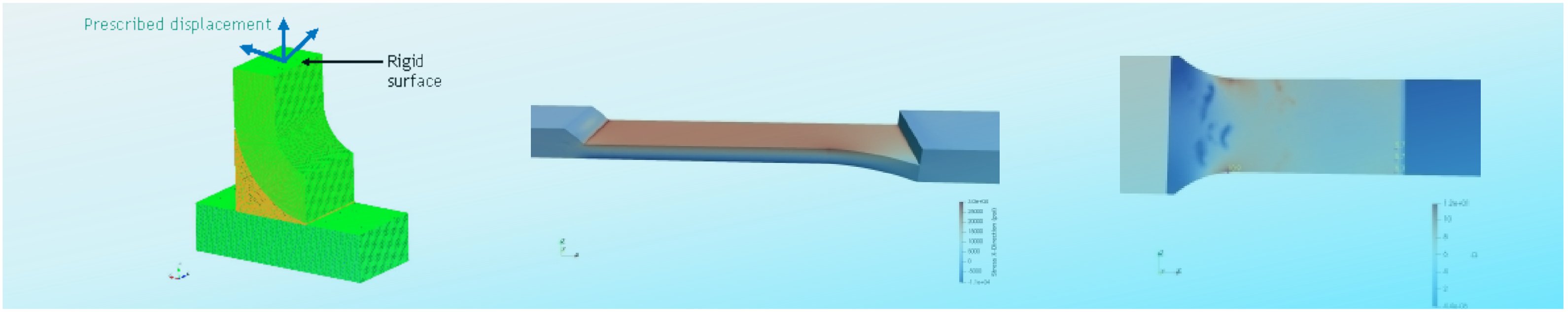
Sandia National Laboratories

SAND2021-6992C

Comparison of Weld Fatigue Methods and the Use of a Multi-Scale Method



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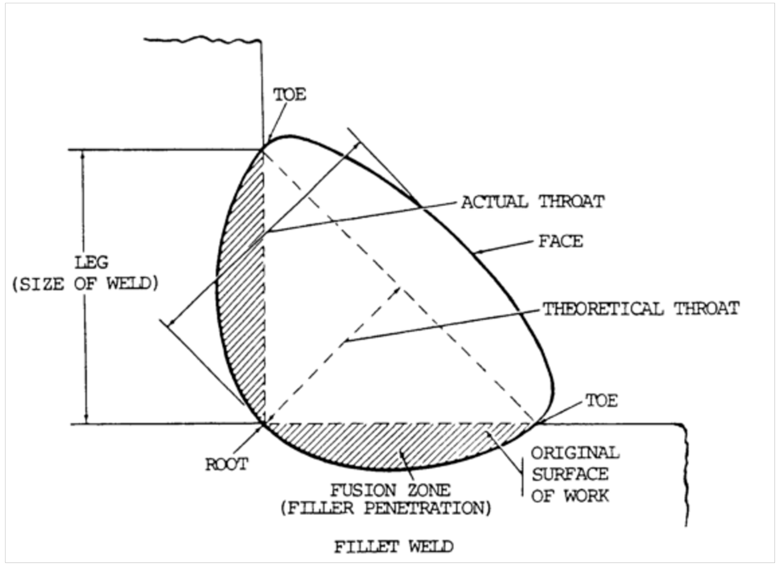
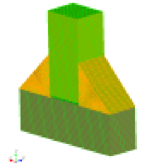
Overview

- Given a large model with several welds, we are asked to determine the fatigue/service life requirement.
- The environments are general transportation environments for the system
  - Random Vibration & Shock
- A *Line Weld* element is used to represent the stiffness of the weld
  - A multi-scale method is used to develop the stiffness for the low-resolution model of the system
- Generally weld failure is seen at the toe of the weld
  - We use ASME Boiler Pressure Vessel Code, Elastic-Plastic fatigue method for the elements at the toe of the weld
- Failure is checked in the weld with a multi-scale method to represent the weld with a high-resolution model and boundary conditions passed to the high-resolution model
- A simple fillet weld example is explored in this talk



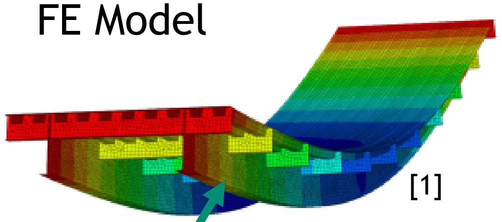
Fatigue Analysis Workflow

High Resolution Weld



Stiffness of
line weld

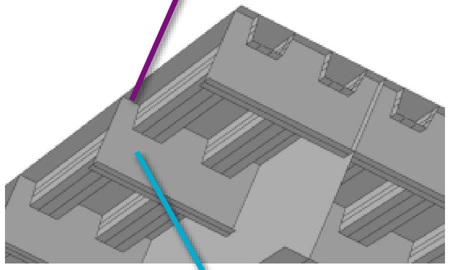
FE Model



[1]

Excitation Input

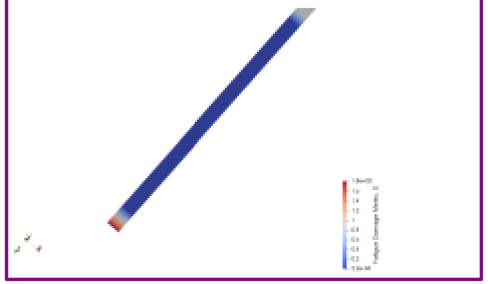
FE sims provide time history of stress at every element near weld



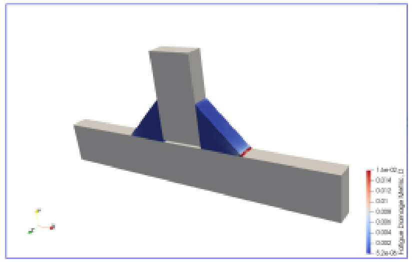
[1]

FE also provides resultant forces and kinematic conditions

Fatigue prediction on element stress that provides overall Damage Metric, D, for each element



Multi-Scale Approach: High- Resolution Weld Model



Fatigue prediction that provides an overall Damage Metric, D, at each element in the weld area.

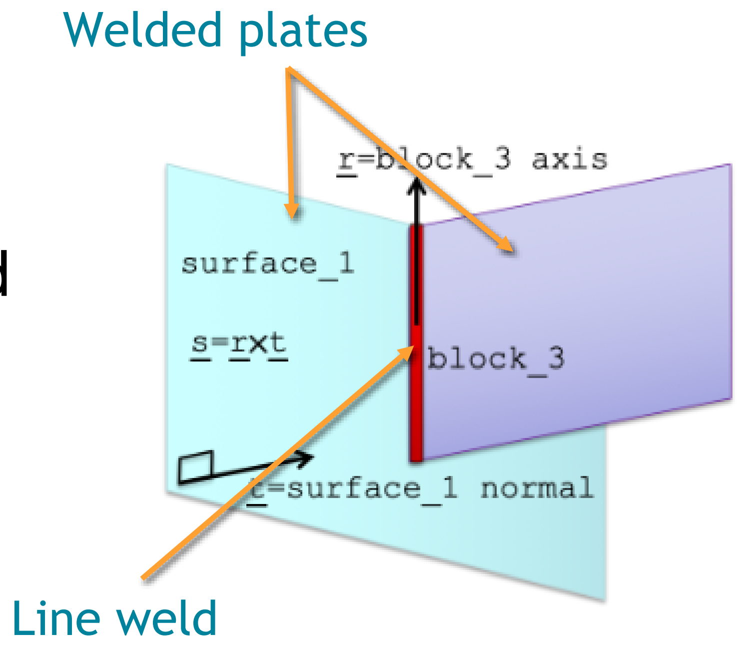
Only at Hot Spots

D<1,
Life is good

[1] Hakansson, J. and H. Wallerman, Finite Element Design of Orthotropic Steel Bridge Decks, *Master's Thesis*, Sweden 2015

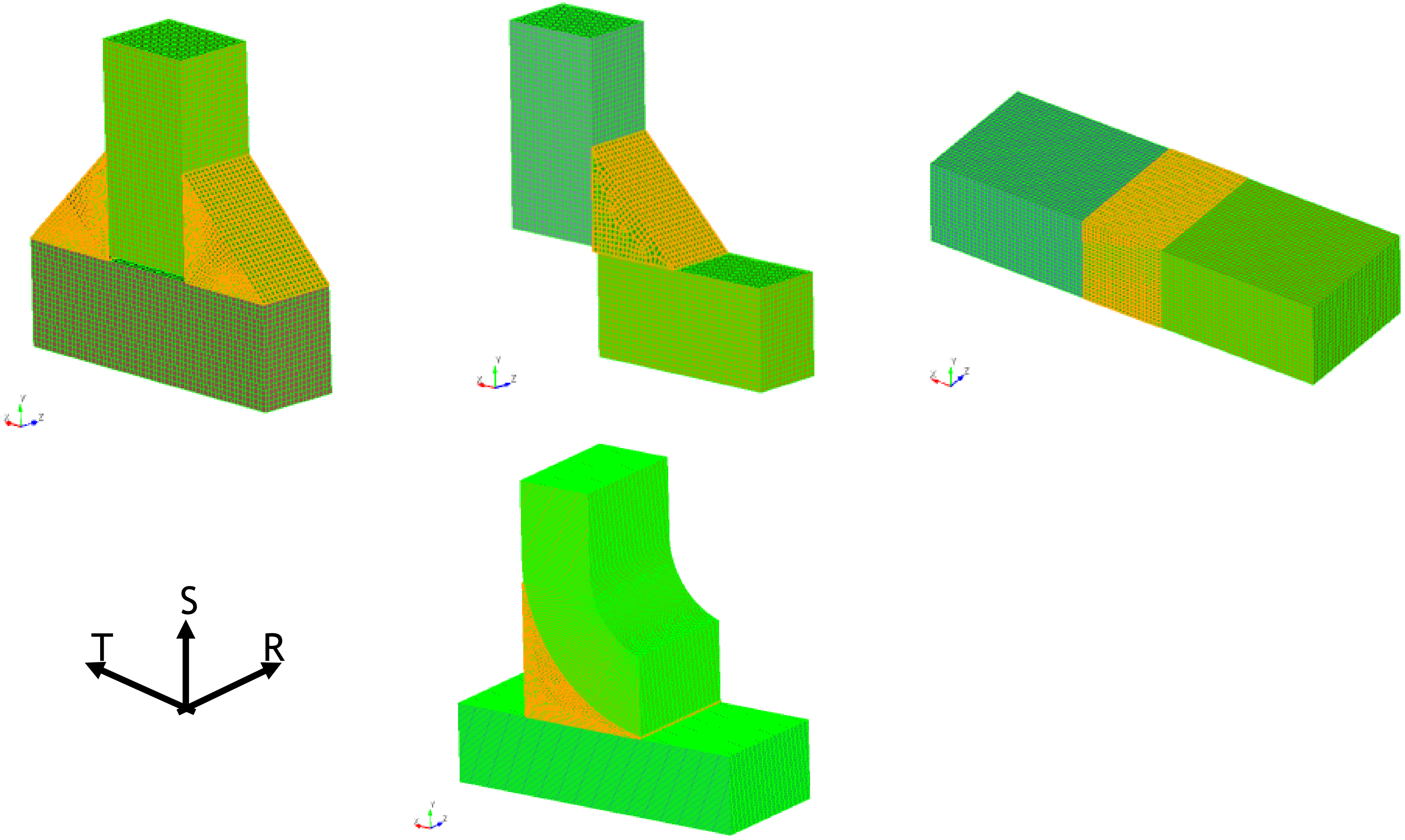
Weld Stress Calculations: Line Load Forces

- Force orientation
  - R force along weld (aligned with 1D element)
  - T force normal to sideset used in line weld definition
  - S right hand rule
  - R moment (torsion along length of weld)
- All forces are force/length



Line weld is contiguously meshed to purple plate.

Development of High Fidelity Weld Submodels

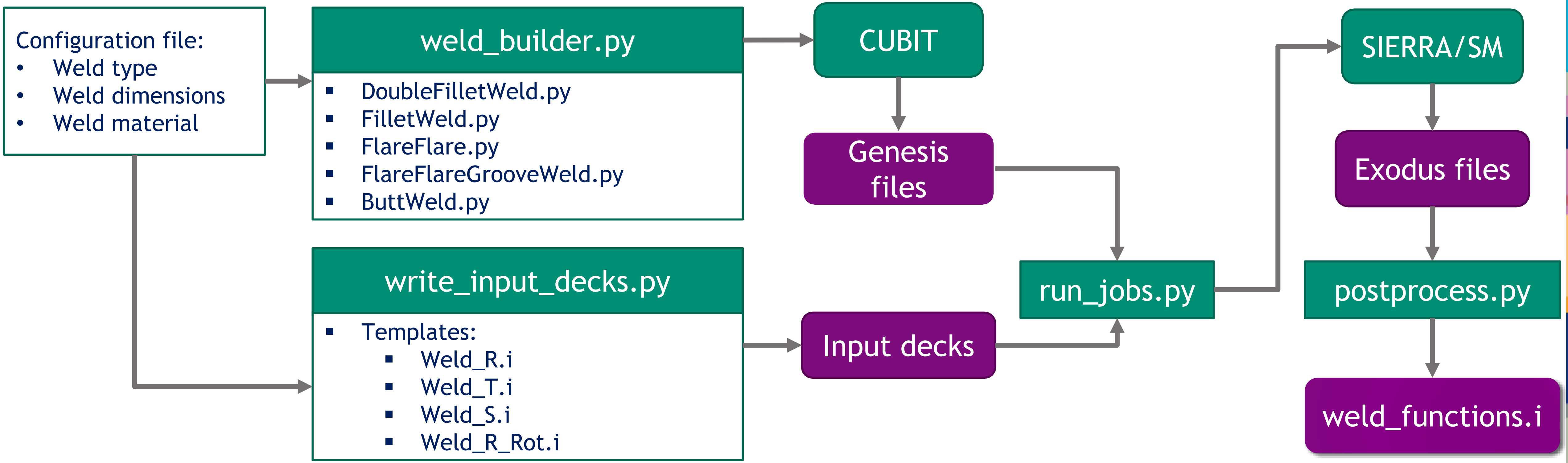


High-fidelity weld submodels were created to apply loads in Sierra/SM and determine the weld stiffness to define *line weld* stiffness functions in Sierra/SM.

The weld had a minimum of 20 elements across the weld depth.

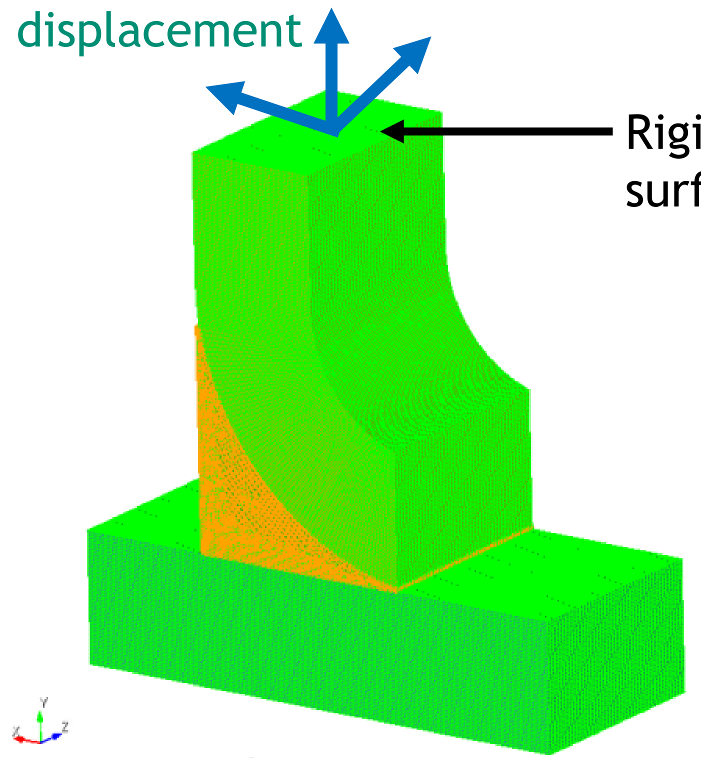
A 0.1 inch section was modeled to reduce runtime.

Model Development Process

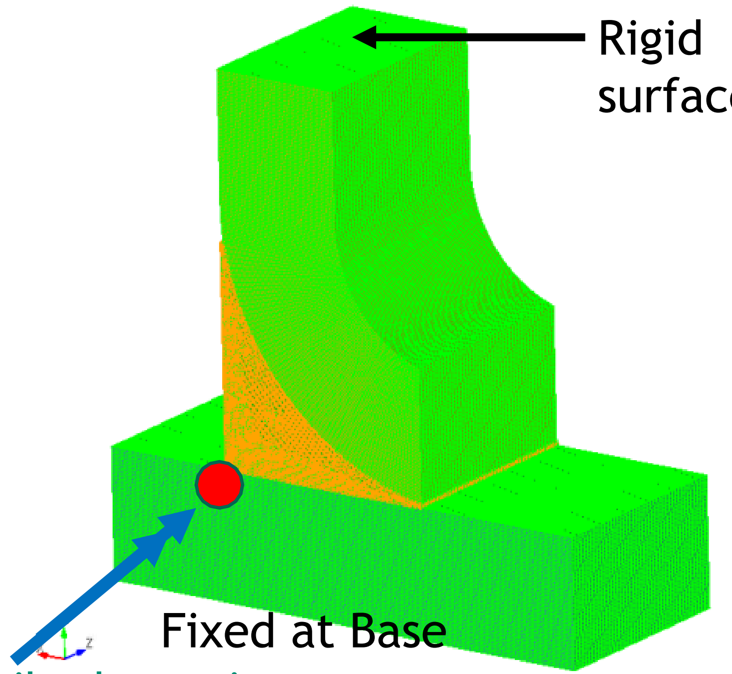


The weld model generation workflow was scripted in Python to automate the mesh and input deck generation, job submission, and postprocessing.

Loads Applied to High Fidelity Weld Models



Force recovered from rigid body reaction force.
Prescribed displacement = weld size
Prescribed rotation = 45 degrees



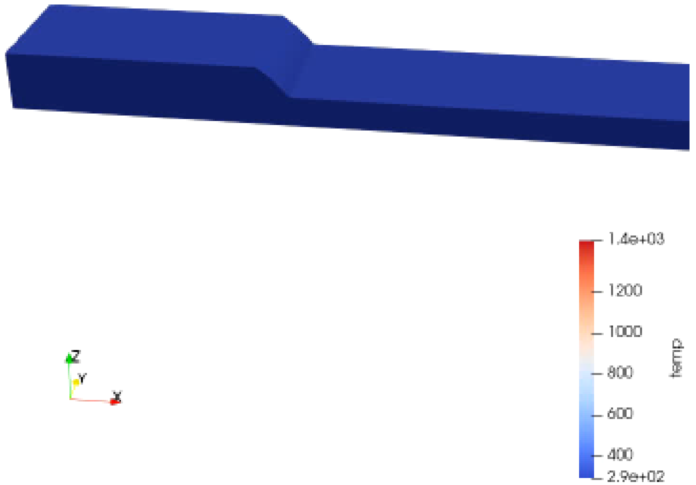
The reaction force/moment was multiplied by 10 to obtain the stiffness of a 1.0 inch long section.

High-Resolution Coupon Model – Residual Stresses

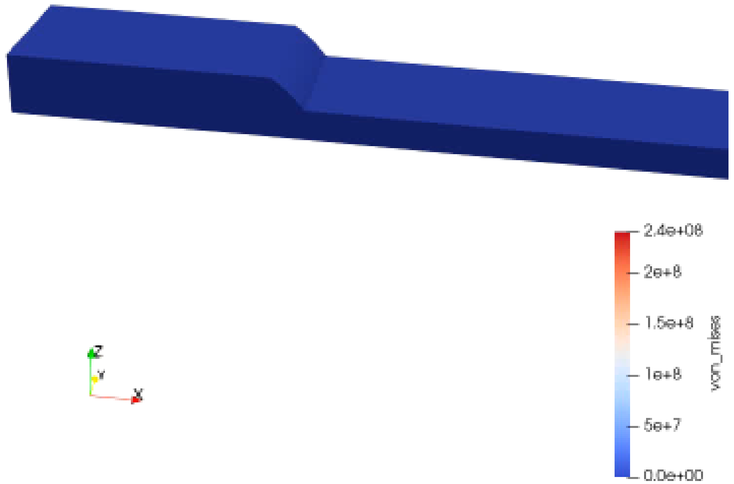
To account for residual stresses, a thermal simulation was conducted to represent the welding process. The thermal simulation was followed by a stress analysis to determine the resulting residual stresses.

The Bammann-Chiesa-Johnson (BCJ) isotropic elasto-viscoplastic internal state variable model is used for the constitutive SS304L material model.

Notional values were used for the laser properties since that information was not available.



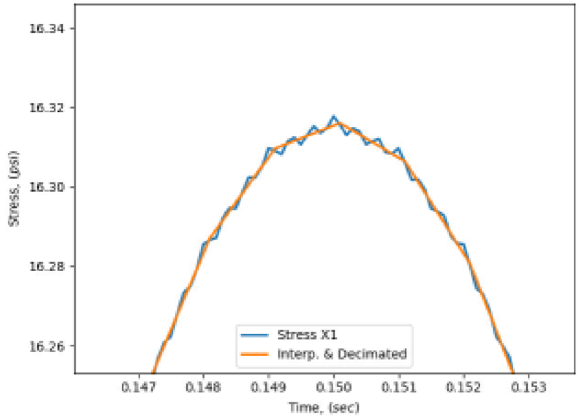
Temperature, K

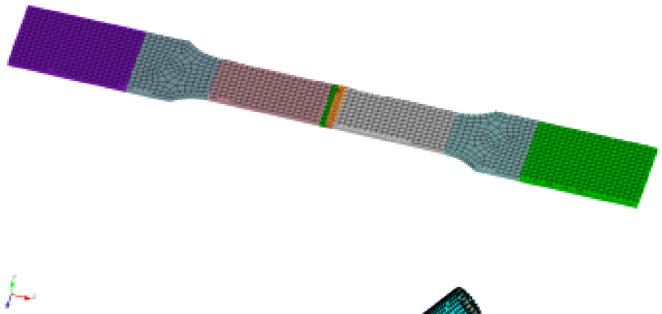


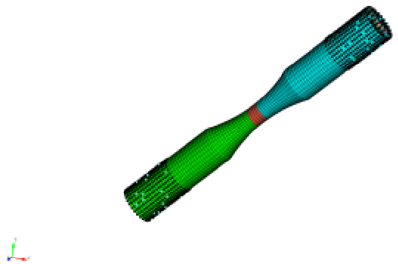
von Mises stress, Pa

Fatigue Methodologies for Welds

- We have 3 implemented fatigue methods for the weld
  - ASME BPVC fatigue methodology: Elastic-Plastic, and Weld Hot Spot
  - Signed von Mises Approach
- With all these methods we implement a filter to remove numerical high frequency chatter above the input Nyquist frequency
- We account for non-zero mean stress with Goodman or Smith-Watson-Topper methods
  - Working on paper for this is novel given the positiveness of von Mises
- We establish credibility in this post processing step with simple regression tests of the codes and comparing to test data
- There are several factors that influence weld fatigue strength: penetration, cold lap size, inner lack of fusion, weld toe transition, porosity, undercut size, heat effected zone, mis-alignment, etc.
  - Without x-ray these have to be accounted for in the S-N data or fatigue reduction factor.
  - We attempt to simulate the heat effected zone

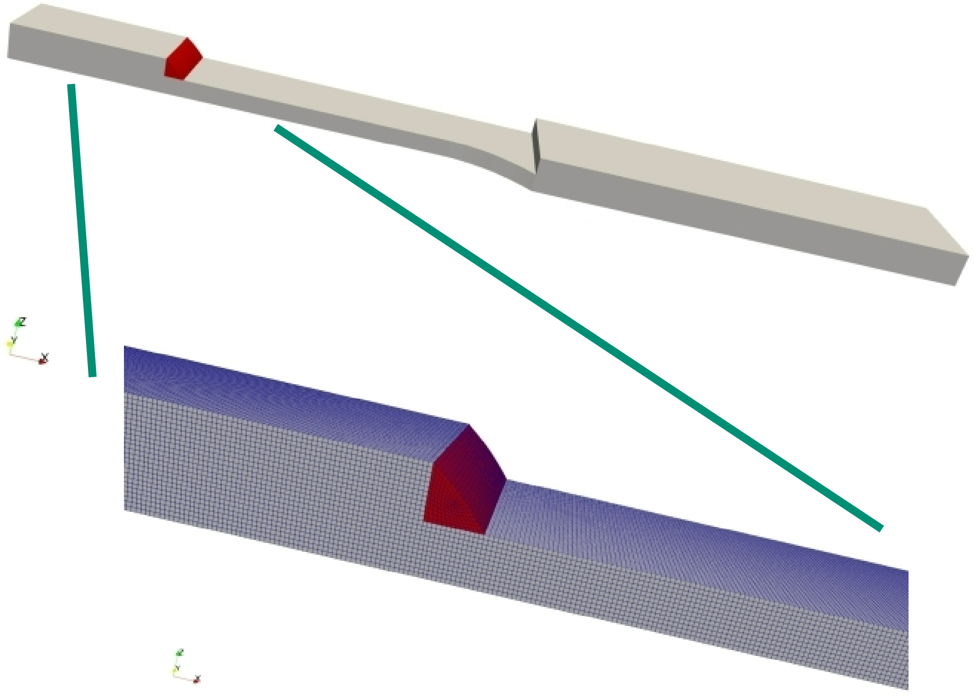




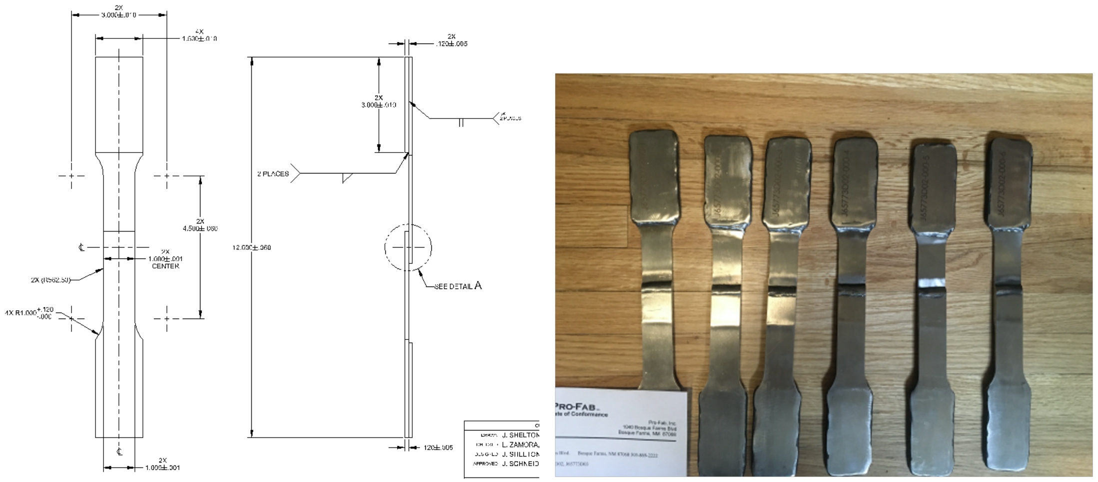


Example Problem: Fillet Weld Test Specimen

- ¼ symmetry high-resolution model
- Low-resolution shell model



High-resolution model



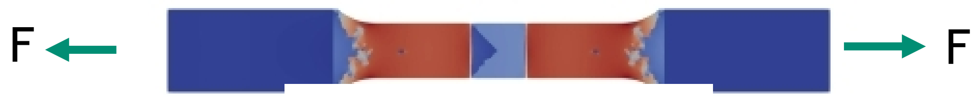
(a) Drawing (b) Actual Specimen

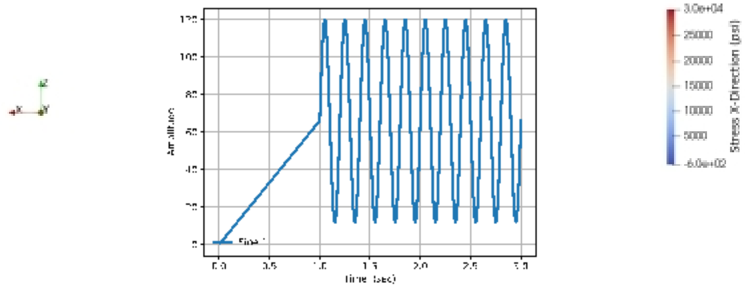
Figure 2: Fillet weld joint specimen.

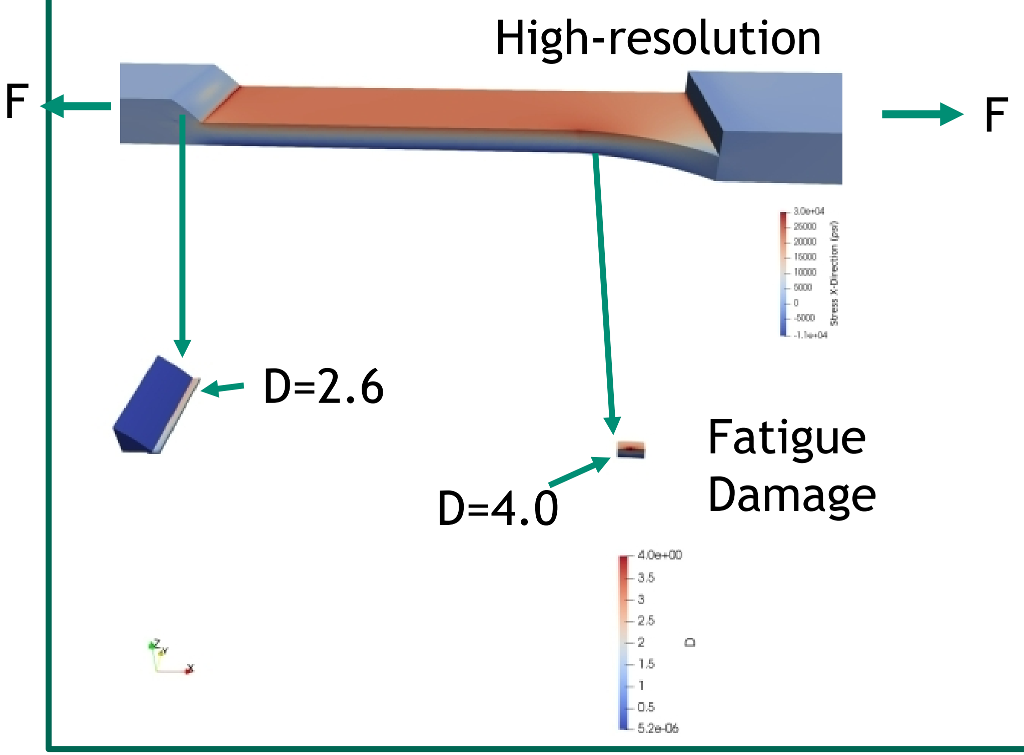
Low-resolution model

Fillet Weld: Axial Load

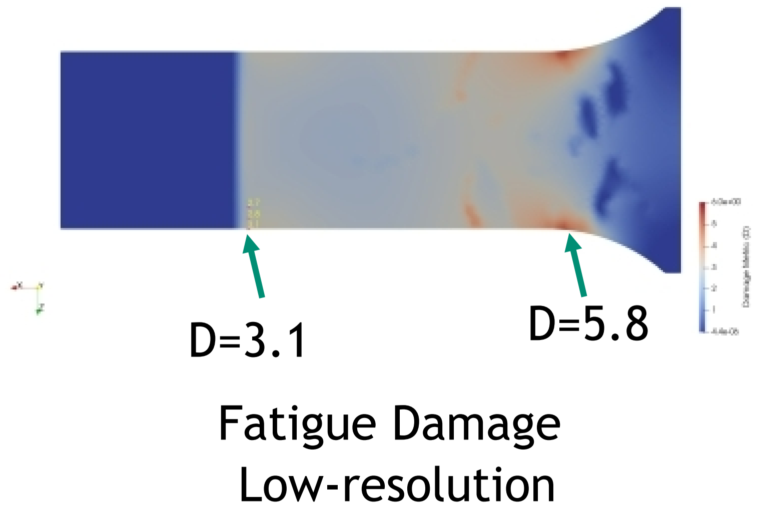
- Apply load to get 30*ksi* at weld in transient stress state with R = 0.1
- $K_f = 1.7$
- 429,941 cycles
- No fatigue Damage in Actual Weld, but at toe





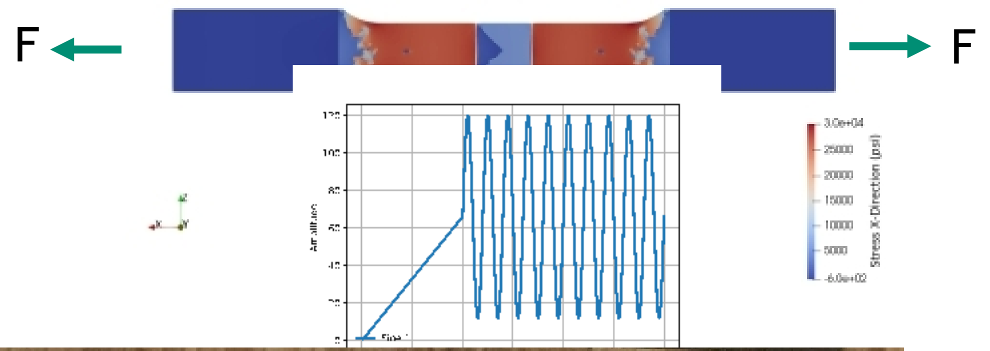


Using S/N curve for Welds throughout



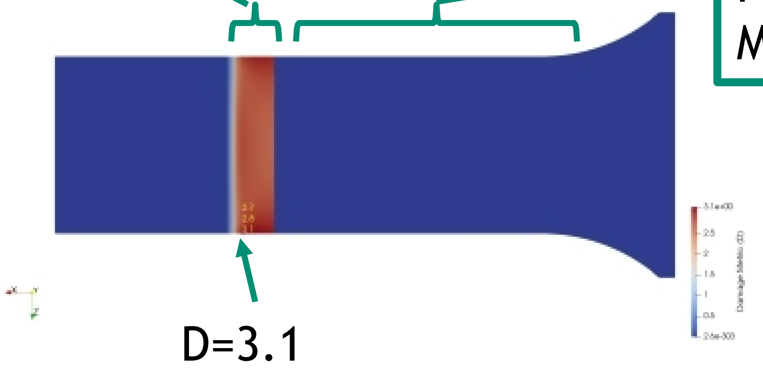
Fillet Weld: Axial Load

- Apply load to get 30*ksi* at weld in transient stress state with R = 0.1
- $K_f = 1.7$
- 429,941 cycles
- No fatigue Damage in Actual Weld, but at toe
- Question comes where do we stop using the S/N curve for the weld and transition to the S/N of the parent material

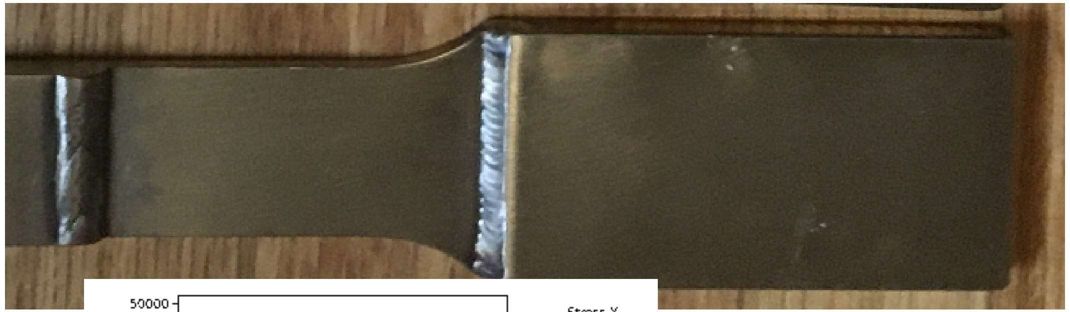


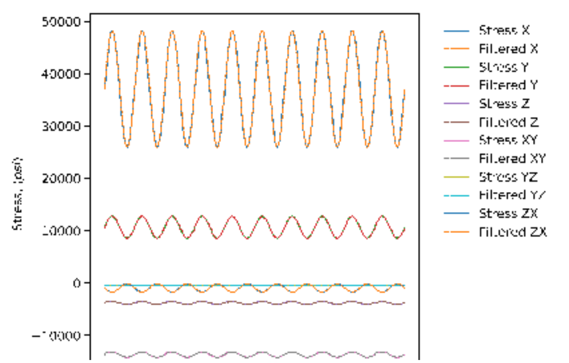
Using S/N curve for Welds

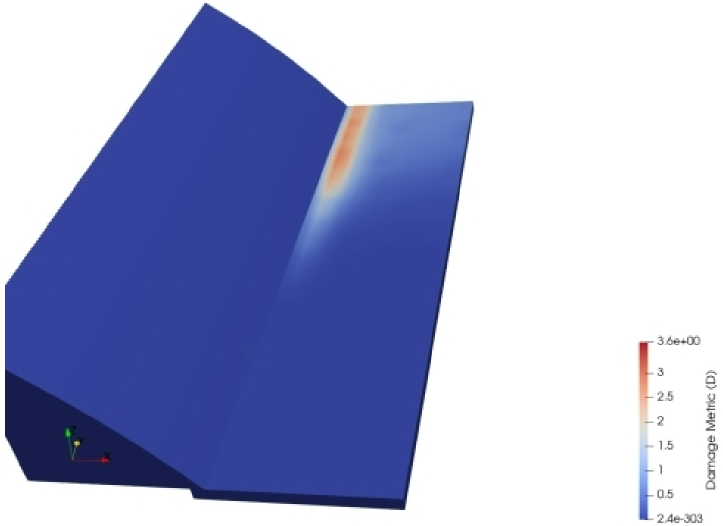
Using S/N curve for Parent Material



Residual Stress Fatigue Predictions







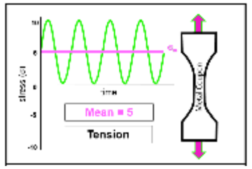
- Superimpose residual stresses on to load stresses
- Use S/N of Parent material
- Need an additional factor of 1.5 multiplying to stresses to get damage to be seen
  - There is roughly a factor of 4 difference between paraent material S/N curve and Weld S/N curve
  - Thus, we think 2.5 is due to residual stress and the other 1.5 is potentially due to ”weld defects”
- Heat affected zone is roughly the length of the

Conclusions

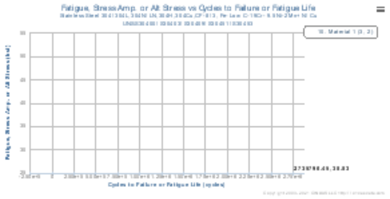
- In this particular example, we observe that the failure of the weld is near the toe of the weld
- The heat affected zone extends from the toe of the weld outwards about the length of the weld in the particular example we looked at.
  - Several factors (material, intensity of heat, etc.) influence this
- Multi-scale process for checking low-resolution model predictions at areas of concern
  - Uses a *line weld* implemented in the SIERRA software
- Future work: Try include other weld defect issues in model

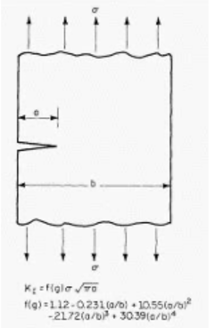
BACK-UPS

Fatigue Lectures

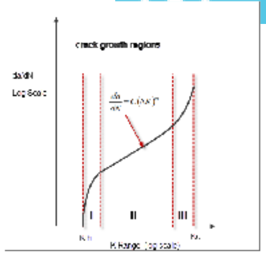


Stress-Life Cycle (S-N)
Approach (Also Strain)





LEFM



Session 1 - Fatigue and Fracture Mechanics

- Introduction to Fatigue analysis
- High Cycle Fatigue methods
- S-N Curve
  - Definition and Usage
  - Endurance Limit
  - Data Sources
- Mean Stress Effects
- Fatigue Correction Factors
- Loading Environment
  - Miner's Rule
- Low Cycle Fatigue methods – overview
  - Strain Life
  - True Stress and Strain
  - Cyclic Stress Strain history
- FEA application of Fatigue Analysis
- Homework

Session 2 – Fatigue and Fracture Mechanics

- Homework Review
- Notch Effects in High Cycle Fatigue
- Low cycle fatigue
  - Notch Effects
  - Neuber Method
  - Peterson Method
  - Stress Gradient Method
  - Worked example
  - True stress strain definitions
  - Mean Stress Effects
- Loading History definition
  - Cycle Counting Methods
- More FEA implications
- Workshops and homework

Session 3 - Fatigue and Fracture Mechanics

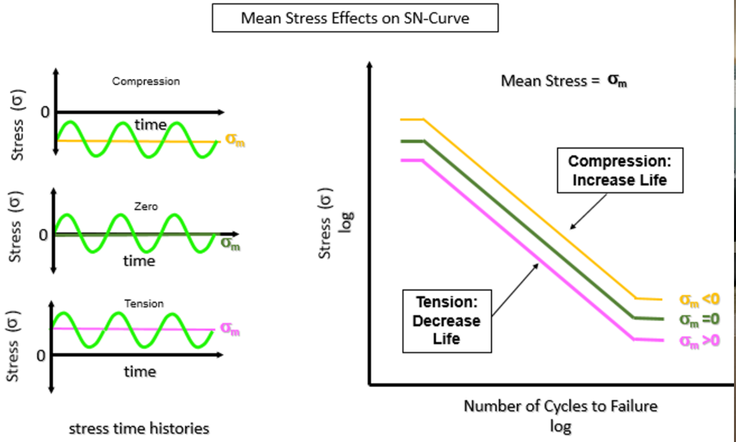
- Homework Review
- Multiaxial Fatigue
  - Proportional Loading
  - Non-Proportional Loading
  - Solution Methods
  - Checking Methods
- Vibration fatigue
  - Review of Random Vibration Analysis
  - Apparent Frequency and RMS values
  - Stress components
  - Von Mises results – caution
  - Damage calculation methods
- Workshops

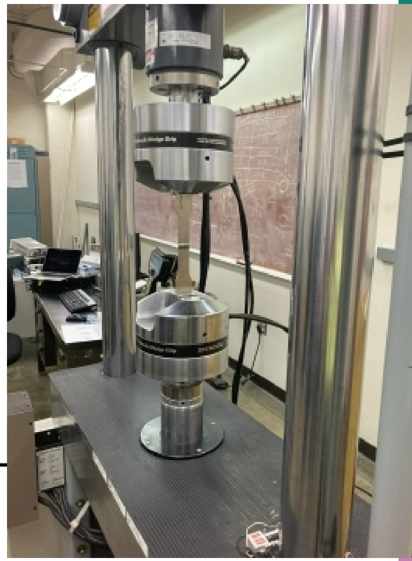
Session 4 - Fatigue and Fracture Mechanics

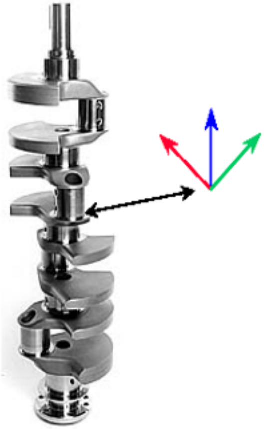
- Introduction to Fracture Mechanics methods
- Fracture mechanics
  - Crack Loading Modes
  - Stress Intensity Factor
  - FEA Implementation Methods
  - Virtual Crack Closure Method
  - Crack growth and re-meshing
- Fatigue in Composites
  - Overview of Fatigue in Composites
  - Micro-mechanical behavior
  - Fatigue Prediction
  - Practical Applications

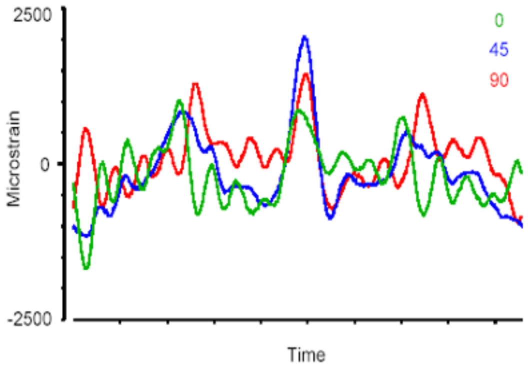
Fatigue Stress-Life Approach

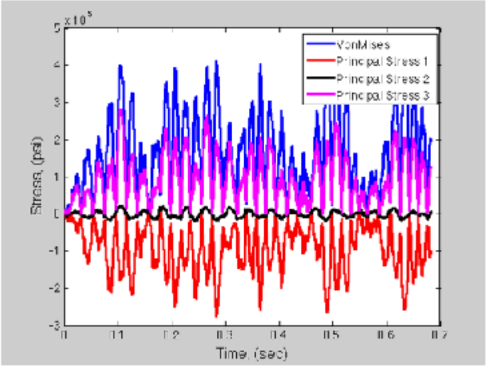
- If the loading was simple and sinusoidal then I could easily compare stress to experiment
- The trick though is with complicated (multi-axial) loading, how do I relate the stress tensor (6 components) to a simple tension fatigue test
  - *Equivalent Stress*
- Get's more complicated with a stochastic process of random vibration.

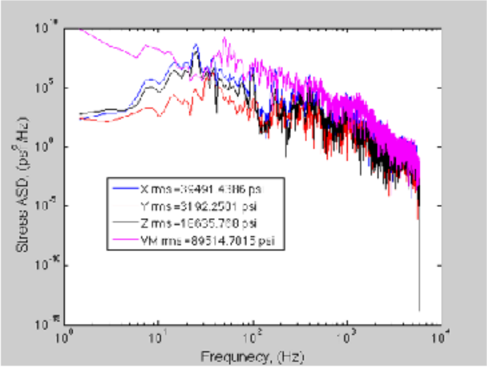






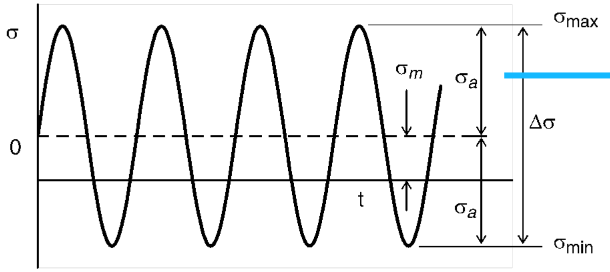






Fatigue Stress-Life Approach

- Ultimately, in some manner we will relate a stress tensor history, $\sigma_{ij}(t)$, in an element to tensile experiment S-N curve.



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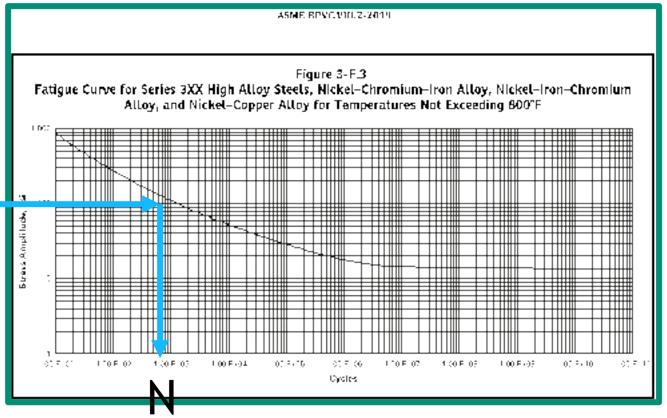

N

- Each cycle gives an *equivalent stress*, Using S-N curve I pick off the number of cycles that *equivalent stress* could last (N),
- Using Miner's Rule we can ultimately form a Damage metric

$$D_{total} = \sum_{k=1}^{M} \frac{n_k}{N_k}$$

D<1, Life is good