THE NEXT GENERATION OF SHAPE MEMORY ALLOY FEA MODELS: DEVELOPMENT OF A USER MATERIAL SUBROUTINE FOR IMPROVED SIMULATION OF TRANSFORMATION-PLASTICITY COUPLING EFFECTS

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ENGINEERING FORWARD

Caltech

Georgia Tech

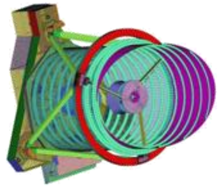
Who is Quartus?

Started as mechanical analysis services provider → **New facilities for hardware & optical systems** → **Turnkey solutions advanced controls, medical devices, & space hardware**

1997

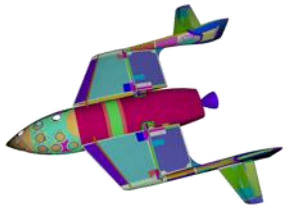
Quartus Founded
- 4 Engineers left SDRC

2002



Mars Reconnaissance Orbiter High Resolution Imaging Experiment (MRO HiRISE)
- Structural support for first optical payload

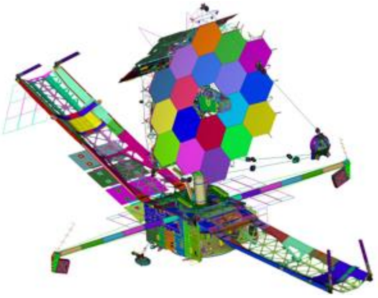
SpaceShipOne
- Structural and flutter analysis



2003

Unmanned Aerial Vehicle
- Delivered first hardware build
- 60 Employees

2005



James Webb Space Telescope [2005-2021]
- Peak JWST support: 25+ Analysts in 2013

2007

Eastern Region
- Opened Office in Metro DC Area

White Knight Two
- Dynamic Analysis and Testing

2009

Cleanroom Work
- First cleanroom built in San Diego

2011

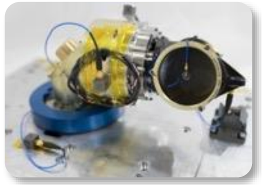
New San Diego HQ
- 17,000 Sq ft Assembly Space
- 5,000 Sq ft Class 10K – 5 Room Cleanroom Complex
- 100+ employees

2015

Volume Hardware
- ISO-9001 certified
- First low-rate prod of 100+ units

2016

LEO Optical System
- 1st Spaceflight Hardware



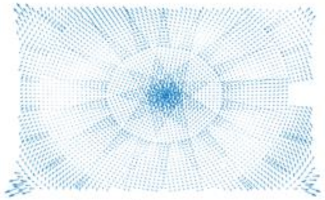
2018

Stratolaunch Aircraft [2009-Present]
- Design and analysis support
- ***First flight April 2019***
- Second flight April 2021

Laser Communications
- 80 cm ground terminal

1st NASA Phase I SBIR
- Semi-custom optical payload development

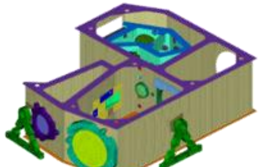
2019



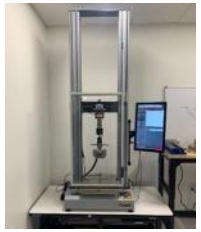
Camera Calibration & Automated Alignment
- Intrinsic and extrinsic camera calibration service
- Automated optical alignment capabilities

2020

NASA SBIR Phase II & II-E
- STOP analysis correlation



2022



Expanded Test Capabilities
- Material characterization
- Instron Universal Testing Machine

25th Anniversary
- Celebrates 25 years

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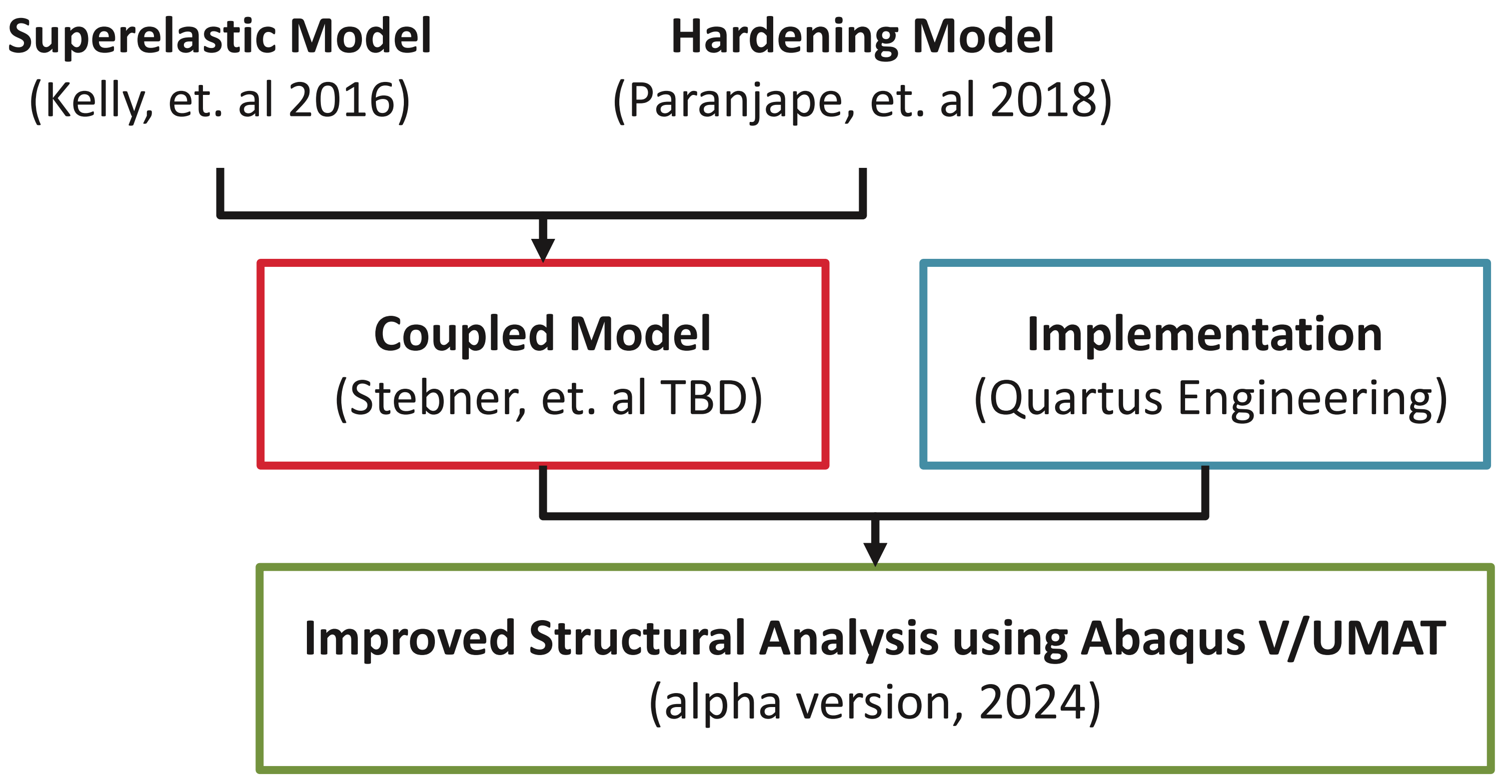
New Model to Improve Structural Analysis of Shape Memory Alloys



Coupled Model: Features

Nonlinear minimization problem:

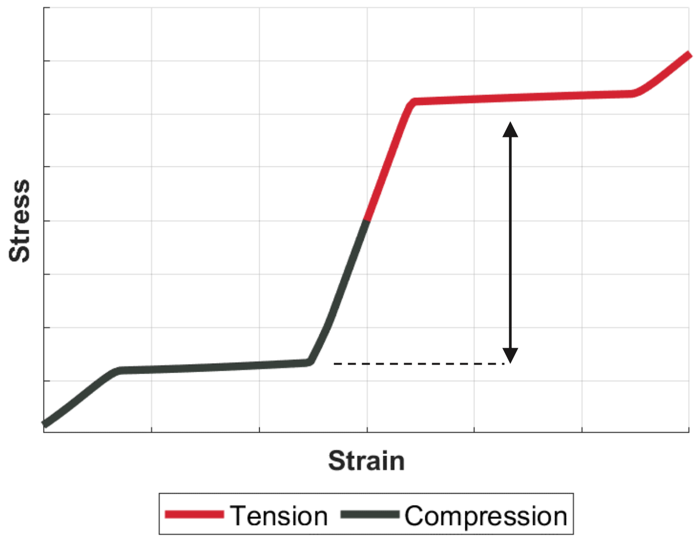
$$\frac{\partial W}{\partial U} - \frac{\partial D}{\partial \dot{U}} \in 0$$

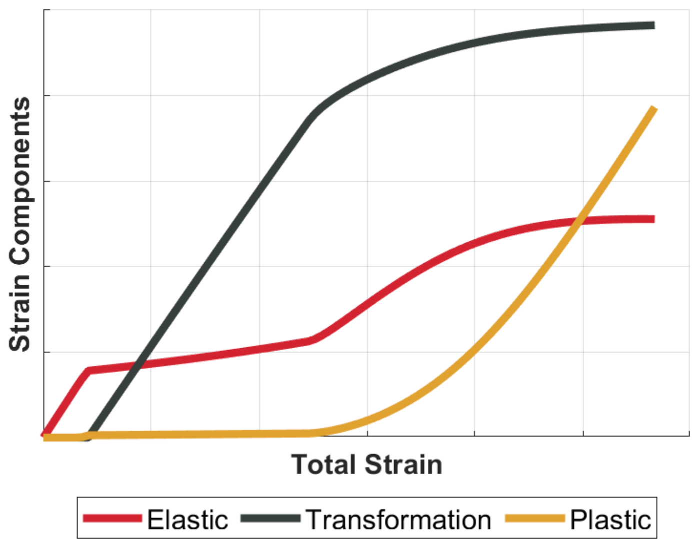
Growth kinetics:

$$D = d_{\lambda}^{cr}\left|\dot{\lambda}\right| + \lambda d_{\varepsilon_m}^{cr}\left|\dot{\varepsilon}_m\right|$$

Gibb’s Free Energy:

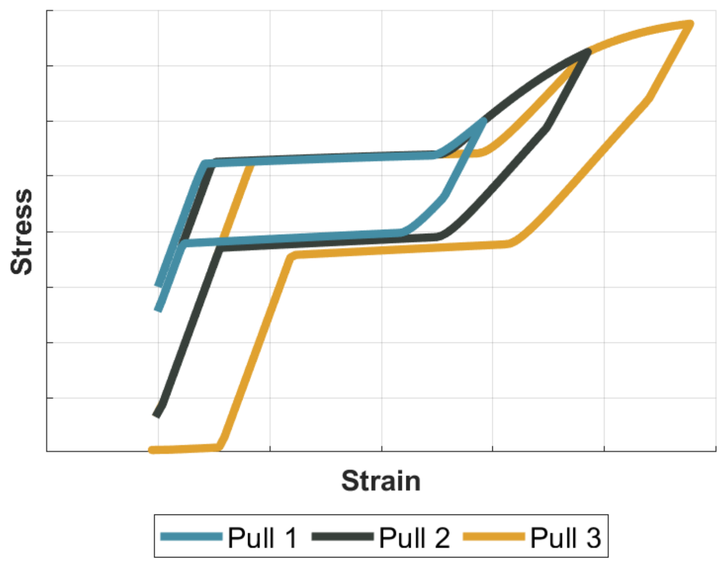
$$W = \frac{1}{2}\left(\varepsilon - \lambda\varepsilon_m - \varepsilon_p\right): C(\lambda): \left(\varepsilon - \lambda\varepsilon_m - \varepsilon_p\right) + \lambda L\frac{\theta - \theta_c}{\theta_c} - c_p(\lambda)\theta \ln\left(\frac{\theta}{\theta_c}\right) + \lambda g_i(\varepsilon_m) + g_s(\lambda\varepsilon_m) + g_\lambda(\lambda) + g_h(a, r) + g_c\left(\lambda\varepsilon_m, \varepsilon_p\right)$$



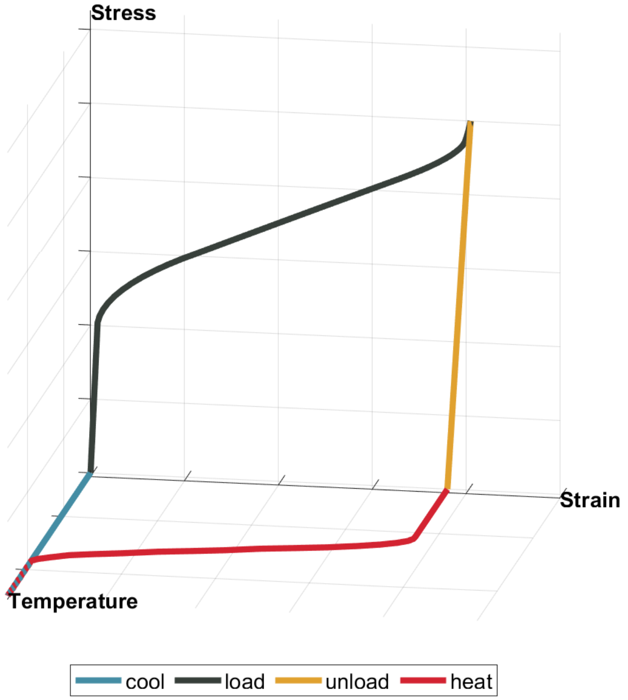


COUPLED MODEL: CAPABILITIES

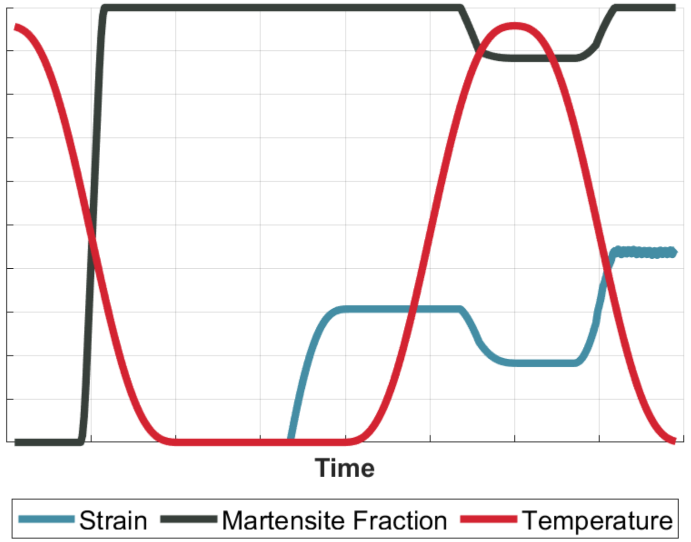
Superelasticity and Stress Ratcheting



Shape Memory



Actuation



Implementation: Solving the Problem

Formulation constrained optimization problem:

Use Intel MKL TRNLSP unconstrained optimization solver

1. Formulate the Lagrange equation based on which state variables are evolving

Predictor:

1. Incoming strain increment is assumed to be elastic
   - Evaluate intermediate stress state
   - Evaluate derivative of free energy
2. Check for inelastic evolution

Corrector:

1. Solve the nonlinear constrained optimization problem
   - Seed the nonlinear solver with elastic state variable results
   - If any constraints are violated, update and resolve new set of equations
2. Return stress and state at end of increment!

The constrained optimization problem:

minimize $\frac{\partial W}{\partial U} - \frac{\partial D}{\partial \dot{U}}$

subjected to

$trace(\varepsilon_m) = 0$

$g_i \leq 0$

$0 \leq \lambda \leq 1$

$\frac{\partial W}{\partial \lambda} \dot{\lambda} \geq 0$

$\frac{1}{\lambda} \frac{\partial W}{\partial \varepsilon_m} : \dot{\varepsilon}_m \geq 0$

$\Lambda \geq 0$

Stress $\frac{\partial W}{\partial \varepsilon} = \sigma = \mathbb{C} : \left(\varepsilon - \lambda \varepsilon_m - \varepsilon_p\right)$

Phase evolution $\dot{\lambda} = 0 \text{ for } \left|\frac{\partial W}{\partial \lambda}\right| < d_{\lambda}^{cr}$

$\dot{\varepsilon}_m = 0 \text{ for } \left|\frac{1}{\lambda} \frac{\partial W}{\partial \dot{\varepsilon}_m}\right| < d_{\varepsilon_m}^{cr}$

Hardening evolution $U_h = 0 \text{ for } \Lambda U_h \cdot \frac{dh}{dU_h} < 1$

Implementation: Usability and Organization

- Custom types are interfaces are implemented to perform tensor operations like standard elementary coding math operations which reduces implementation errors and improves readability.

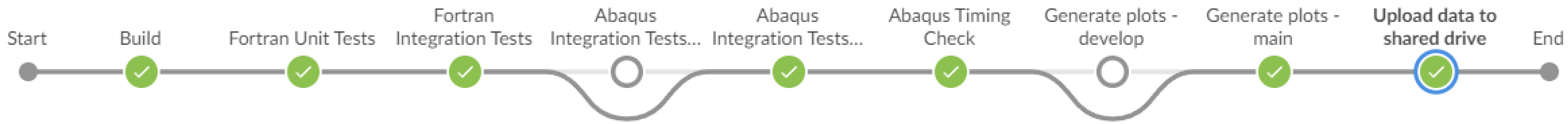
$A\!:B = A_{ij}B_{ij}$	`A.ddot.B`
$A\!:\boldsymbol{C} = A_{ij}B_{ijkl}$	`A.ddot.C`
$\bar{A} = A_{ij} - \frac{1}{3}A_{kk}$	`dev(A)`
$g_c = -k\lvert\varepsilon_p\rvert^m\,\varepsilon_p\!:\lambda\varepsilon_m$	`-k*mag(ep)**m * (ep.ddot.(lam*em))`

- Code is modular to improve reusability and organization

```
use tensor
use math, only : minimize
use hypersurfaces, only : coupling
```

IMPLEMENTATION: QA TESTING

- Testing, automated in Jenkins

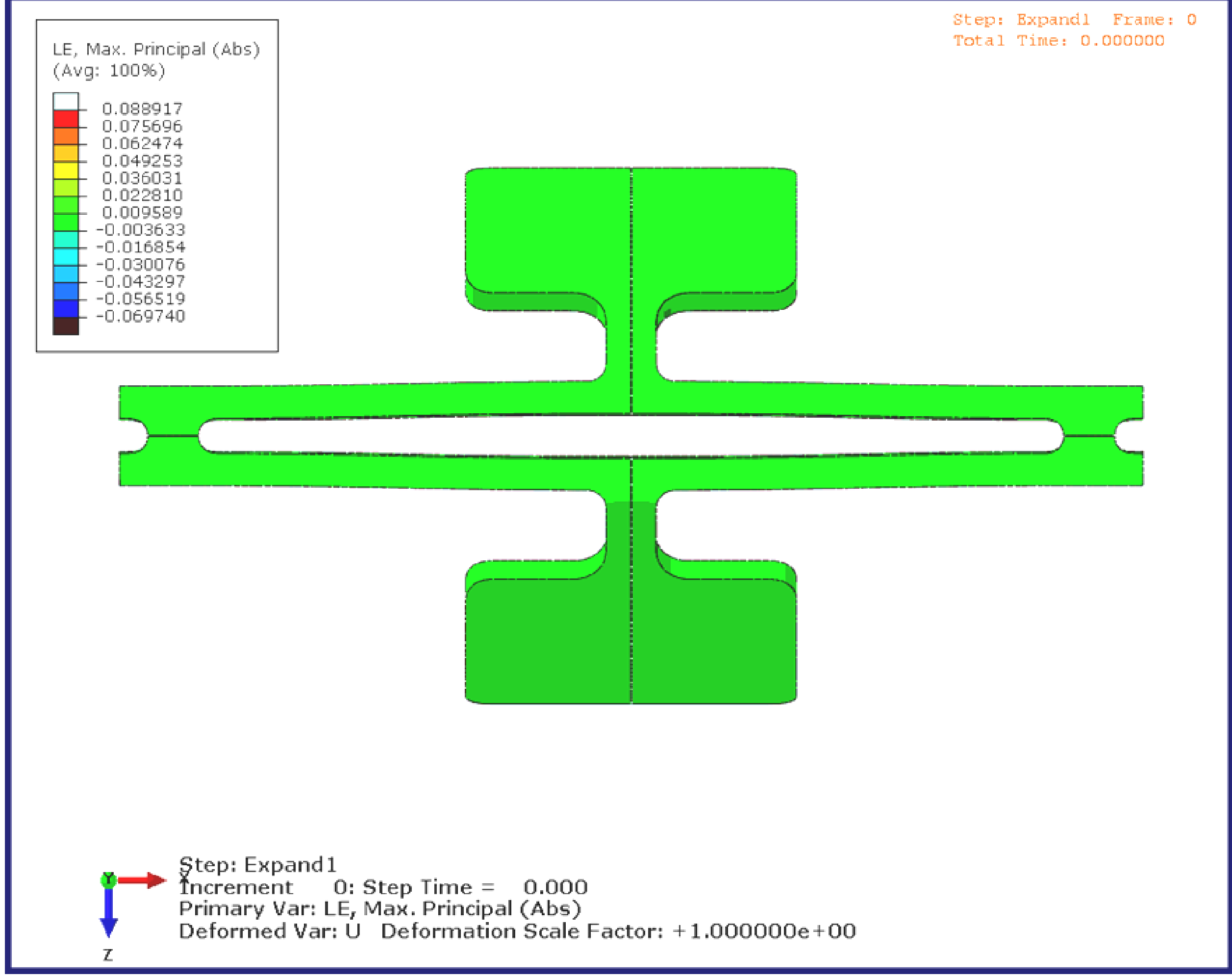


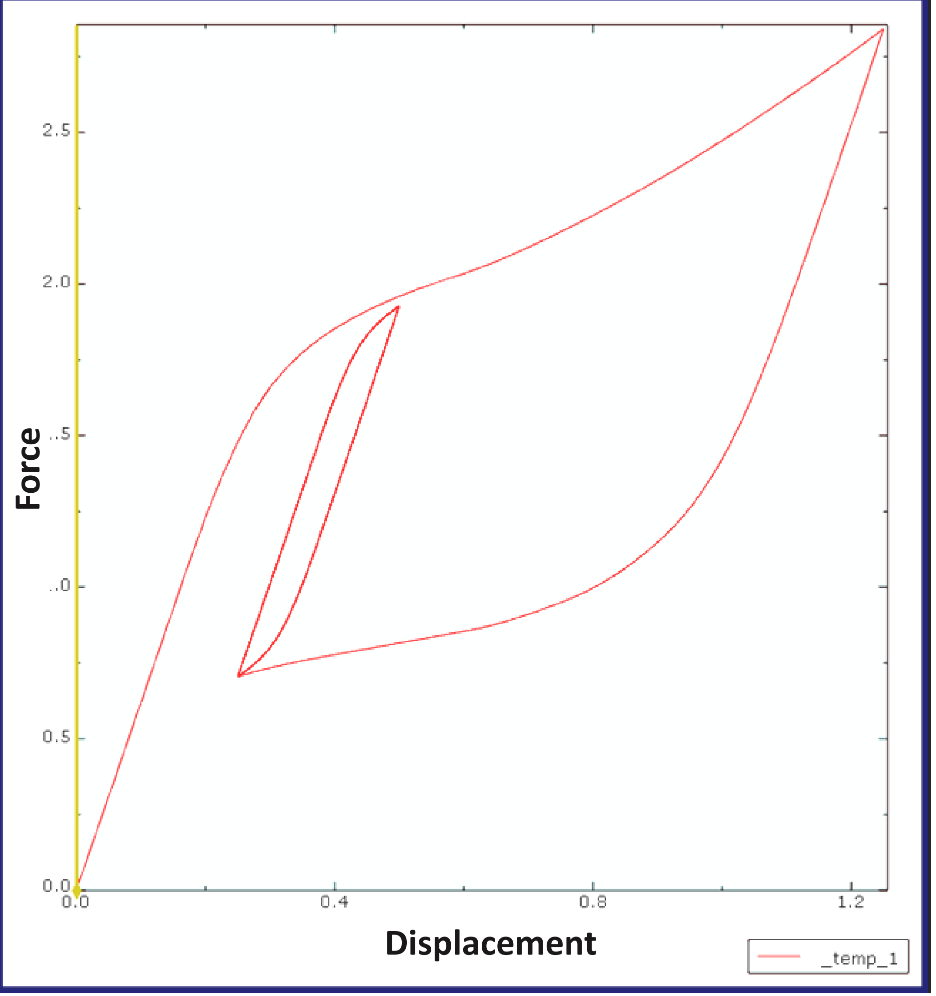
  - **Build Test:** No compile errors
  - **Fortran Unit Tests:** Individual functions are tested for correctness
  - **Fortran Integration Tests:** Select cases are tested against an analytical solution
  - **FEA (Abaqus) Integration Tests:** Select cases are tested against an analytical solution for a unit cube
  - **Abaqus Timing:** ensure code changes did not make the code slower
  - **Generate plots:** archive results

- Additional testing
  - Arbitrary inputs (strain, stress, temperature, material constants) can be generated with a simple json input file and be used to compute an analytical solution and compare against Fortran/Abaqus depending

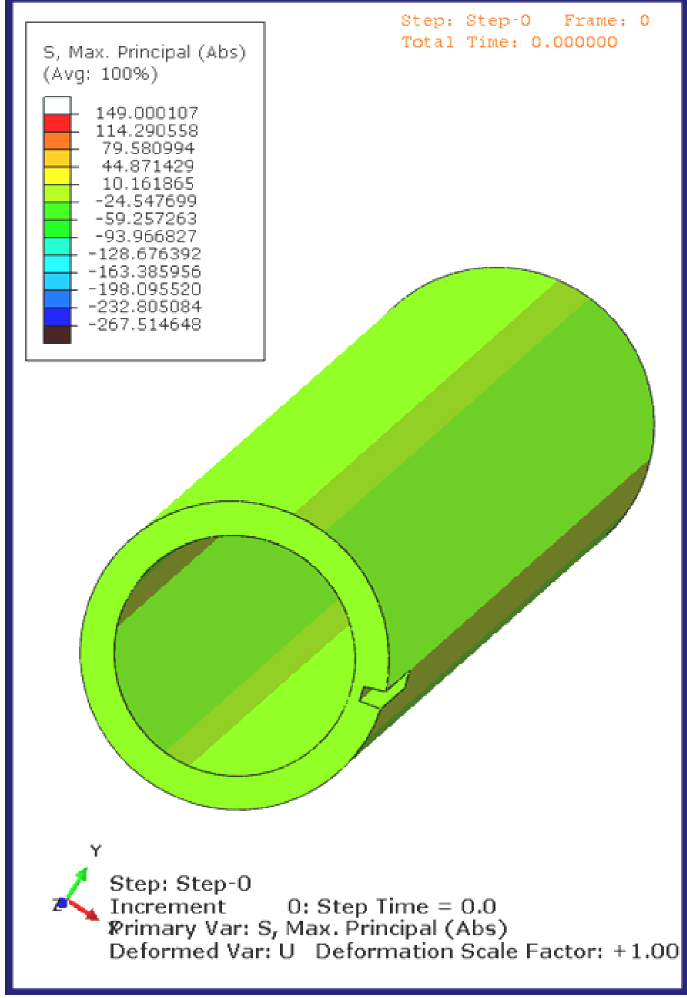
DEMONSTRATION: DIAMOND SURROGATE

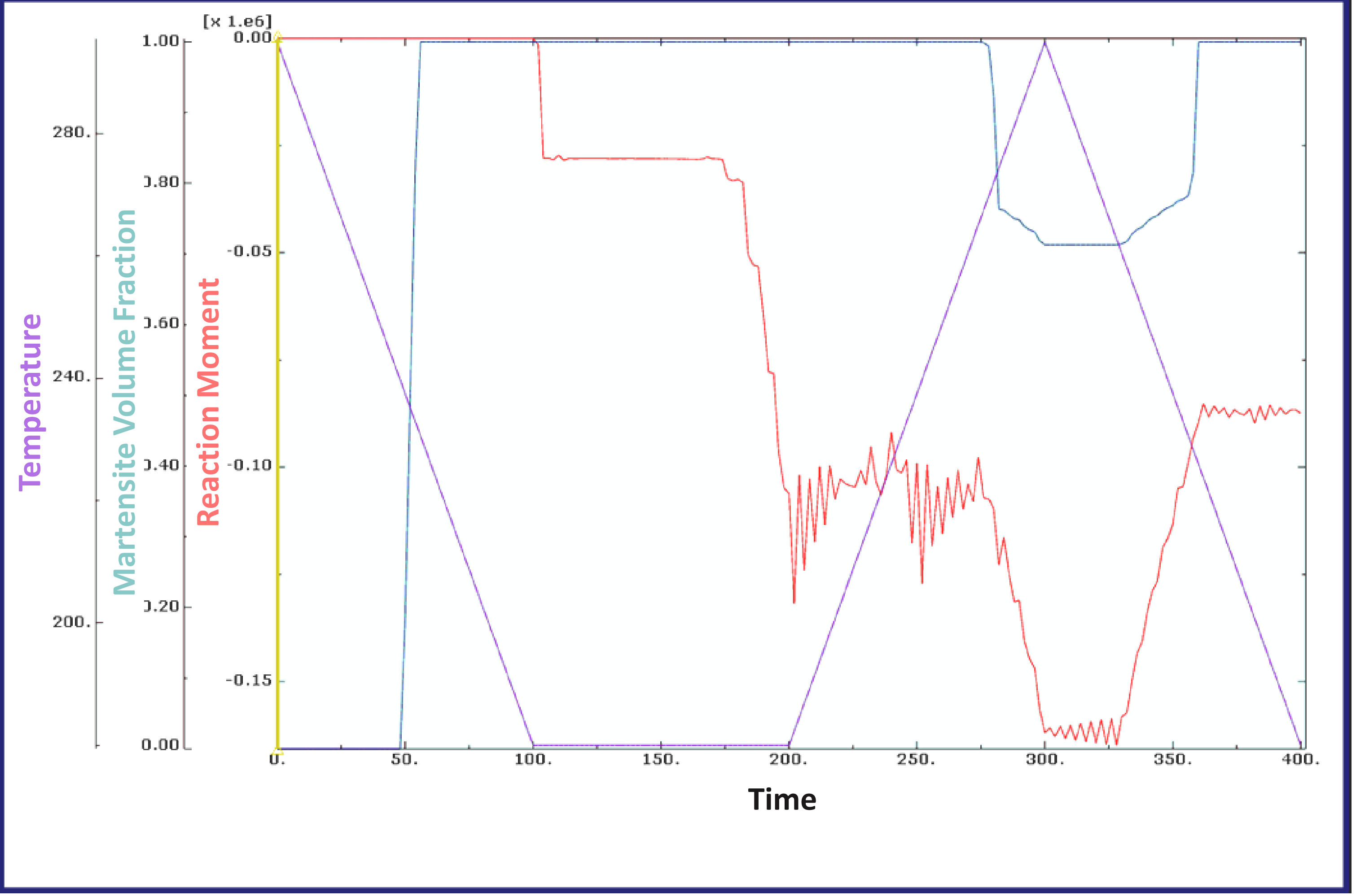
Force vs Displacement



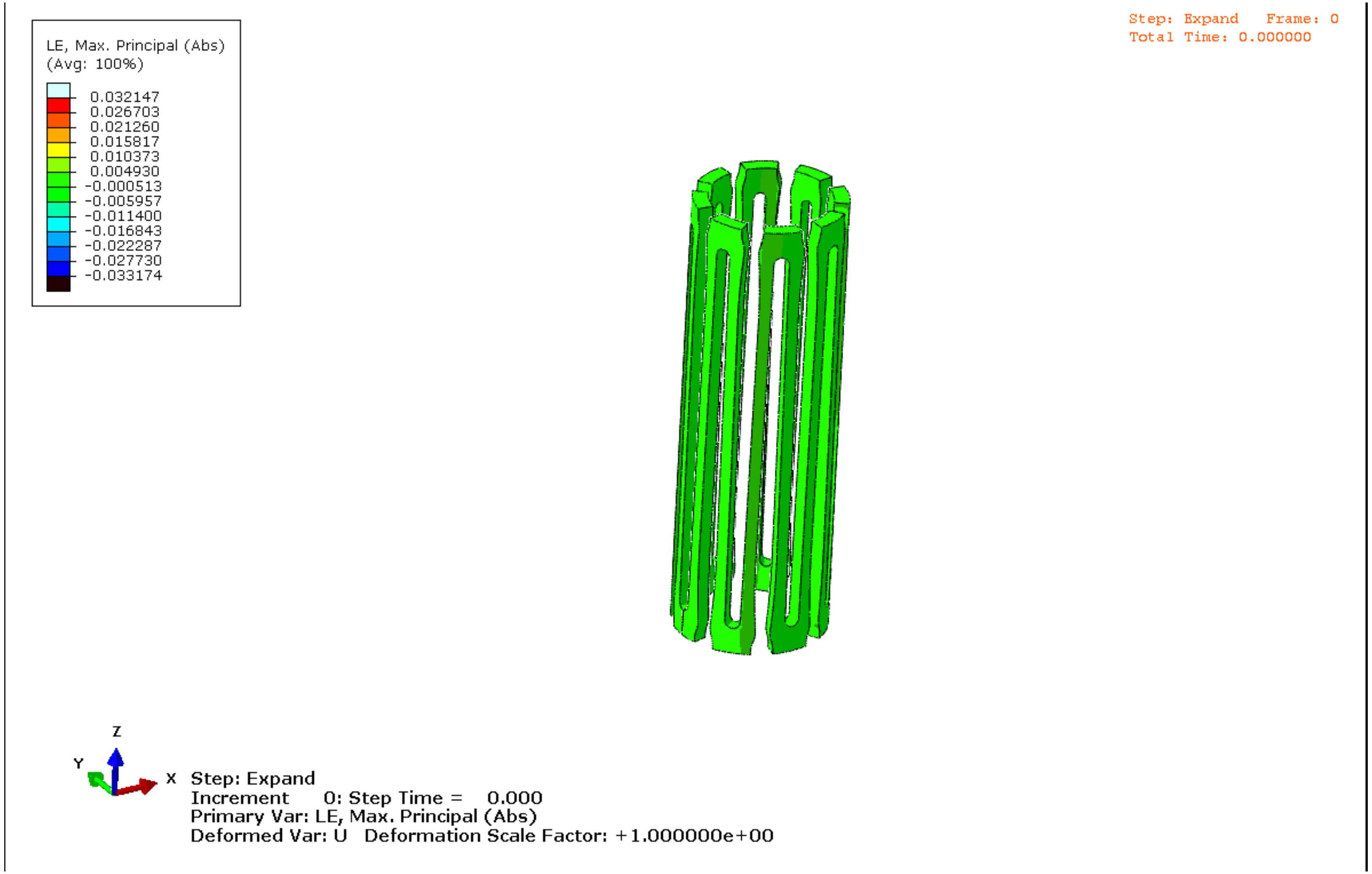


DEMONSTRATION: TORQUE TUBE ACTUATION





Demonstration: Stent



CONCLUSION

- Future Work
  - Replace Cazacu yield surface theory with Brunson
  - Optimized code for speed
  - Write adjacent program to automate calibration and minimize tests

- Overview
  - Available for use in Abaqus as a UMAT or VUMAT
  - New model is micro-mechanical inspired
    - Anisotropic
    - Tunable Tension-Compression Asymmetry
    - Coupled thermal-mechanical loading
    - Coupled phase transformation – plasticity

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