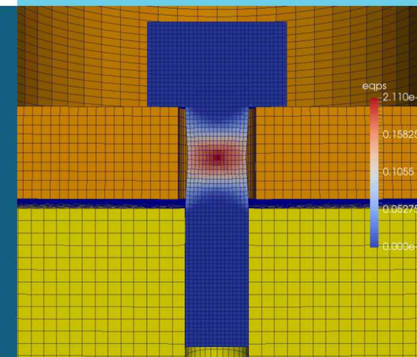
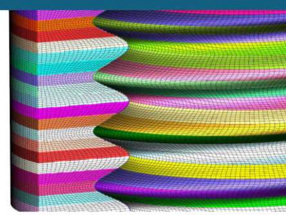
SAND2018-14347C

Modeling Empirical Size Relationships on Load-Displacement Behavior and Failure in Threaded Fasteners





2019 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference

January 7-11, 2019, San Diego, California, United States

PRESENTED BY

Peter W. Grimmer, ***John P. Mersch***, Jeffrey A. Smith, Yuriy B. Veytskin, Donald F. Susan

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Motivation

Finite element analysis of complex, full system structures is increasingly relied upon to inform engineering decision-making.

We're especially interested in abnormal environments where predicting failure is important, and the numerous fasteners in these system models can be:

- Different sizes
- Subjected to diverse loadings
- Loaded at various rates

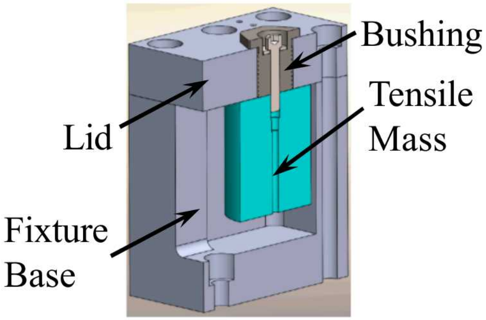
Difficulties:

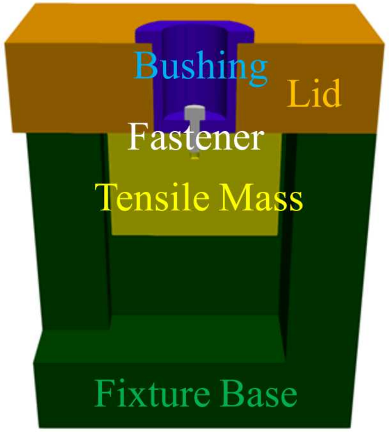
- Modeling fidelity requirements of system level models.
- Testing each individual component in these complex systems and structures is often infeasible.

Goal: Gain a fundamental understanding of threaded fasteners through exploration of testing procedures, modeling processes, and the underlying physics/material science principles.

Integrated Effort

Trying to develop our knowledge in three main areas:



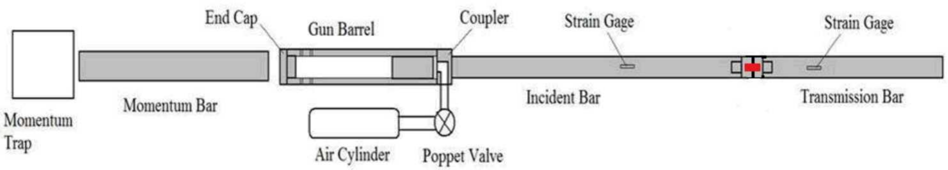


Modeling capabilities:

- Strain Rate Effects
- Analysis Best Practices
- Size Effects
- Multiaxial Loading

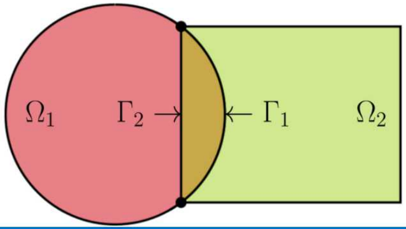
Testing of Threaded Fasteners:

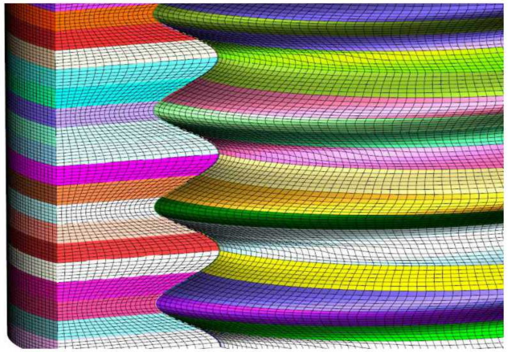
- Strain Rate Effects
- Testing Best Practices
- Size Effects[1]
- Multiaxial Loading



Fundamental Physics, Mat Sci, and High Fidelity Modeling:

- Schwarz Method[2] (Multiscale)
- Grain Size/Structure
- 3D Helical Fastener Model





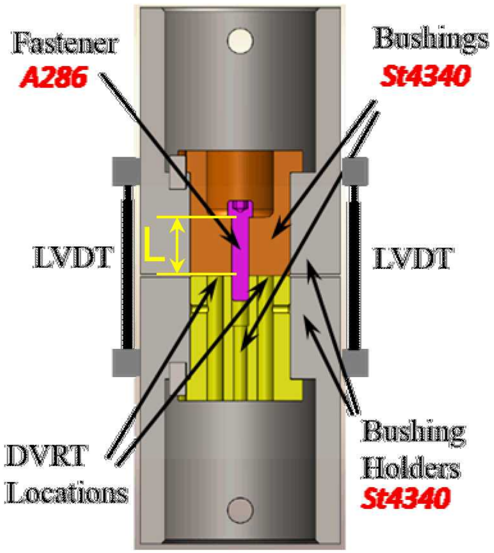
This presentation focuses on size effects observed in fastener testing and analysis

[1]Veytskin, Y. B., Bosiljevac, T.R., "Testing the Influence of Size Effects on Load-Displacement Behavior and Failure in Threaded Fasteners" 2019 SEM Annual Conference, Society for Experimental Mechanics, Reno, NV, 2019. *Submitted for Publication*.

[2]Mota, A., Tezaur, I., Alleman, C., "The Schwarz alternating method in solid mechanics," *Comput. Methods Appl. Mech. Engrg*. Vol. 319, 2017, pp. 19-51.

Our Study: Response of Various Sized Fasteners

A series of quasistatic tension tests were performed on #00, #02, #04 #06 and #4 (1/4") ***A286 stainless steel fasteners***[3].



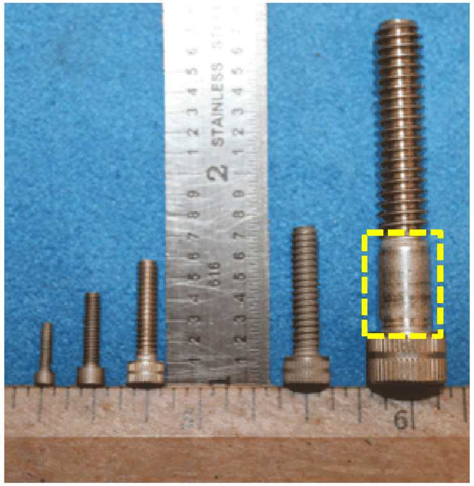
Incorporated multiple measurement instruments to validate data.

- Stroke
- LVDT
- Differential Variable Reluctance Tranducers (DVRTs)

Dimensions of fasteners:

- #00: L=0.120 in, d=0.060 in
- #02: L=0.172 in, d=0.086 in
- #04: L=0.224 in, d=0.112 in
- #06: L=0.276 in, d=0.138 in
- #4: L=0.150 in*, d=0.250 in

$$\frac{d}{L} \approx K$$



Fasteners: #00-#4

DVRTs in Top Bushing

Test Setup

[3]AIA/NAS – Aerospace Industries Association of America Inc., 2016, "English -- SCREW, CAP, SOCKET HEAD, UNDRILLED AND DRILLED, PLAIN AND SELF-LOCKING, ALLOY STEEL, CORROSION-RESISTANT STEEL AND HEAT-RESISTANT STEEL, UNRC-3A AND UNRC-2A - Rev 13", AIA/NAS NAS1351/1352.

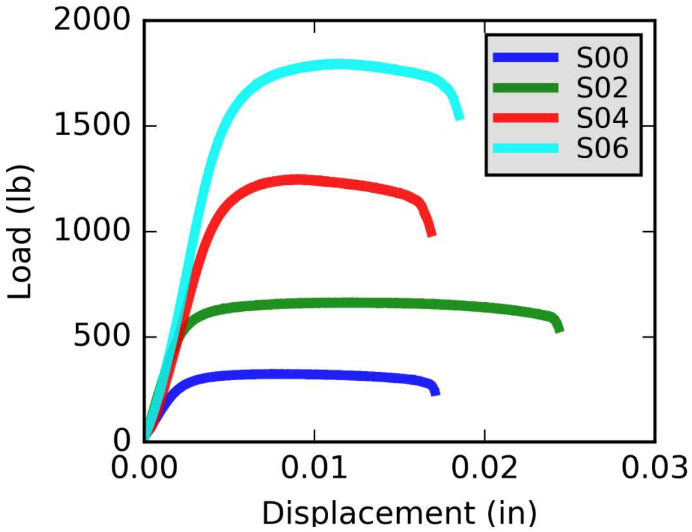
Test Results

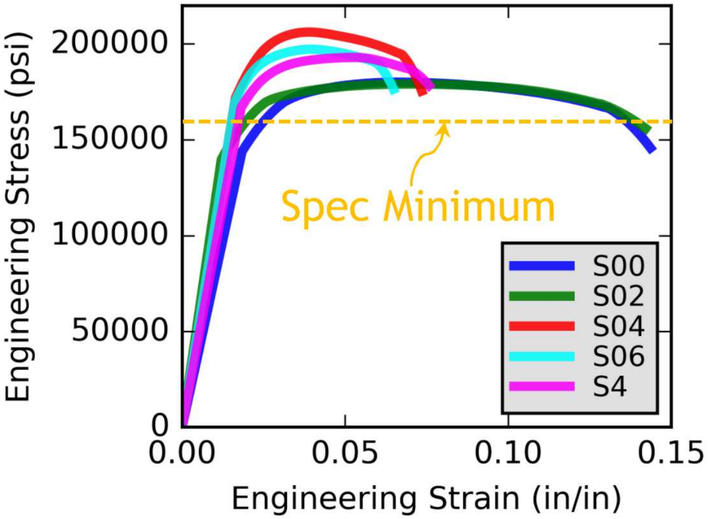
Load-displacement results reveal predictable failure load trends, but inconsistent failure displacements

Engineering stress-strain plots suggest similar inconsistencies

- Smaller fasteners have lower yield and ultimate, larger strain-to-failure.

Fasteners: #00-#4





<u>What is causing these differences?</u>

- Lot-to-lot variability?
- Structural size effects (geometric dependence)?
- Microstructural differences?

<u>Can we predict these trends?</u>

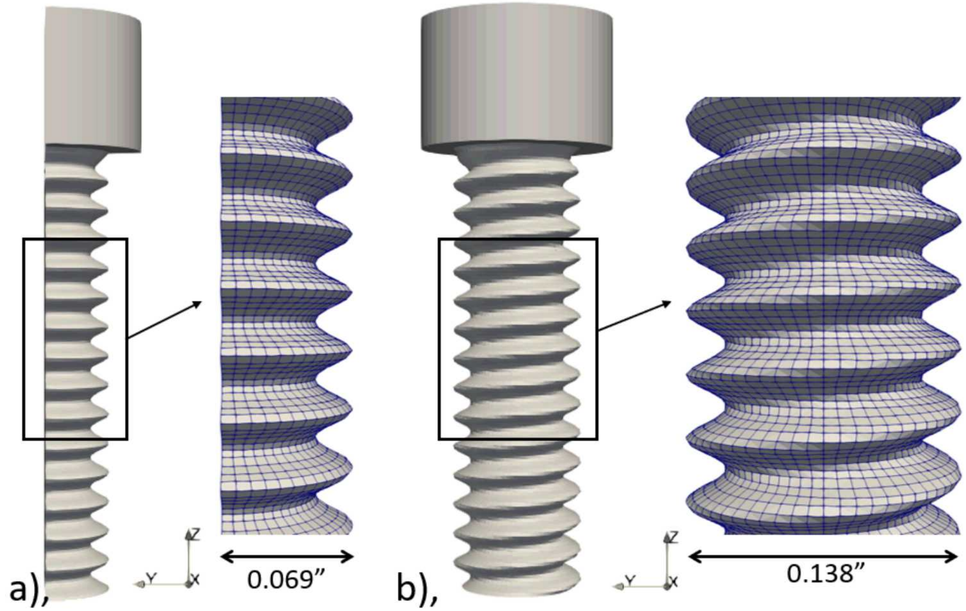
Build a high-fidelity fastener model to identify root cause of this behavior and investigate predictive capabilities.

High-Fidelity Modeling

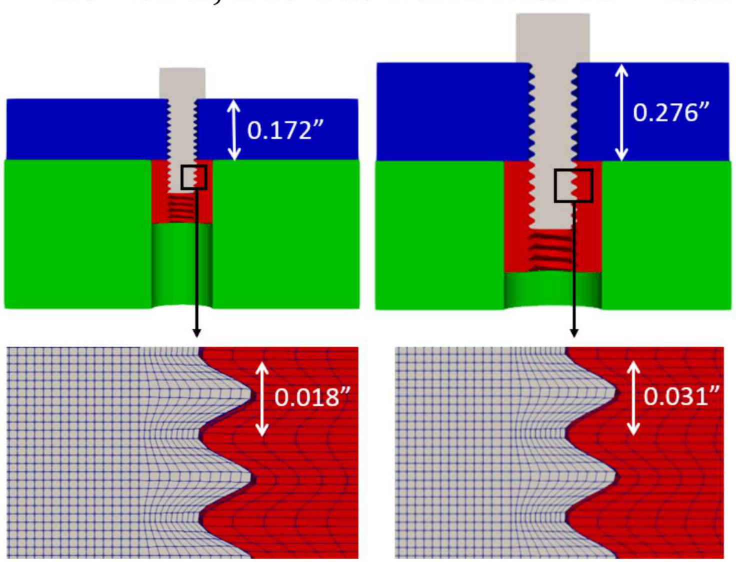
Constructed two high-fidelity models

- Axisymmetric Threaded
- Helical Threaded
  - #02
  - #06

Helical model includes all hexahedra elements, but was nontrivial to mesh



Axisymmetric *Helical*



#02 *#06*

Constitutive Model Hardening Function

$$\sigma_y = y + \frac{h}{r}\left[1 - \exp\left(-r\epsilon_p\right)\right]$$

Extrapolate material parameters to see if model can predict differences observed in testing

Calibration

Independently calibrated #02 and #06 helical models to test data.

Model parameters are qualitatively consistent with engineering stress-strain.

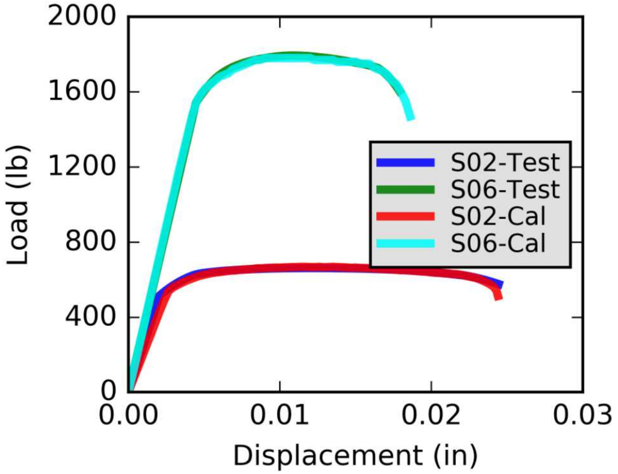
- #02: lower yield, larger $\epsilon_{p,crit}$
- #06: higher yield, smaller $\epsilon_{p,crit}$

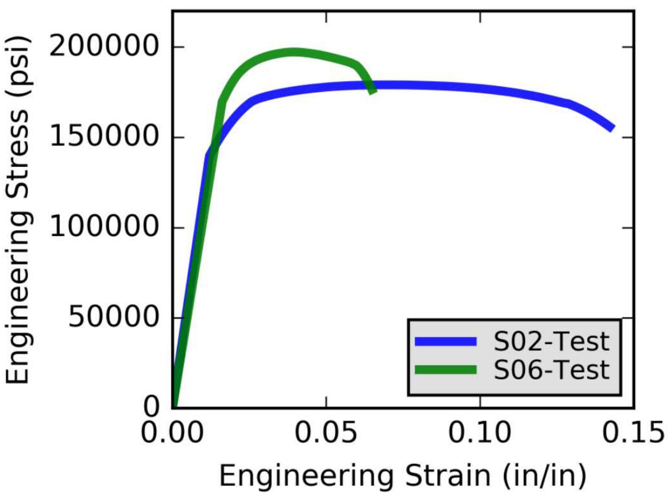
Calibrated an equivalent plastic strain (eqps) death criterion to capture displacement-to-failure.

Constitutive Model Hardening Function

$$\sigma_y = y + \frac{h}{r}\left[1 - \exp\left(-r\epsilon_p\right)\right]$$

Model	y	h	r	$\epsilon_{p,crit}$
#02	160 ksi	1,000 ksi	30	0.43
#06	185 ksi	1,000 ksi	120	0.17





Material Parameter Extrapolation

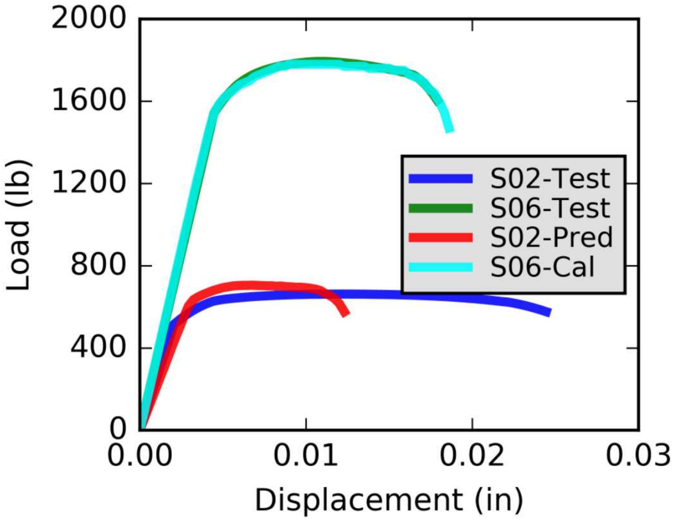
Applied calibrated #06 material properties to the #02 model.

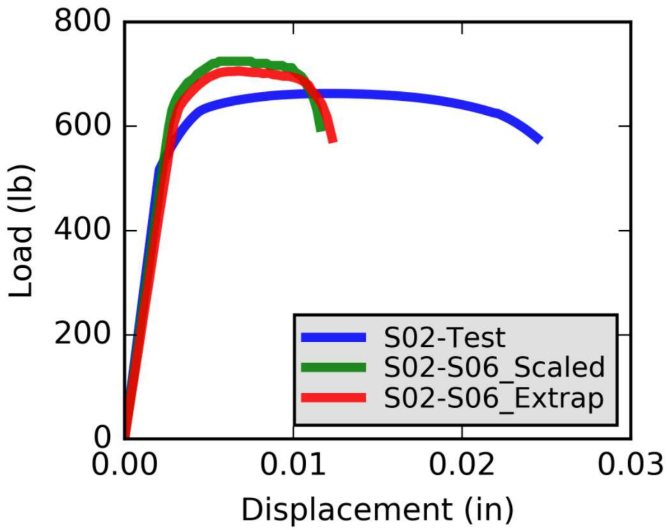
- Load: 706 lb to 663 lb (6% difference)
- Failure Displacement: 0.013 in to 0.024 in (54% difference)

What happened???

Model did not elicit different response

- Extrapolated #06 properties provide nearly the same response as simply scaling the #06 load-displacement curve.
- High fidelity model cannot produce the different responses observed in the test data.





Geometry of different sized fasteners does not seem to be causing the difference in P-δ response

Microstructural Analysis

Performed microstructural analysis of fasteners with Electron Backscatter Diffraction (EBSD) mapping

- IPF X

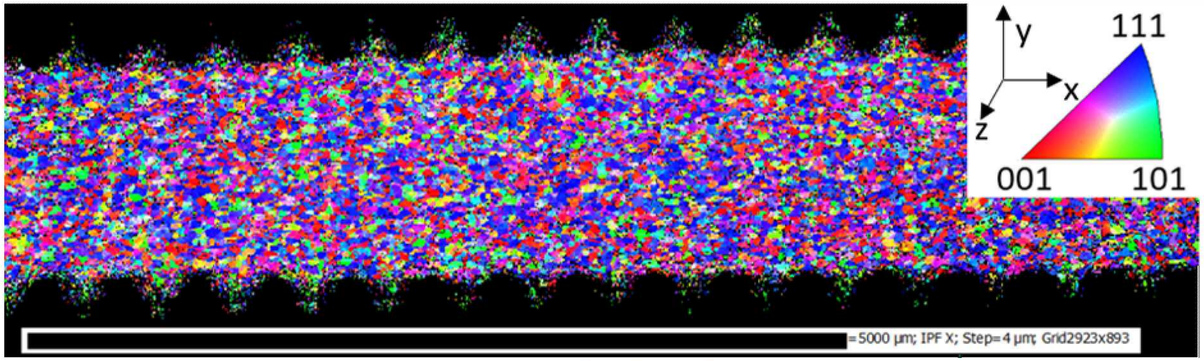
#02 Fastener:

- Equiaxed Grains
- Defined Grain Boundaries
- Balanced Color Distribution
- Evidence of Annealing

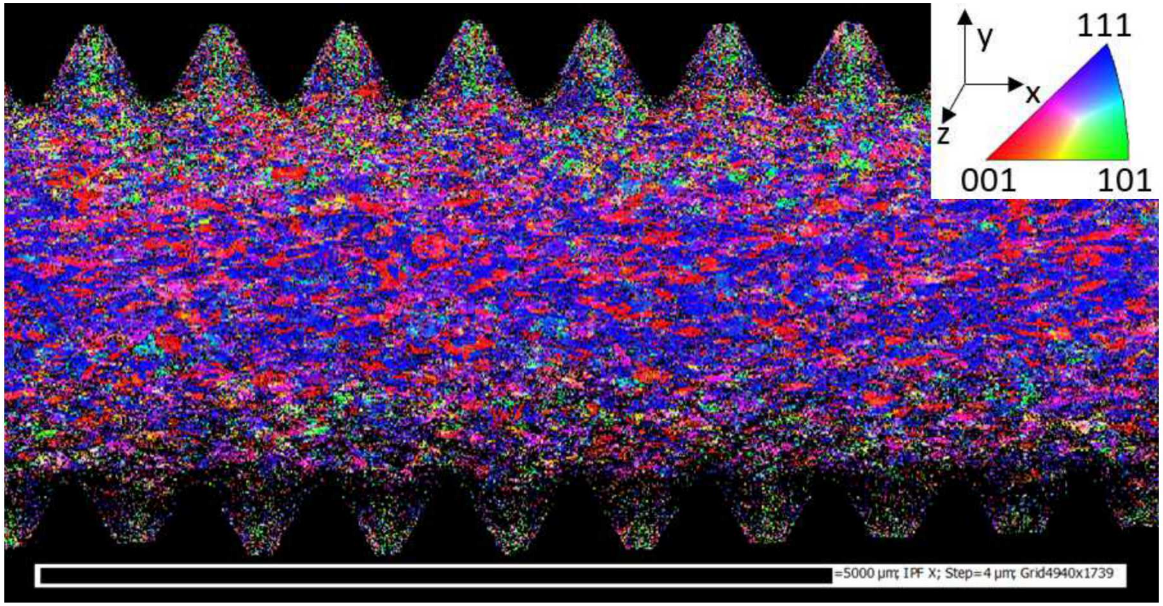
#06 Fastener:

- Elongated Grains
- Columnar Pattern
- Affinity for Red, Blue
- Evidence of Cold Working

Microstructures of the fasteners are different!



EBSD Map of #02 fastener



EBSD Map of #06 Fastener

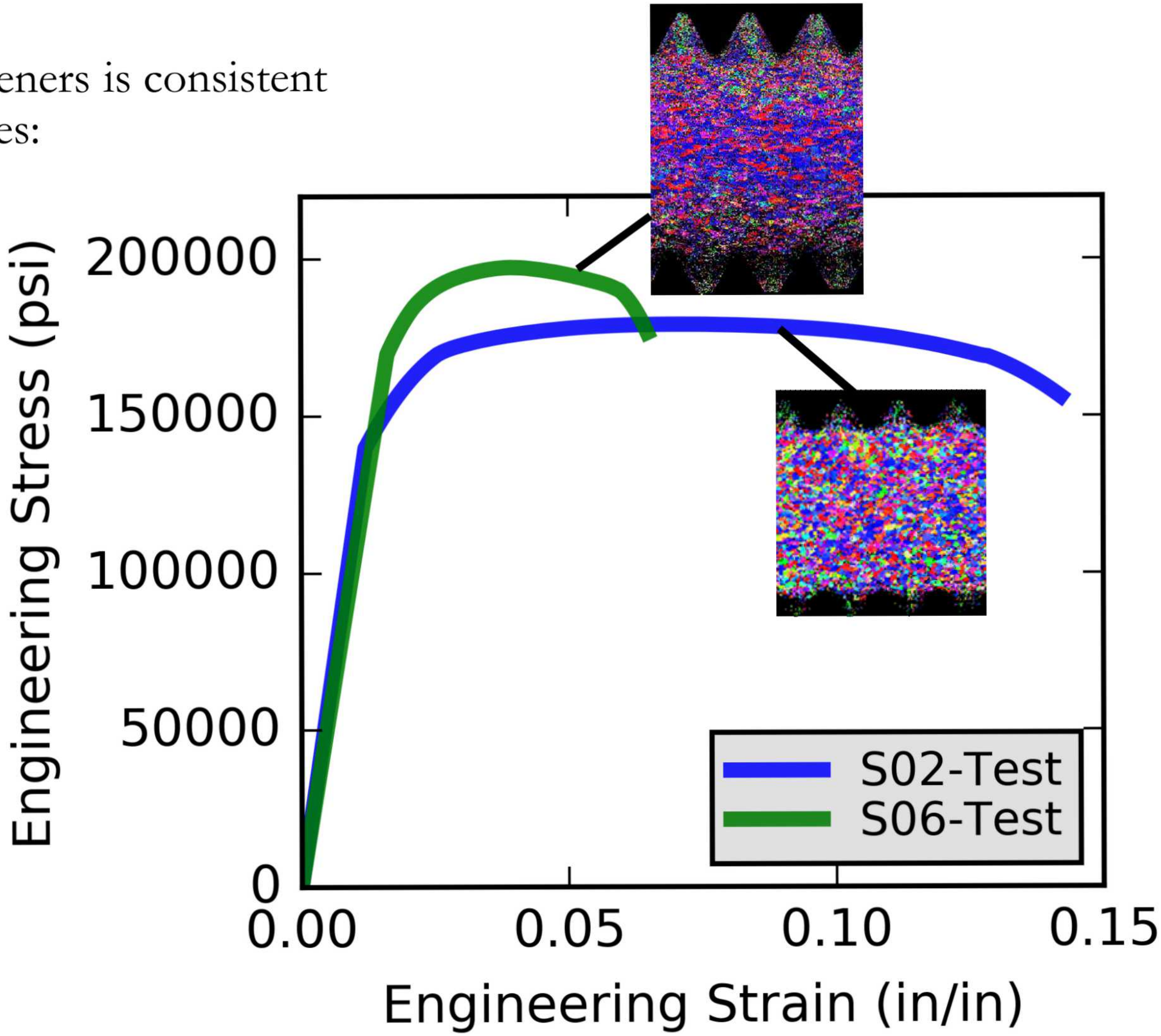
Microstructure and Stress-Strain Response

The microstructure of the fasteners is consistent with their stress-strain responses:

Cold Working↑ = Yield ↑

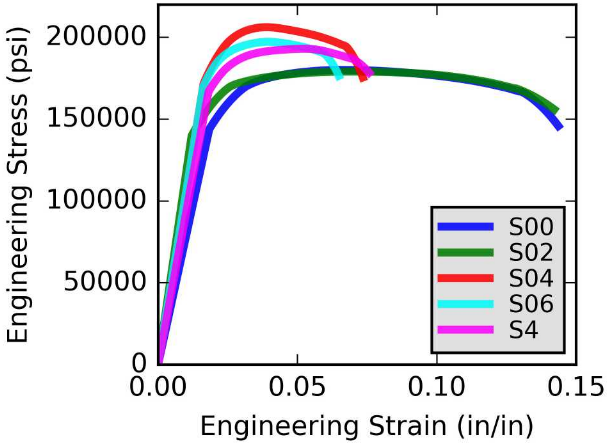
Cold Working↑ = Ultimate↑

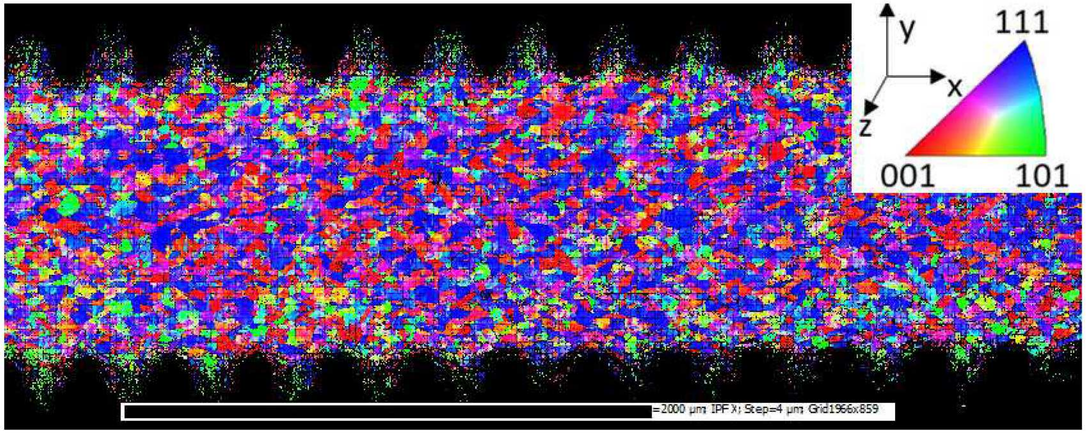
Cold Working↑ = Ductility↓



What will the microstructures of the #00 and #04 look like?

Microstructural Analysis

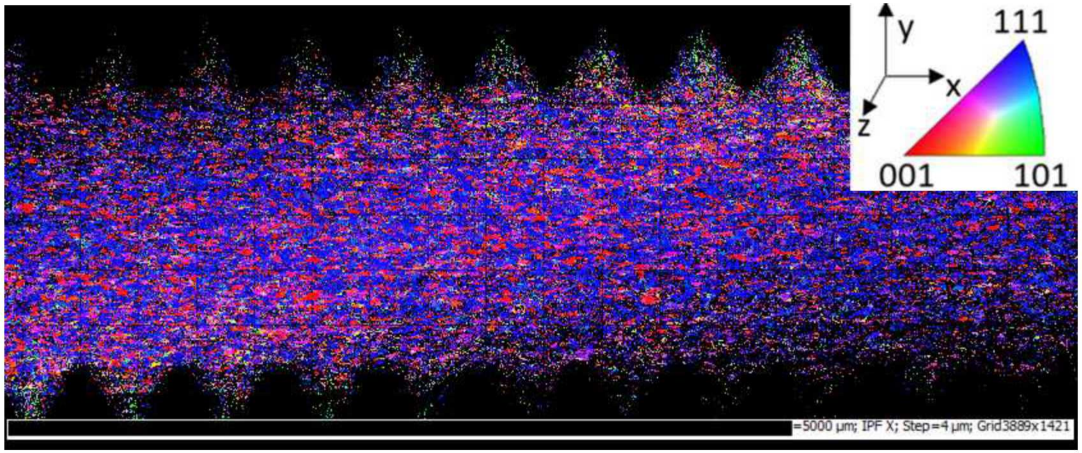




EBSD Map of #00 fastener

#00 Fastener:

- Equiaxed Grains
- Balanced Color Distribution
- Evidence of Annealing



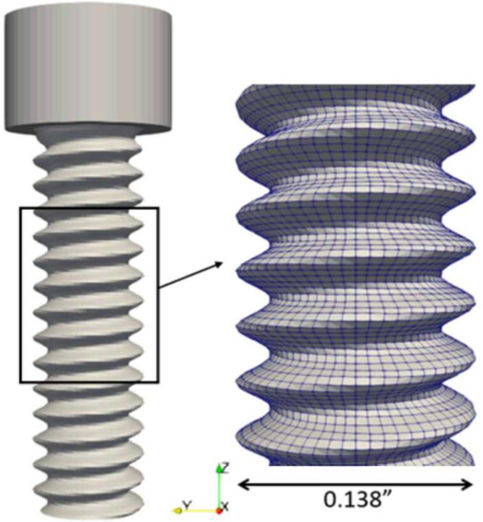
EBSD Map of #04 Fastener

#04 Fastener:

- Elongated Grains
- Affinity for Red, Blue
- Evidence of Cold Working

Microstructures of all fasteners consistent with corresponding stress-strain response

Conclusions/Lessons Learned

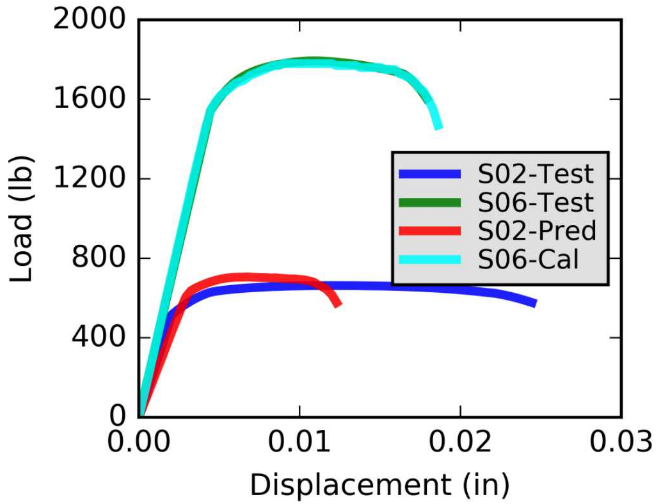


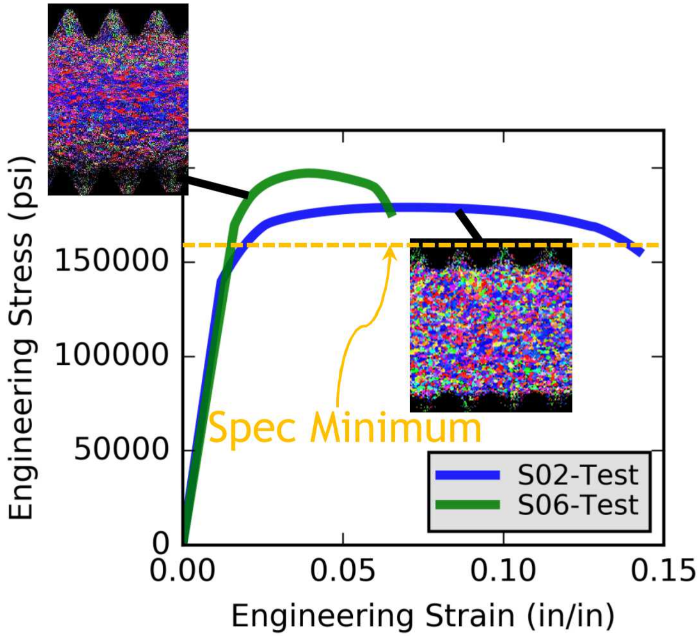
It is difficult to predict performance of fasteners without test data or material information!

- Peak loads have up to 14% difference.
- Ductilities differ by a factor of 2.

High-fidelity models could not accurately predict differences in load-displacement behavior.

Microstructure and stress-strain response seem to correlate.





We can significantly improve our predictive capabilities with material information

Future Work

Increased emphasis on materials science and the information it can provide to modeling and simulation.

Higher order calibration routines: can we improve our predictive capabilities when more information is available?

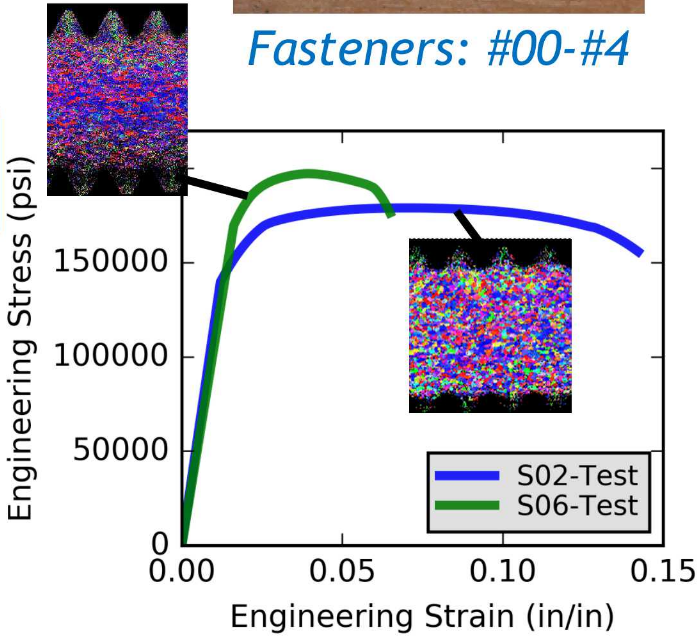
- NAFEMS World Congress
- Rate-dependent model

Thank You!

Normal environments response:

- Preload effects
- Dynamic environments (NOMAD 2019)

Fasteners: #00-#4



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Acknowledgements

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