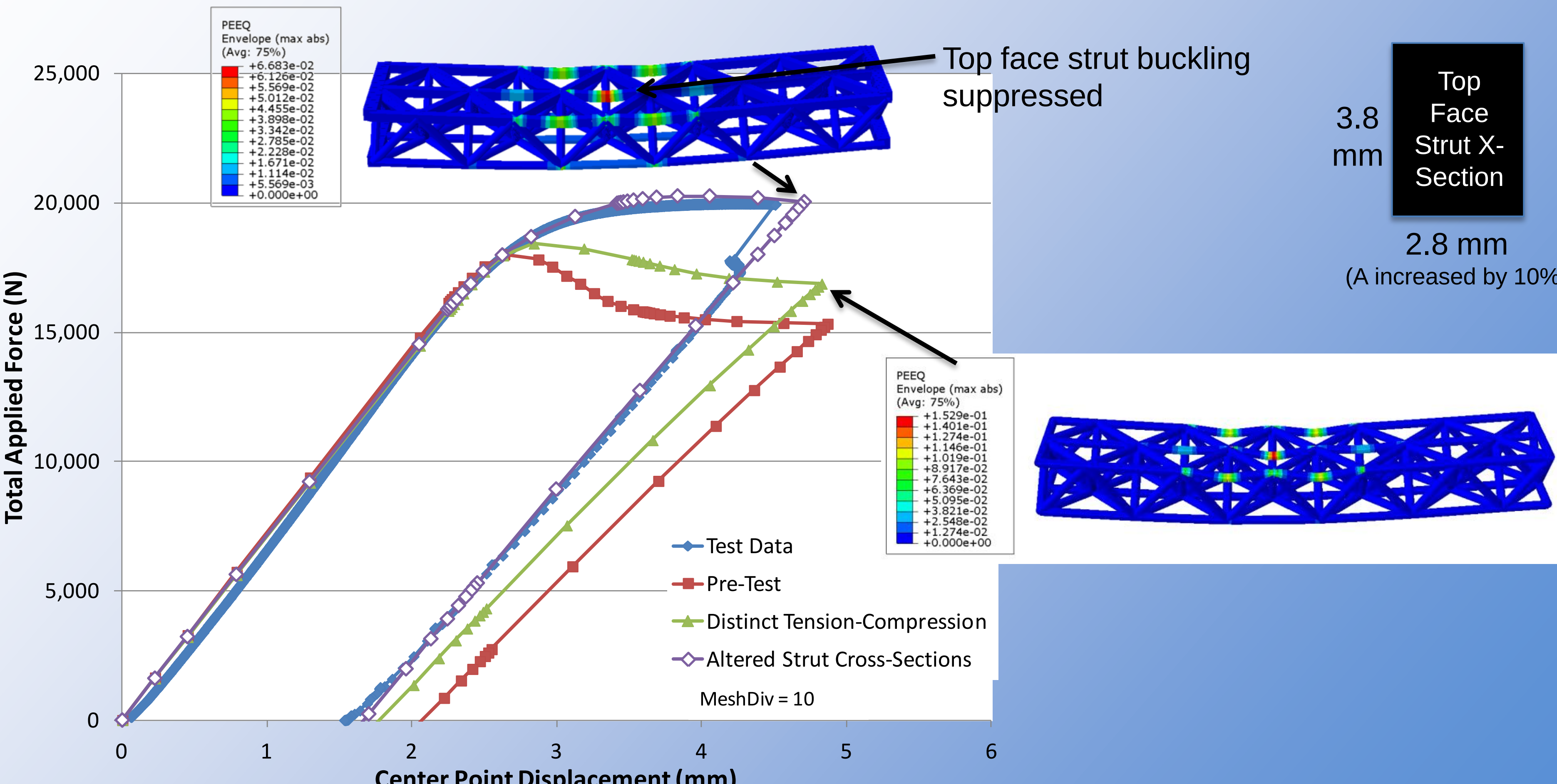
- Modeled using existing Abaqus constitutive model that accurately correlates to ligament data
  - Allows c



Examine Strut Cross-Section Effects

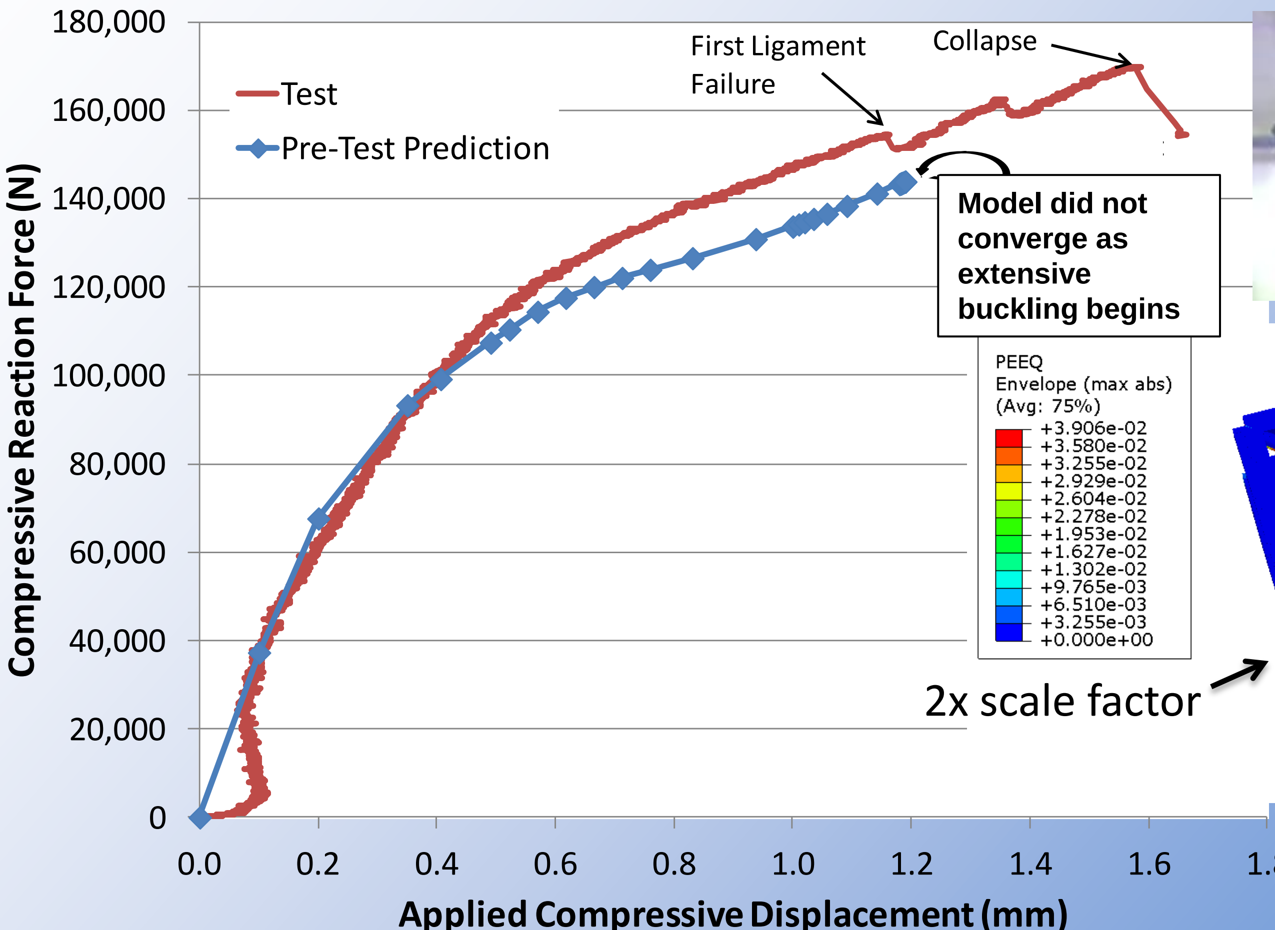
NARI

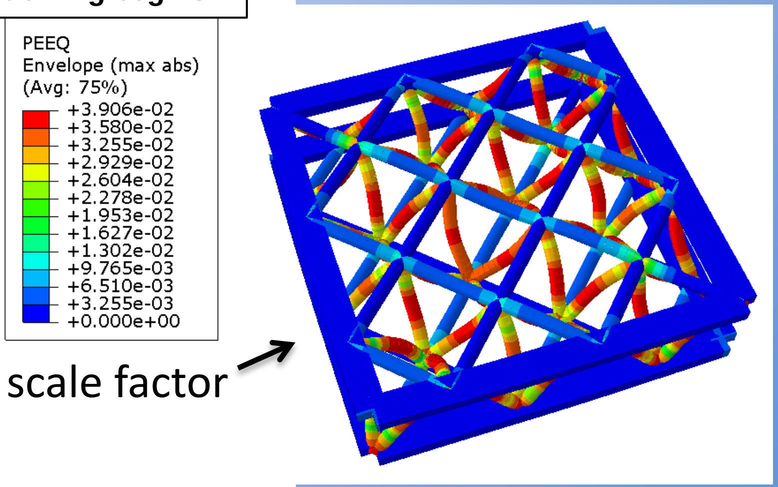
- Can match data well by treating top face struts as rectangular (suppresses buckling)



Predicted And Experimental Data For Compression Testing Of SMA Lattice

NARI





Summary

NARI

Accomplishments to date:

1. Ligament testing methods developed and testing completed on sound castings.
   a) Confirmed mechanical behavior of the alloys maintained by the casting process
   b) Data used to calibrate finite element model
   c) Demonstrated shape memory behavior
2. Lattice testing of Ti-6-4 in bending and SMA in compression
   a) The lattice structure maintains considerable strength and deformation capability even after individual ligaments begin to fail.
   b) In bending, top compression struts plastically deformed before the first bottom strut tensile rupture was discovered, a benefit in service where an observable sign of distress before structural failure is desired
   c) Flaws in SMA casting did not influence lattice deformation until after perimeter frame cracked.
3. Finite element model accurately predicted panel stiffness, deviations from linearity and individual ligament buckling
   a) Improved accuracy of model expected from capturing more realistic geometry of lattice

Results hampered by delays in casting delivery from T45 SBIR.

1. Extra trials needed to minimize casting defects
2. Limited SMA lattices and ***no*** auxetics available for testing

Next Steps

NARI

1. **Final Month of Phase I**
   - Shape memory tests of deformed lattice blocks
   - Model refinements to account for actual lattice geometry
   - Review with T45 scheduled for mid-June on casting process improvements
2. **Publications**
   - At least one report (summer 2012) and one conference presentation (CY13).
   - MS Thesis for Wilmoth
3. **Proposed Phase II**
   - Expanded testing for Ti-6-4: especially auxetic structures
   - Expanded testing for SMAs: higher quality castings; more loading modes; thermal cycling under load; auxetic structures.
   - Testing of superelastic lattices
   - Modeling: pre-test prediction and post test validation of all configurations
   - Modeling refinements: stochastic treatment of defects; structural optimization
   - Down-select component for development