Simulation-Aided Design of Compression Specimens for Accessing New States of Stress During Ductile Fracture

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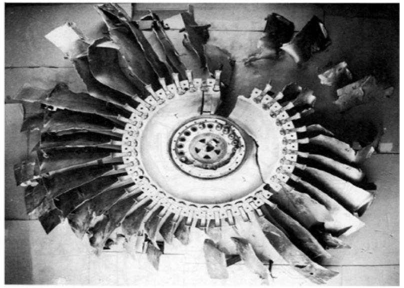
Introduction

Blade-off and rotor-burst events in gas turbine engines

- Blade-off and rotor-burst are rare, but pose a safety concern if debris is **uncontained**
- FAA requires full-scale destructive testing for new or derivative gas turbine engine designs
    - Difficult and expensive to conduct
- Provides a need for advanced predictive simulations (**simulation-aided certification**)



First-stage fan disc that has been reconstructed from recovered engine fragments [1].

1989 McDonnell-Douglass DC-10 crash as result of failure [2].

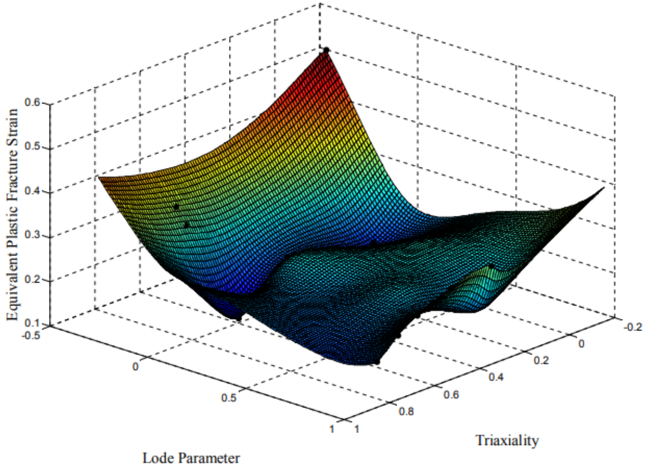
Rolls Royce Engine "Blade-Off" Test [3].

1. National Transportation Safety Board. *United Airlines Flight 232 Aircraft Incident Report.* NTSB Report No. AAR-90-06, 1989.
2. https://www.nycaviation.com/2014/07/disaster-miracle-united-flight-232/34639
3. https://www.youtube.com/watch?v=Lzq519I5bhs

Research Opportunity

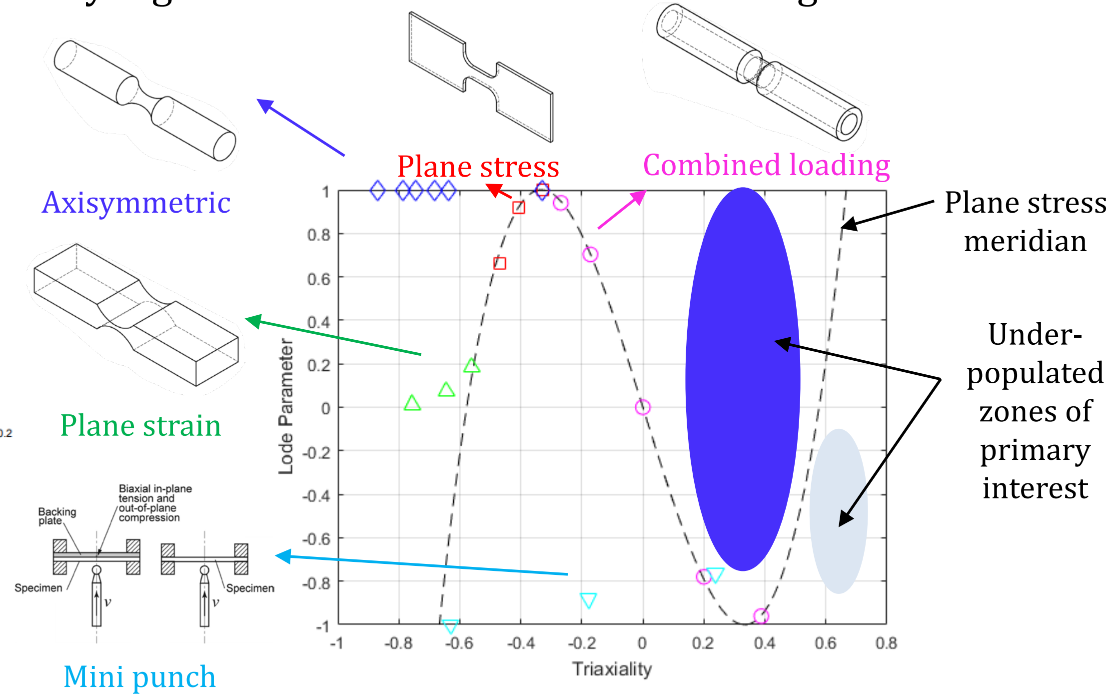
The **failure locus** is a key ingredient in ductile fracture modeling

2024-T351 aluminum 3D failure locus [1]



$$\mu = \frac{27}{2}\frac{J_3}{\bar{\sigma}^3}$$

$$\sigma^* = \frac{\sigma_m}{\bar{\sigma}}$$

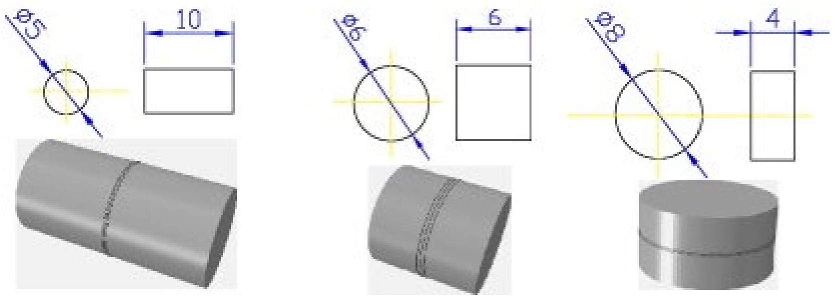


Positive triaxiality (compressive) regime is underpopulated with data

1. J.D. Seidt. *Plastic Deformation and Ductile Fracture of 2024-T351 Aluminum Under Various Loading Conditions*. Ph.D. Dissertation, The Ohio State University, 2010.

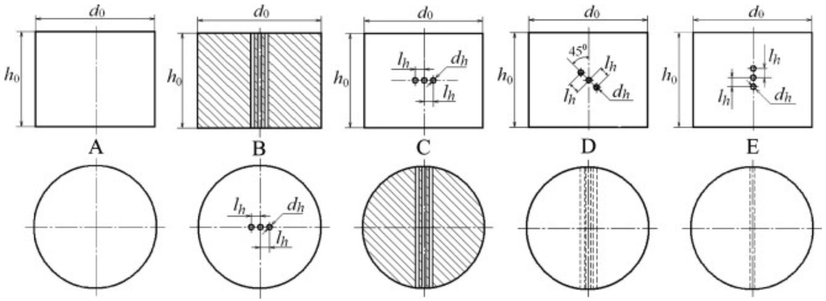
Objectives

- Model and simulate **novel design permutations of compression specimens** to achieve *unprecedented stress states* with positive (compressive) triaxialities
- Initially using **AA 2024-T351**
  - Ti-6Al-4V titanium alloy, Inconel 718 nickel alloy, and 410 stainless steel



Cylindrical upsetting specimens with different aspect ratios [1]

Tunable geometric irregularities & asymmetric features



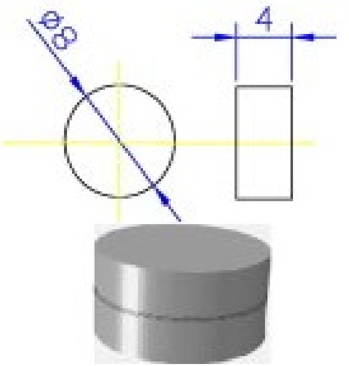
Cylindrical upsetting specimens with internal voids [2].

1. H. Li, M.W. Fu, J. Lu, and H. Yang. "Ductile fracture: Experiments and computations." *Int. J. Plast.* 27, 147–180, 2011
2. N. Tutyshkin, W.H. Müller, R. Wille, and M. Zapara. "Strain-induced damage of metals under large plastic deformation: Theoretical framework and experiments." *Int. J. Plast.* 59, 133–151, 2014.

Methodology

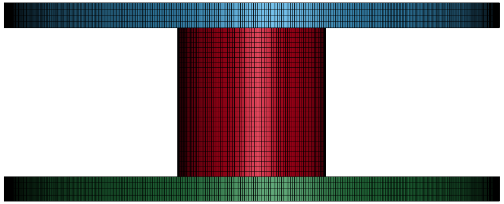
Specimen design → Compression testing → Simulate test using FEA

Vary aspect ratio



[1]

Extract stress state and equivalent plastic strain



This methodology allows for multiple stress states to accessed with a **single test setup** through geometric specimen alterations (plug-n-play).

1. https://www.endolab.org/implanttesting.asp?cat1=10&id=243&tab=2&topic=Compression%20test%20of%20metallic%20cellular%20materials%20DIN%2050134&desc=Compression%20test%20of%20metallic%20cellular%20materials%20DIN%2050134&key=axial,%20compression,%20metallic%20cellular,%20material,%20DIN,%2050134

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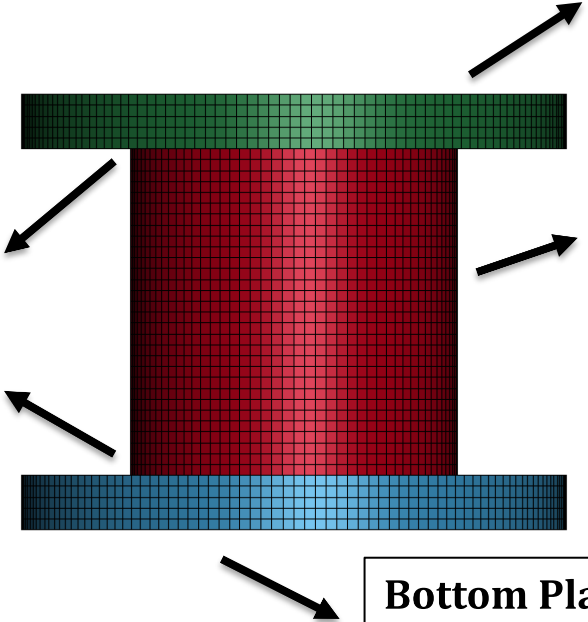
Methodology

FEA Model Overview



Top Platen:

- MAT_020 (rigid)
- Fixed DOF: CMO = 1, CON1 = CON2 = 7
- Element size = 0.075 mm

Interfaces:

- Automatic surface-to-surface contact
- SOFT = 1
- FS = 0.03, FD = 0.01
- DEPTH = 3
- Defaults otherwise

Specimen:

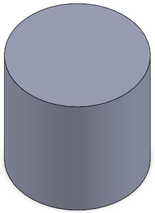
- MAT_224 for **AA 2024-T351**
  - SR = 1E-3 (iso-rate), failure off
- ELFORM = 1 (underintegrated hex)
- HG control: IHQ = 6, QH = 0.1
- Element size = 0.1 mm, 2:1 AR

Bottom Platen:

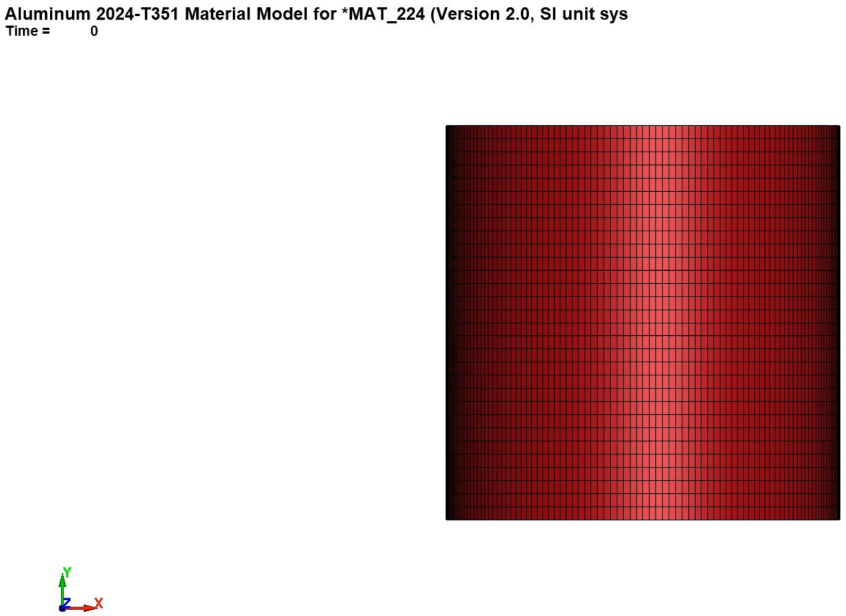
- MAT_020 (rigid)
- Only vertical motion: CMO = 1, CON1 = 6, CON2 = 7
  - Boundary prescribed motion (V = 300 mm/s)
- Element size = 0.075 mm

Results: Cylindrical Upsetting Specimen

H/D = 1

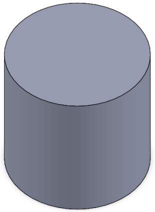


Animation for H/D = 1

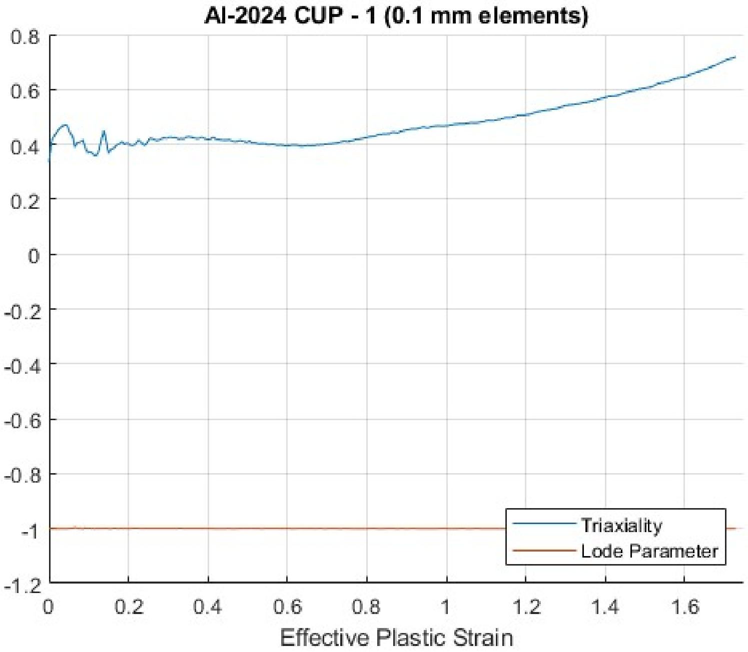


Results

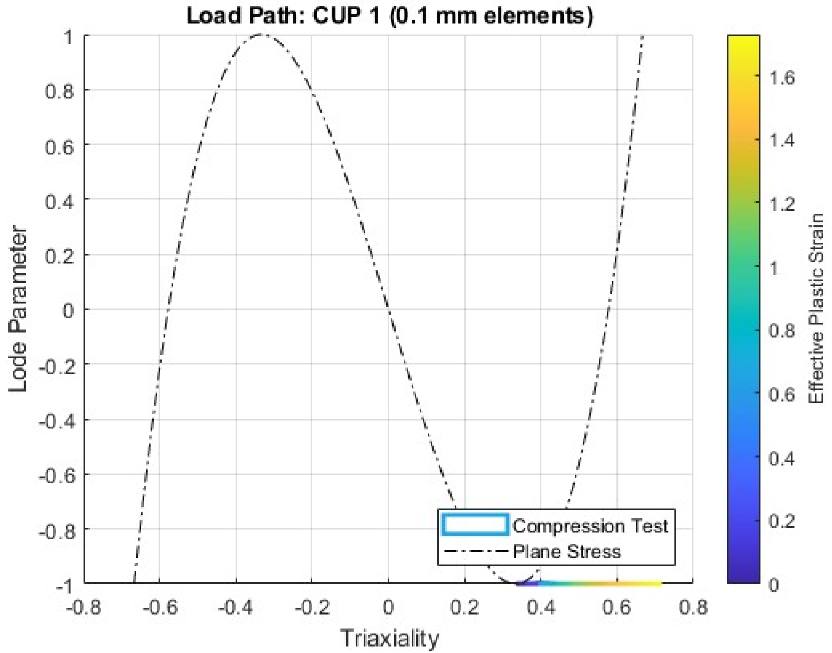
H/D = 1



Stress state history



Load path

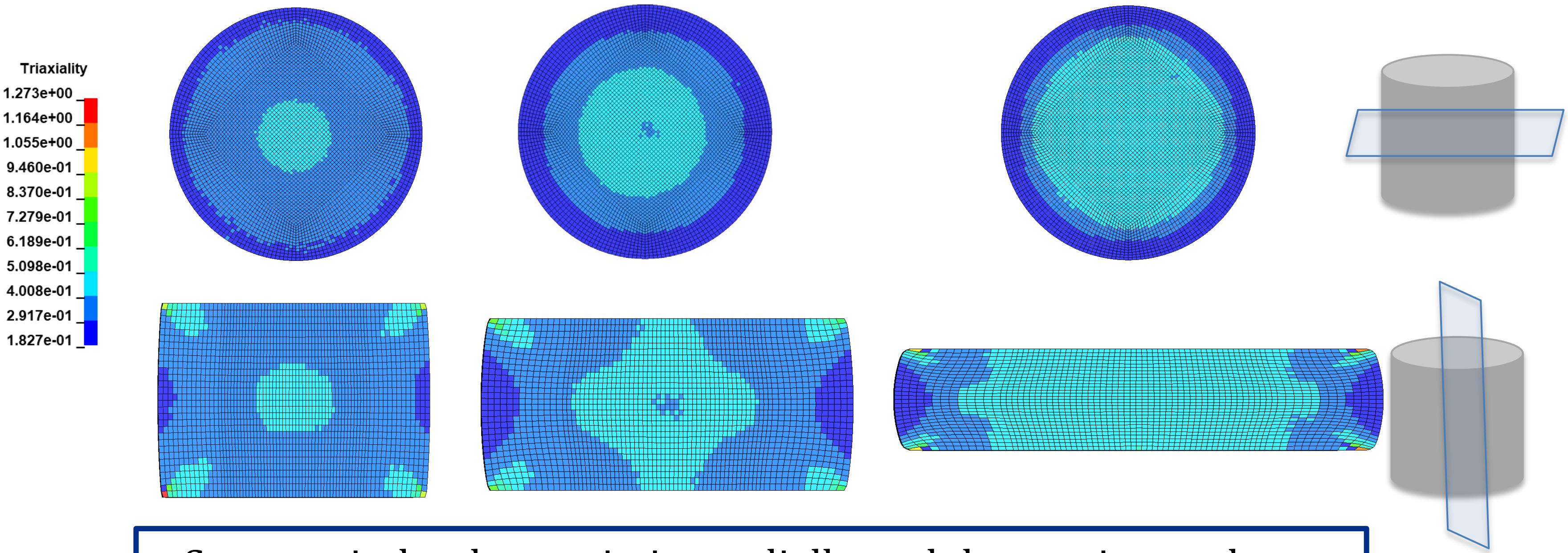


Results

$$\sigma^* = -\frac{\sigma_m}{\bar{\sigma}}$$

Triaxiality at different engineering strains

20% Engineering Strain | 40% Engineering Strain | 60% Engineering Strain



Symmetric, but has variation radially, and the specimen-platen interfaces have significant increases (most likely from friction).

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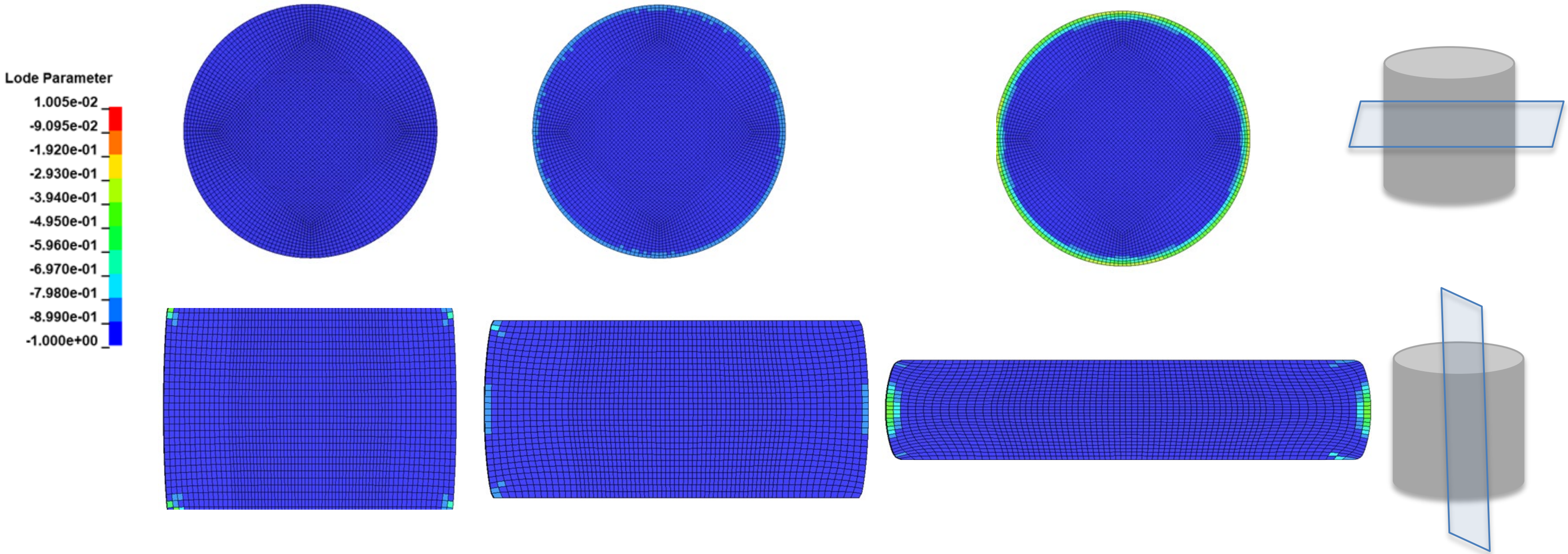
Results

$$\mu = \frac{27}{2}\frac{J_3}{\bar{\sigma}^3}$$

Lode parameter at different engineering strains

20% Engineering Strain | 40% Engineering Strain | 60% Engineering Strain



Inhomogeneous at the free edge because of barreling (friction).

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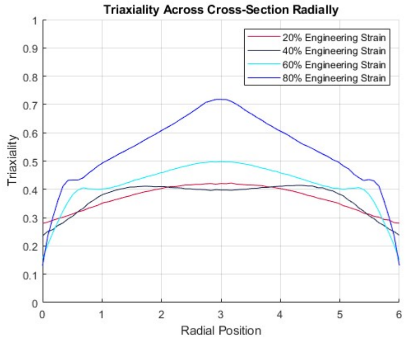
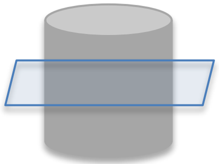
Results

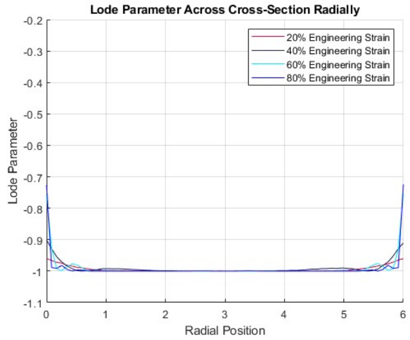
Triaxiality

Lode Parameter

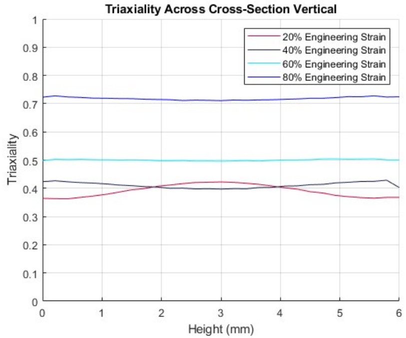
Radially

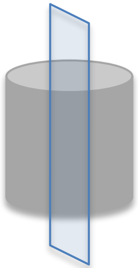


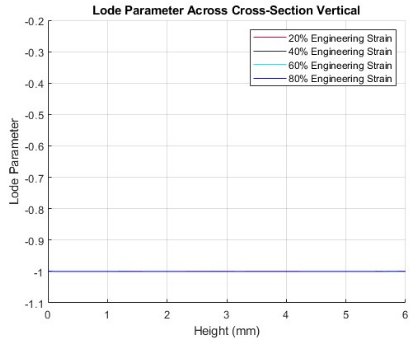




Vertically







Triaxiality increases with engineering strain and is higher towards the center of the specimen. Lode parameter, however, stays consistent at -1.

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Conclusions and Future Directions

Summary

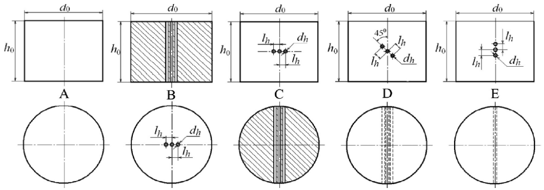
- Results show a working, robust, and trustworthy simulation deck
- With this deck, future design permutations should be plug-and-play
  - These permutations should provide positive (compressive) triaxiality data to enhance the failure locus of aerospace metals

Future Work

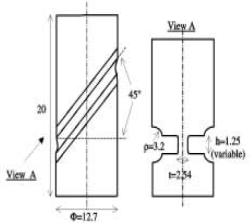
- Simulation of specimens with through holes
  - Adjustable design parameters: hole size, orientation, number, spacing

Outcomes Expected

- Enhance the fidelity of predictive models used to simulate impact physics of blade-off and rotor-burst events



[1]



[2]

[3]

1. N. Tutyshkin, W.H. Müller, R. Wille, and M. Zapara. "Strain-induced damage of metals under large plastic deformation: Theoretical framework and experiments." *Int. J. Plast.* 59, 133–151, 2014.
2. D. Rittel, S. Lee, and G. Ravichandran. "A shear-compression specimen for large strain testing." *Exp. Mech.* 42, 58–64, 2002.
3. P. Kubik, F. Sebek, J. Hulka, and J. Petruska. "Calibration of ductile fracture criteria at negative stress triaxiality." *Int. J. Mech. Sci.* 108-109, 90–103, 2016.

Acknowledgments

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