Application of Bayesian Inference for Increasing Rocket Engine Reliability and its Uncertainty Quantification

Presenter: Dani McDowell |**Co-Authors:** Shreyas Lakshmipuram Raghu

Advisor: Dr. L. Dale Thomas

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Complex Systems Integration Laboratory

Presentation Agenda

- **Introduction** — Project Overview & Context
- **Background** — Foundations of the Structural Margin Approach
- **Methods** — Probabilistic Approaches to Development
- **Results & Discussion** — Application to Aerospace Materials
- **Conclusion** — Summary & Future Work

Introduction

Project Overview & Research Context

Research Team

Dani McDowell
Industrial & Systems Engineering
Graduate Researcher

Shreyas Lakshmipuram Raghu
Aerospace Systems Engineering
Ph.D. Candidate

L. Dale Thomas, Ph.D.
CSIL Director, Professor & Eminent Scholar of Systems Engineering

Gang Wang, Ph.D.
Mechanical & Aerospace Engineering
Associate Professor

RS-25 Affordability Project Overview

Context

The RS-25 Engine

Space Shuttle Main Engine

Space Launch Systems Core Stage Engines

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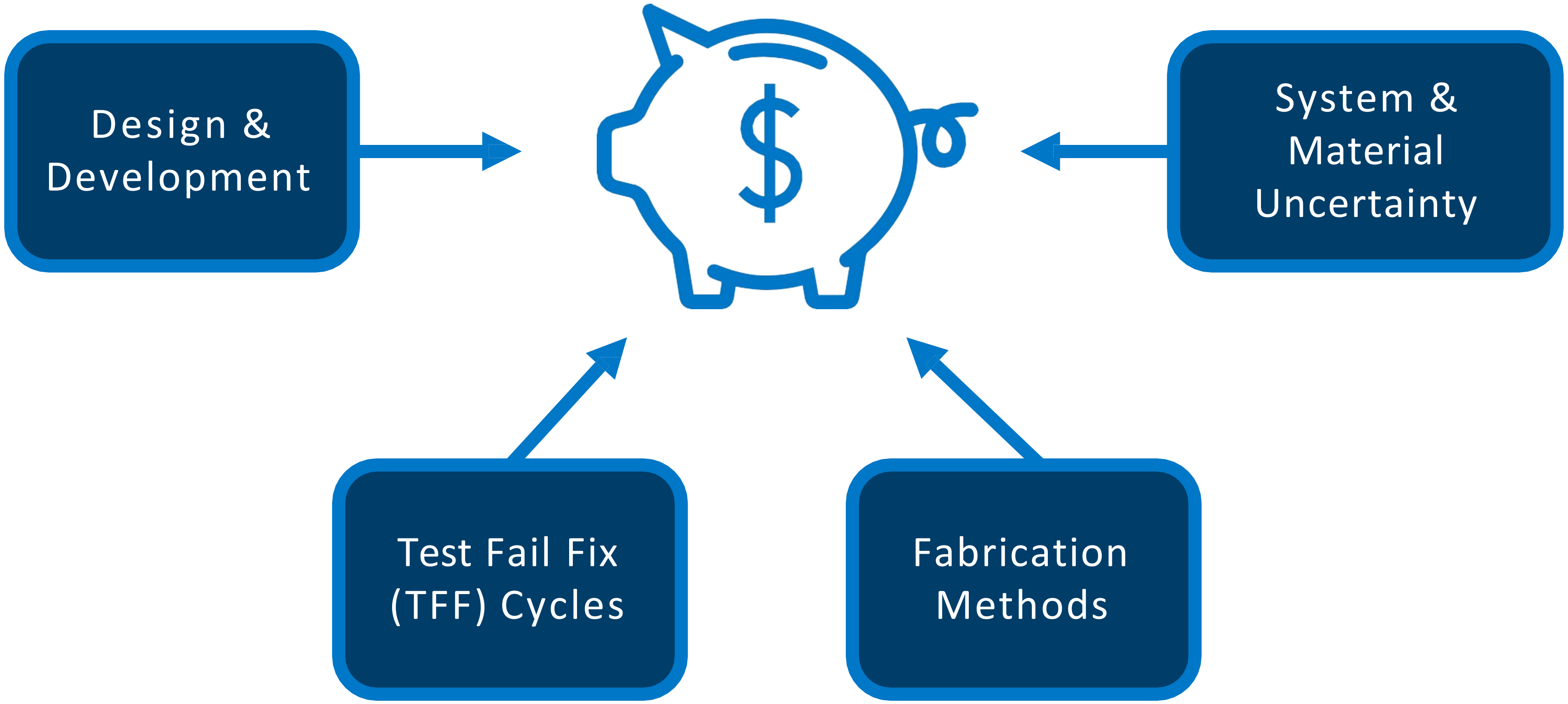
RS-25 Affordability Project Overview

Driving Forces of Cost



RS-25 Affordability Project Overview

Research Strategies to Address Costs

Design & Development
↓
Prioritize reliability early using Systems Engineering (SE) & MBSE tools

Test Fail Fix Cycles
↓
Implement probabilistic approaches to reduce failures

Fabrication Methods
↓
Explore the use of additive manufacturing (AM) methods

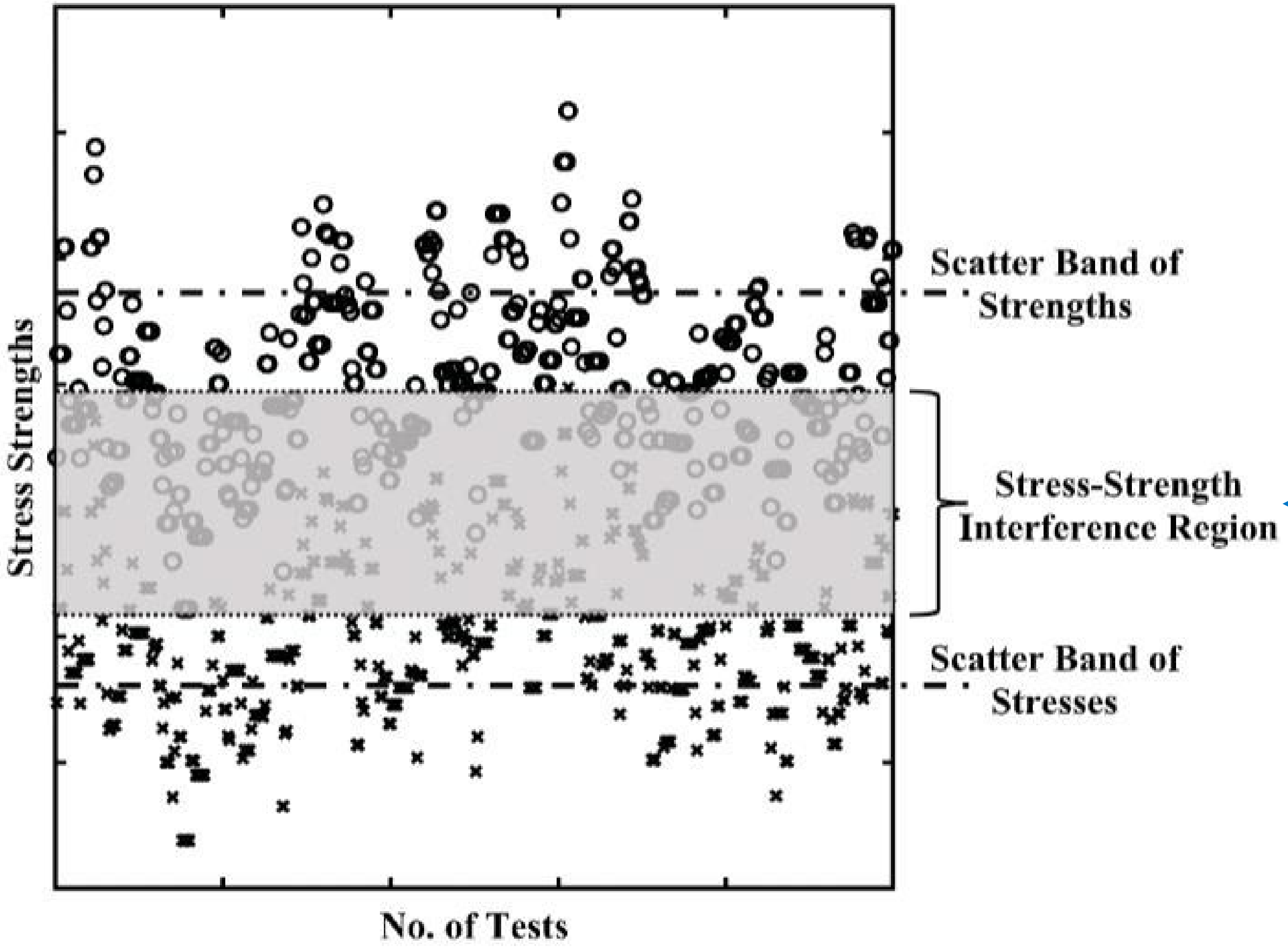
System & Material Uncertainty
↓
Explore uncertainty quantification (UQ) methods to characterize process & material relationships

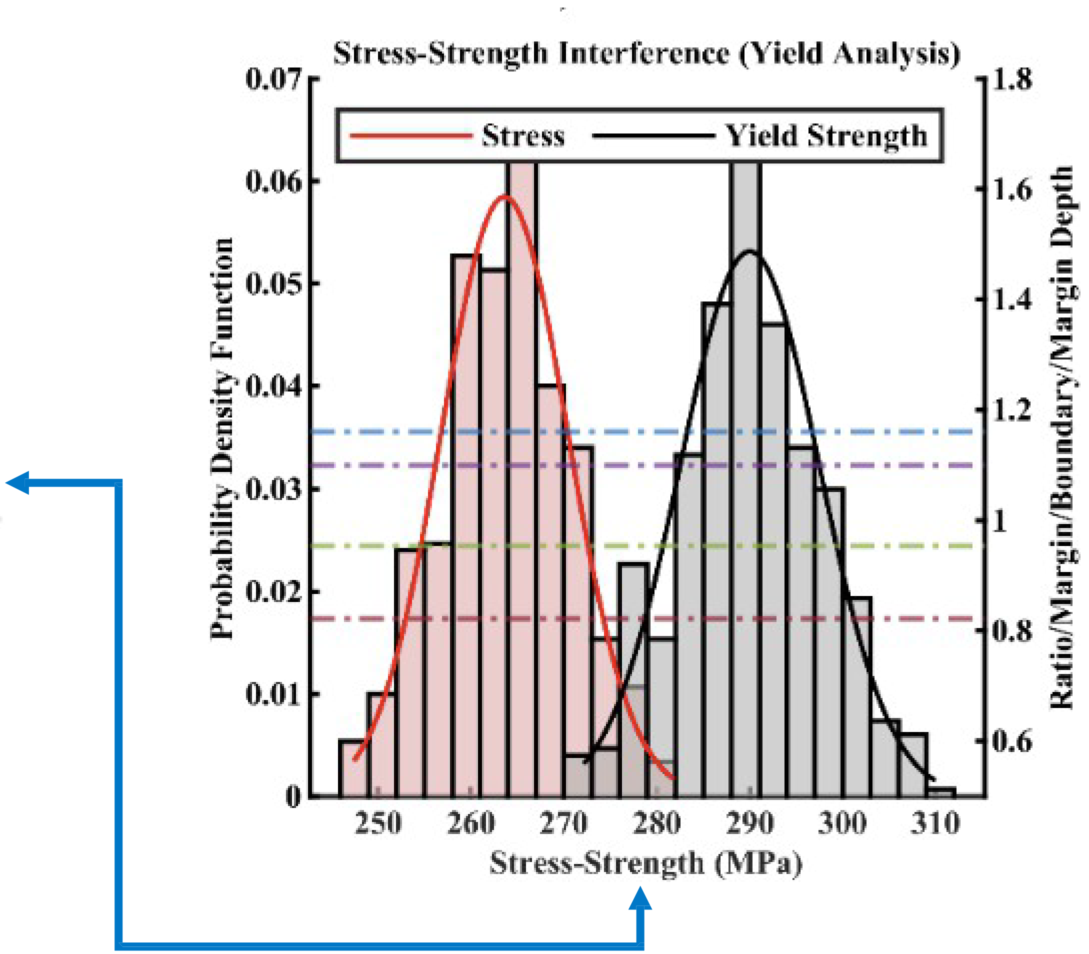
Background

Foundations of the Structural Margin Approach

Defining Failure Potential

Stress-Strength Interference





Deterministic Factors of Safety

$$\text{Factor of Safety (FOS)} = \frac{\text{Ultimate Tensile Strength}}{\text{Applied Stress}} \quad \text{OR} \quad \frac{\text{Yield Strength}}{\text{Applied Stress}}$$

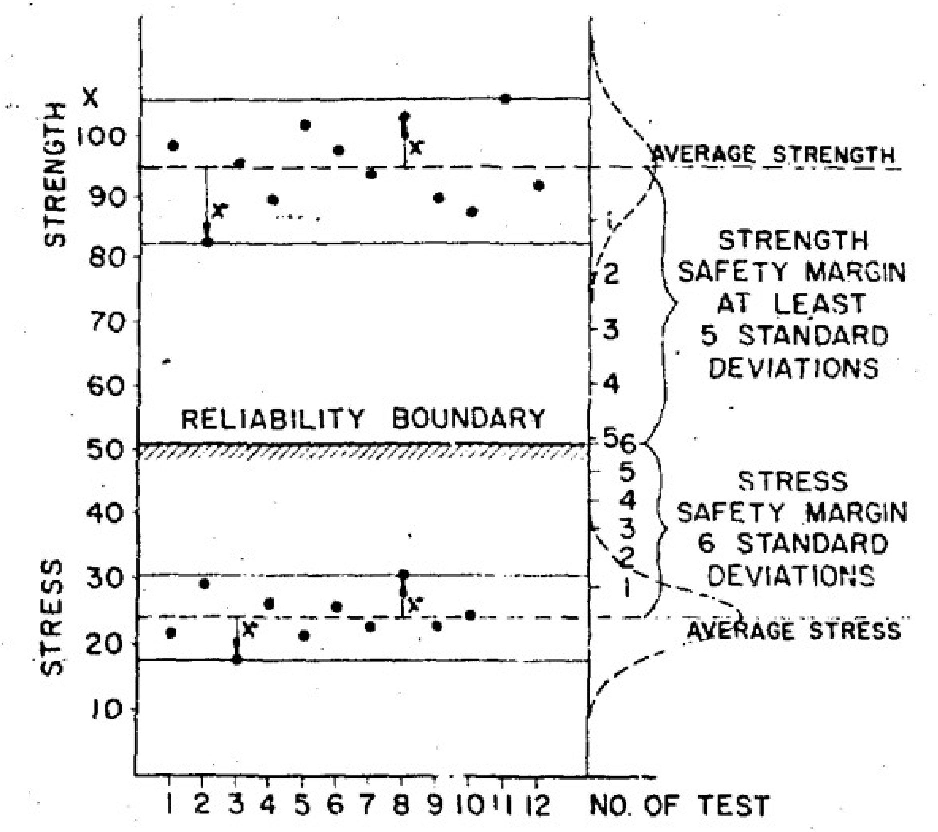
*Common values are 1.4 for Ultimate Analysis, and 1.1 for Yield Analysis

Lusser's Method

Developing Safety Margins

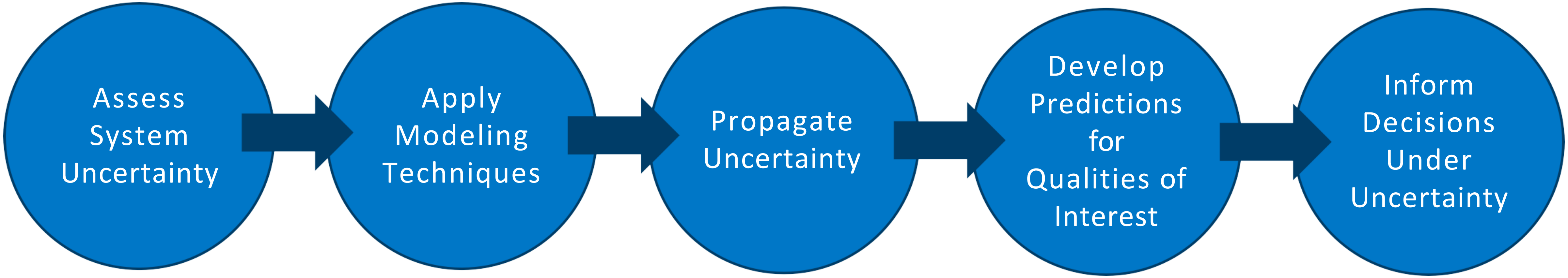
- Accounts for inherent variation relative to material strength and applied stress measurements

- Focusses on developing suitable safety margins based on standard deviations



How Scatterbands of Stress and Strength Shall be Separated by a Reliability Boundary [1]

Uncertainty Quantification for AM

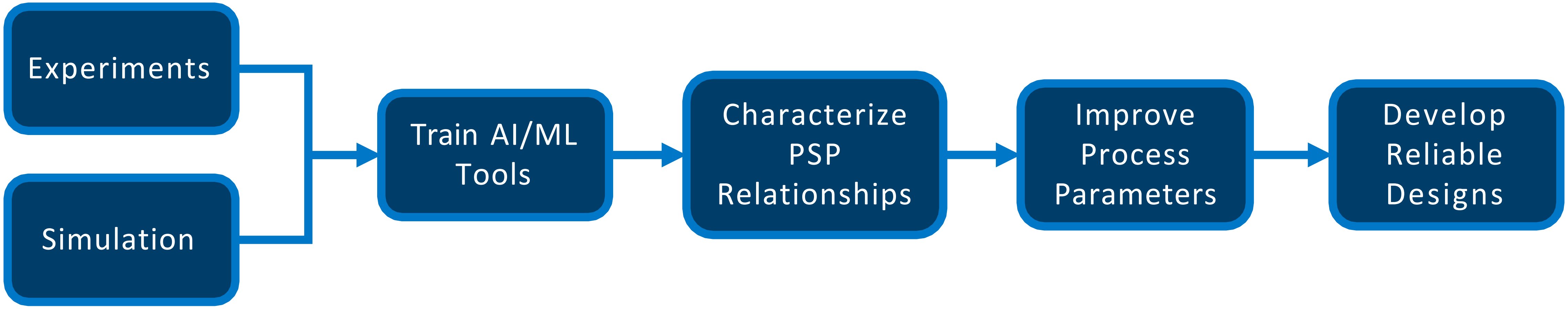


- Uncertainty quantification (UQ) is a tool used to characterize and evaluate uncertainties present in both physical systems and the computational tools used to model them
- Extensively used to understand Process-Structure-Property relationships for AM materials

Uncertainty Quantification

Usage of AI & Machine Learning Techniques

- Opportunity to learn more from experimental and training data
  - Possible integration with digital engineering tools and AM part production
  - Potential approach to enhancing performance and reliability

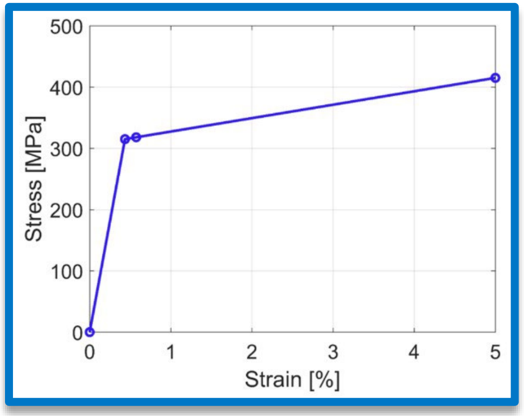


Methods

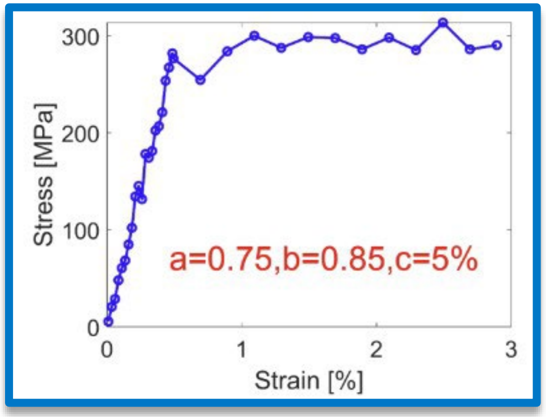
Probabilistic Approaches to Rocket Engine Development

Structural Margin Approach

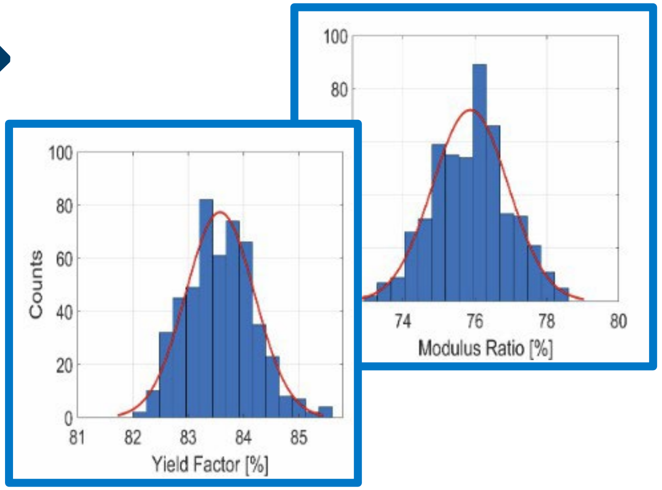
Overview



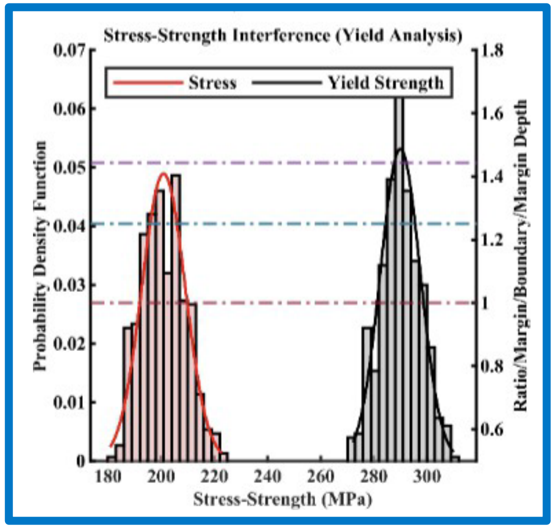
Develop Bilinear Stress-Strain Curves



Apply Noise & AM Reduction Effects



Develop Material Property Distributions



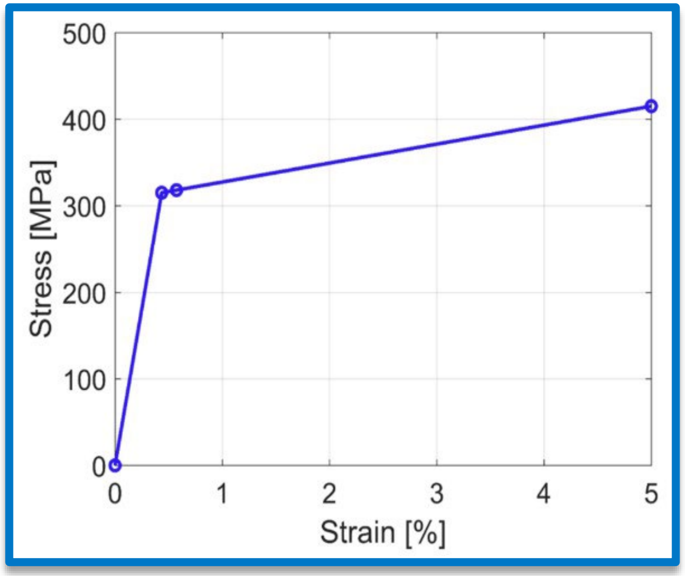
Create Stress-Strength Interference Plots

Obtaining Stress Strain Curves

Finite Element Analysis

- A simple, 1D rod was selected as the finite element
- Incremental load application formulas are employed to obtain uniaxial tensile load responses
- **Assumptions:**
  - Bilinear constitutive stress-strain relationship
  - Constant fracture strain

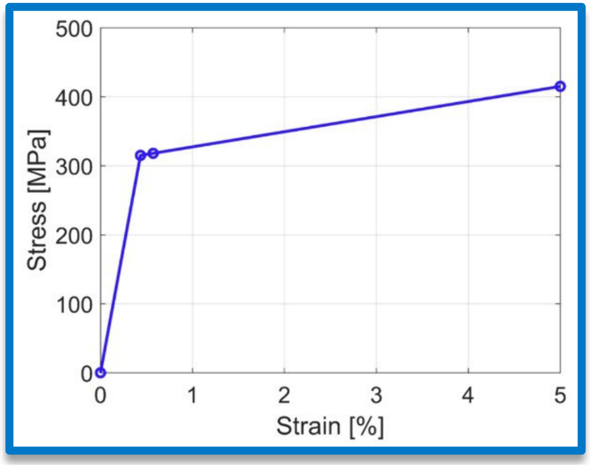
Nominal Material Properties:
Young's Modulus (E)
Yield Stress (Sy)
Strength (Su)
Fracture Strain (ε_u)

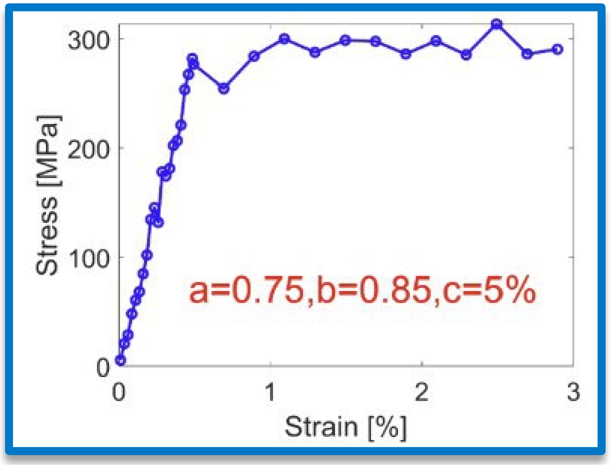


Introducing Uncertainty

AM Reduction Parameters & The Noise Factor

- Random noise is applied to simulate realistic data variation
- Reduction parameters are employed to simulate material property degradation due to AM
  - $E = aE$
  - $S_y = bS_y$

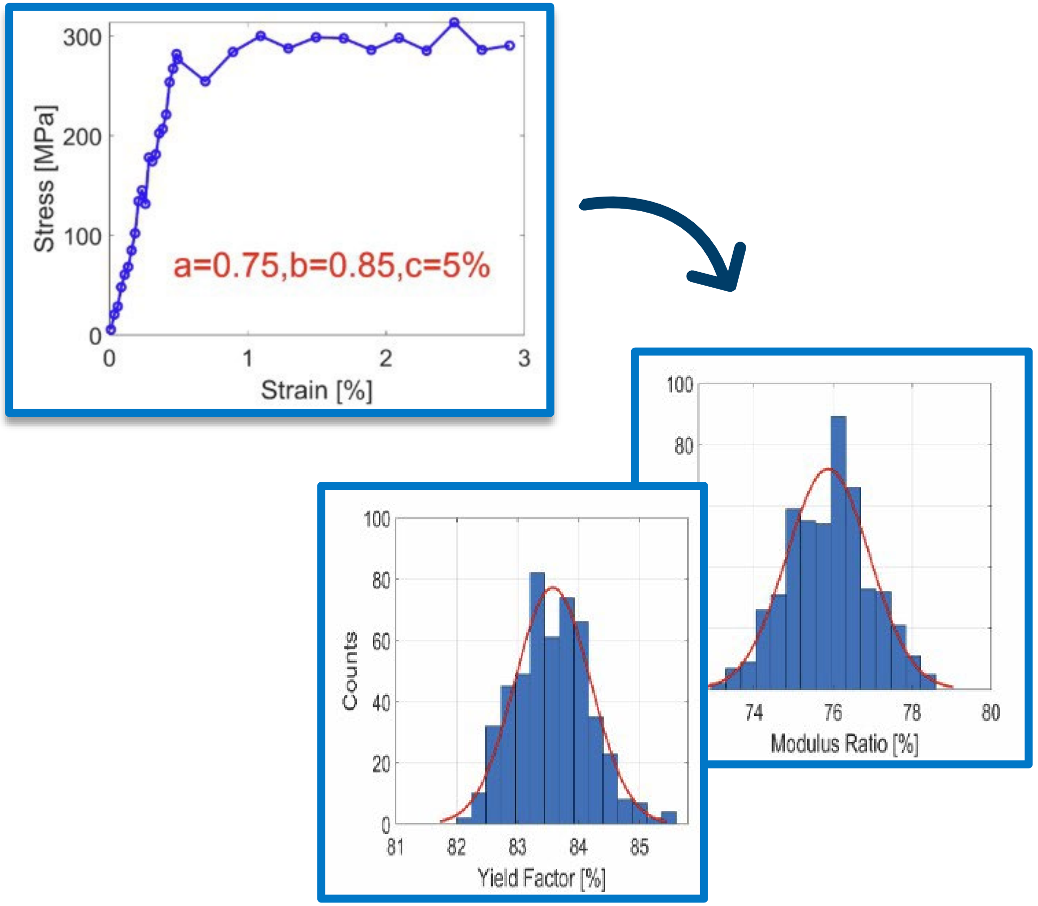




The Bayesian Inference Module

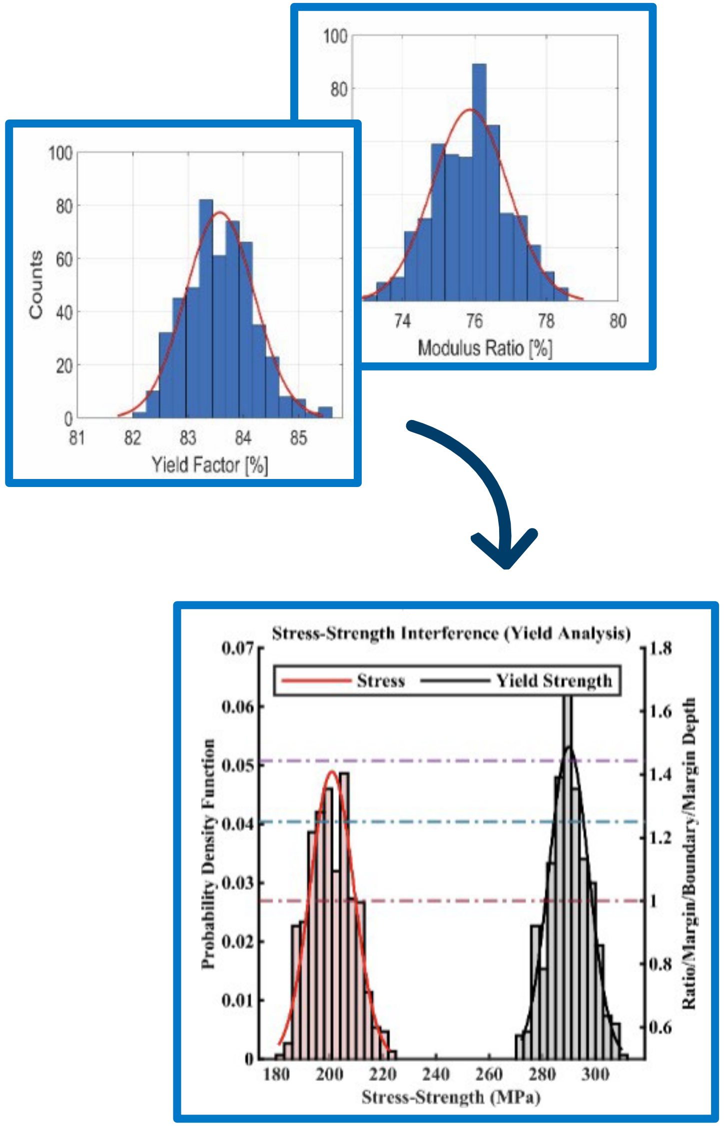
Markov Chain Monte Carlo (MCMC) Simulation

- Data with applied uncertainty is treated as a prior distribution and used to initiate an MCMC using the Random Walk Metropolis Algorithm
- The MCMC relies on the principles of Bayes Theorem to develop posterior distributions for the Yield Factor and Modulus Ratio from this data



Developing Stress Strength Interference Plots

- MCMC data is used to calculate:
  - A Yield Margin
  - A Reliability Boundary
  - Strength Distributions
  - Allowable stress distributions are calculated based on traditional FOS values and formulations from Lusser's method



Removing the Potential for Failure

Important Formulations

Derived From Lusser's Method

- **Reliability Boundary** $\equiv$ RB = $S + d(6\ STD_S)$
- **Yield Margin** = YM = $Sy - d(5\ STD_{Sy})$
  - d = correction factor based on sample size

Introduced in the Structural Margin Work

- **Margin Depth Variable** = MD = YM/RB
  - Used to assess potential failures
  - When **MD < 1**, a failure due to stress-strength overlap is expected
  - When **MD = 1**, no overlap is observed

Results & Discussion

Application to Aerospace Materials

Application of the Structural Margin Approach

Material System Studied: Al-2024T6

- Al-Cu alloy, desirable for its high strength-to-weight ratio
- Common material used in the aerospace industry
- Suitable material for research in AM

Reduction Factors & Noise

- 64 possible combinations
- Example Shown: a=75%, b=90%, c=15%

FOS Based Stress Strength Interference Plot

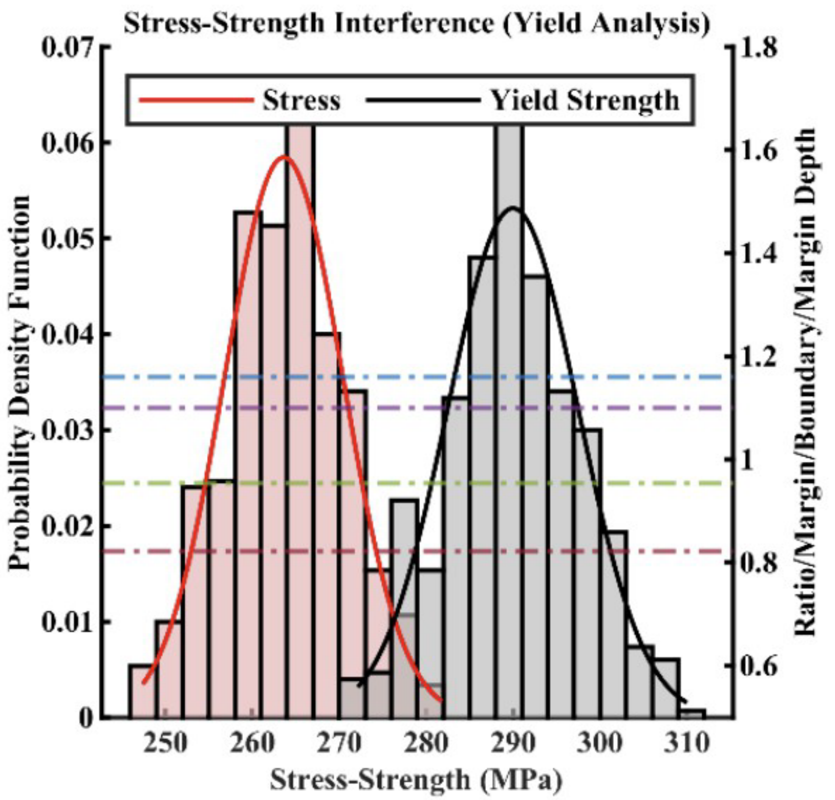
Applied Stress:

$$S = \frac{Sy}{FOS}$$

Strength:

$$Su = Sy + 0.03E\left(\varepsilon_u - \frac{Sy}{E}\right)$$

Ex: a=75%, b=90%, c=15%



(RB = 1.16, YSR = 1.1, YM = 0.9533, MD = 0.8219)

Structural Margin Based Stress Strength Interference Plot

Sets YM=RB → **MD is always 1**

Ex: a=75%, b=90%, c=15%

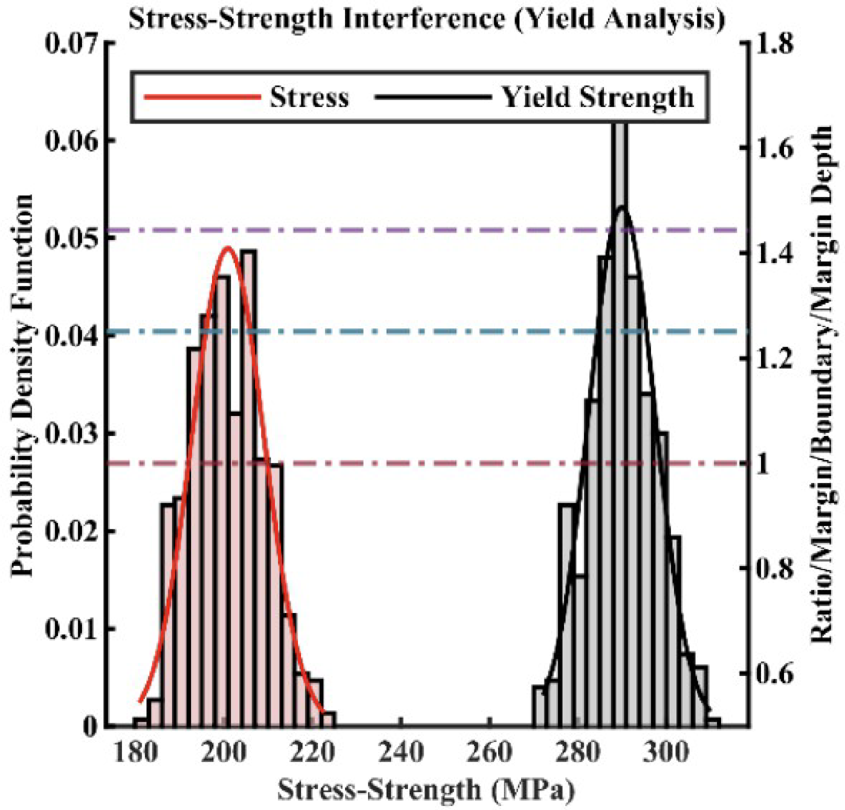
Applied Stress

$$\varepsilon = \frac{\overline{Sy} - d(5\ STD_{Sy})}{\overline{E} + d(6\ STD_{E})}$$

$$S = E\varepsilon$$

Strength

$$Su = Sy + 0.03E\left(\varepsilon_u - \frac{Sy}{E}\right)$$



(RB = 1.2509, YSR = 1.4433, YM = 1.2509, MD = 1.0)

Results

FOS Approach

Of the 64 cases studied, **50 resulted** in stress strength interference

- Higher failure potential
- Highlights inefficiencies of the FOS approach

Structural Margin Approach

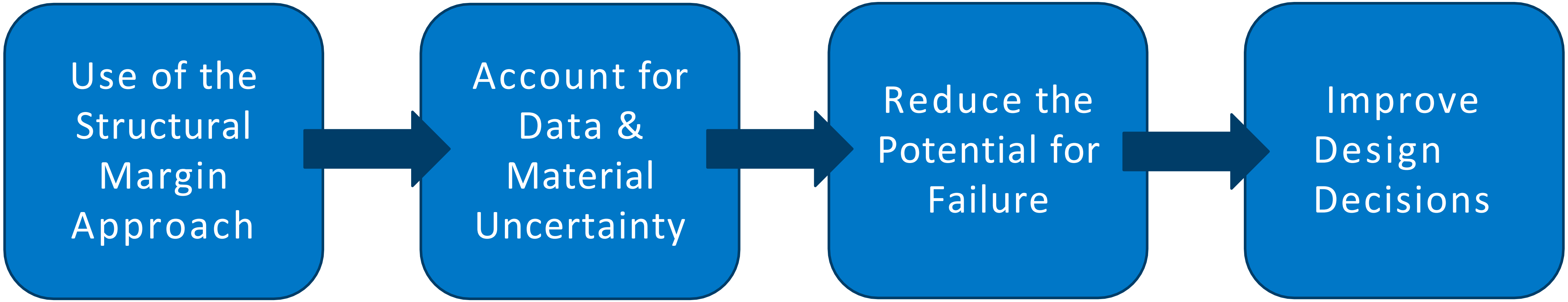
For all 64 cases, **no stress strength interference** was observed

- No failures due to the constrained MD value

Conclusion

Summary & Future Research

Impact



Our research supports the integration of digital engineering tools early in the design cycle to better inform decisions and promote system reliability

Future Research Efforts

AM Considerations

- Introduce more complex geometries
- Study the impact of fatigue and residual stress on engine performance

Additional Materials

- Expand the application of the Structural Margin Approach to promising materials
  - Inconel 718, Inconel 625, NASA-HR1, JBK-75
- Address material properties at elevated temperature conditions

Acknowledgements

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(*Credits: NASA*)

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Thank You!

Any Questions?

Dani McDowell
Industrial & Systems Engineering
Graduate Research Assistant (GRA)
djm0052@uah.edu

Shreyas Lakshmipuram Raghu
Aerospace Systems Engineering
GRA/Ph.D. Candidate
sr0101@uah.edu

L. Dale Thomas, Ph.D.
CSIL Director,
Professor & Eminent Scholar of Systems Engineering
dale.thomas@uah.edu

Gang Wang, Ph.D.
Mechanical & Aerospace Engineering
Associate Professor
gang.wang@uah.edu