REFERENCE STRESS ESTIMATION FOR ANISOTROPIC MATERIALS USING LINEAR ELASTIC FINITE ELEMENT RESULTS

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Condition Based Engineering

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- **Legal Disclaimer:**

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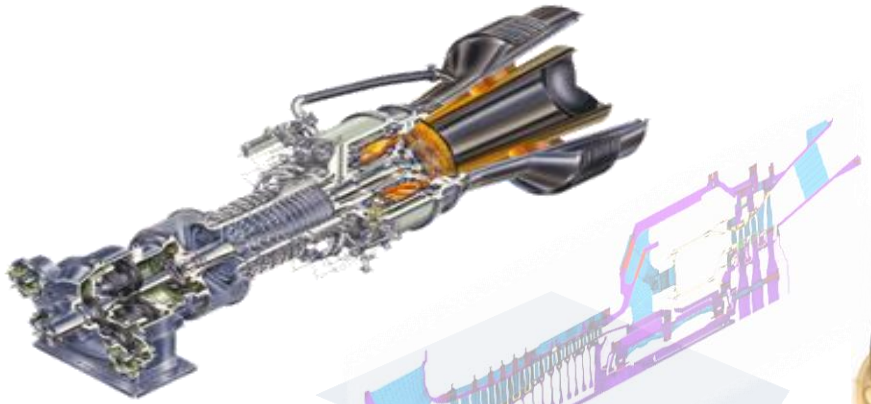
Overview of Condition Based Engineering

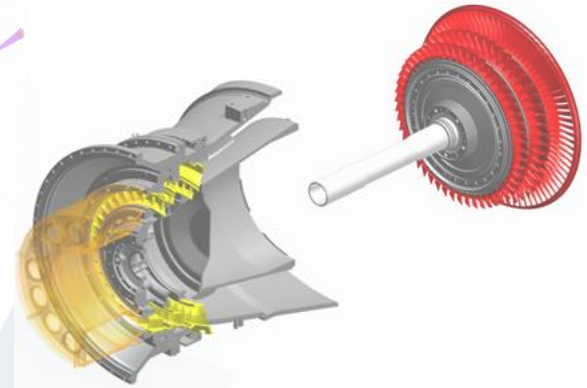
Condition-Based Engineering

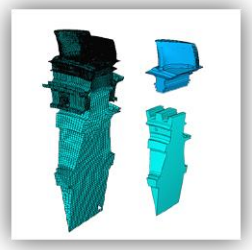
- Develop and Deploy Digital Assists
  - Combines Machine Data with First Principle Engineering
    - Blending physics based and data driven models to create functional replica's of physical assets operating in the field

- Asset Optimization:
  - To forecast a continuous and accurate risk profile for optimal asset management
  - Improving life cycle costs

Digital Asset Definition

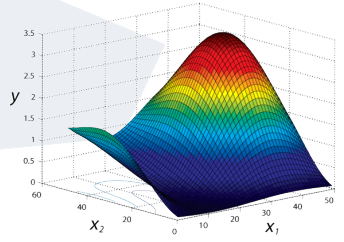


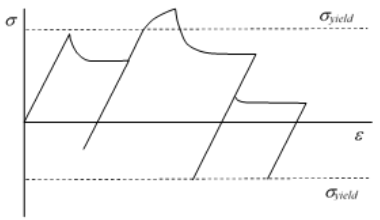




- Collection of data driven, physics based & hybrid models which replicates the key aspects of the engine

- Models which utilize operational data to predict the actual condition of the engine





- Enhancing Equipment Health Management (EHM)

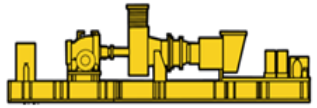
- To optimize the equipment and maximize value for the customer

Benefits of a Condition Based Approach

- Condition based approaches predict the non linear response, and don't rely on time to set the service interval
- To predict the actual status of the engine, (in place of assumption)

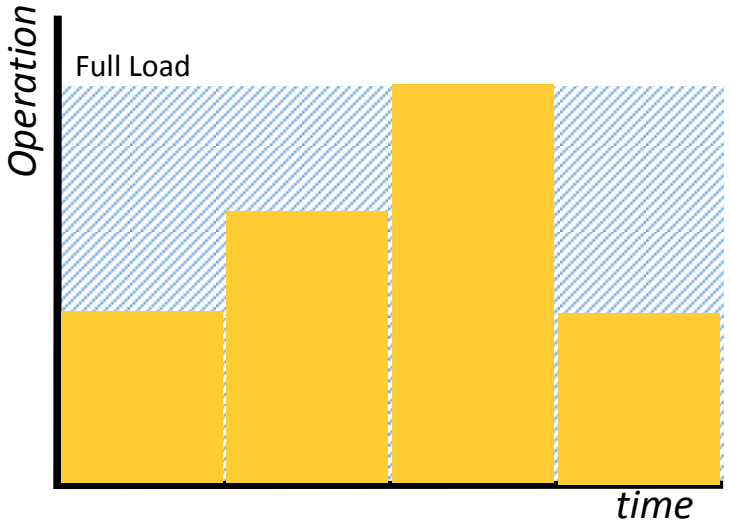
Physical Asset

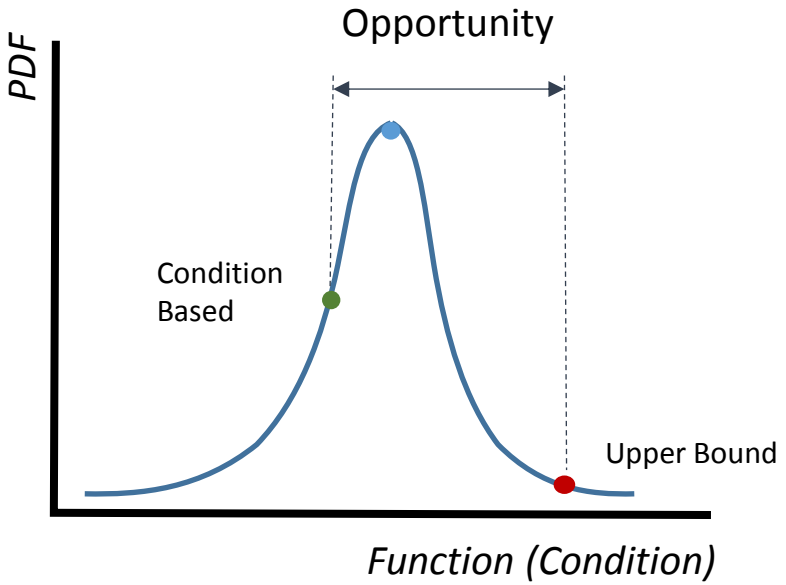
Operational Data



Digital Asset

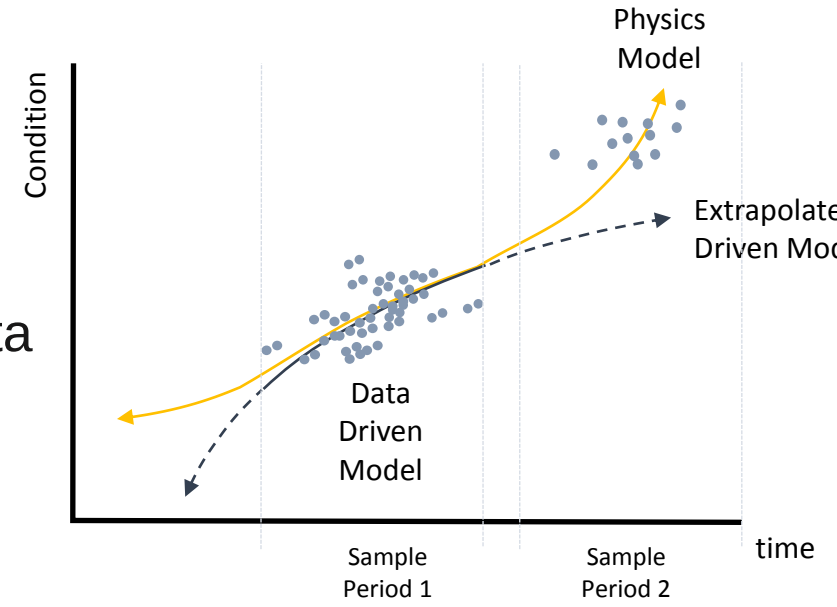
Predicts Remaining Useful Life





Value of Physics Based Models

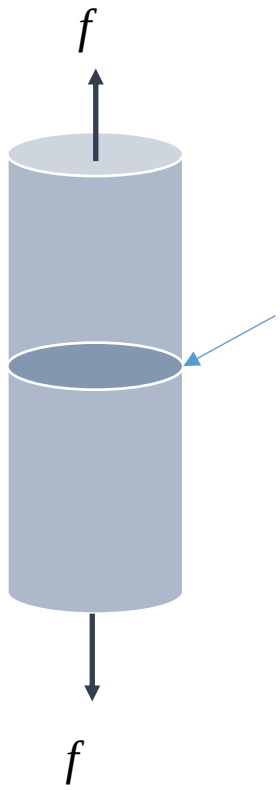
- First Principal Engineering:
  - Bound models that require specific (coupled) data
- Capable of modeling complex behaviors
  - Structured and predictable, requiring specific inputs
  - Do not require constant validation or large data sets
  - Benefit from correlation with causation
  - Can be extrapolated with confidence
- The challenge of physics based models
  - Traditional approaches can be computationally inefficient



The data driven model can be updated to include the new data, but requires constant validation and large data sets in order to function

Reduced Order Models (ROMs)

- Simplified models which simulate physics to improve computational efficiency and speed
  - Hybrid Models:
    - Combined data driven & physics models to create a specific output
    - Physics based model with unbound (non physical) coefficients
  - Engineering Approximations:
    - Applicable to specific conditions taking advantage of simplified boundary condition or empirical data
    - Examples:
      - Equivalent Stress, (von Mises or Hill)
      - Uniaxial stress
      - Stress concentration factors (K_t)
      - Notch root hypothesis
      - **Reference Stress**



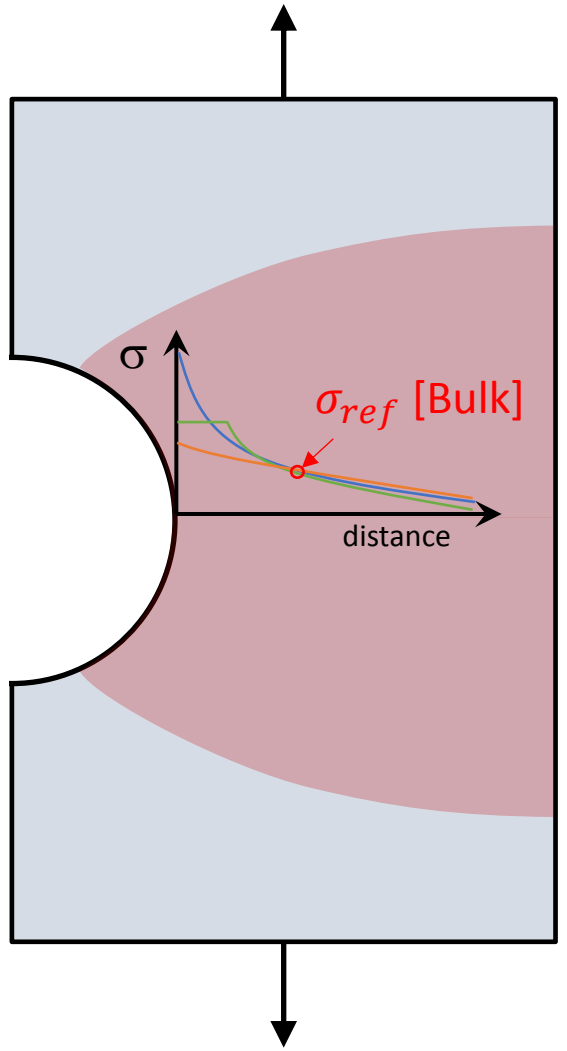
$$\sigma = \frac{f}{a}$$

Simple approximation of a stress tensor, taking advantage of the uniaxial boundary conditions

Can be combined with a stress concentration to approximate localized stresses at a notch or feature

Reference Stress

- Represents a generalized stress state (Bulk) within a structure
  - Can be used to assess structural integrity of components
  - Single value of stress that remains constant throughout the life of the component
  - For simple geometries, handbook solutions can be referenced
  - Complex geometries require a calculation method
  - Limited to applications that do not undergo gross plasticity (plastic collapse)



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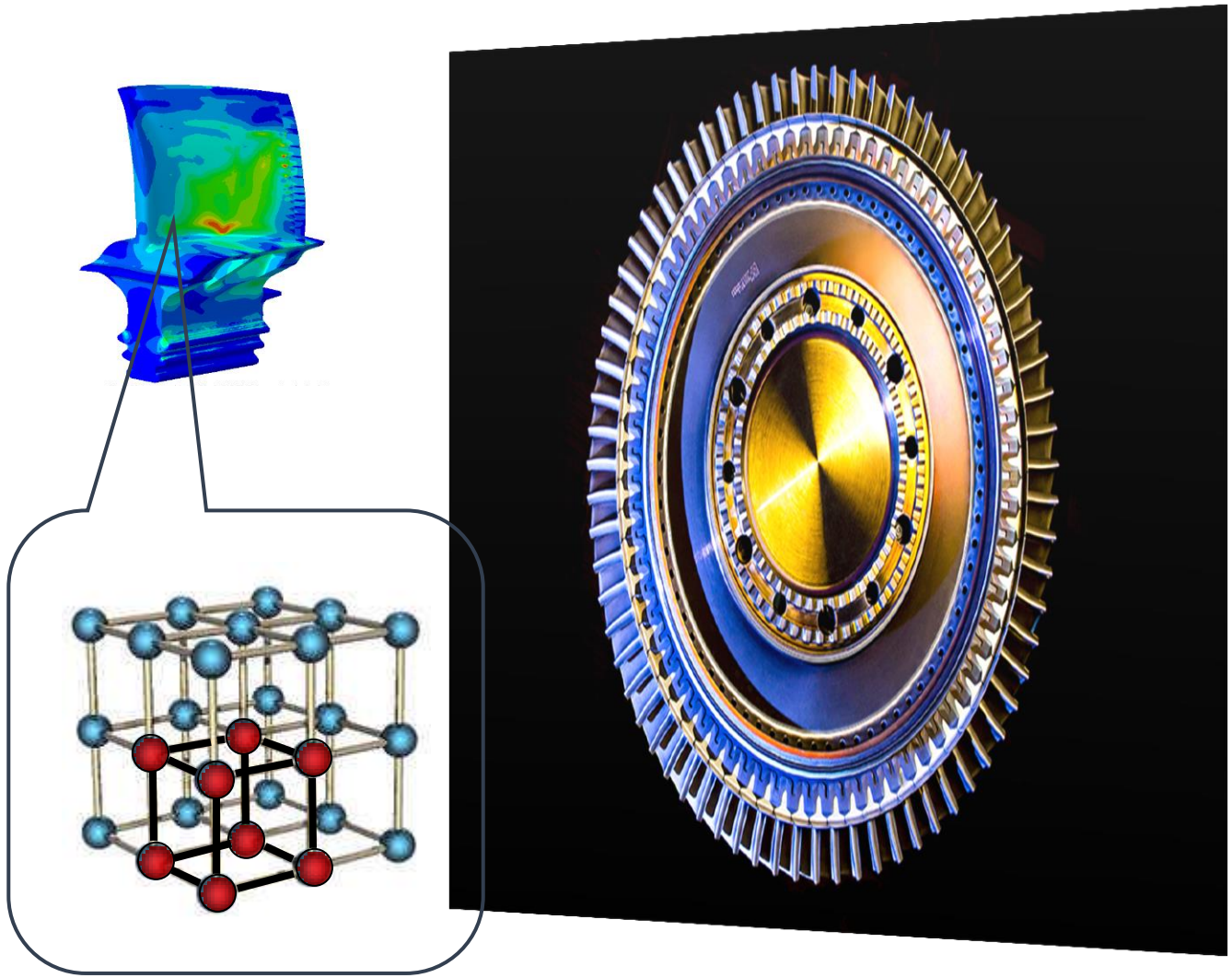
Reference stress for Single Crystal blades

What is Anisotropy?

- Components such as turbine blades can be cast as a single crystal
  - No grain boundaries

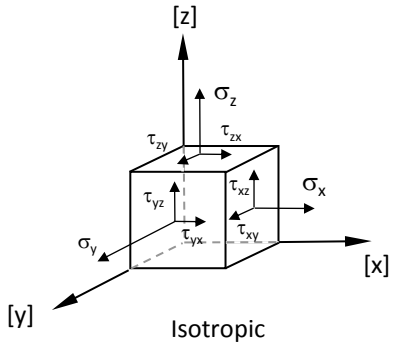
- Single Crystals are anisotropic materials and have directionally dependent behavior
  - Provide improved high temperature capabilities
  - Creep Resistance



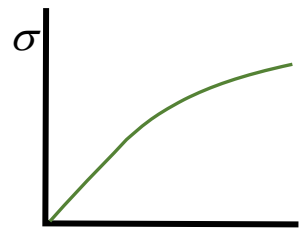
Challenges of Anisotropy

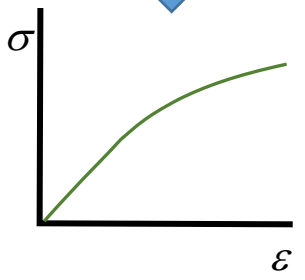
- Difficult to predict stress state
  - Need to predict shear strains on the active slip systems
- Damage accumulation is non linear and therefore path dependent
- Significant challenge
  - Typically addressed with constitutive models
  - High fidelity numerical analysis (FEA)
  - How do we accomplish this for Digital Assets?

FCC Isotropic System

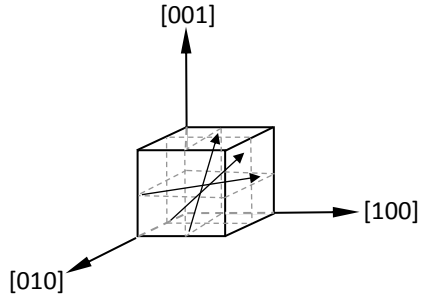


Isotropic

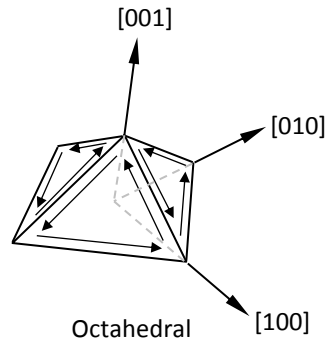




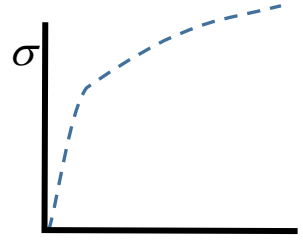
FCC Anisotropic System

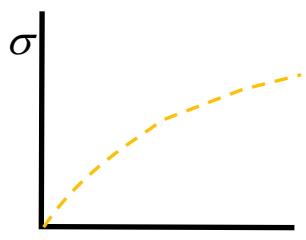


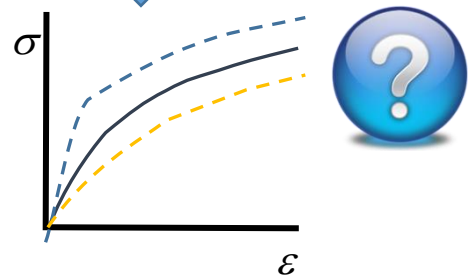
Cubic



Octahedral



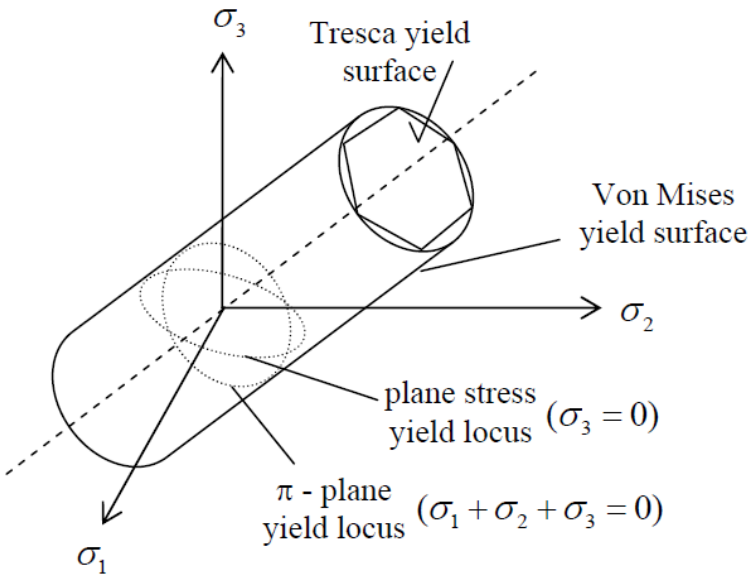




Negating Isotropic hardening affects

Simplified Approach to Anisotropy

- Hill Model
  - Provides a unified yield criteria needed for bulk integration
    - Avoids modeling individual shear strains on the active slip systems
  - Yield condition can be estimated using Hill yield criterion
    - combines anisotropic yield properties into one equation
  - Sufficiently accurate for bulk plasticity estimations



$$f(s_{ij}) = \frac{1}{2} C_{ijkl} s_{ij} s_{kl} - 1$$

Hill equation

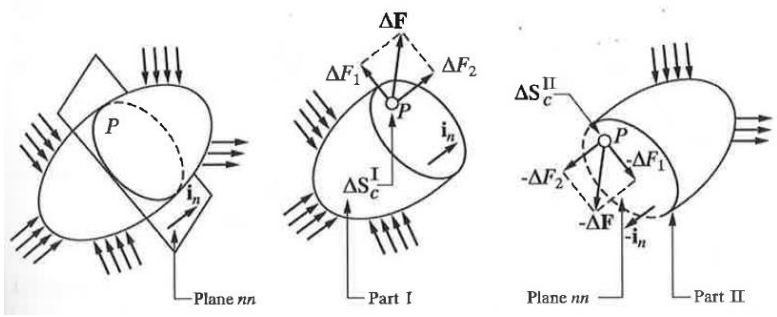
Ref. Hill, R., The Mathematical Theory of Plasticity, Oxford University Press, 1950, pg 318-320

Simplified Approach to Anisotropy

- Energy Balance
  - Using this approach to balance external loads with the internal forces
  - We can integrate anisotropic yield properties from the Hill criterion into this model
  - From this we can determine the limit load multiplier

$$F = \int_V s_{ij}\frac{1}{2}(v_{i,j} + v_{j,i})dV + \int_V \sigma\delta_{ij}v_{i,j}dV - \int_{S_V} R_i v_i dS - m\left(\int_{S_T} T_i\, v_i dS - 1\right) - \int_V \mu\left[f(s_{ij}) + \phi^2\right]dV$$

Mura, T., Lee, S.L., Applications of Variational Principles to Limit Analysis, Q. Appl. Math, Vol 21, No. 3, 1963, pg 243-248



Armenakas, A.E., Advanced Mechanics of Materials and Applied Elasticity, Taylor & Francis Group, 2006, pg. 67.

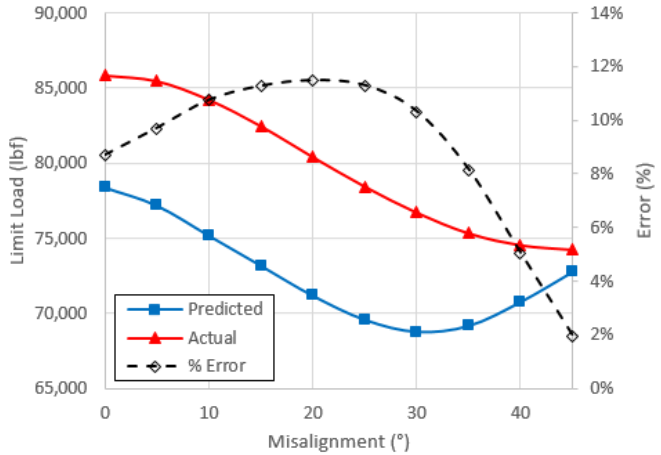
$$m' = \frac{m^0}{1+G}$$

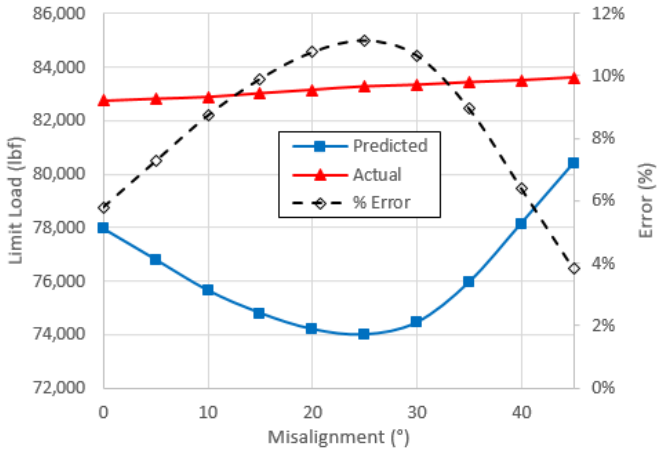
$$m^0 = \sqrt{\frac{V_T}{\int_{V_T}\frac{1}{2}C_{ijkl}s_{ij}s_{kl}dV}}$$

$$G = \frac{1}{2}\sqrt{\frac{\int_{V_T}\left[\frac{1}{2}(m^0)^2 C_{ijkl}s_{ij}s_{kl} - 1\right]^2 dV}{V_T}}$$

Simplified Approach to Anisotropy

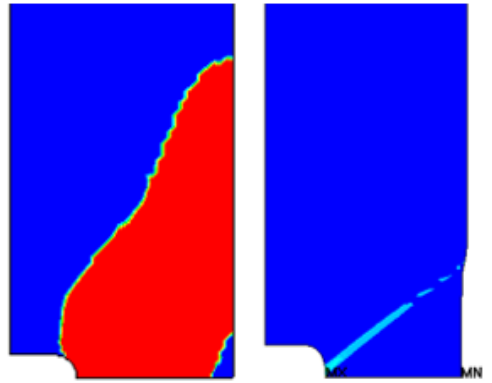
- Validation
  - Compared prediction to non-linear FEA
    - Tested at various orientations
    - Results are in a relatively good agreement for a reduced order model (~10%)
    - Conservative for bulk redistribution regions with large deviation in orientations
  - Findings
    - Once bulk yielding had occurred, the stress tensors aligned with load
      - Implication is that once bulk yielding occurs, misalignment is insignificant
    - This could be a potential source of anisotropic yield strengthening
      - Material testing should validate this hypothesis

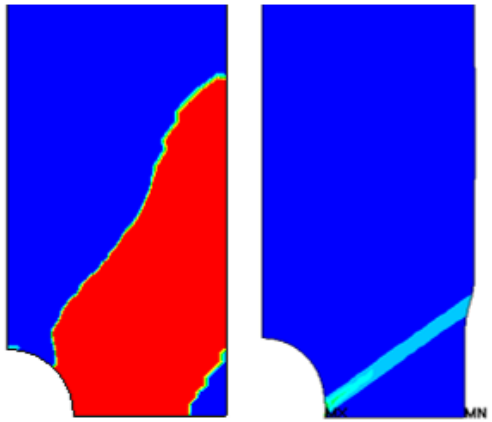




Ref Stress macro – Estimated Redistribution region

FEA with Hill Criteria





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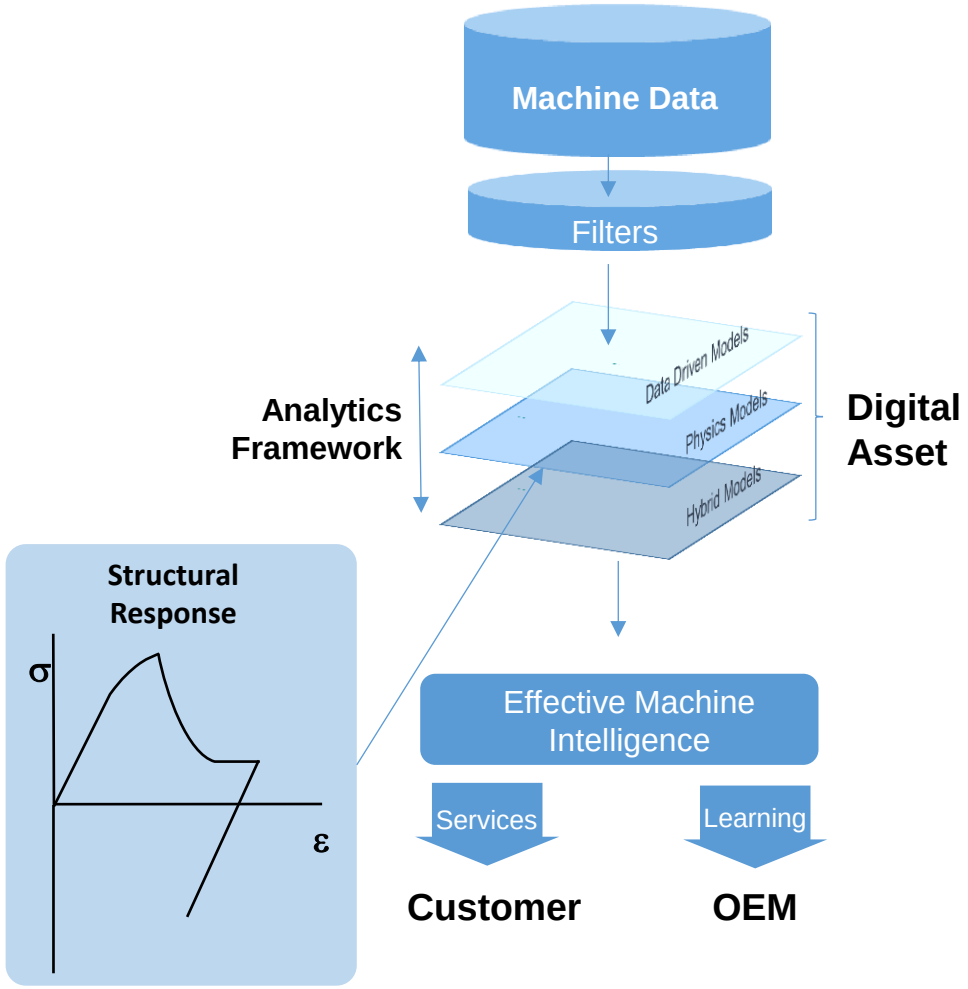
Conclusions

Conclusions

- Digital Assets:
  - Use operational data with a blend of data driven and computationally efficient physics based models in order to effectively manage risk
    - Predicting the life of critical hot section components such as SC blades is key to managing the health of the equipment
- Physics Models:
  - 1D approximations are highly effective within specific constraints
    - Reference stress is a key element for a reduced order approach to component life prediction
    - An anisotropic reference stress models is proposed which agrees reasonably well with the full order model
- Creep – Fatigue Interaction
  - Reference stress is used to model more advanced material behavior
    - Such as stress relaxation and rupture reference stress which are key to modeling creep-fatigue interaction



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