Department of MECHANICAL ENGINEERING
THE UNIVERSITY OF UTAH

HILL ENGINEERING

Lab

# Leveraging machine learning to support modern-day fracture mechanics analyses of aerospace structures


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**Contributors**: Eric Lindgren, (*AFRL*), Zach Harris (*Pitt*),
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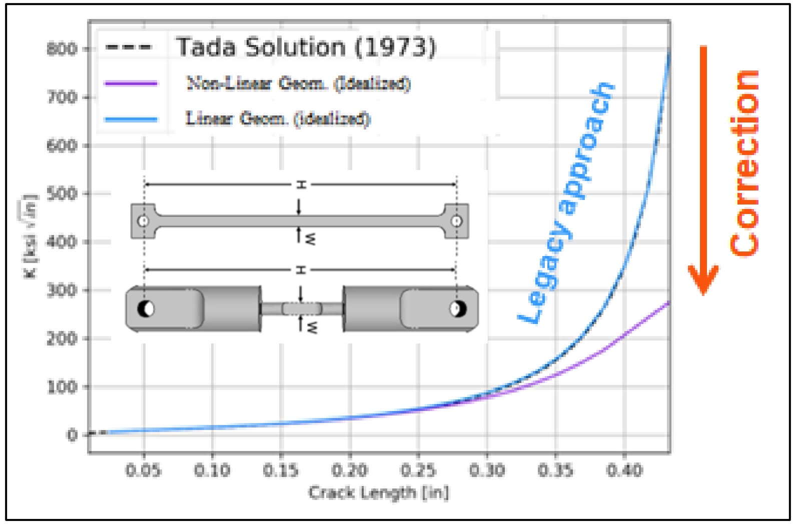
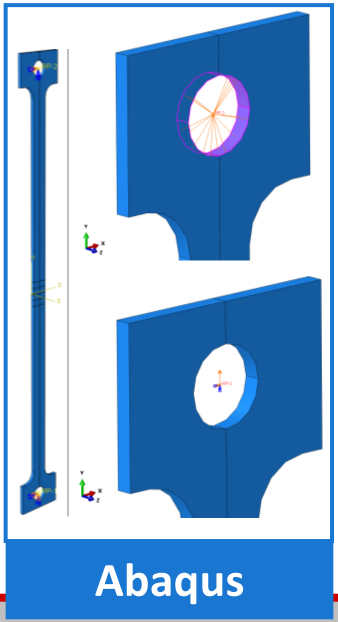
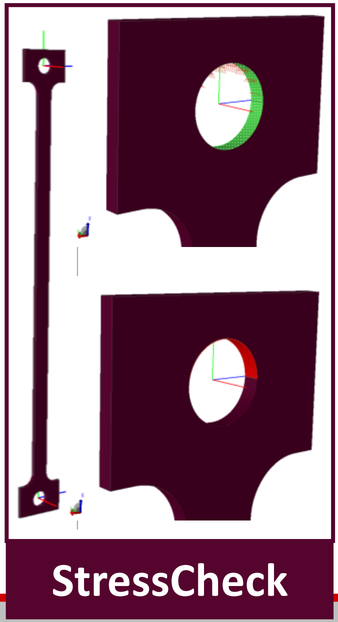
# STTR Phase I

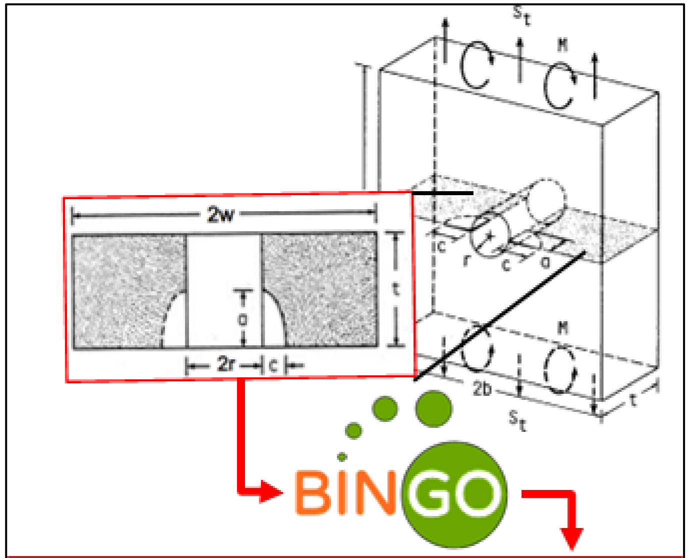


- In January 2024, Hill Engineering and the University of Utah were awarded STTR Phase I
- Machine Learning (ML) used to develop model for SEN(T) specimen
- Served as a proof-of-concept for using ML to develop K-solutions
  - Selected because of results demonstrating errors in Tada K-solution
- ML model significantly less complex in terms of mathematical operations required
- Phase I proof-of-concept demonstrated using ML to develop more accurate K-solutions
  - 50-300% error reduction compared to legacy solutions



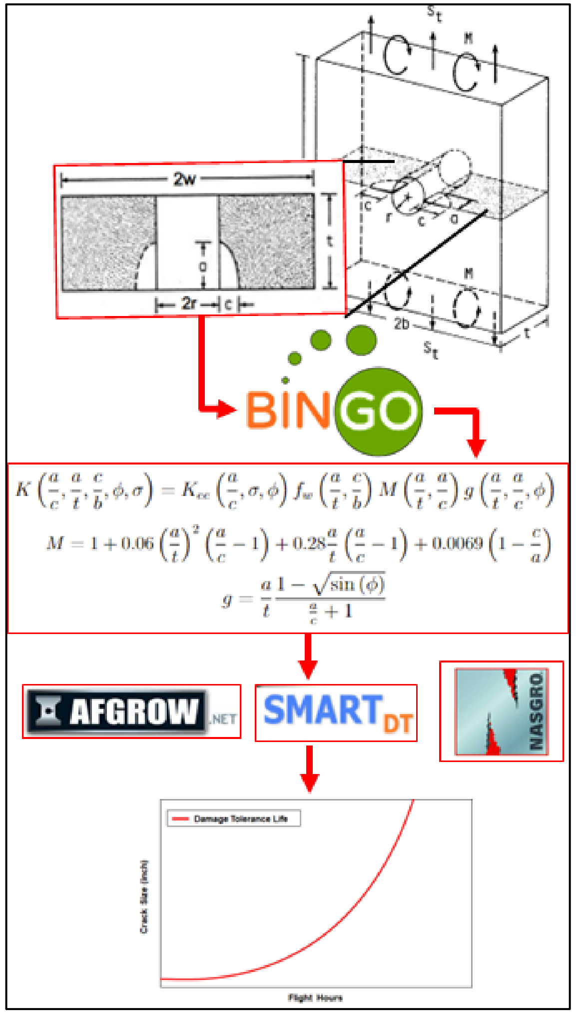

$$K\left(\frac{a}{c},\frac{a}{t},\frac{c}{b},\phi,\sigma\right)=K_{ce}\left(\frac{a}{c},\sigma,\phi\right)f_w\left(\frac{a}{t},\frac{c}{b}\right)M\left(\frac{a}{t},\frac{a}{c}\right)g\left(\frac{a}{t},\frac{a}{c},\phi\right)$$

$$M=1+0.06\left(\frac{a}{t}\right)^2\left(\frac{a}{c}-1\right)+0.28\frac{a}{t}\left(\frac{a}{c}-1\right)+0.0069\left(1-\frac{c}{a}\right)$$

$$g=\frac{a}{t}\frac{1-\sqrt{\sin(\phi)}}{\frac{a}{c}+1}$$

# Proposed STTR Phase II

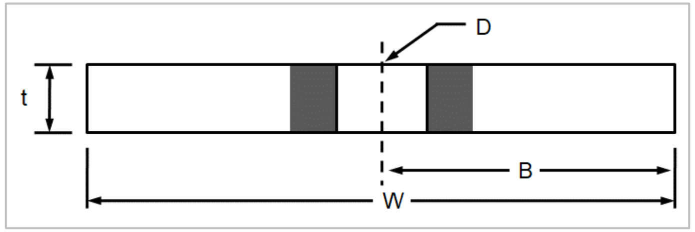
- In May 2024, Hill Engineering and the University of Utah were invited to submit a STTR Phase II proposal
  - Was not selected for award, but the team members were PRETTY good
- Proposal focus
  - Developing ML methodology
  - Defining aircraft-related cases for utilization
  - Performing associated model verification
- Would allow for improved accuracy of the most commonly used handbook solutions
  - Leveraging existing USAFA dataset to train Bingo models for already well-studied use cases
  - Bingo-produced K-equations will be compared to existing handbook solutions

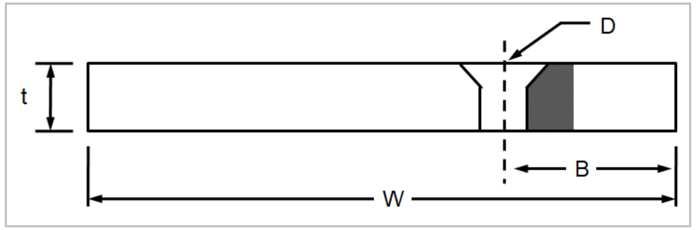


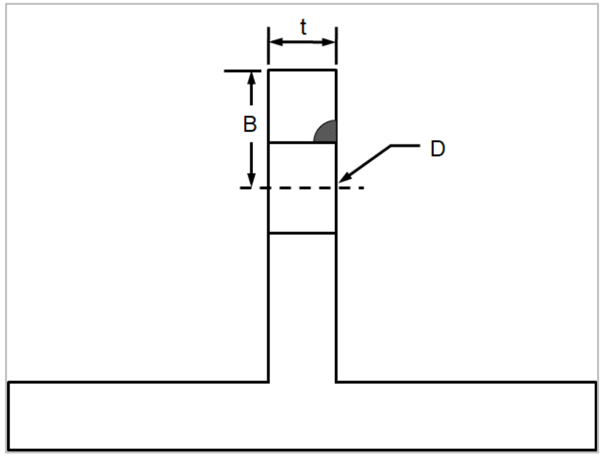
# Proposed STTR Phase II



- Extend K-solution methods to more complex conditions
    - Accomplished by generating new training data using ABAQUS and StressCheck
    - Bingo used to develop interpretable K-solutions to be compared between the two software to ensure training data quality
    - At least 3 cases will be identified, increasing in level of complexity
        - Case 1: A representative basic handbook-type condition (e.g. double through crack at a centered hole in a plate)
        - Case 2: Minor variation from basic handbook-type condition (e.g. through crack at a countersunk offset hole in a plate)
        - Case 3: Increased geometric complex condition (e.g. corner crack in a T-shape cross-section with an offset hole in the vertical flange)
        - Additional cases will be considered for application (e.g. bearing load cases that have been difficult to fit K-solution curves to in the past)

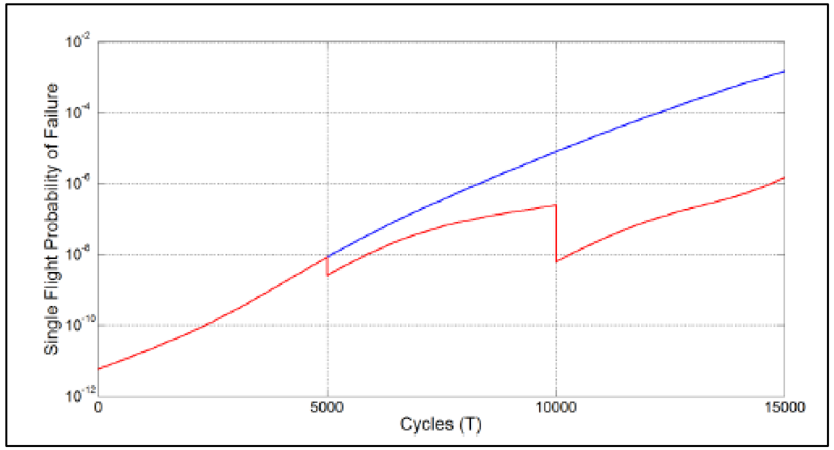


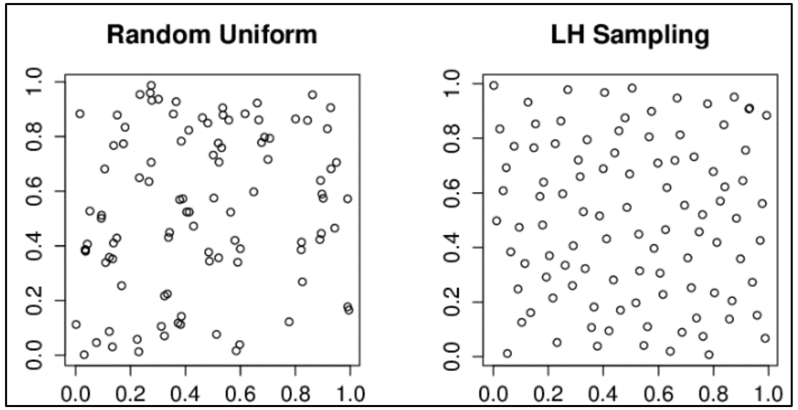



# Proposed STTR Phase II

- Conduct a comparison between new and legacy solutions using ultrafast crack growth code and a risk-based criterion across the entire design space
- Utilize a robust verification scheme to establish credibility
  - Evaluate cases using ML model and ABAQUS at specific locations using Latin Hypercube sampling



# Introducing
# Dr. Jake Hochhalter

NASA

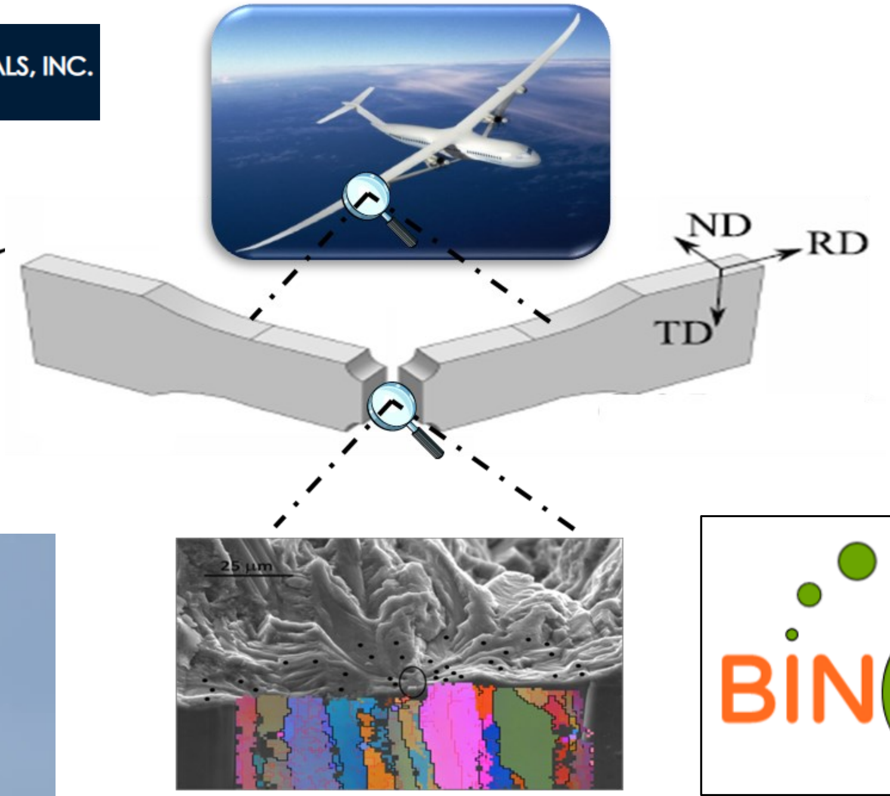
AS&M ANALYTICAL SERVICES & MATERIALS, INC.

NORTHROP GRUMMAN

SPACEX

Sandia National Laboratories

LOCKHEED MARTIN



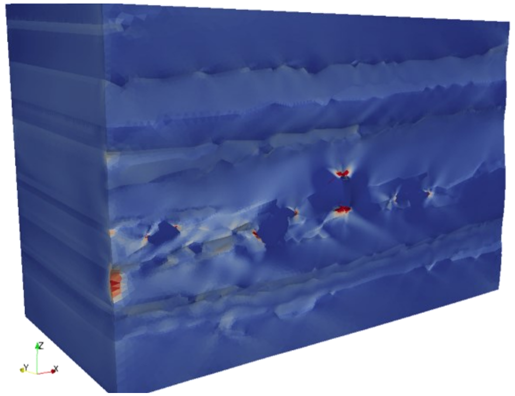

Microstructure

Lab

BOISE STATE

NEW MEXICO

CORNELL UNIVERSITY FOUNDED A.D. 1865



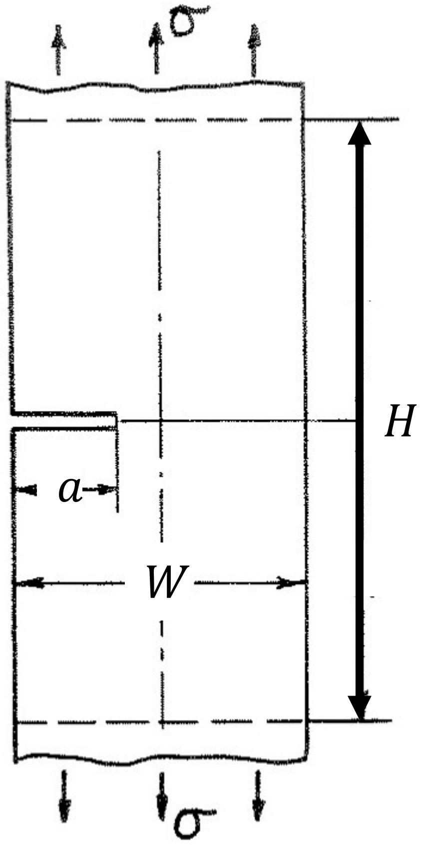
BINGO

SCIFEN

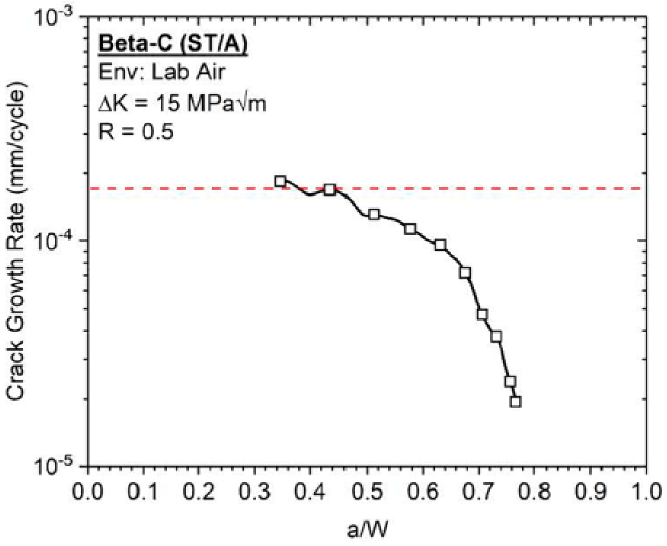
# SEN(T) Constant-ΔK Tests

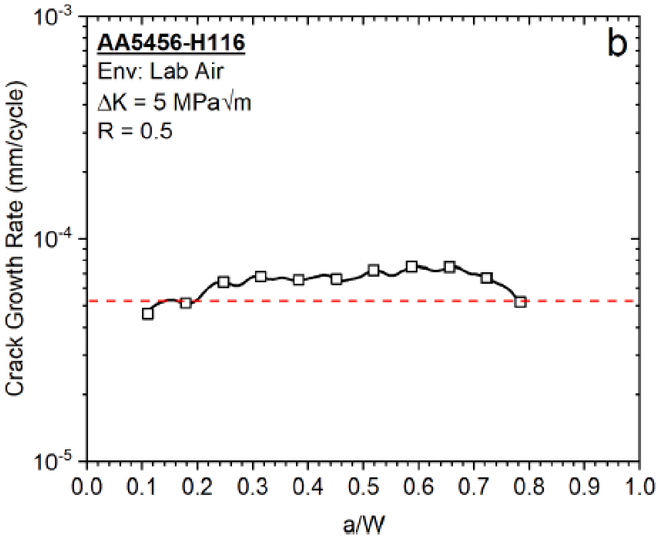
$$K = \sigma\sqrt{\pi a}\left\{\sqrt{\frac{2W}{\pi a}\tan\left(\frac{\pi a}{2W}\right)}\left[\frac{0.752 + 2.02\left(\frac{a}{W}\right) + 0.37\left(1 - \sin\left(\frac{\pi a}{2W}\right)\right)^3}{\cos\left(\frac{\pi a}{2W}\right)}\right]\right\}$$

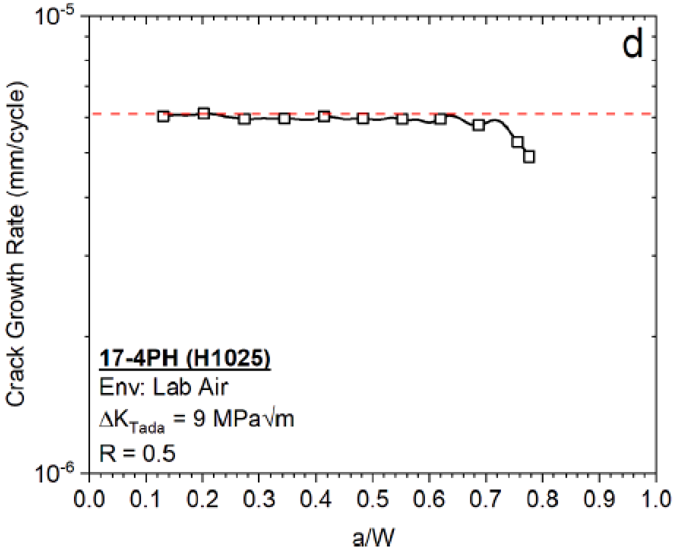
$$where\ far\ field\ stress: \sigma = \left(\frac{P}{BW}\right)$$



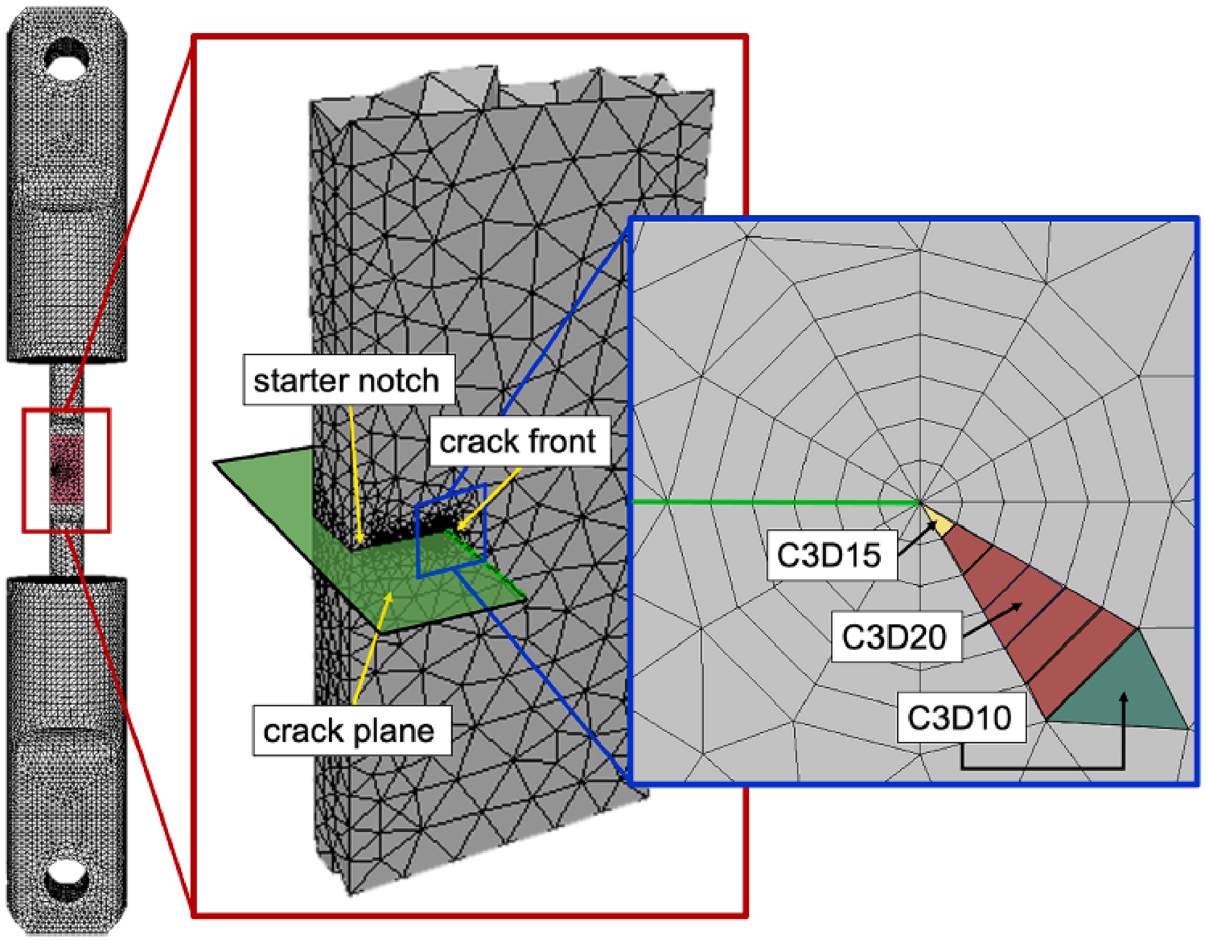

**Accuracy:** better than 0.5% for any a/W
H. Tada et al., Stress Analysis of Cracks Handbook, **1973**

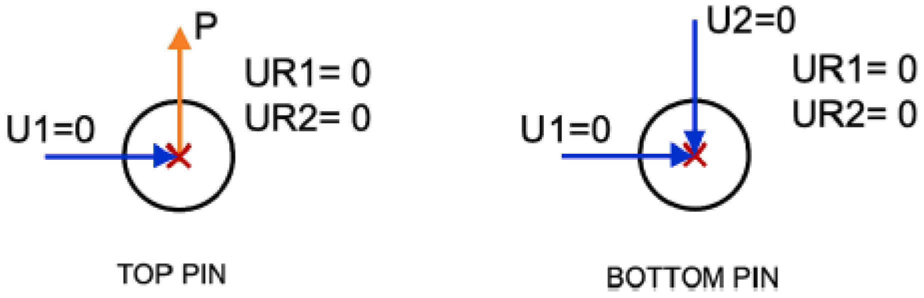


# Abaqus and Franc3D Modeling



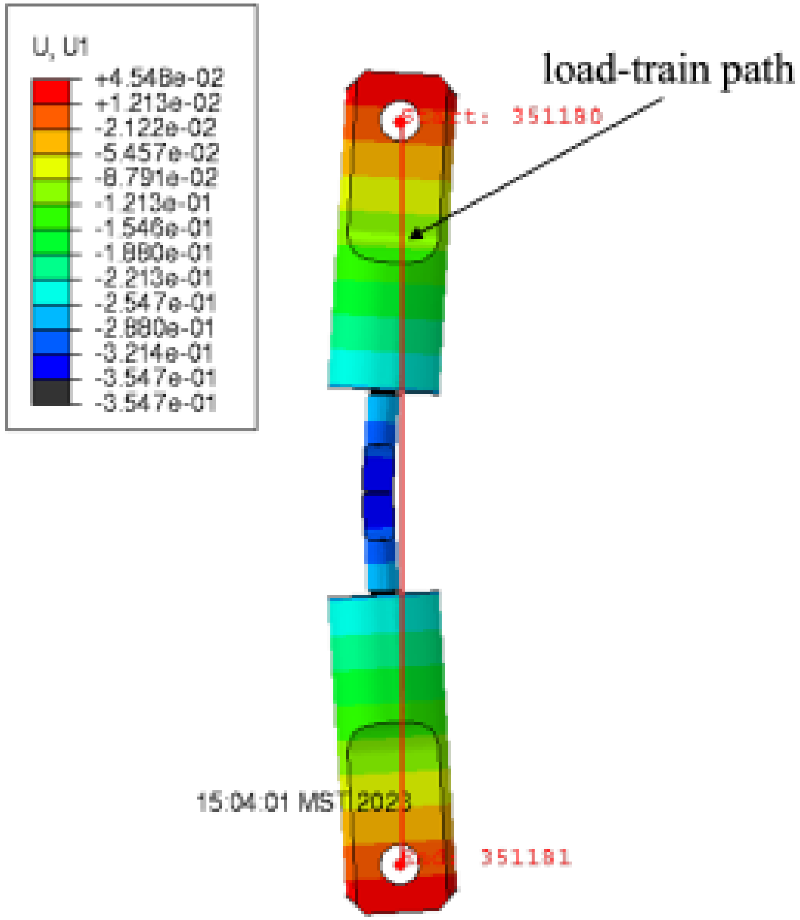




| Material | Modulus of Elasticity [GPa] |
|---|---|
| Al-7075T | 75 |
| Beta-Ti | 100 |
| Inconel 718/Steel | 200 |

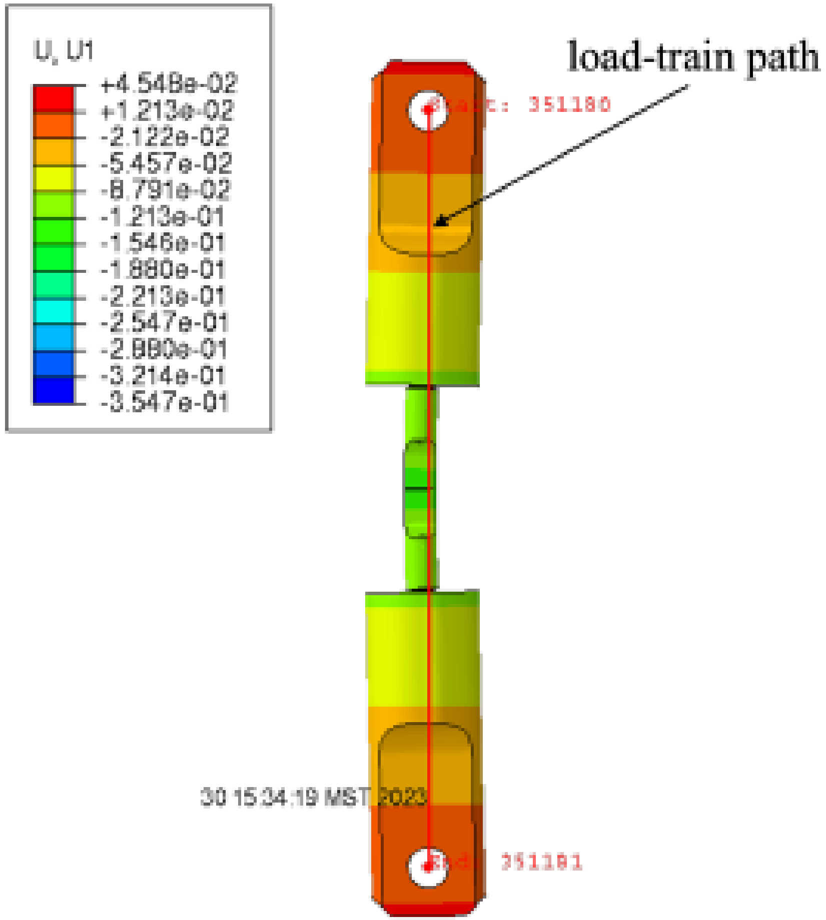
h/W can reach 29 for environmental fatigue crack growth testing

# Effect of Linear Geometry Assumption





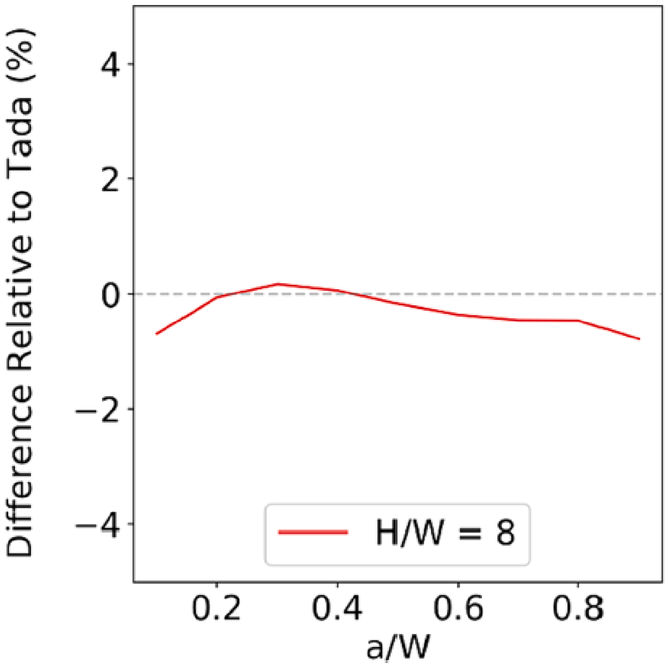

Linear-Geometry



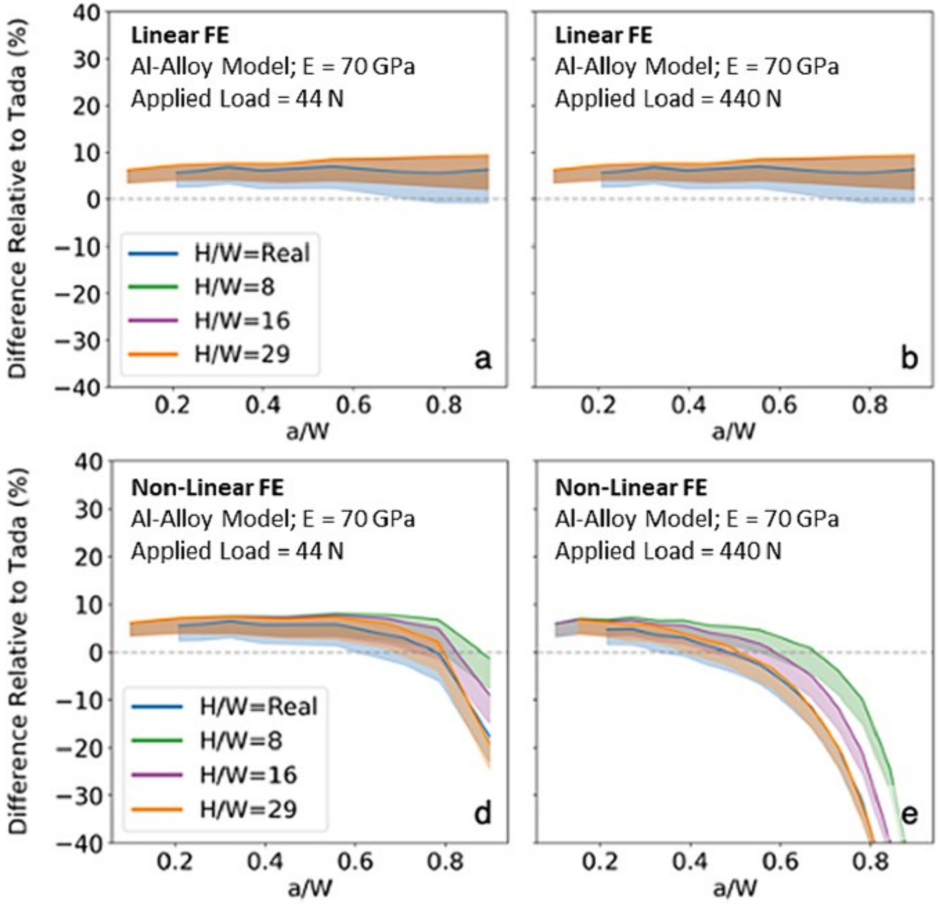

Non Linear-Geometry

# Modeling Differences from Tada

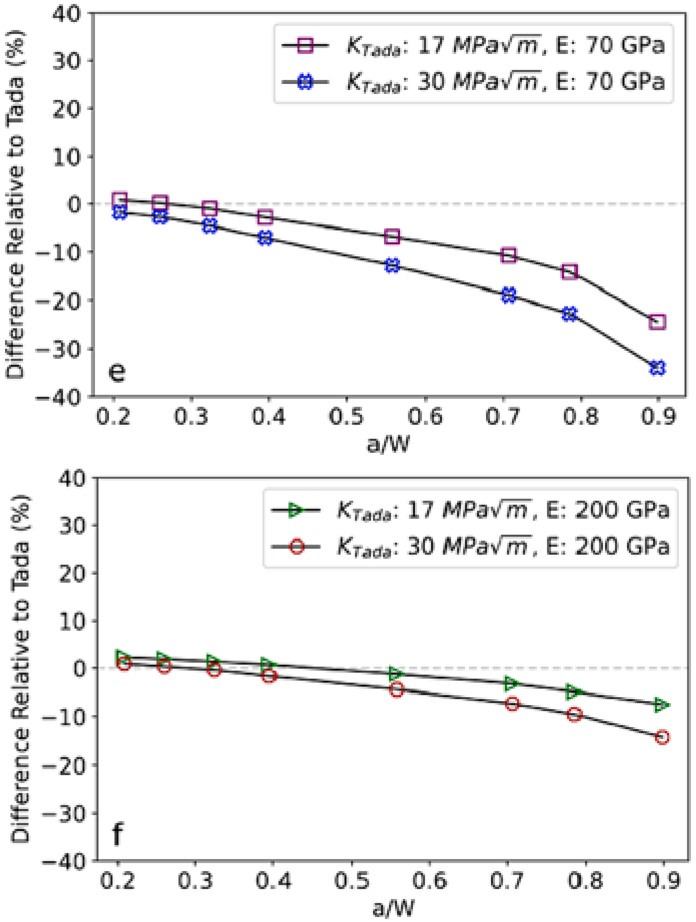
- Linear geometry
- 2D plane strain



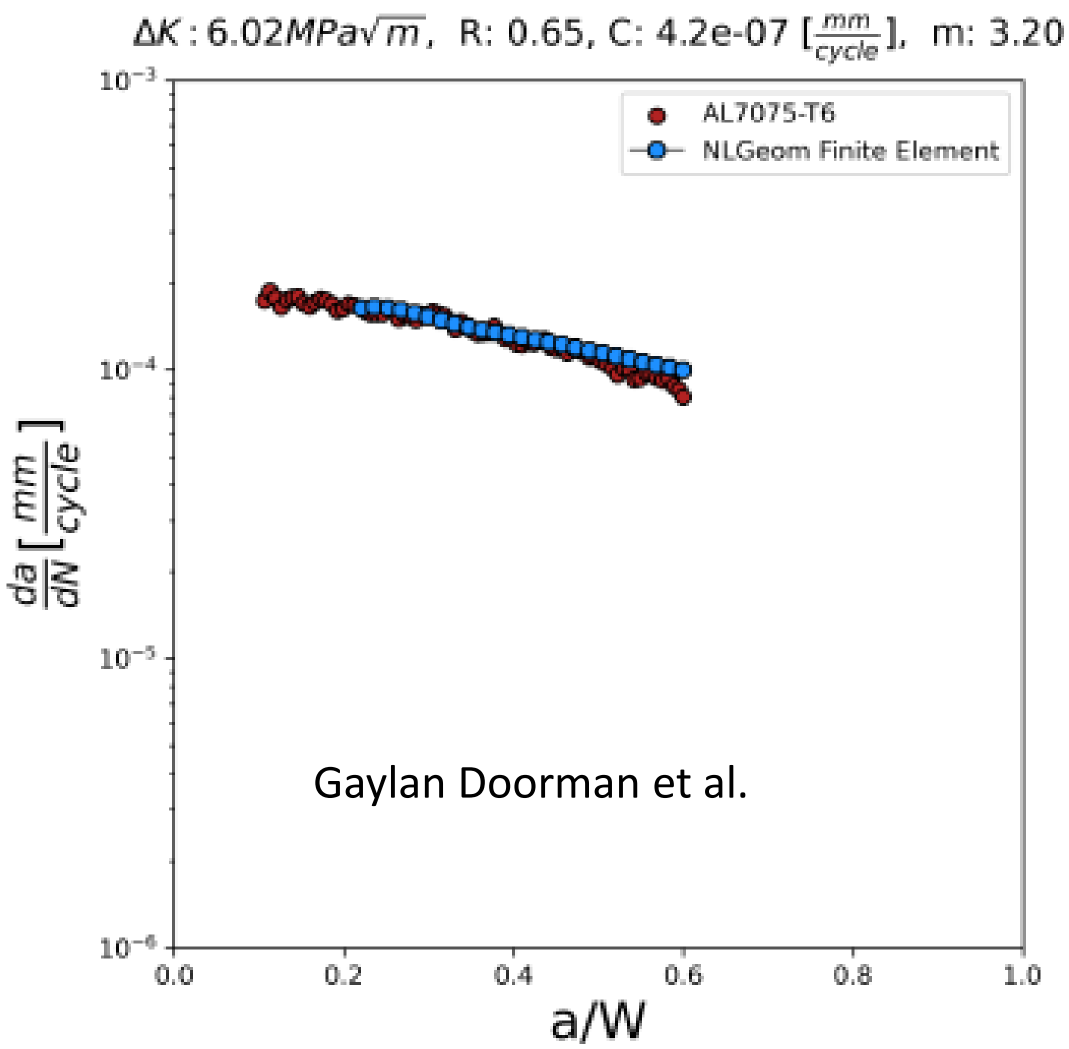

- Linear geometry
- 3D



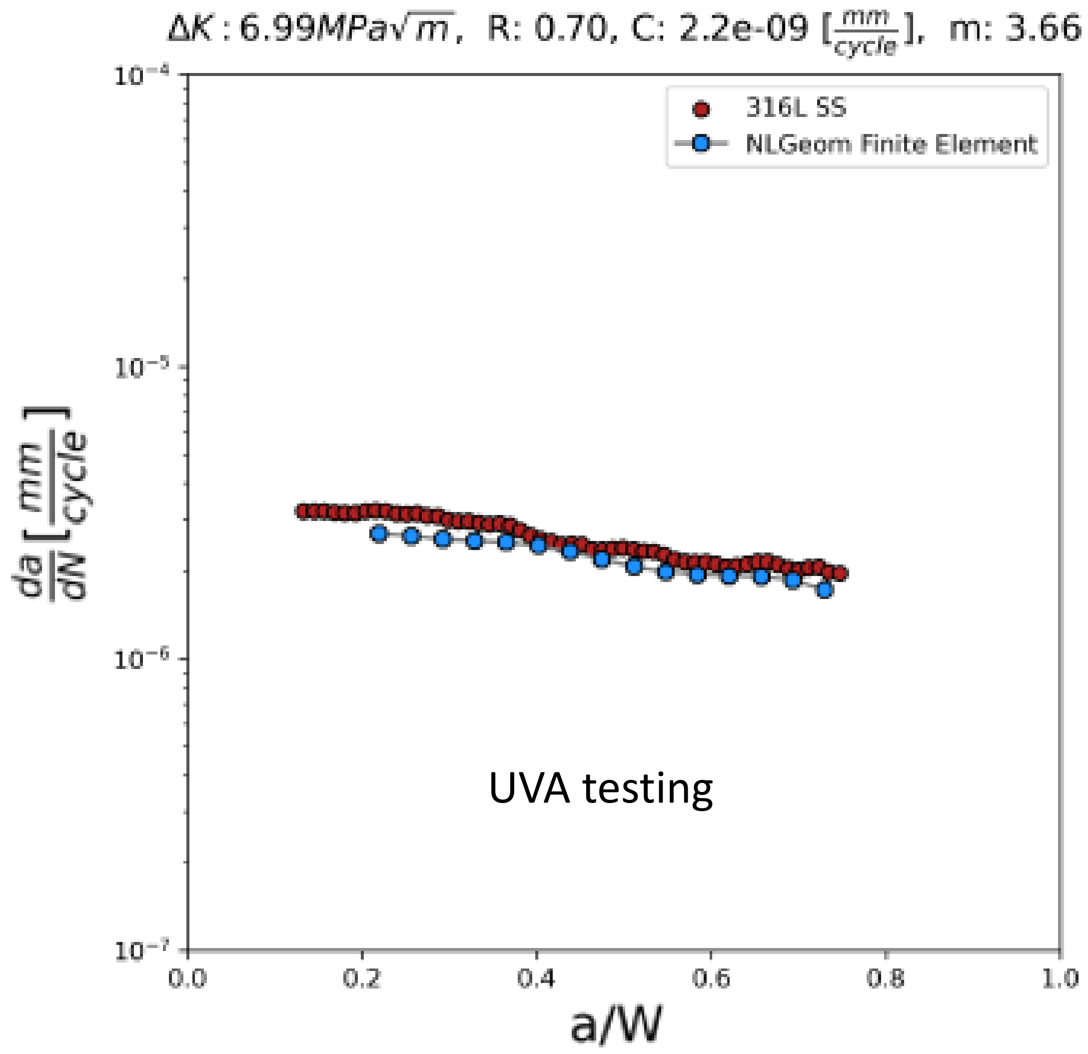

- Nonlinear geometry



# Comparison to Experiment Data




Gaylan Doorman et al.



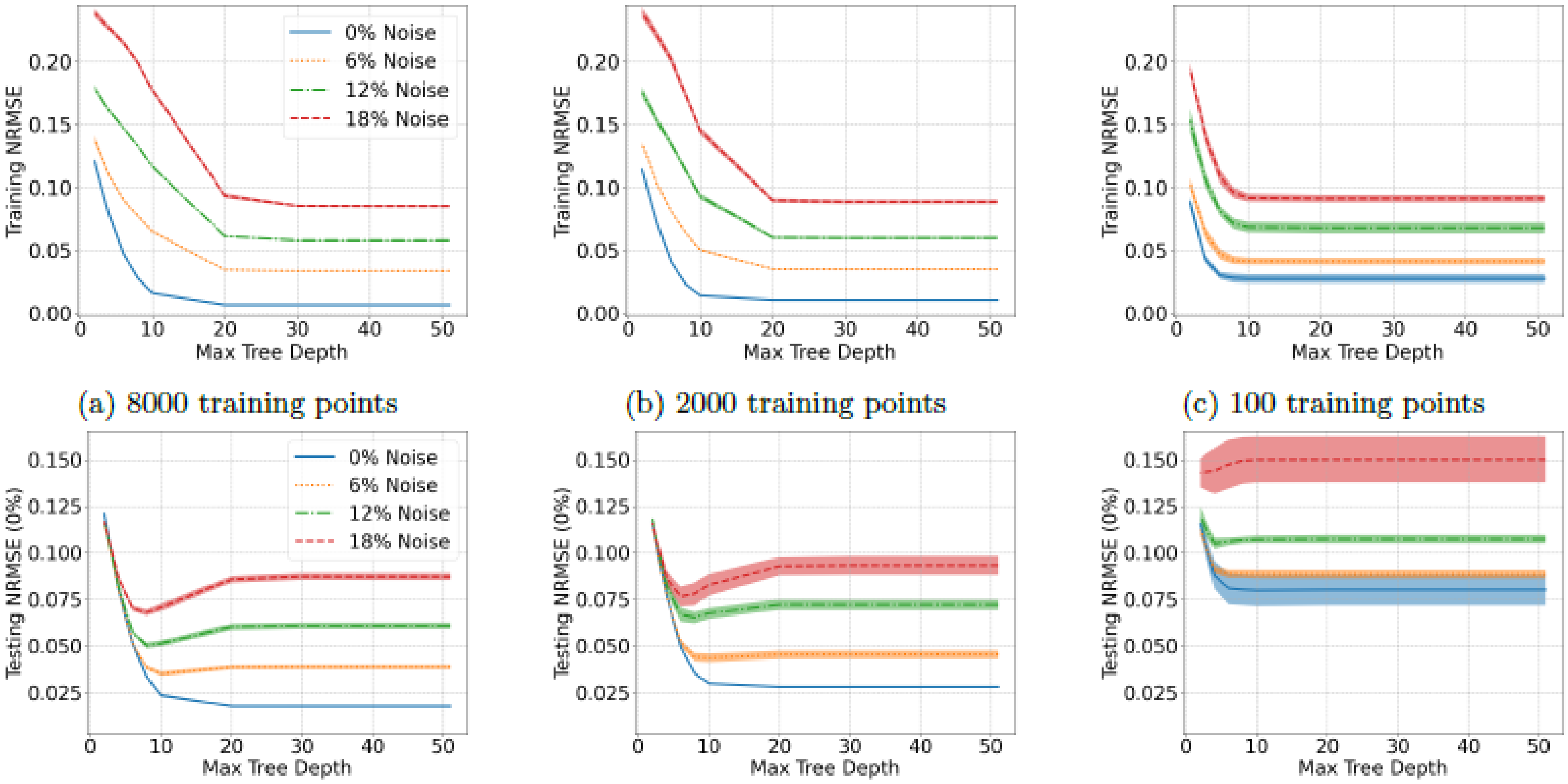

UVA testing

# Machine Learning for Updated K Solutions



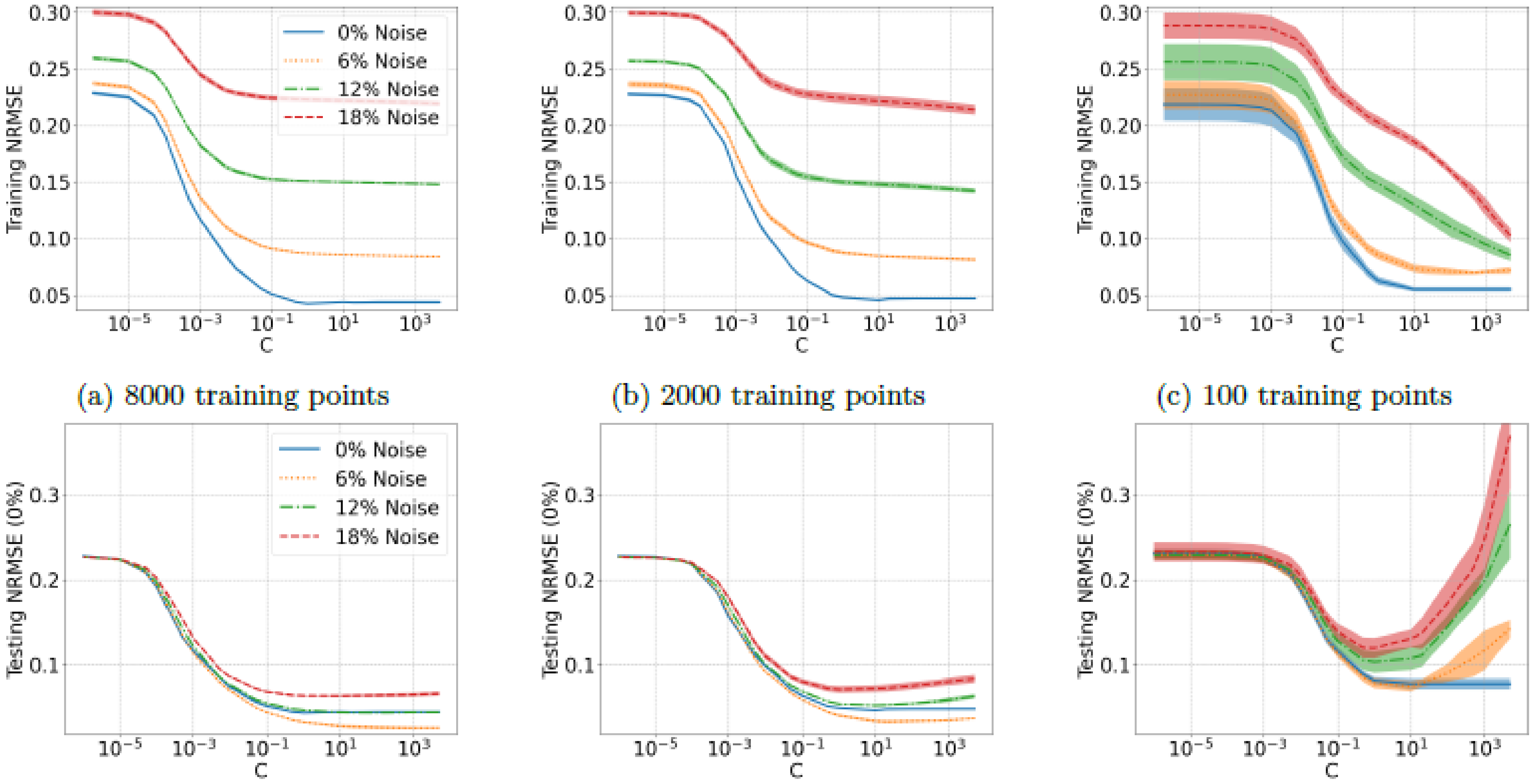
- Parameterize finite element model, e.g., a/W, h/W, etc.
- Compute SIFs using Abaqus + Franc3D
- Extract SIFs along p or homogenize as single representative value
- Test common machine learning (ML) methods
  - Random Forest Regression
  - Support Vector Machines
  - Neural Networks
- All ML methods have hyperparameters that govern model training
- Develop guidelines for method selection as function of data quality, quantity, and method stability

# Random Forest Regression




(a) 8000 training points
(b) 2000 training points
(c) 100 training points
(d) 8000 training points
(e) 2000 training points
(f) 100 training points

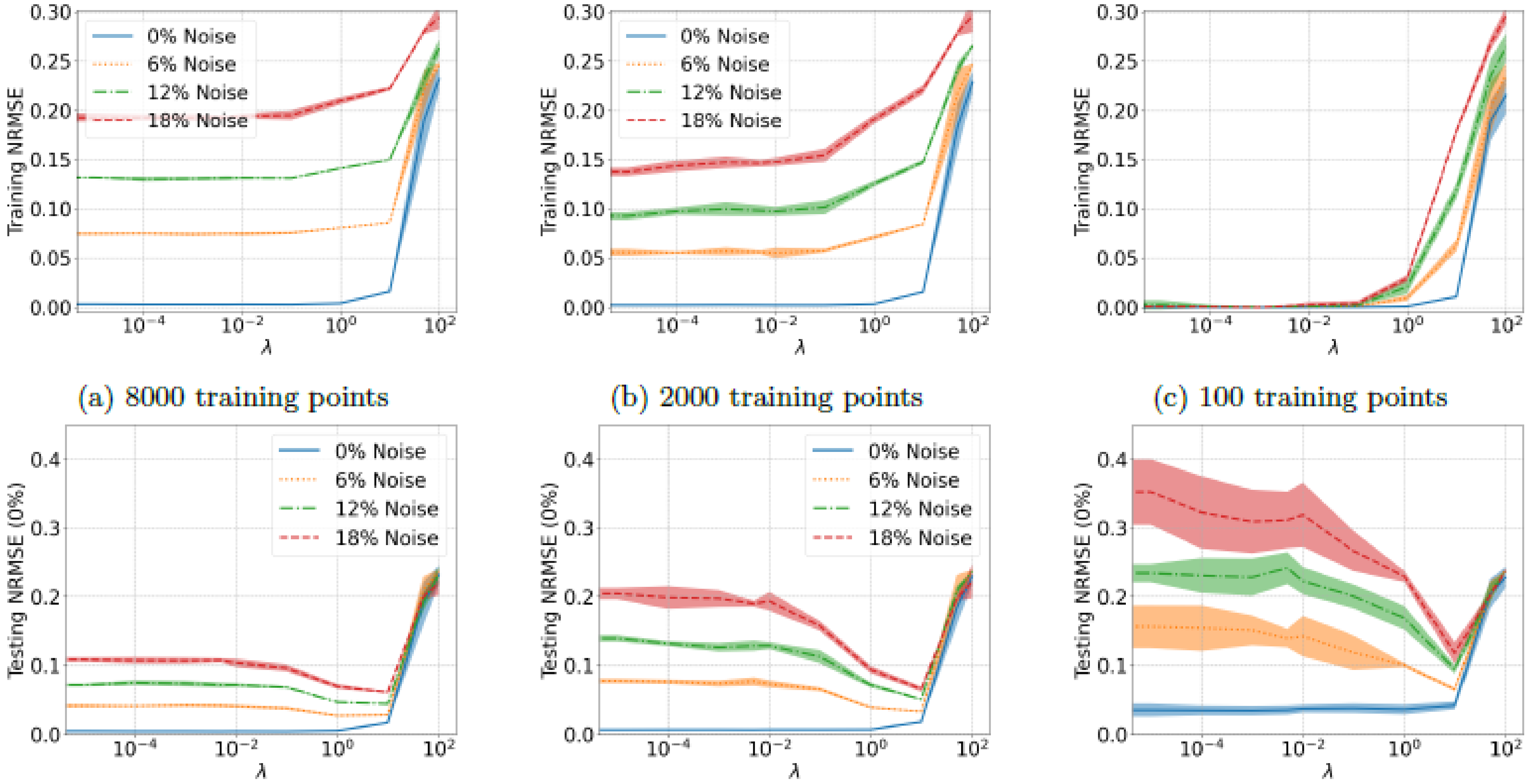
# Support Vector Machines




(a) 8000 training points (b) 2000 training points (c) 100 training points

(d) 8000 training points (e) 2000 training points (f) 100 training points

# Neural Networks




(a) 8000 training points (b) 2000 training points (c) 100 training points

(d) 8000 training points (e) 2000 training points (f) 100 training points