

DESIGNING NON-PNEUMATIC, STRUCTURAL TIRES FOR SPACE: CHALLENGES AND SOLUTIONS FOR A DIFFICULT APPLICATION

Dr. Santo Padula II| ASM Symposium on SMAs | November 2nd, 2022

PRESENTATION OUTLINE

1. Introduction to Mars Rover Challenges
   - Curiosity Wheels Taking on Damage
   - Non-Pneumatic, Compliant Tires as Solution
2. Basics of Modeling Framework Used for SMA Tire Design
3. Brief Discussion on Mechanics Principles Important to the Problem
   - Traditional Mechanics of Metals
   - Differences with respect to SMAs
4. Application to Solving Rover Design and Qualification

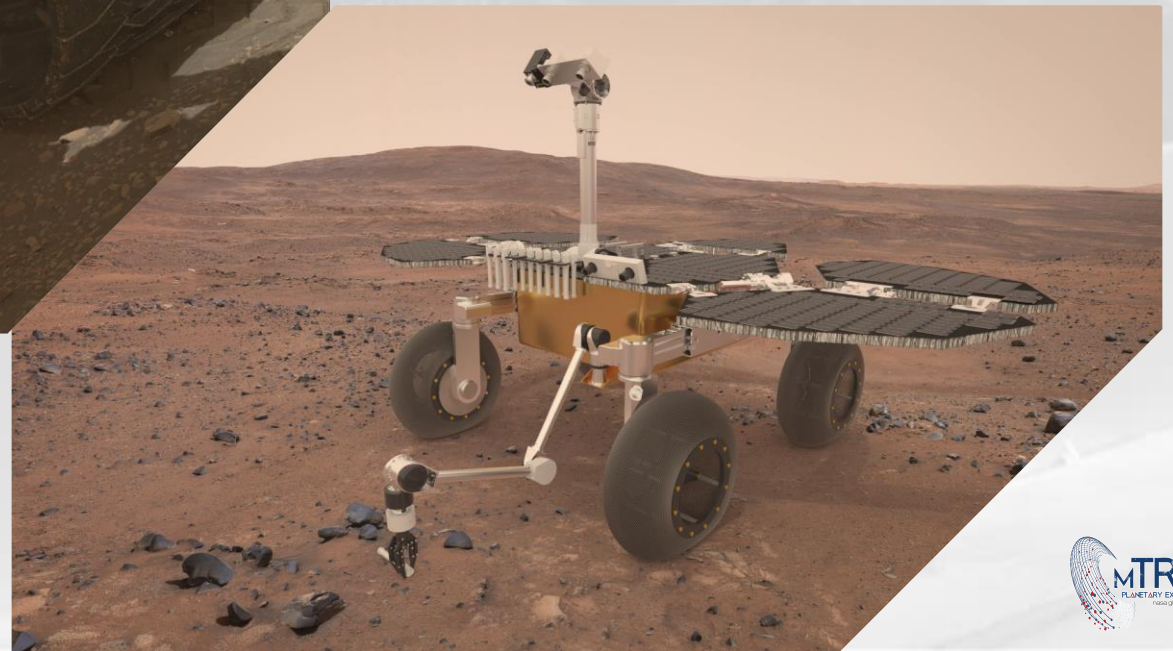
SAMPLE FETCH ROVER (SFR) - MARS SAMPLE RETURN (MSR) CAMPAIGN

In 2013, a little over a year after the Mars Curiosity Rover landed on Mars, engineers noticed that the rover was experiencing significant wheel damage.

Curiosity Rover Wheel damage due to higher-than-expected forces while traversing Martian regolith



Shape Memory Alloy (SMA) compliant tires chosen for Sample Fetch Rover (SFR) due to superior performance observed in similar terrain



COMPLIANT SHAPE MEMORY ALLOY (SMA) SPRING TIRES

Performance advantages derived through attributes of both the material capability and the complex structure

- Complicated structure comprised of two separate geometric elements:
  1. Spring having wire diameter (d), coil diameter (D) and pitch (p)
  2. Interconnected toroid mesh having spring length (L), mesh void size (v), rim spacing width (W) and tire diameter (D_{tire})
- Multiple design parameters must be optimized to provide best performance for competing requirements
- Global forces and displacements easily measured but nature of structure makes it impossible to measure material stresses and strains
- Understanding of stresses/strains important to ensure design will survive in extreme environment while meeting ALL other mission requirements
- Design through “build and test” too costly and time intensive and makes it difficult to qualify hardware for flight



BEST APPROACH IS TO DESIGN THROUGH MODELING

MECHANICS OF MATERIALS 101

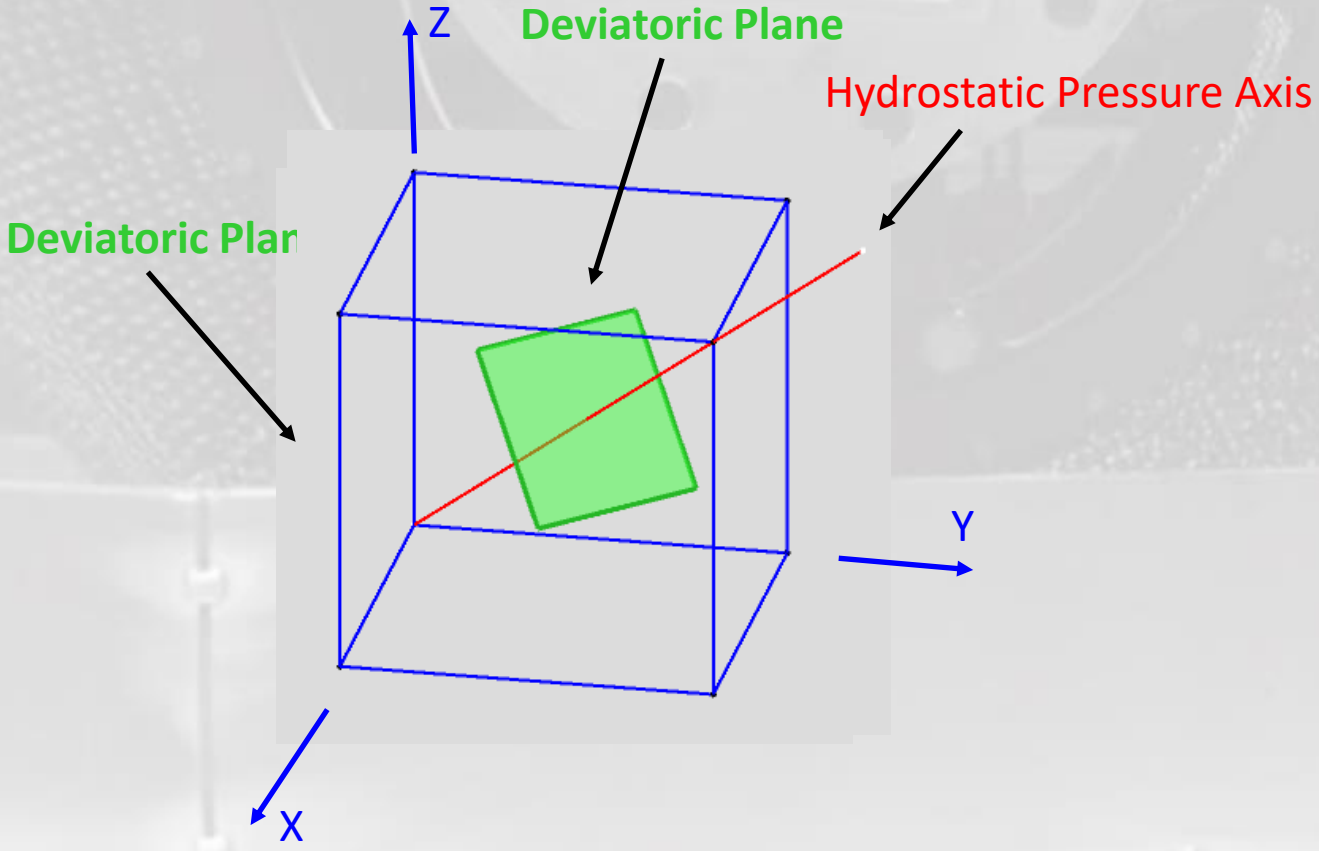
Stress and Strain are Tensors (2nd Rank) → Need 9 Components to Define Them

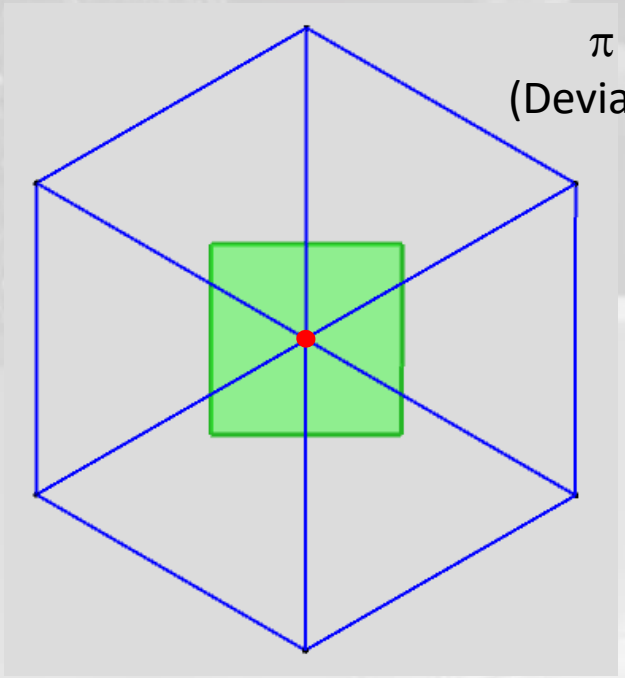
Total Stress tensor for a material element point is:

$$\sigma_{ij} = \begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix}$$

Total Stress = Hydrostatic Stress + Deviatoric Stress

$$\sigma_{ij} = A*\sigma_{kk} + s_{ij}$$





MECHANICS OF MATERIALS – CONVENTIONAL METALS

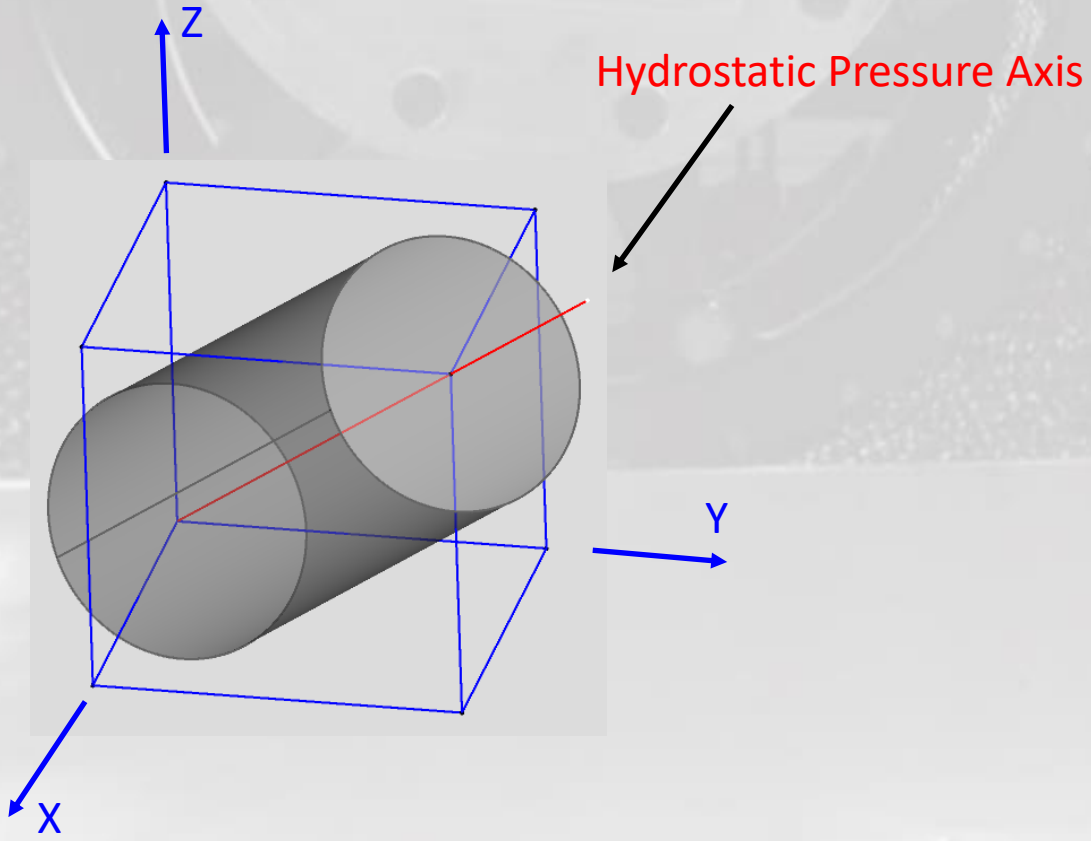
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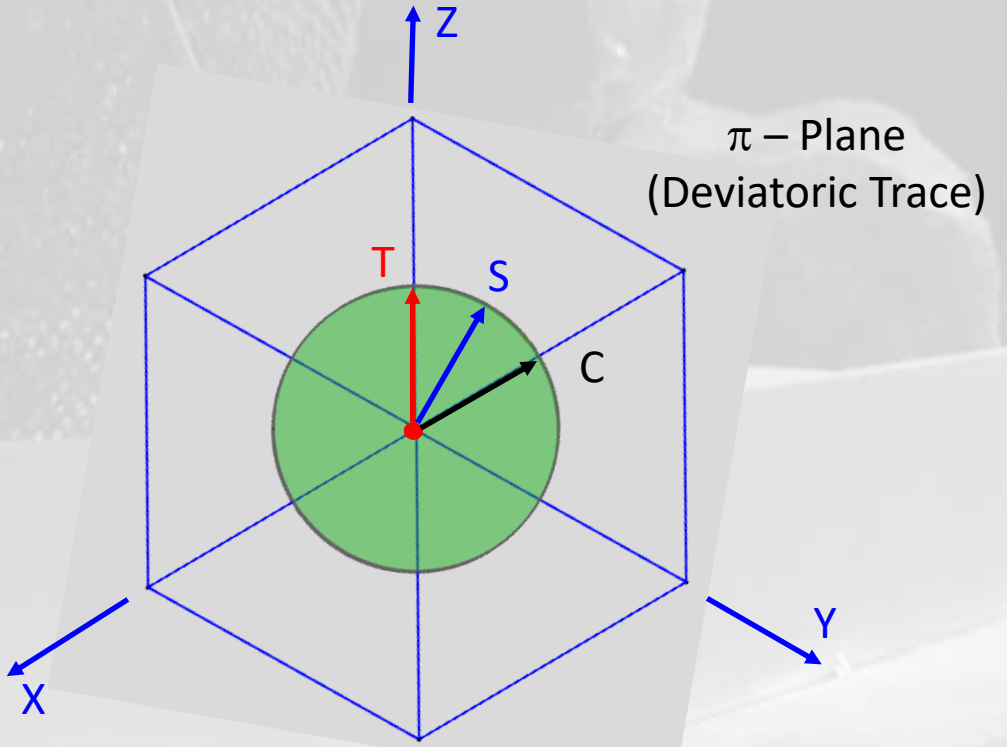
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Total Stress = Hydrostatic Stress + Deviatoric Stress

$$\sigma_{ij} = A^{*}\sigma_{kk} - S_{ij}$$





MECHANICS OF MATERIALS 101

Stress and Strain are Tensors (2nd Rank) → Need 9 Components to Define Them

Total Stress tensor for a material element point is:

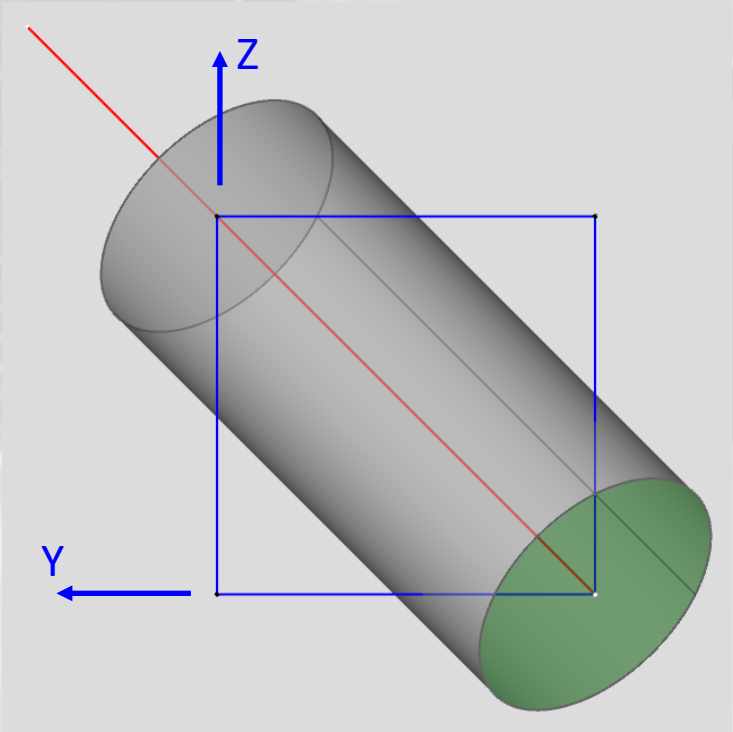
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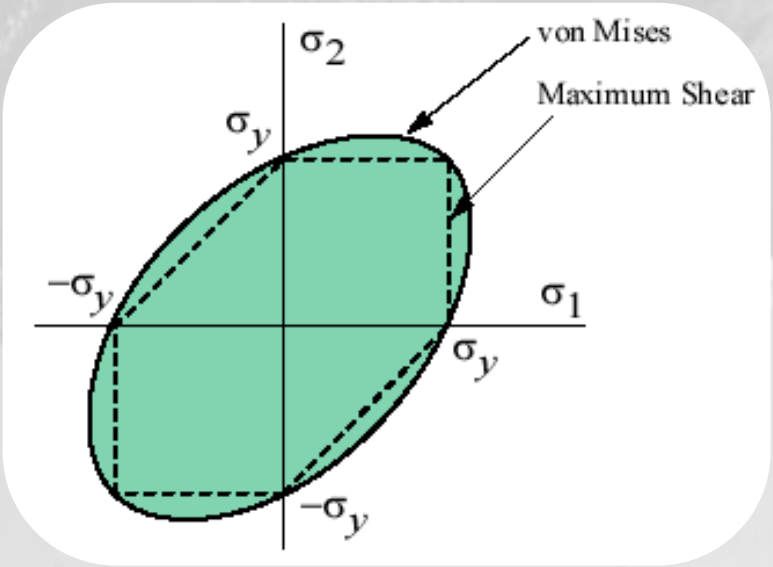
Total Stress

Hydrostatic Stress

Deviatoric Stress

$$\sigma_{ij} = \sigma_{kk} - s_{ij}$$



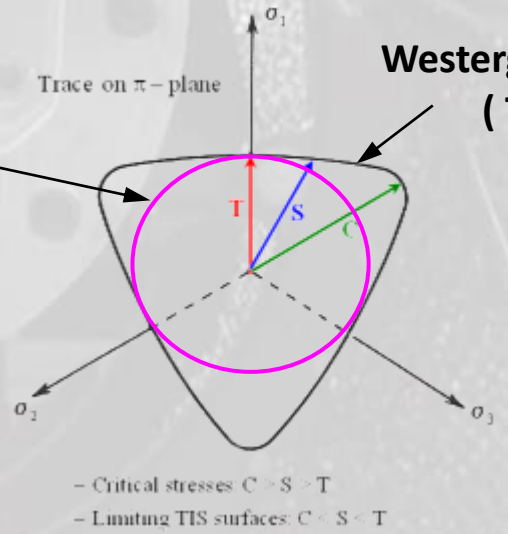


DIFFERENCES IN THE MULTIAXIAL RESPONSE OF METALS

Multiaxial Response of SMA Requires Non-Traditional Formulation

To Account for Marked Differences in Tension, Compression, Shear

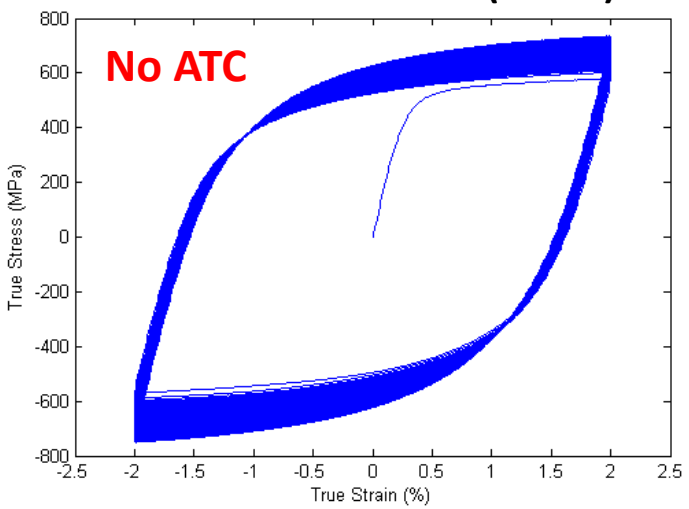
Conventional Metals (J2)
(T = C = S)



Westergaard Stress Space
(T ≠ C ≠ S)

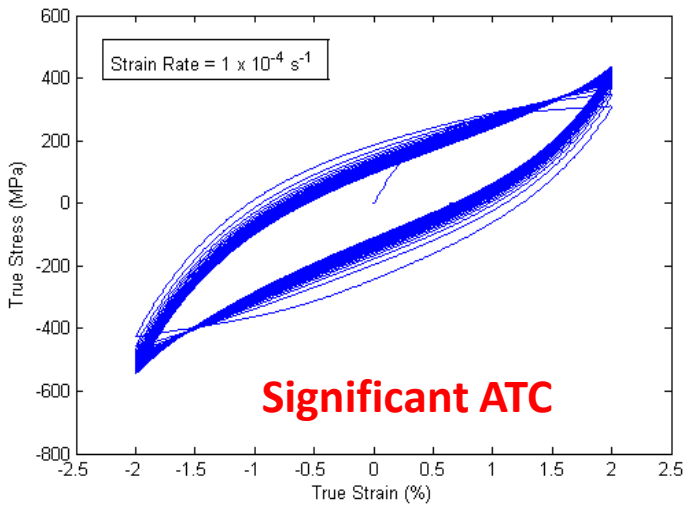
J2 – Von Mises

Conventional Metal (304SS)



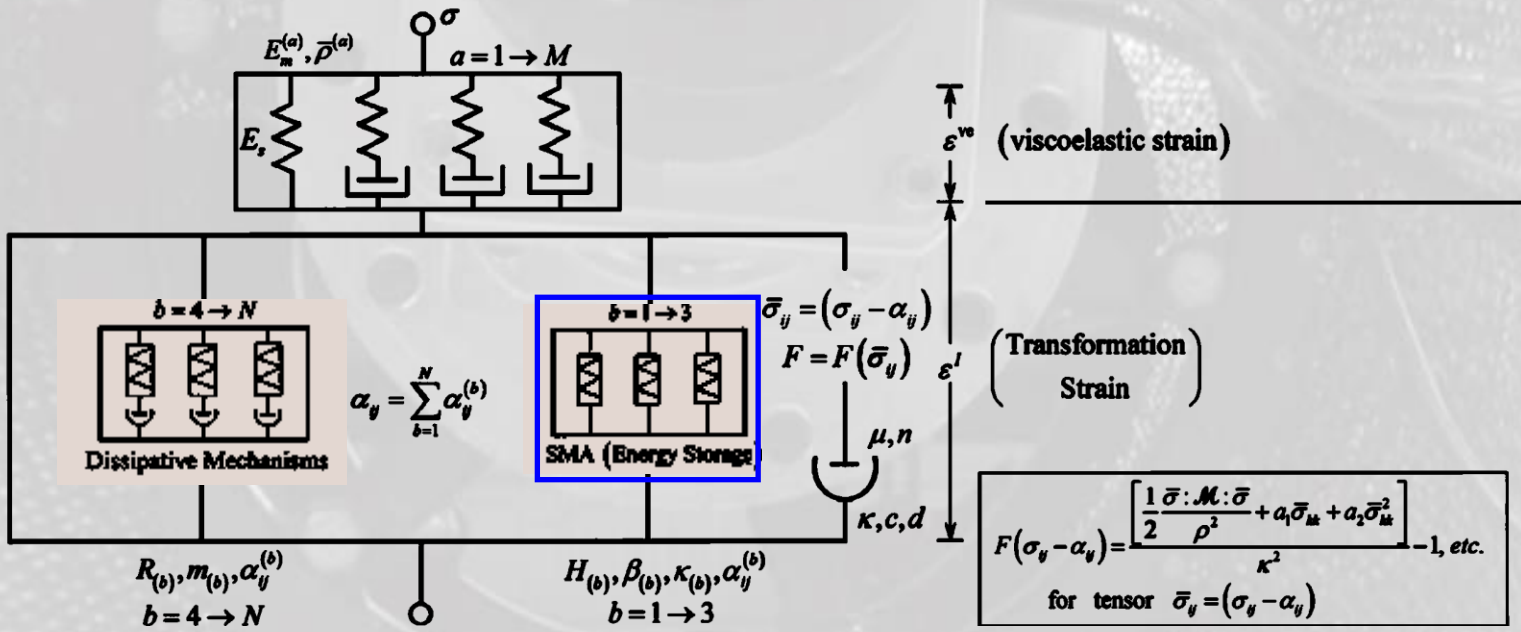
Westergaard

SMA (NiTi)



ATC = Asymmetry in Tension/Compression

SMA-GVIPS MODEL: UNIQUE EXTENSION OF MULTIPLE MECHANISMS



Mathematical Idealization	Material Science
Reversible	Bond Stretch
Inelastic / Transformation strain	**Microstructural Rearrangement**
Reversible (NEW)	**e.g., twinning, phase transformation**
Irreversible (Classic)	e.g., dislocation

The present work is an “extension” of decade and a half of prior NASA / UofA work on “conventional” metallic alloys wherein a **multi-mechanism, viscoelastoplastic** GVIPS framework was developed

Arnold, S. M., and Saleeb, A.F., Jnl of Int. Plasticity, Vol. 10, No. 3.,pp. 263-278, 1994
Saleeb, A.F. and Arnold, S. M.; JEMT, Vol. 123, 2001, pp.51-64.
Arnold, S. M., Saleeb, A.F., Castelli, M.G.; JEMT, Vol. 123, 2001, pp. 65-73.
Saleeb, A.F., Arnold, S.M., Castelli, M.G, Wilt, T.E., and Graf, W.E., Int. Jnl. Of Plasticity, Vol. 17, No. 10, pp. 1305-1350. 2001
Saleeb, A.F. and Arnold, S.M. ; *Int. Jnl of Plasticity*, Vol. 20, pp. 2111-2142, 2004

NEW Extension to SMA: SMA-GVIPS

Saleeb, A.F. and Kumar, A., Journal of Aerospace Engineering 22, 438 (2009).
Saleeb, A.F., Padula II, S.A. and Kumar, A., International Journal of Plasticity, 27: 655-687 (2011).
Saleeb, A.F., Kumar, A., Padula II, S.A. and Dhakal, B., Mechanics of Materials (2012a - in review)
Saleeb, A.F., Dhakal, B., Padula II, S.A. and Gaydosh, D. J. , Journal of Intelligent Material Systems and Structures (2012b - Accepted).

SMA-GVIPS MODEL CALIBRATION

Objective: Characterization of the Shape Memory alloy (SMA) User Material Routine (UMAT) for use in the FE software ABAQUS

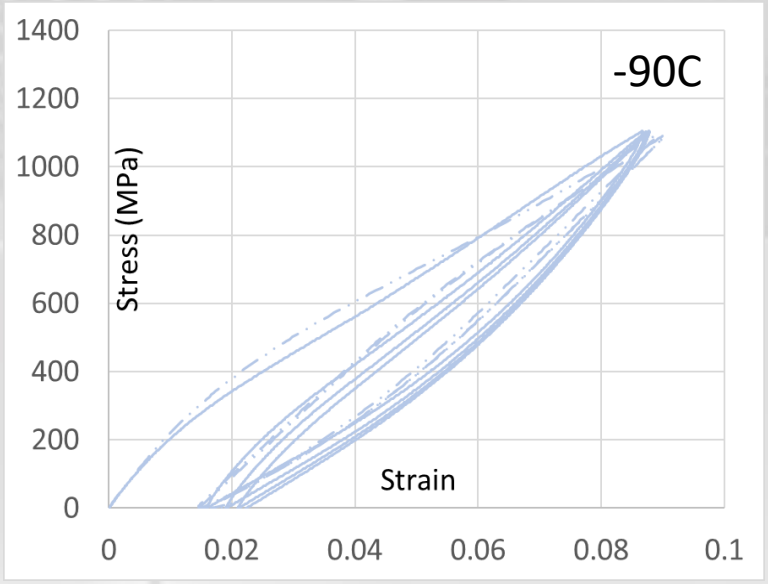
Method:

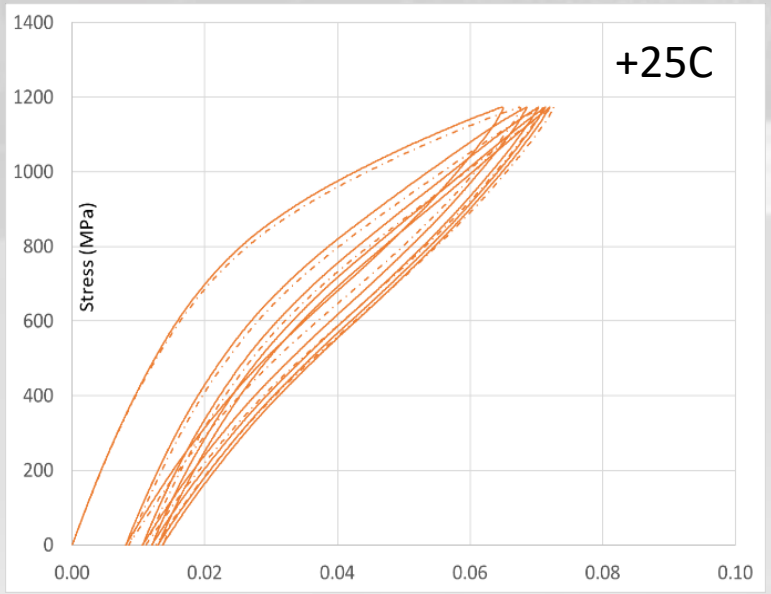
- ❑ Perform cyclic tests (Tension, Compression, Shear, etc.) to produce material-level stress-strain response.
- ❑ Conduct testing at multiple temperatures throughout the temperature range of interest.
- ❑ Perform FEA analysis on a single element loaded in same manner as tests were conducted using the finite element software, ABAQUS.
- ❑ Adjust and fine-tune the main model parameters (α_{ij} and H_b) for each of the temperatures (see Table-I) until correlation with experiments is achieved.

Useage:

Once good agreement between the numerical analysis and experimental data is obtained (See Figure-I) the calibrated modeling framework can be used to analyze ***ANY structure*** comprised of the calibrated material.

Figure I: *Comparison of experimental data with SMA-GVIPS model predictions at various temperatures*





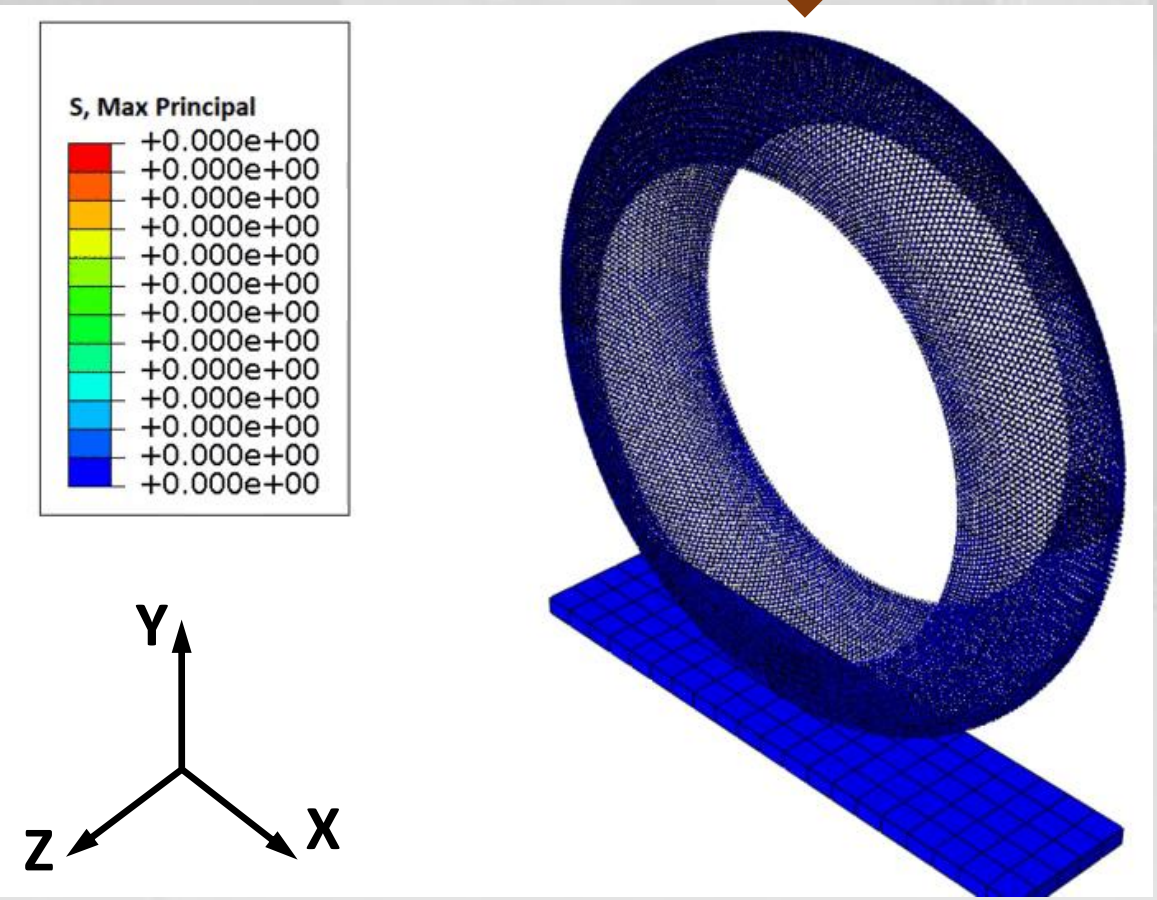
SMA-GVIPS is a True Material Model

Table I: *Temperature-dependent user-defined model parameters for SMA UMAT*

Model Parameter	T=-90 C	T= +25 C
Kappa	2	10
Alfa $_1$	160	500
Alfa $_2$	160	500
Alfa $_3$	125	200
Alfa $_4$	100	100
Alfa $_5$	120	400
Alfa $_6$	500	50
H $_1$	24000	32000
H $_2$	24000	32000
H $_3$	800	800
H $_4$	1000	1000
H $_5$	4250	8000
H $_6$	5150	15000

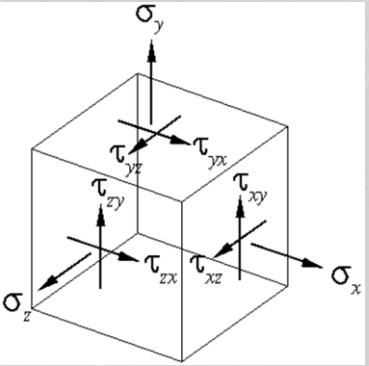
MARS SPRING TIRE: PROBLEM OVERVIEW

Rover Weight Distributed Load (Global)



- ***Global <u>Loads</u>*** applied to tire are distributed into ***Local <u>Stress</u> and <u>Strain</u> Fields*** within the structure
- Local Stress and Strain fields are:
  - Heterogeneous throughout the structure
  - A function of the global deformation fields
  - Arbitrarily defined based on choice of global coordinate system
- Need to translate results for Stresses and Strains into ***Invariant*** (frame-independent) values
  - Independent of arbitrary coordinate system chosen
  - Can be used to determine appropriate conditions at material level

CALCULATING PRINCIPAL STRESSES IN 3D ELEMENTS



The most general state of stress at a point may be represented by 9 components

Normal stresses: σ_{xx} , σ_{yy} , σ_{zz}

Shear stresses: τ_{xy} , τ_{xz}, τ_{yx}, τ_{yz} , τ_{zx}, τ_{zy}

Total Stress tensor for a material element point is:

$$\sigma_{ij} = \begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix}$$

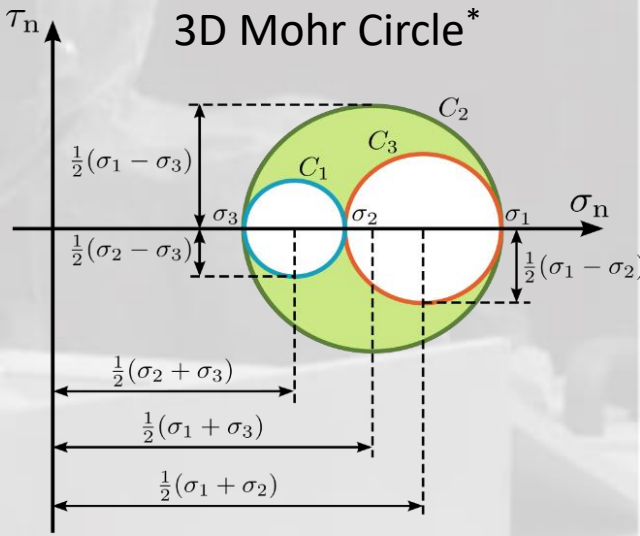
Deviatoric Stress tensor:

$$s_{ij} = \sigma_{ij} - \sigma_{kk} = \begin{bmatrix} \sigma_{xx}-\sigma_{kk} & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_{yy}-\sigma_{kk} & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_{zz}-\sigma_{kk} \end{bmatrix}$$

Hydrostatic Stress is:

$$\sigma_{kk} = \frac{I_1}{3} = \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3}$$

3D Mohr Circle*



Calculation of Eigen-values in a given stress tensor for construction of principal stress tensor

$$\begin{vmatrix} \sigma_{xx}-\sigma & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_{yy}-\sigma & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_{zz}-\sigma \end{vmatrix} = 0$$

$$\sigma^3 - (\sigma_{xx}+\sigma_{yy}+\sigma_{zz})\,\sigma^2 + (\sigma_{xx}\sigma_{yy}+\sigma_{yy}\sigma_{zz}+\sigma_{zz}\sigma_{xx} - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{zx}^2)\,\sigma - (\sigma_{xx}\sigma_{yy}\sigma_{zz} + 2\,\tau_{xy}\tau_{yz}\tau_{zx} - \sigma_{xx}\,\tau_{yz}^2 - \sigma_{yy}\,\tau_{zx}^2 - \sigma_{zz}\,\tau_{xy}^2) = 0$$

Expanding the determinant

Characteristic Equation of the Stress Tensor:

$$\sigma^3 - I_1\sigma^2 + I_2\sigma - I_3 = 0$$

Since this Equation is cubic in σ, it has 3 possible roots: **σ_1, σ_2, σ_3**, which represent the **Principal stresses** for a given 3D element point.

Principal stress Tensor:

$$\sigma_{principal} = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix}$$

Min principal stress

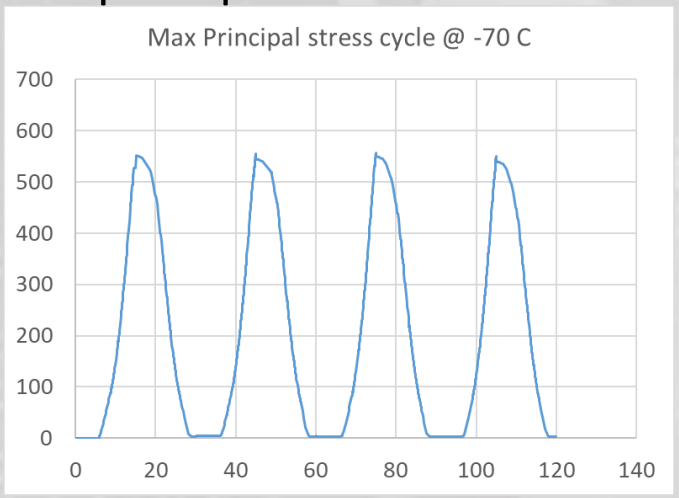
Where $\sigma_1 > \sigma_2 > \sigma_3$

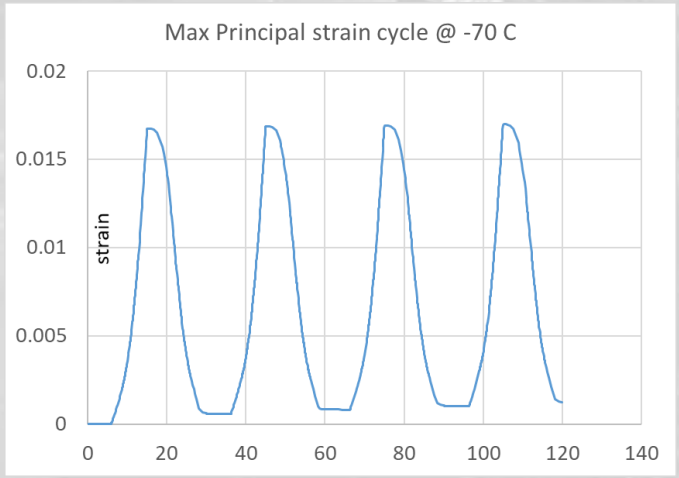
Max principal stress

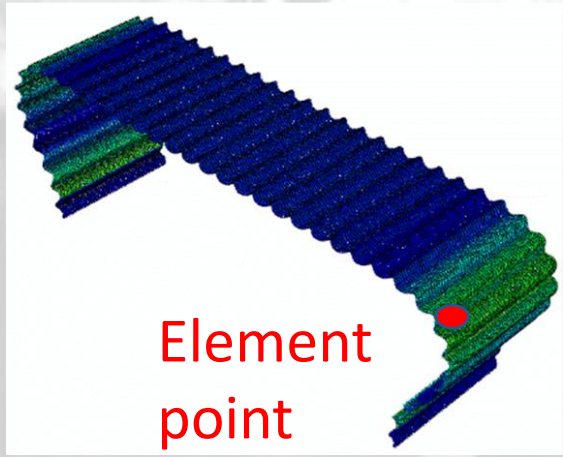
COMPARISON OF PRINCIPLE STRESSES AND STRAINS IN 3D ELEMENTS

Example: Load to create ½ sidewall height deflection

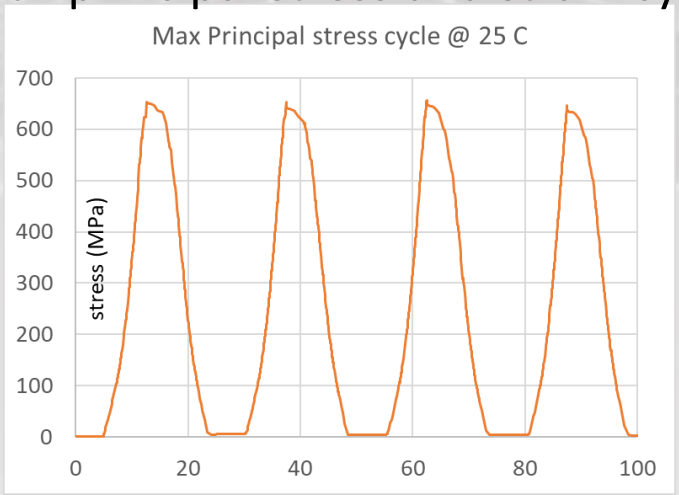
Max principal stress and strain cycles at the given element point in the shoulder area @ -70C

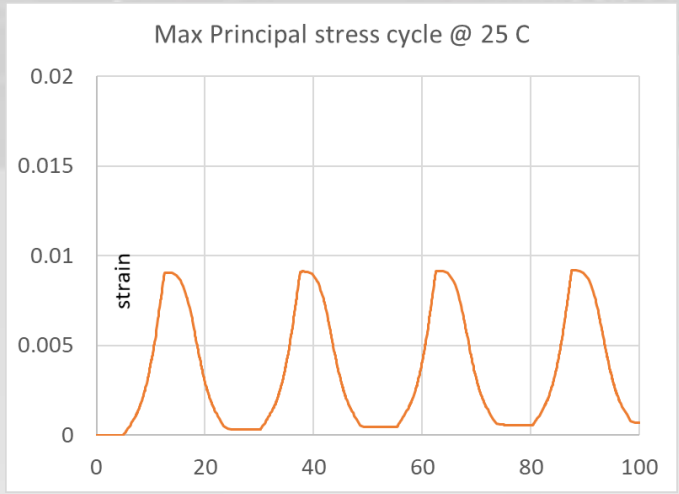


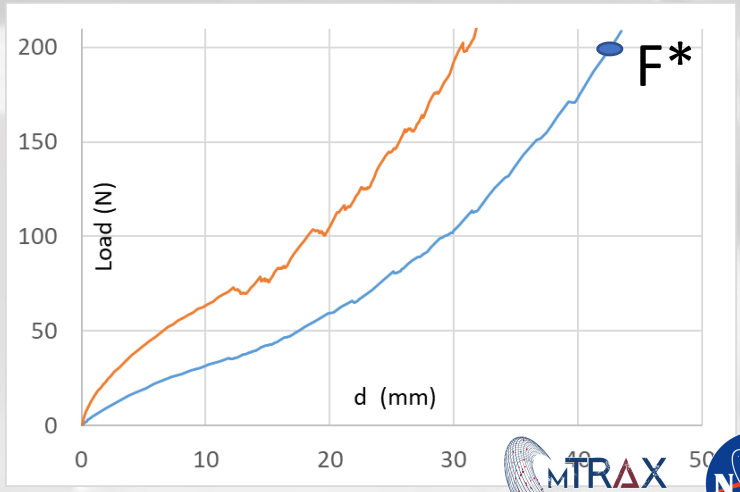




Max principal stress and strain cycles at the given element point in the shoulder area @ 25C for load F*

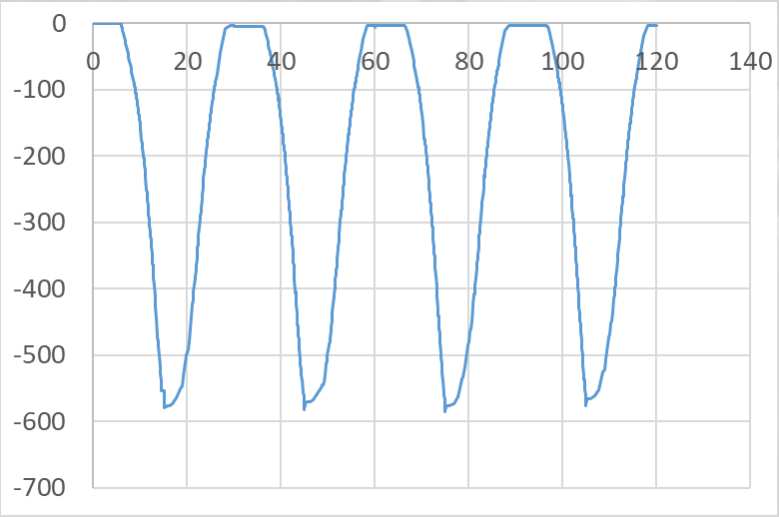






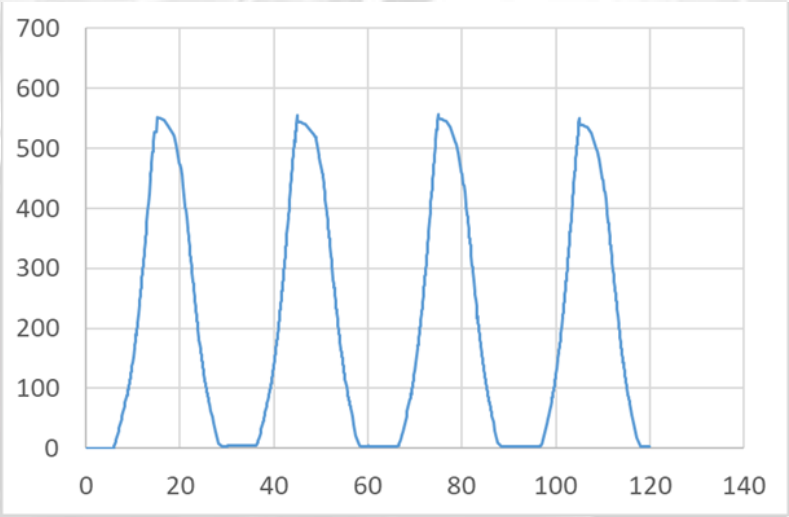
ASSESSMENT OF LOCAL FIELDS THROUGHOUT WIRE

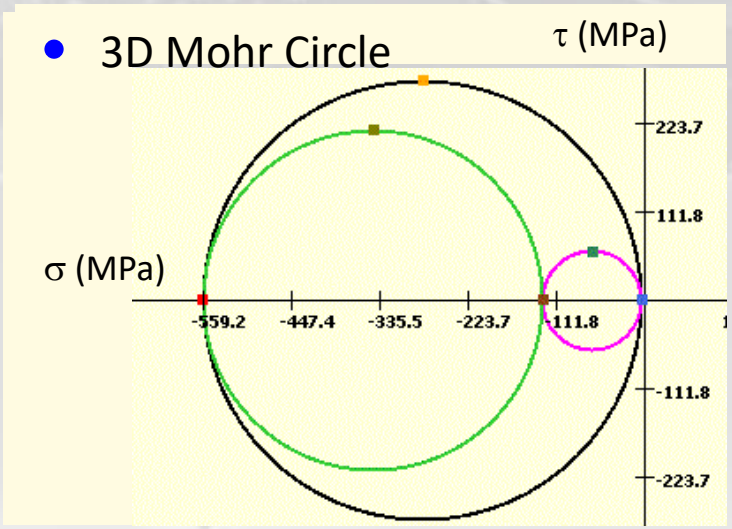
Max Principal stress (compression side)



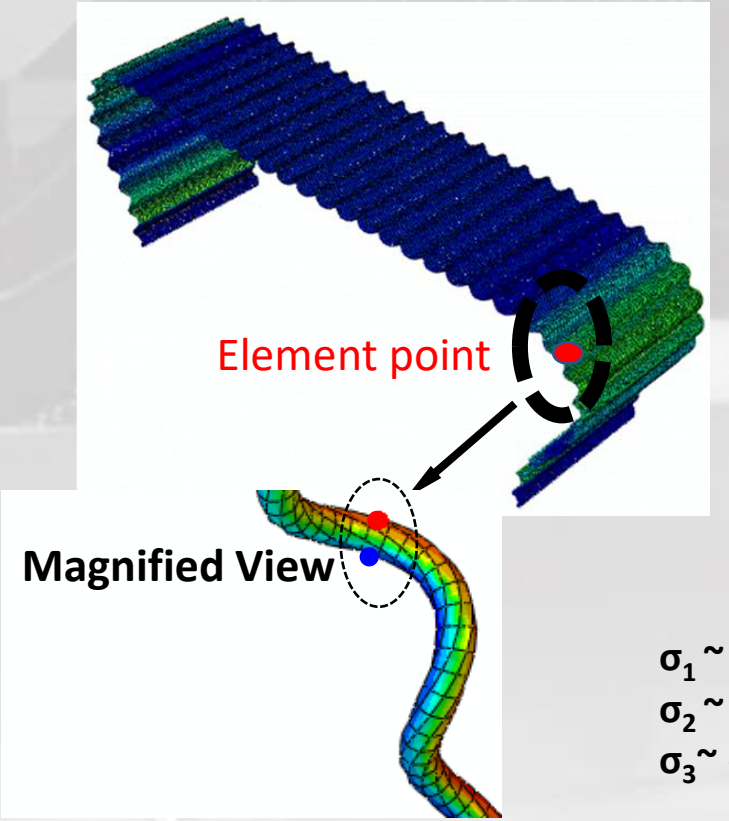
- Interrogation of ***SINGLE ELEMENT*** in mesh doesn't provide whole picture
- Need to understand state throughout entire wire diameter
- However, application of "Tension side" cyclic stress range to wire sample will ***AUTOMATICALLY*** apply full range

Max Principal stress (Tension side)

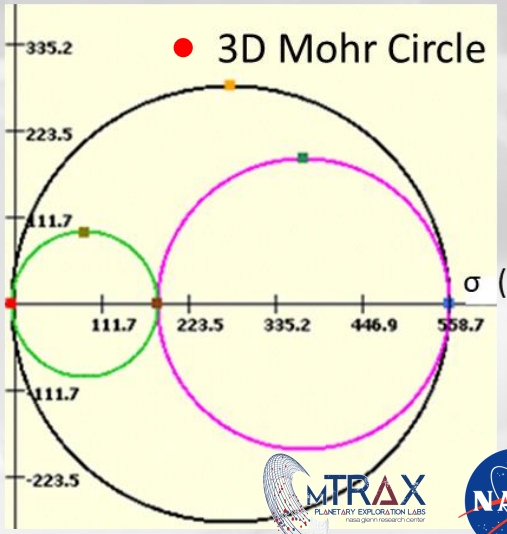




σ_1 ~ -5 MPa
σ_2 ~ -130 MPa
σ_3~ -575 MPa

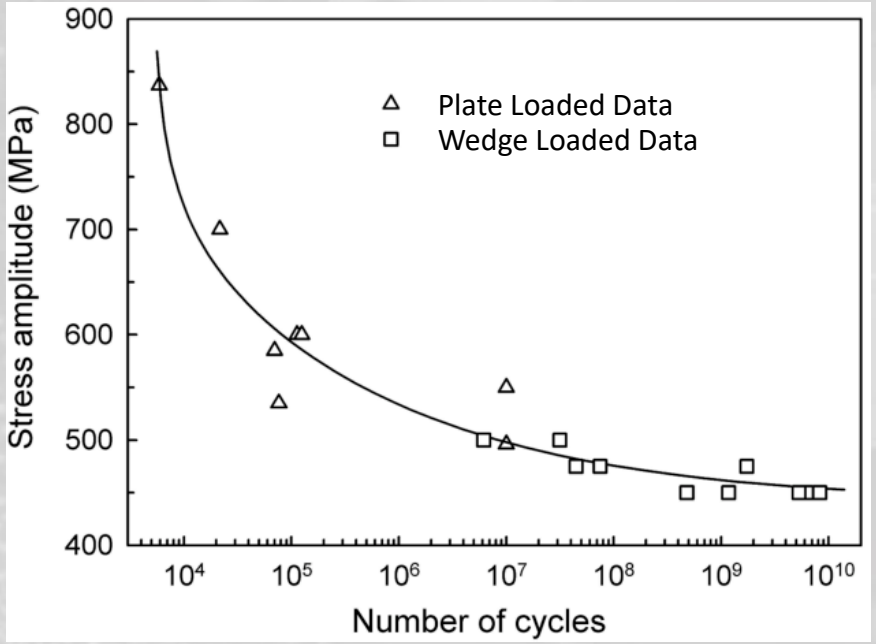


τ (MPa)



σ_1 ~ 558 MPa
σ_2 ~ 182 MPa
σ_3~ -5 MPa

MODEL-DRIVEN DURABILITY ASSESSMENT APPROACH



- Determine ***critical loading conditions*** within requirements space that will drive life considerations
- ***Use full-tire model*** to elucidate correct ***Intensities*** to apply during material level testing program
- Run tests on wire samples in bending for various ***Intensities*** to determine time/cycles to failure
- Repeat above for ***critical temperatures*** of interest important to requirements space
- Develop ***Endurance Curves*** for design and material system
- Use ***Endurance Curves*** combined with ***Full Tire Durability Testing*** to determine ***Level of Risk –*** relative to mission requirements

Replaces Conventional Linear Elastic Fracture Mechanics (LEFM) approach to Fracture Control since LEFM doesn't apply to SMAs

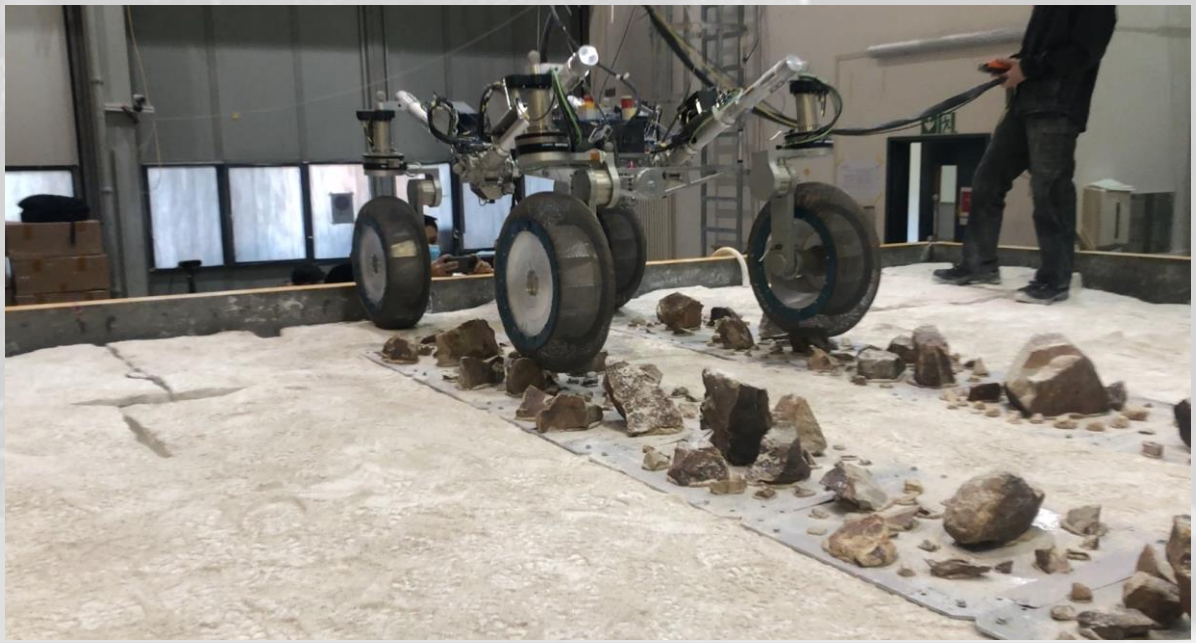
SUCCESSFULLY DESIGNED TIRES

By using a properly formulated modeling framework:

1. *Successfully design tires to meet both global and local performance metrics with the minimum amount of "build and test" cycles to validate design performance*
2. *Properly inform testing program to complete Verification and Validation (V&V) requirements needed to qualify space-flight hardware*



Obstacle and Slope traversal testing



Rock traversal testing

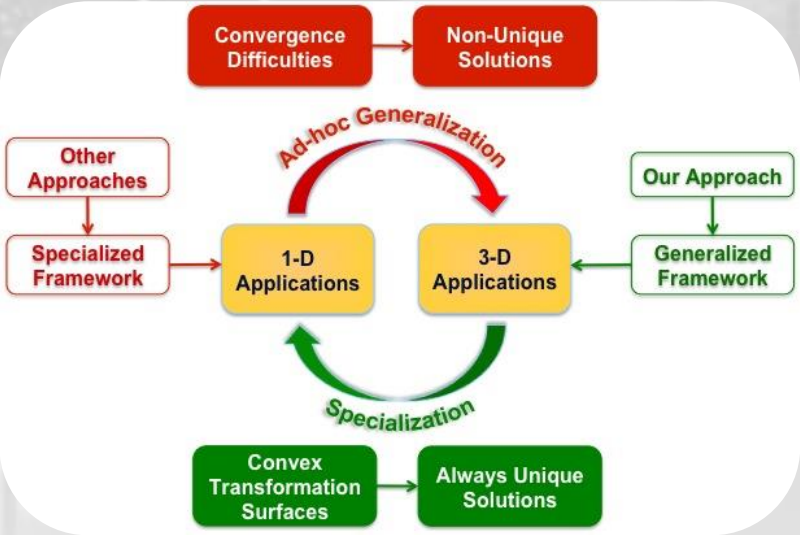
Result: Compliant Tires that meet Design Requirements for Mission


MTRAX
PLANETARY EXPLORATION LABS
nasa glenn research center
THANK YOU FOR YOUR ATTENTION.
QUESTIONS?
NASA
MTRAX
NASA

BENEFITS OF GENERALIZED PHENOMENOLOGICAL APPROACH

Previous State of the Art

- Based on 1-D approach that assumes stabilized behavior (completely avoids evolution).
- Limited success in predicting transformation strains correctly.
- Select parameterizations based on specific boundary value problem (BVP) – not applicable to alternate problems.



Saleeb, A.F. and Kumar, A., Journal of Aerospace Engineering 22, 438 (2009).
Saleeb, A.F., Padula II, S.A. and Kumar, A., International Journal of Plasticity, 27: 655-687 (2011).

Properly formulated Potential Framework (e.g. SMA-GVIPS) has the following advantages:

- Avoids any pitfalls in extending classical plasticity theories.
- Maintains the desirable attributes of potential structures, (i.e, uniqueness).
- Can be easily specialized to handle 1-D & 2-D.
- Ensures efficiency in large scale computations.

Current Approach

- Focuses on developing true material model that can account for evolutionary response and can be implemented in FEA packages.
- Once parameterized, can be used to solve any boundary value problem (BVP).
- Developed specifically for 3-D implementations with rate-dependency in mind.
- Automatically captures various aspects of SMA behavior:
  - ✓ Evolution of strain (varying rates)
  - ✓ Transient phenomena associated with changes in stress and/or temperature
  - ✓ Smooth nature of transformation