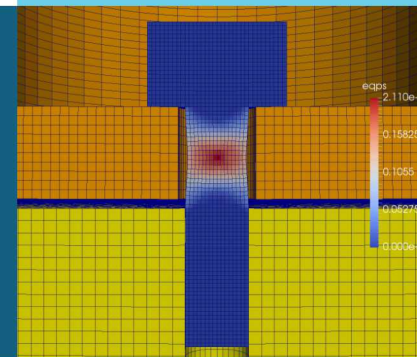
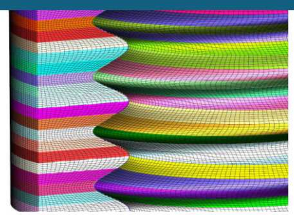
SAND2019-0690PE

Fastener Failure in Abnormal Environments





Department of Mechanical and Aerospace Engineering

Jan 25th, New Mexico State University, Las Cruces, NM

PRESENTED BY

John P. Mersch, Mechanical Engineer, Comp. Sci. & Mech.

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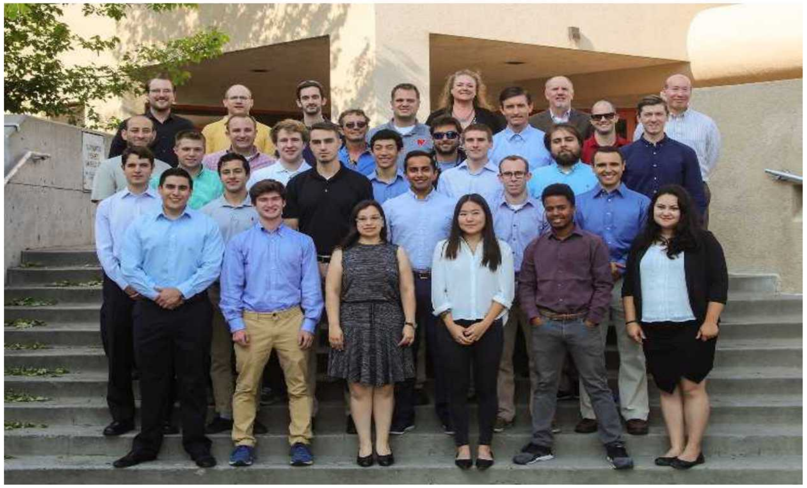
- Hosted by Sandia National Laboratories and University of New Mexico
- Collaborative opportunity to work on research in topic areas across nonlinear mechanics and dynamics
- 7 week program held in Albuquerque, New Mexico; open to graduate and highly qualified undergraduate level students
  - Mentorship opportunities for faculty



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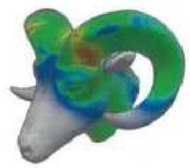

Research and Applications of Mechanics of Structures (RAMS) Institute

National Security Mission

Sandia National Laboratories delivers essential science and technology to resolve the nation's most challenging security issues. A strong science, technology, and engineering foundation enables Sandia's mission through a capable research staff working at the forefront of innovation, collaborative research with universities and companies, and mission directed research projects. We recruit the best and the brightest, equip them with world-class research tools and facilities, and provide opportunities to collaborate with technical experts from many different scientific disciplines.

Institute Description

Sponsored by Sandia's Engineering Sciences Center, the Research and Applications of Mechanics of Structures (RAMS) Institute provides students an opportunity to work with outstanding technical staff in providing engineering solutions to national security mission deliverables. Institute participants will research, develop, and apply computational capabilities to define mechanical environments and simulate response of complex structural systems subjected to extreme loading conditions.

Students work in a collaborative environment and participate in frequent technical and team building activities throughout their internship, including career discussions, tours, and invited speakers.

Interns Needed

Highly qualified graduate and undergraduate engineering students with an interest in structural mechanics research and applications, including environments definitions, structural mechanics simulation, material mechanics, and shock physics are needed to support on-going programs during the summer of 2018. Undergraduate students transitioning from the Junior to Senior year and graduate students having completed at least one year of studies toward an MS or Ph.D. degree are preferred. Successful candidates will be assigned a staff mentor and work as part of a team of interns from across the United States. Students will be challenged to conduct independent and group work and to actively engage in mission activities.

Applying

Minimum GPAs of 3.0 on a 4.0 scale are required at Sandia for student internships. Preference will be given to students that meet a more rigorous standard of 3.5 undergraduate and 3.7 graduate GPA. Applicants must be eligible to pursue a Department of Energy security clearance. More information and application is available at the Sandia recruiting web site: http://www.sandia.gov/careers
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Please direct any questions to Cassie Miller at cmille@sandia.gov.

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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.

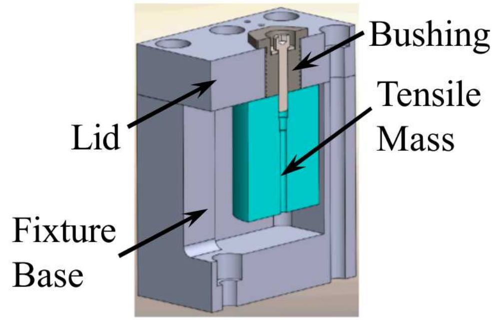
Goal: Gain a fundamental understanding of threaded fasteners through exploration of testing procedures, modeling processes, and the underlying physics/material science principles.

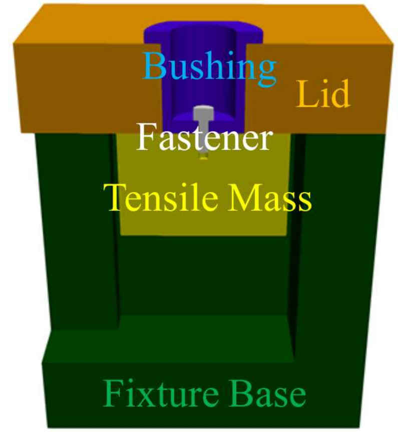
Integrated Effort

Trying to develop our knowledge in three main areas:

Modeling capabilities:

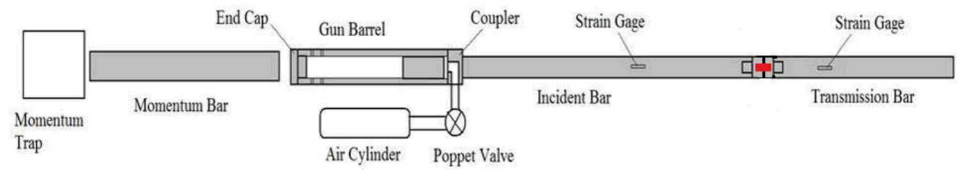
- Strain Rate Effects
- Analysis Best Practices
- Size Effects
- Multiaxial Loading[1]





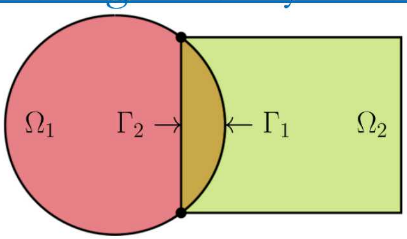
Testing of Threaded Fasteners:

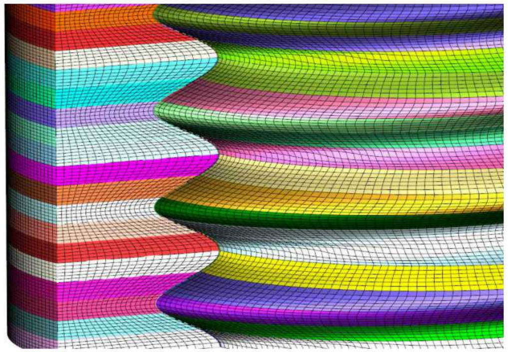
- Strain Rate Effects
- Testing Best Practices
- Size Effects[2]
- Multiaxial Loading



Fundamental Physics, Mat Sci, and High Fidelity Modeling:

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





[1]Camarena, E, Quintana, A., Yim, V. et. al., "Multiaxial Loading of Threaded Fasteners", 2019 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA SciTech Forum, AIAA2019-2271, San Diego, CA, 2019.

[2]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.*

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

Outline

Best Practices for Testing and Modeling[1] (15 Minutes)

- *"Evaluating the Performance of Fasteners Subjected to Multiple Loadings and Loadings Rates and Identifying Sensitivities of the Modeling Process"*

Recognizing and Modeling Dynamic Effects[2] (5 Minutes)

- *"A Case Study for the Low Fidelity Modeling of Threaded Fasteners Subjected to Tensile Loadings at Low and High Strain Rates"*

Investigation of Size Effects in Fasteners[3] (15 Minutes)

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

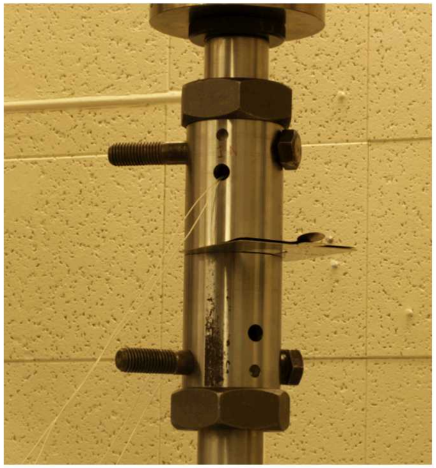
[4]Mersch, J. P., Smith, J. A., Johnson, E. P., Bosiljevac, T., "Evaluating the Performance of Fasteners Subjected to Multiple Loadings and Loading Rates and Identifying Sensitivities of the Modeling Process," 2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA SciTech Forum, AIAA2018-1896, Kissimmee, FL, 2018.
[5]Mersch, J. P., Smith, J. A., Johnson, E. P., "A CASE STUDY FOR THE LOW FIDELITY MODELING OF THREADED FASTENERS SUBJECT TO TENSILE LOADINGS AT LOW AND HIGH STRAIN RATES," ASME Pressure Vessels and Piping Conference, PVP2017-65518, ASME, Waikoloa, HI, 2017.
[6]Grimmer, P.W., Mersch, J.P., Smith, J.A., Veytskin, Y.B., Susan, D.F., "*Modeling Empirical Size Relationships on Load-Displacement Behavior and Failure in Threaded Fasteners*", 2019 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA SciTech Forum, AIAA2019-2271, San Diego, CA, 2019.

Original Test Series

Performed quasistatic and dynamic testing for pure tensile and shear loadings on NAS1352-06-6P threaded fasteners in hardened steel bushings.

Calibrate reduced order modeling approaches to quasistatic test data.

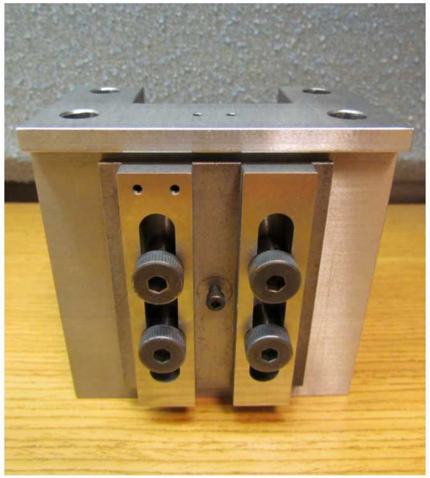
Assess these common approaches.



Quasistatic Tension Test Setup

Quasistatic Shear Test Setup

Dynamic Tension Test Setup



Dynamic Shear Test Setup

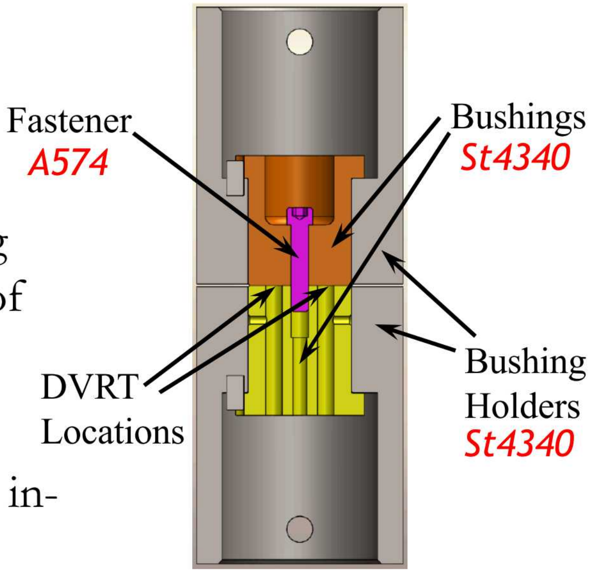
How well do our calibrated models extrapolate to other loads and loading rates?

Quasistatic Tension Tests

Test fixtures made of tool steel.

Four DVRTs located in bottom bushing take local displacement measurements of bushing separation.

Tests performed on both preloaded (20 in-lb) and hand-tightened fasteners.



Quasistatic Tension Test Setup

NAS1352-06-6P Fastener

DVRT Locations in Bushing

NAS1352-06-6P	SML6-3	SML6-7	SML6-12	SML6-13	SML6-22	SML6-31	SML6-33	Model
Head Diameter, A (in)	0.222	0.223	0.222	0.224	0.224	0.221	0.224	0.226
Head Height, H, (in)	0.1367	0.1365	0.1372	0.1372	0.1371	0.1372	0.1369	0.138
Shank Length, L, (in)	0.3688	0.364	0.3673	-	0.3639	0.3618	0.3686	0.375
Major Diameter, D, (in)	0.134	0.133	0.134	0.134	0.135	0.134	0.135	N/A
Tensile Stress Area, A_s, (in^2)	0.0084	0.0083	0.0084	0.0084	0.0086	0.0084	0.0086	0.0084

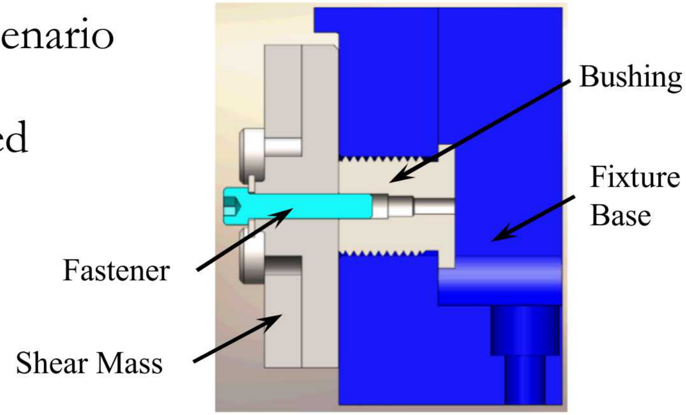
High Strain Rate (Dynamic) Tests

To create a dynamic loading scenario test fixtures were bolted to the carriage of a bungee accelerated drop table.

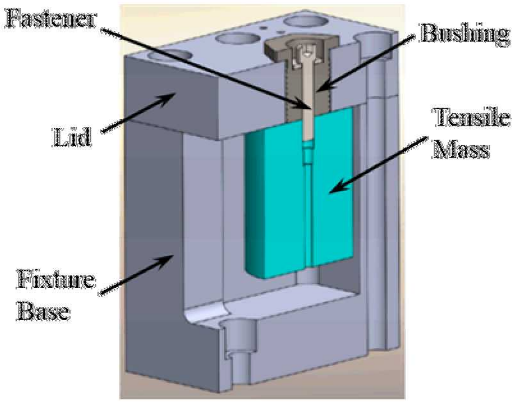
When the drop table carriage impacts the reaction mass the fastener experiences a tensile loading caused by the acceleration of the tensile mass.

Multiple accelerometers placed on test fixture for validation metrics.

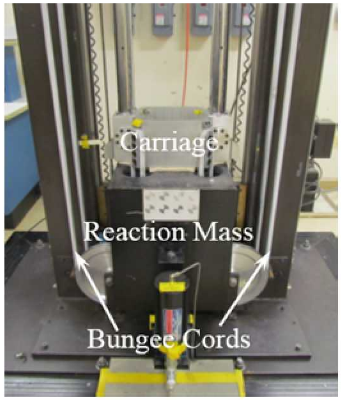
All tests were performed with the fasteners preloaded to 22 in-lb.



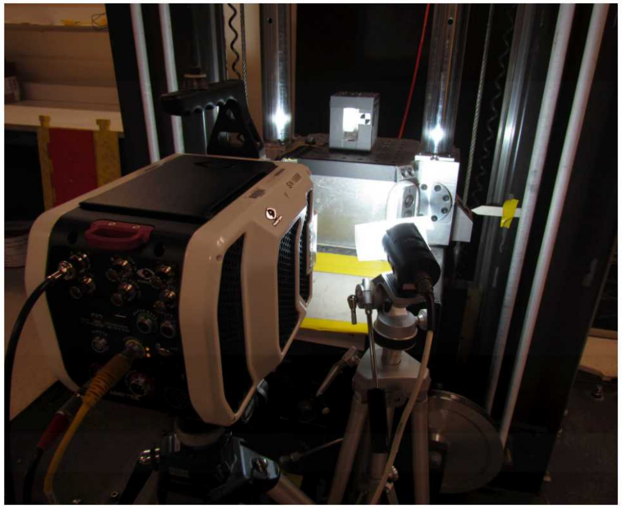
Dynamic Shear Test Fixture



Dynamic Tension Test Fixture



Drop Table



Drop Table Experimental Setup

Dynamic Tests

Main objective: determine failure load of fastener while varying shape of pulse acceleration.

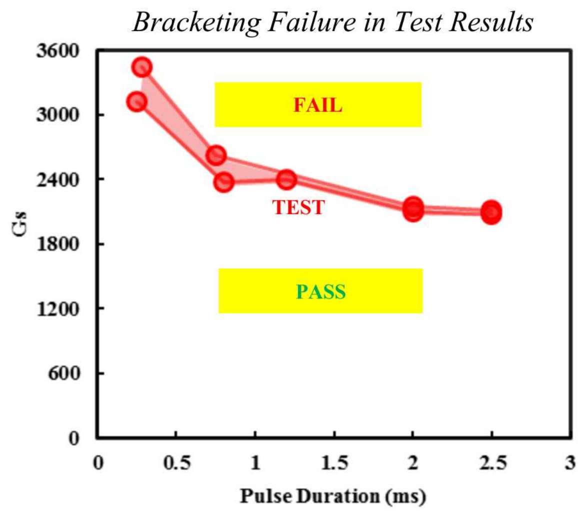
Five pulse levels were chosen that spanned the entire range of the drop table capability.

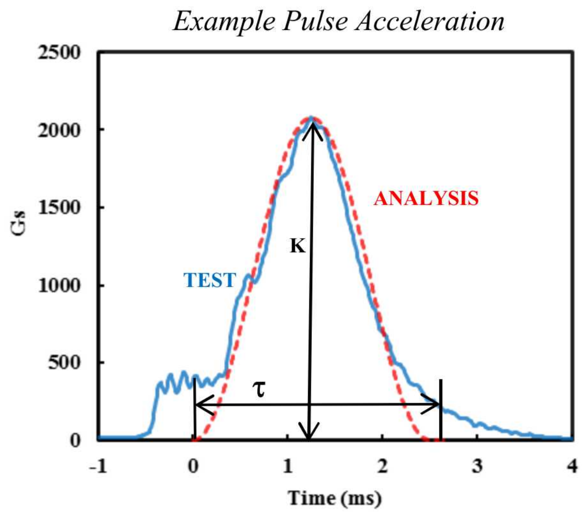
- Strain rates ranged from ~100-1,000 ε/s

With only four screws to test at each velocity level it was critical to bracket the failure point by achieving both a catastrophic failure and a non-failure within the four tests.

"Pulses" approximately take the form of a haversine function.

$$K sin^2\left(\frac{\pi t}{\tau}\right)$$



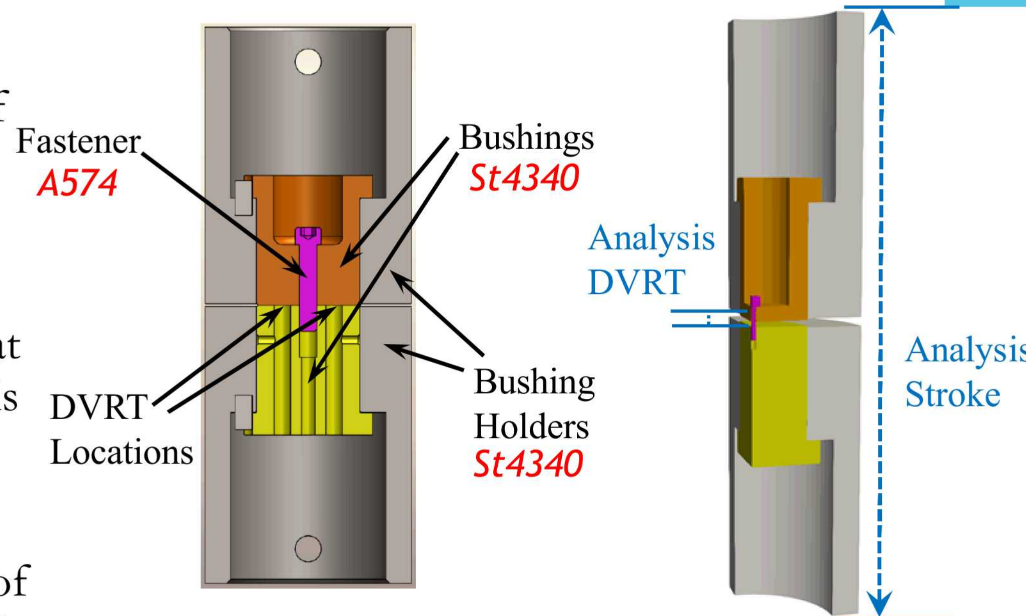


Analysis Models

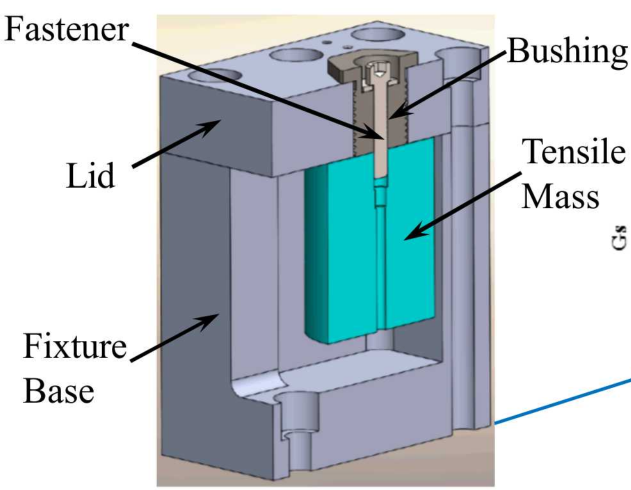
One-quarter (quasistatic) and one-half (dynamic) of the test setups were modeled utilizing symmetry.

Displacements analytically measured at DVRT locations on quasistatic analysis model.

Pulse acceleration applied to bottom of fixture base in dynamic analysis model.

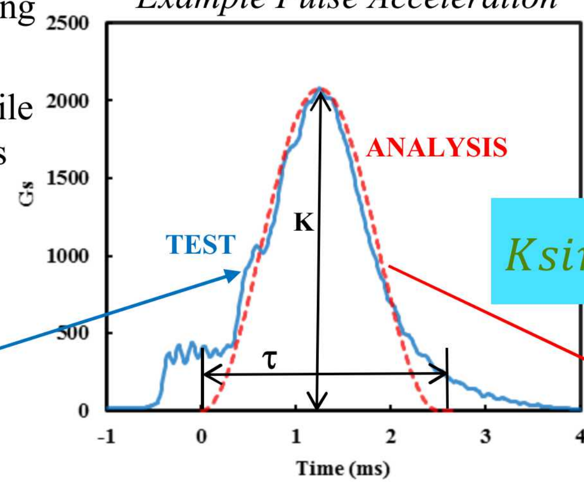


Quasistatic Tension Test Setup and Analysis Model

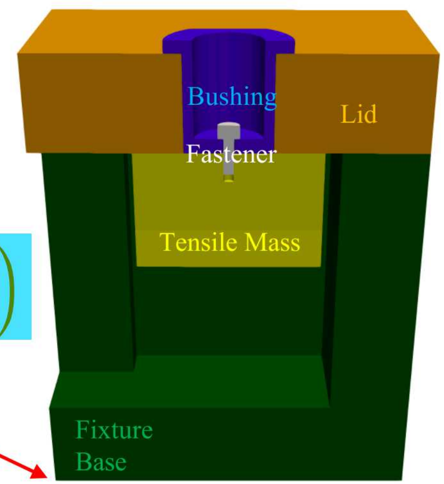


Dynamic Tension Test Fixture

Example Pulse Acceleration



$$K\sin^2\left(\frac{\pi t}{\tau}\right)$$



Dynamic Tension Analysis Model

Reduced-Order Modeling Approaches

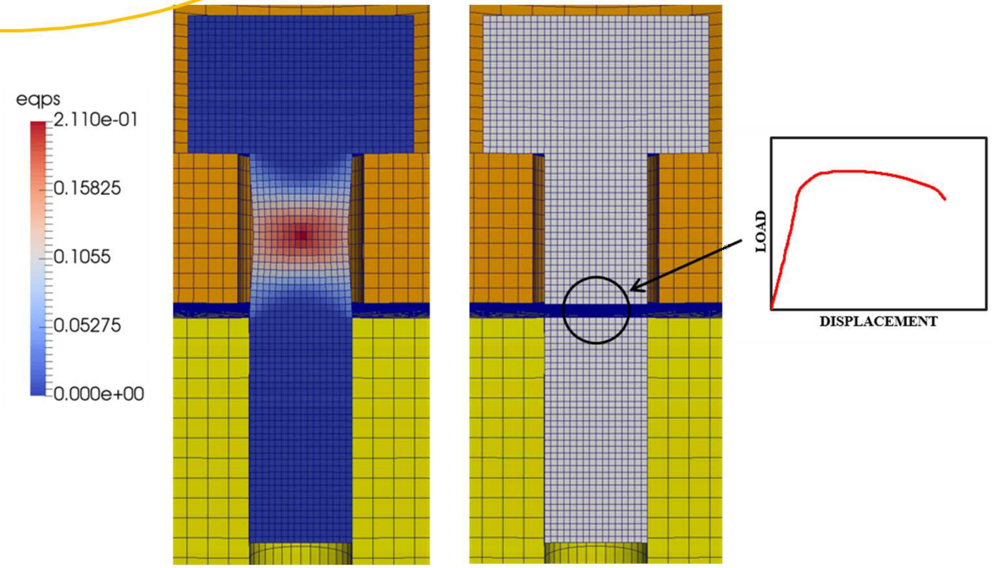
Study two low-fidelity modeling approaches: Plug and Spot Weld

Plug

- Hex elements
- Elastic-plastic constitutive model
- Piecewise-linear hardening
- EQPS death criterion

Spot Weld

- Hex elements
- Non-linear elastic constitutive model
- P-δ defined relationship
- Fails at end of P-δ curve

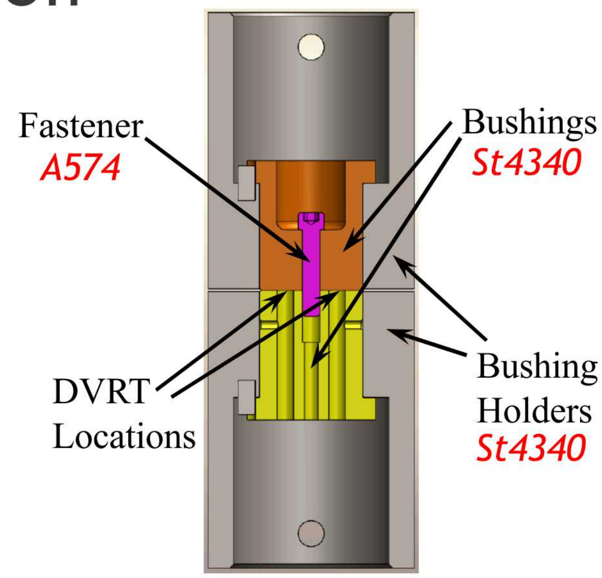


Test Results – Quasistatic Tension

Displacement measurements from stroke and DVRTs were very different.

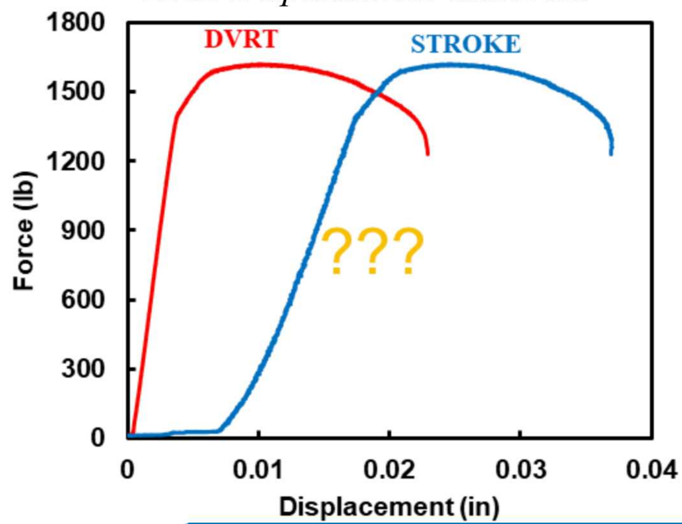
Compliance significantly contributes to data acquisition.

Where does this compliance come from?

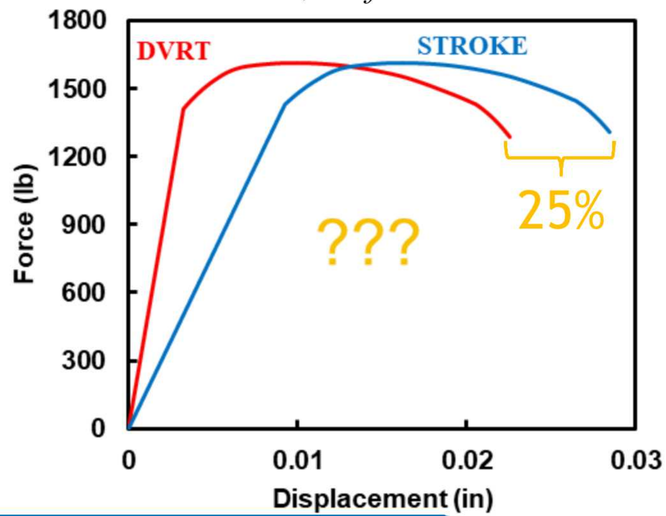


Quasistatic Tension Test Setup

Load-Displacement Test Data



Smoothed, Shifted Test Data



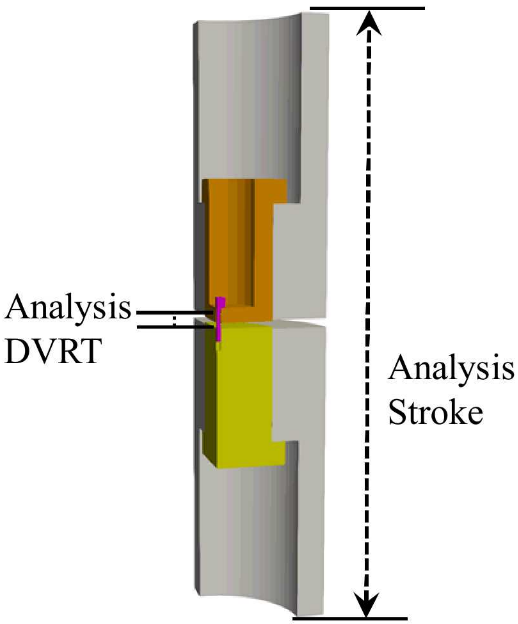
To which set of data should we calibrate?

Calibration

Performed calibrations for both the DVRT and stroke data using plug model.

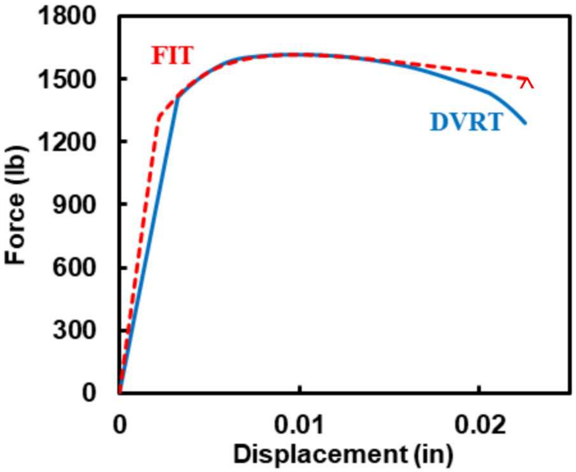
Used quasistatic tension load-displacement data to calibrate.

Fitted DVRT and Stroke test data with representative analysis measurement.

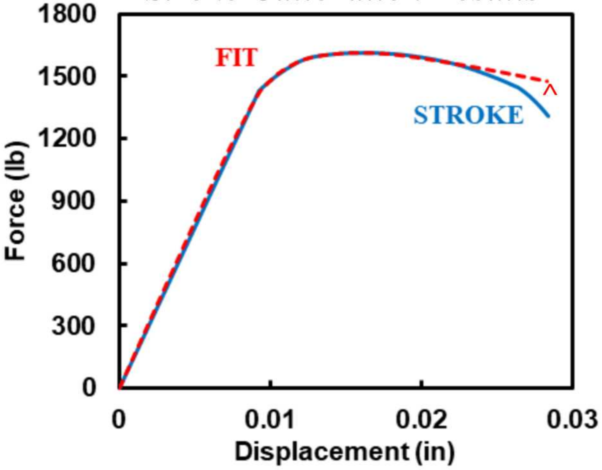


Quasistatic Tension Analysis Model

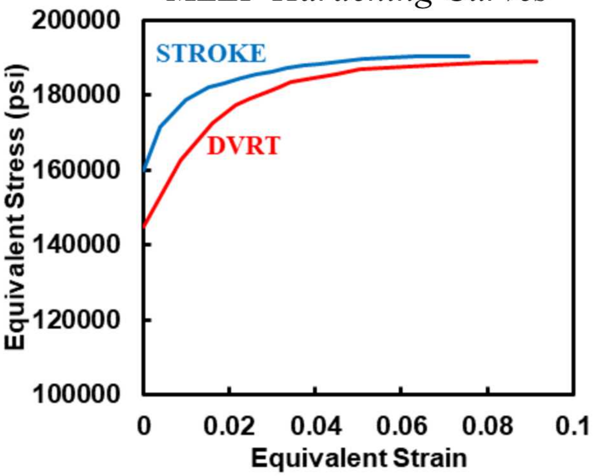
DVRT Calibration Results



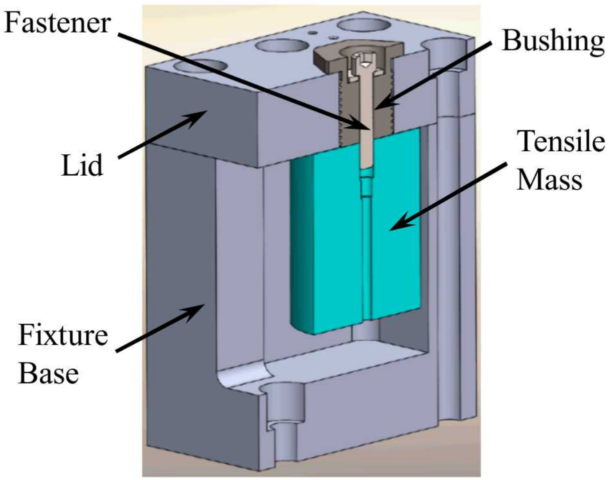
Stroke Calibration Results



MLEP Hardening Curves

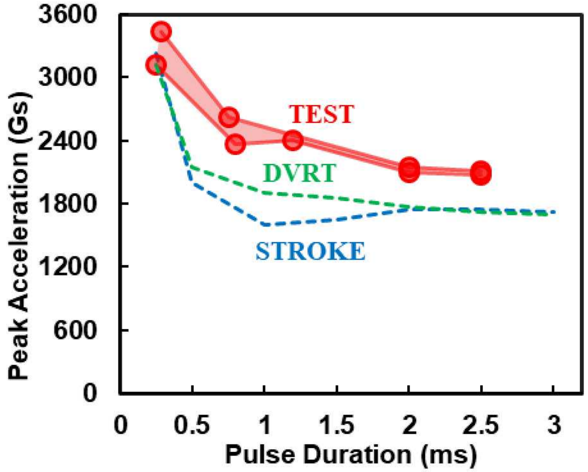


Analysis Results – Dynamic Tension

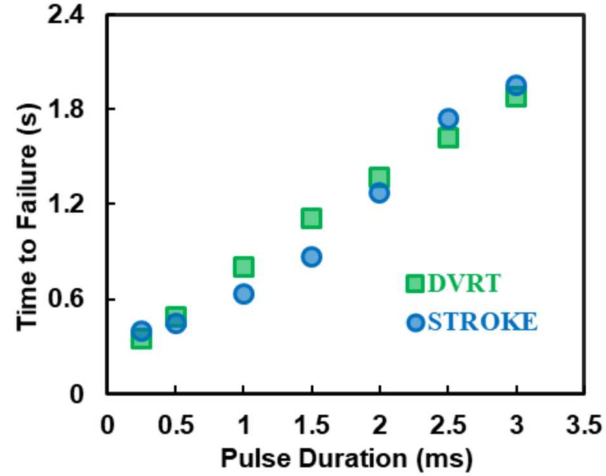


Dynamic Tension Test Fixture

Failure Load Test-Analysis Comparison



Analysis Time-to-Failure

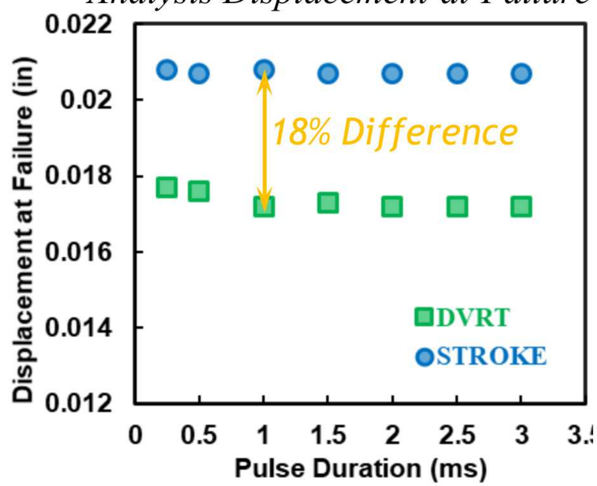


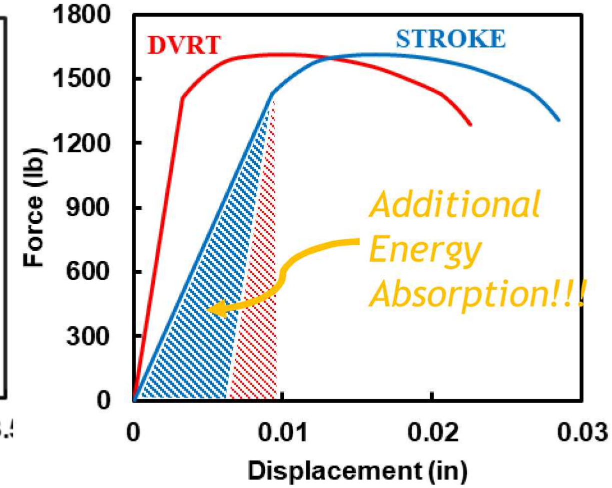
Common QoIs

- Failure Load
- Time to Failure
- Displacement at Failure

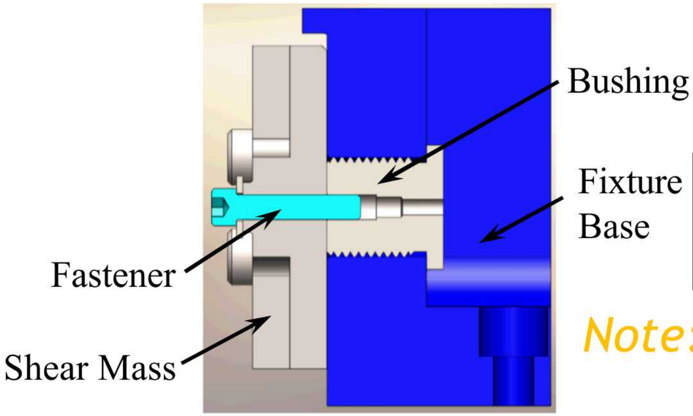
Note: Same Pulse Applied

Analysis Displacement-at-Failure





Analysis Results – Dynamic Shear

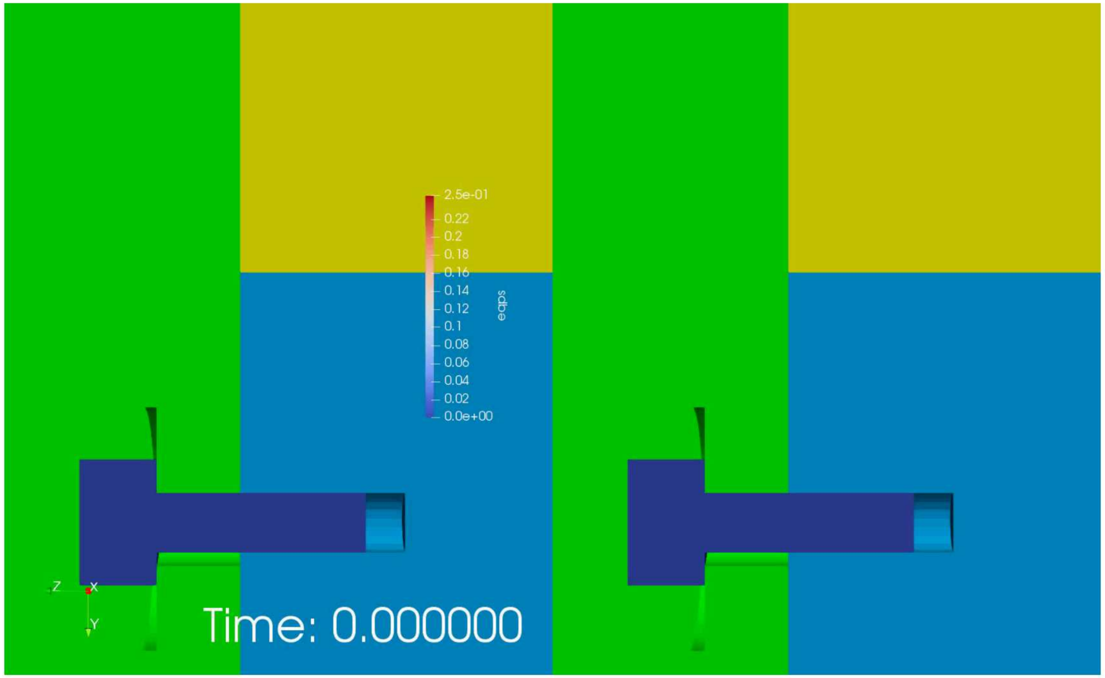


Dynamic Shear Test Fixture

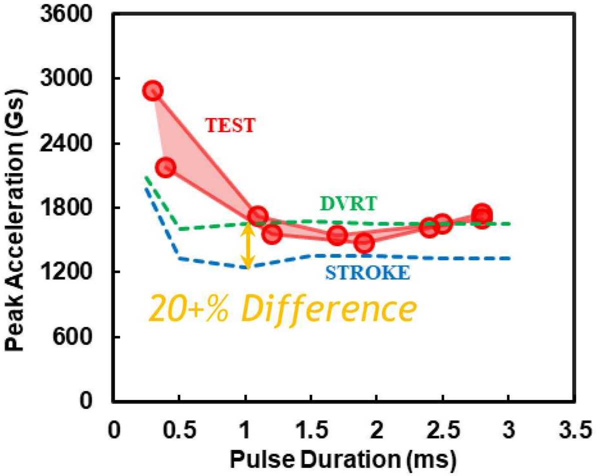
Common QoIs

- Failure Load
- Time to Failure

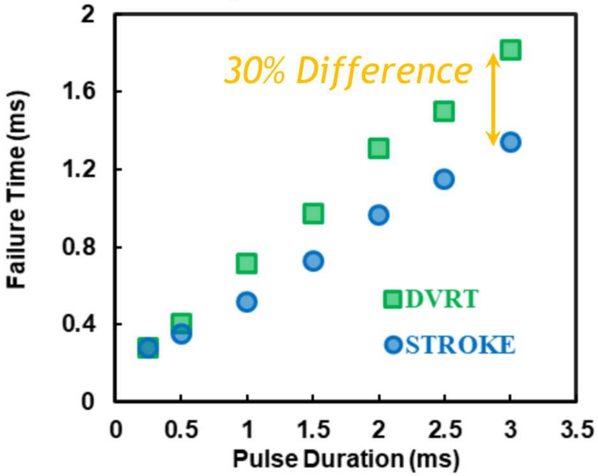
Note: Same Pulse Applied



Failure Load Test-Analysis Comparison



Analysis Time-to-Failure



Reflecting on the Results – What Happened?

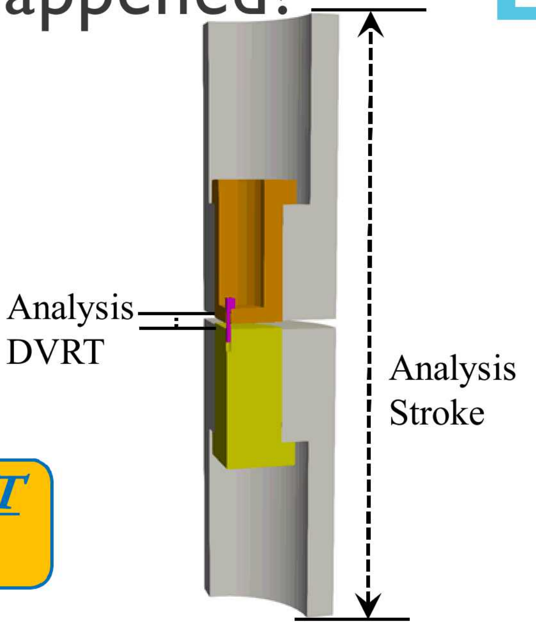
DVRT and stroke are very different in testing, but equivalent in analysis.

Young's Modulus was reduced by a factor of 5 to match stroke test data.

More common than one may think:

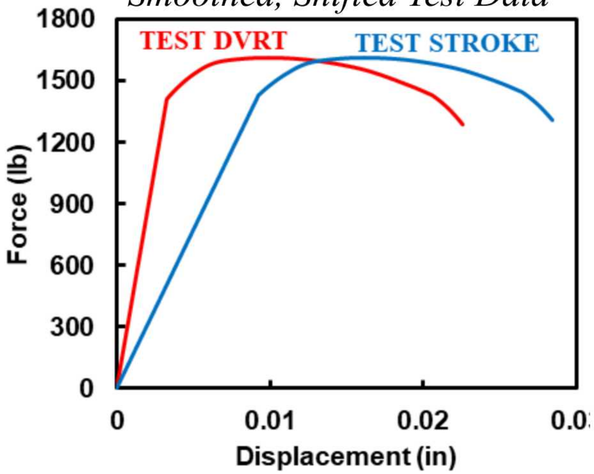
- Properties from literature
- One source of displacement data

Tests are obtaining *JOINT* behavior, not fastener

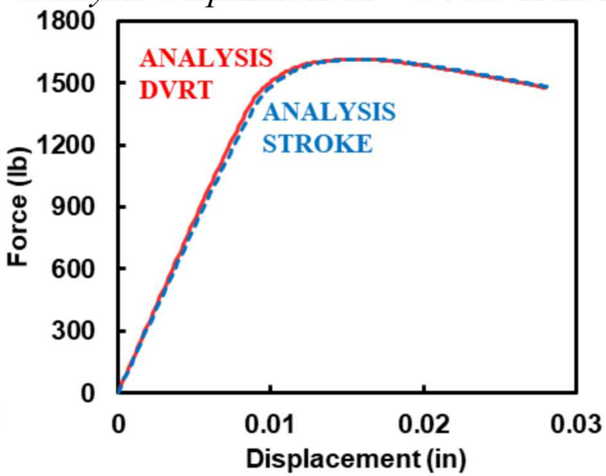


Quasistatic Tension Analysis Model

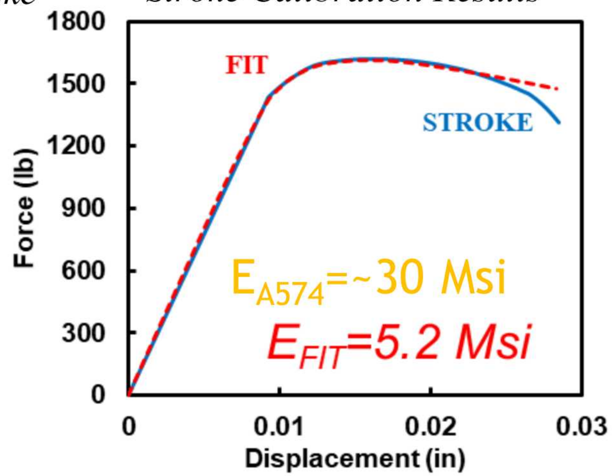
Smoothed, Shifted Test Data



Analysis Displacements – DVRT & Stroke



Stroke Calibration Results



Calibration techniques can be a large contributor to uncertainty and error

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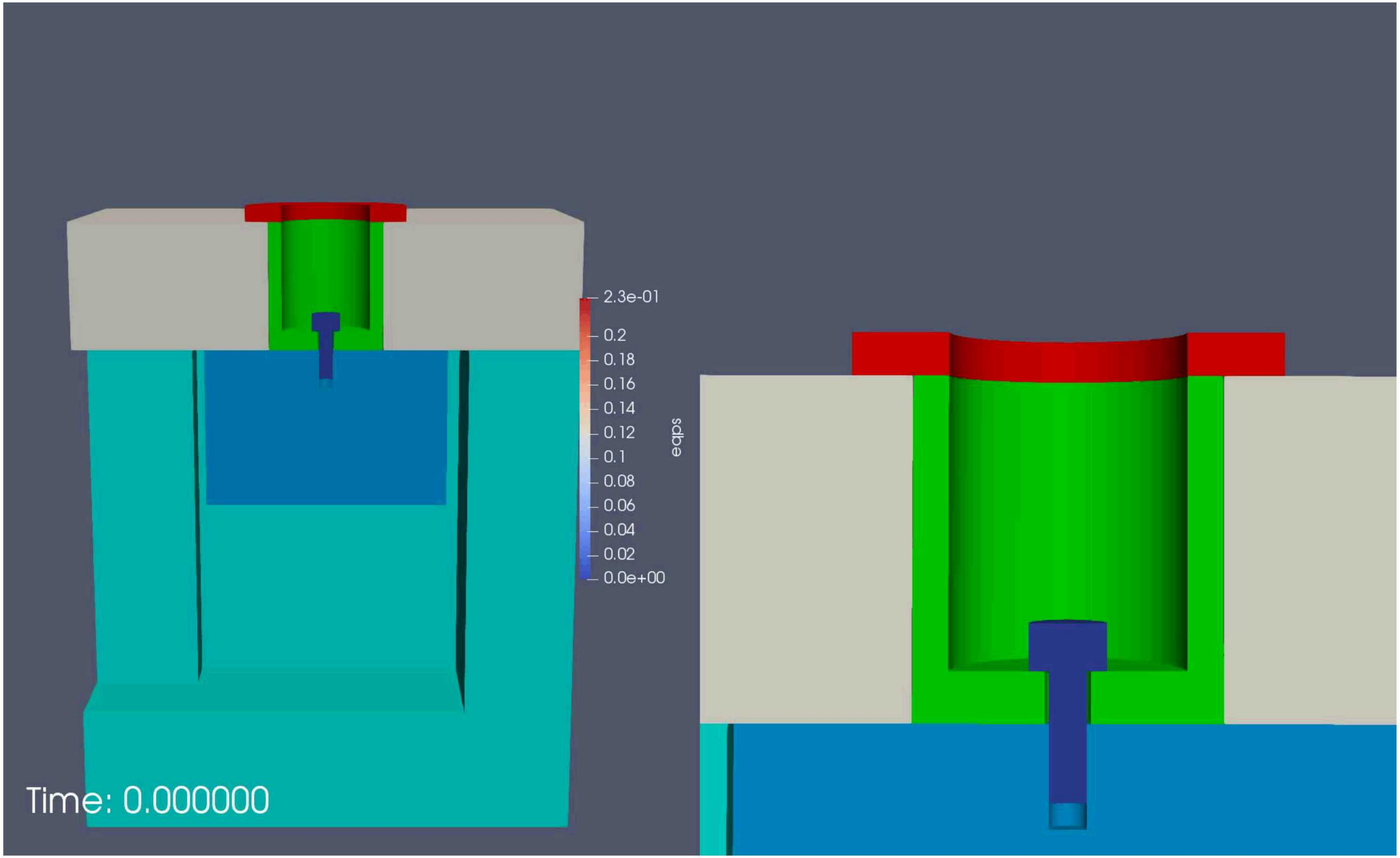
[6]Grimmer, P.W., Mersch, J.P., Smith, J.A., Veytskin, Y.B., Susan, D.F., "*Modeling Empirical Size Relationships on Load-Displacement Behavior and Failure in Threaded Fasteners*", 2019 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA SciTech Forum, AIAA2019-2271, San Diego, CA, 2019.

Dynamic Tension Simulation

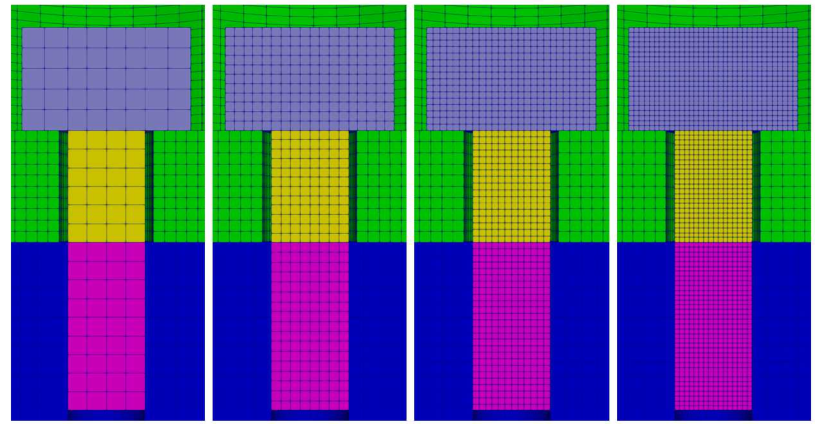


Analysis Results – Dynamic Tension

Dynamic failure curves were reproduced with each modeling method.

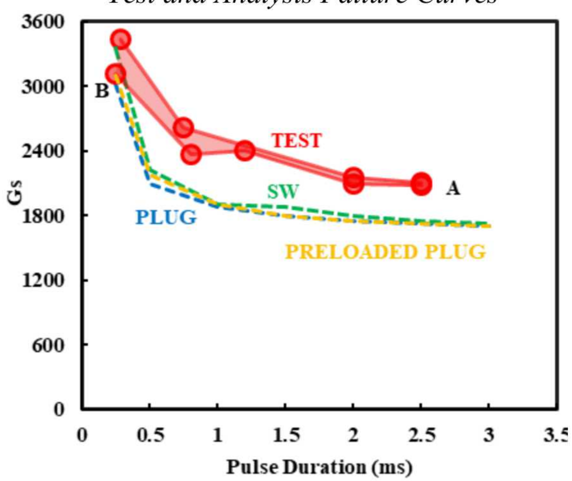
Failure defined as complete cross-section separation.

Sensitivity study performed to further assess modeling approaches.

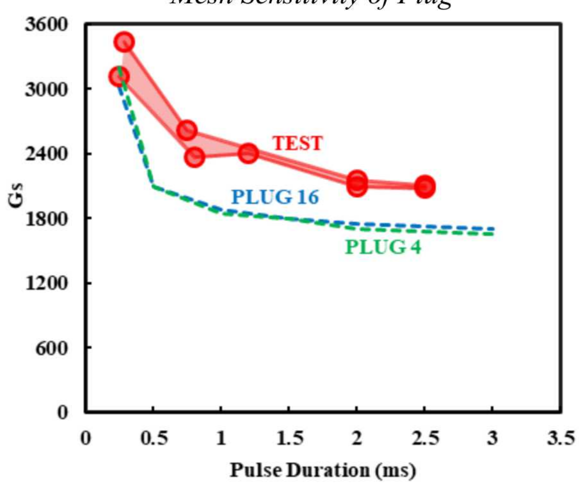


Meshes in Sensitivity Study

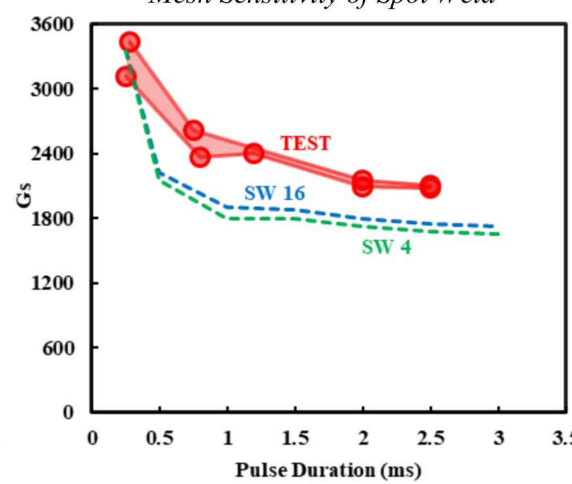
Test and Analysis Failure Curves



Mesh Sensitivity of Plug



Mesh Sensitivity of Spot Weld

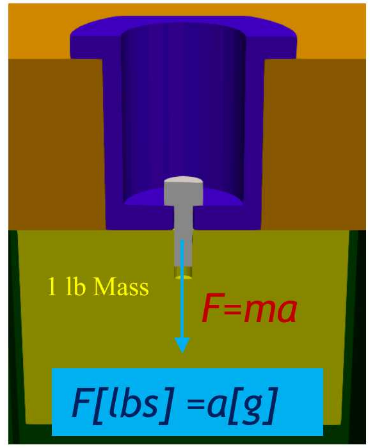


Modeling methods produced similar results, but underpredicted failure

A Closer Look…

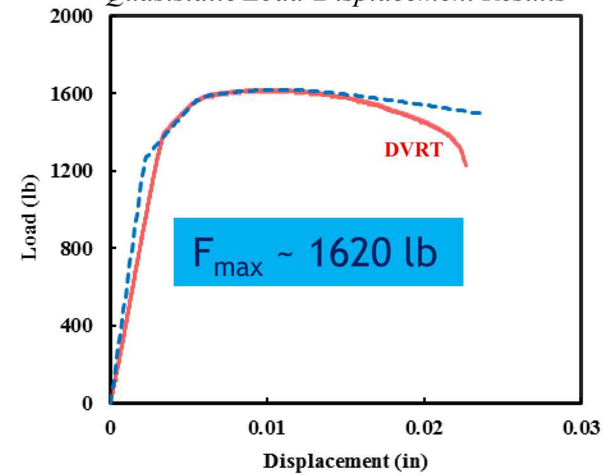
FBD shows load on fastener is equal to tensile mass acceleration.

Test accelerations 20% higher than ultimate load in quasistatic tests.

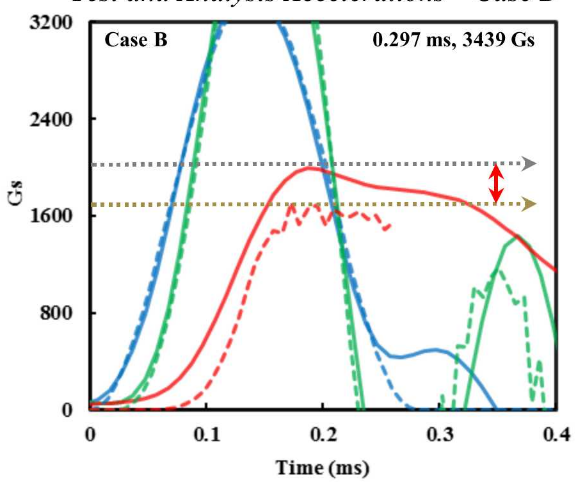


Load on Fastener

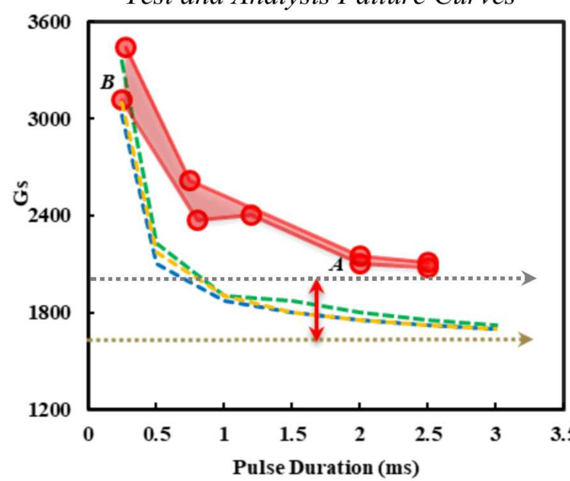
Quasistatic Load-Displacement Results



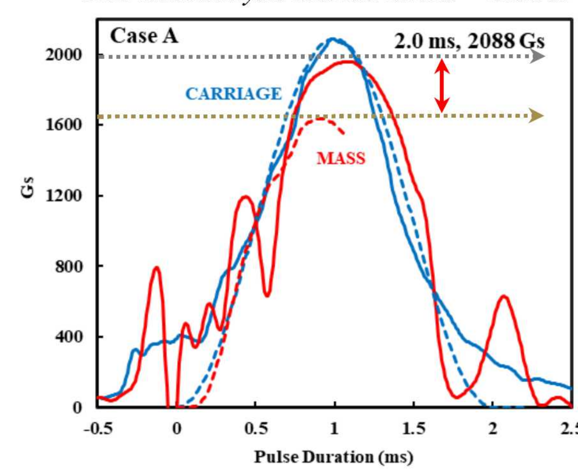
Test and Analysis Accelerations – Case B



Test and Analysis Failure Curves



Test and Analysis Accelerations – Case A



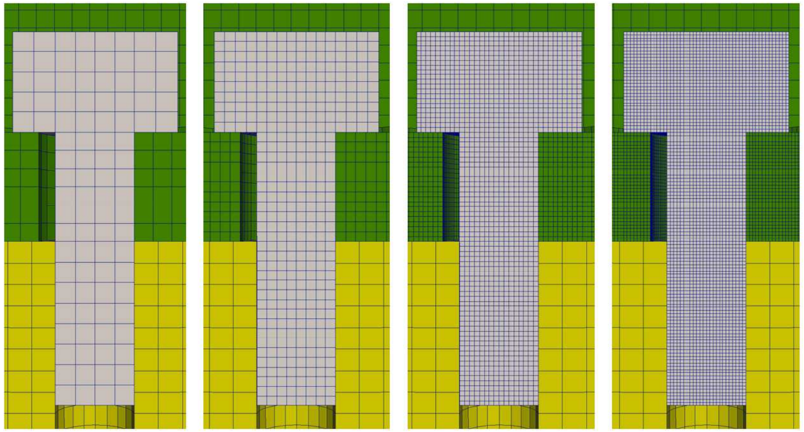
Strain rate effects likely causing models to underpredict failure load

Mesh Sensitivity

Mesh sensitivity was assessed in dynamic tension and shear models

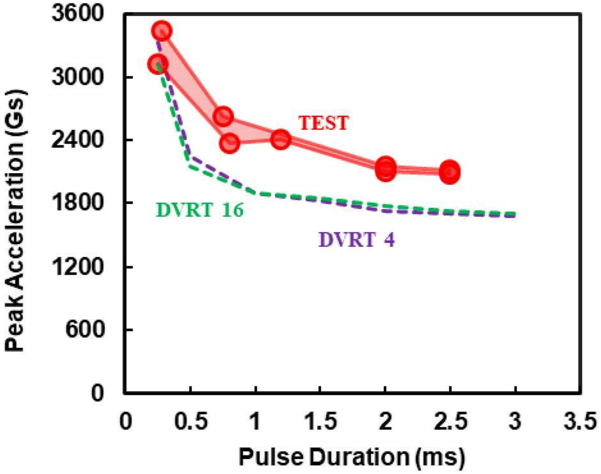
Tension analysis was insensitive to mesh

Shear analysis was **very sensitive** to mesh, and all results were nonconservative

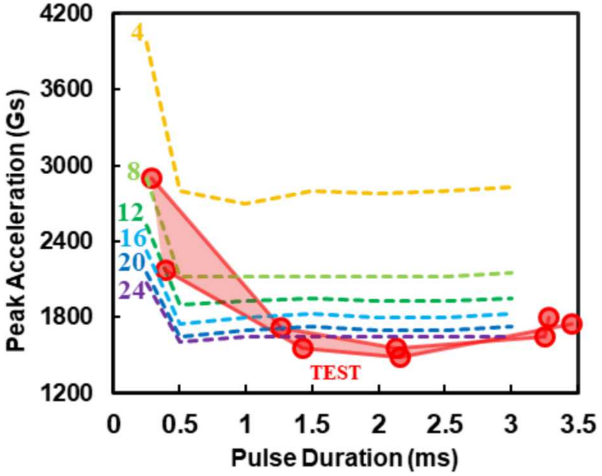


Meshes in Sensitivity Study (4, 8, 16, 24)

Mesh Sensitivity – Dynamic Tension



Mesh Sensitivity – Dynamic Shear



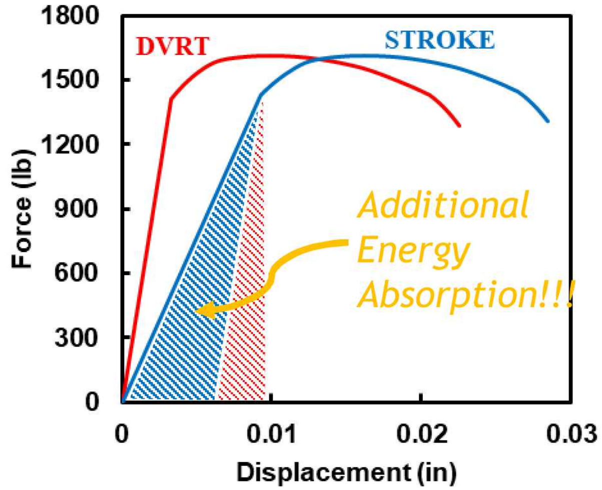
Relative difference in mesh sensitivity will make it difficult to capture both behaviors accurately

Conclusions

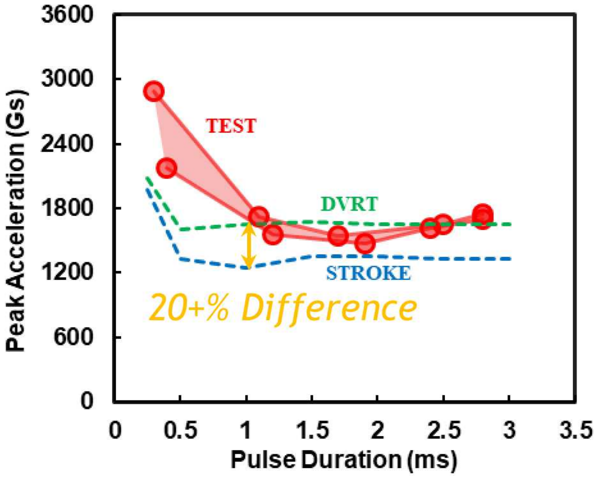
Measurement techniques play a significant role in data acquisition and analysis must account for all relevant bodies and compliance.

Mesh sensitivity of shear applications makes obtaining robust, accurate reduced-order fastener models increasingly difficult.

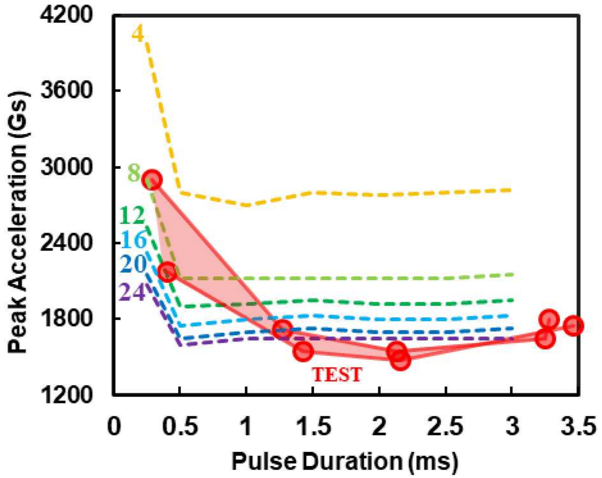
Strain rate effects can also contribute to error and uncertainty.



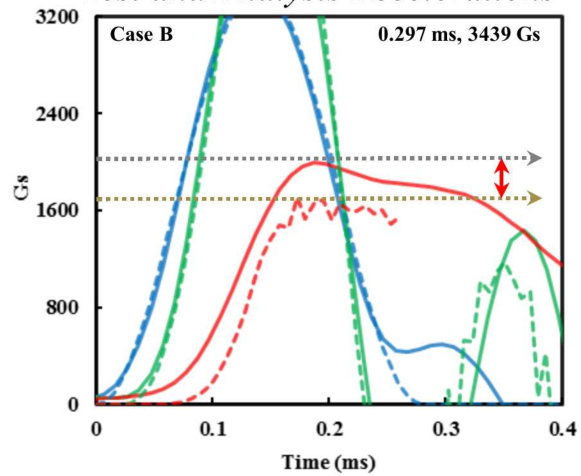
Failure Load Test-Analysis Comparison



Mesh Sensitivity – Dynamic Shear



Test and Analysis Accelerations



Outline

Best Practices for Testing and Modeling[1] (15 Minutes)

- *"Evaluating the Performance of Fasteners Subjected to Multiple Loadings and Loadings Rates and Identifying Sensitivities of the Modeling Process"*

Recognizing and Modeling Dynamic Effects[2] (5 Minutes)

- *"A Case Study for the Low Fidelity Modeling of Threaded Fasteners Subjected to Tensile Loadings at Low and High Strain Rates"*

Investigation of Size Effects in Fasteners[3] (15 Minutes)

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

[4]Mersch, J. P., Smith, J. A., Johnson, E. P., Bosiljevac, T., "Evaluating the Performance of Fasteners Subjected to Multiple Loadings and Loading Rates and Identifying Sensitivities of the Modeling Process," 2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA SciTech Forum, AIAA2018-1896, Kissimmee, FL, 2018.
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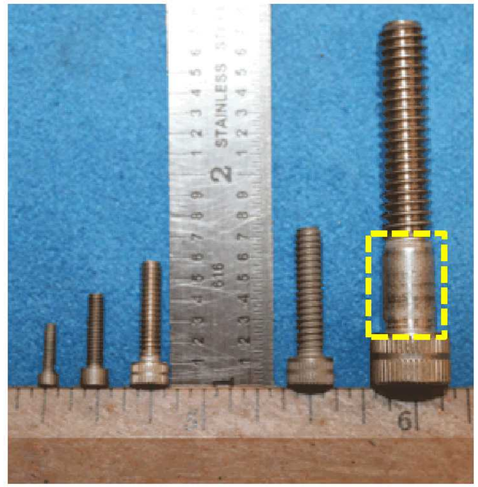
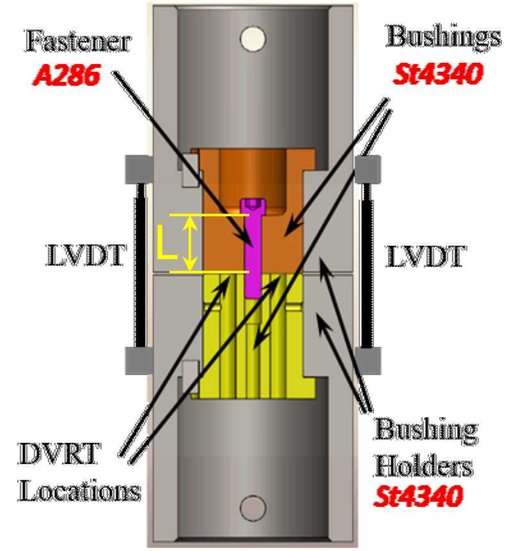
Our Study: Response of Various Sized Fasteners

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



Fasteners: #00-#4



Incorporated multiple measurement instruments to validate data.

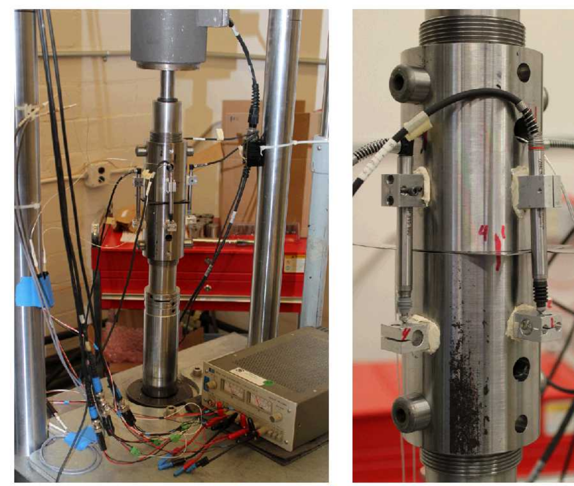
- Stroke
- LVDT
- Differential Variable Reluctance Tranducers (DVRTs)

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

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

DVRTs in Top Bushing



Test Setup

[4]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.

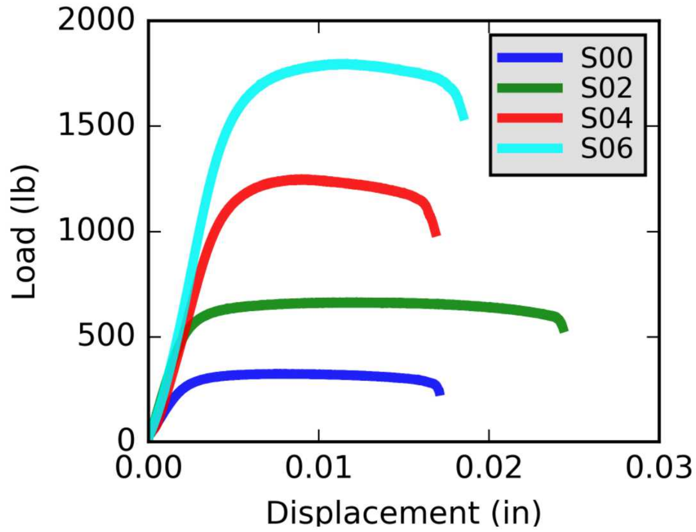
Test Results

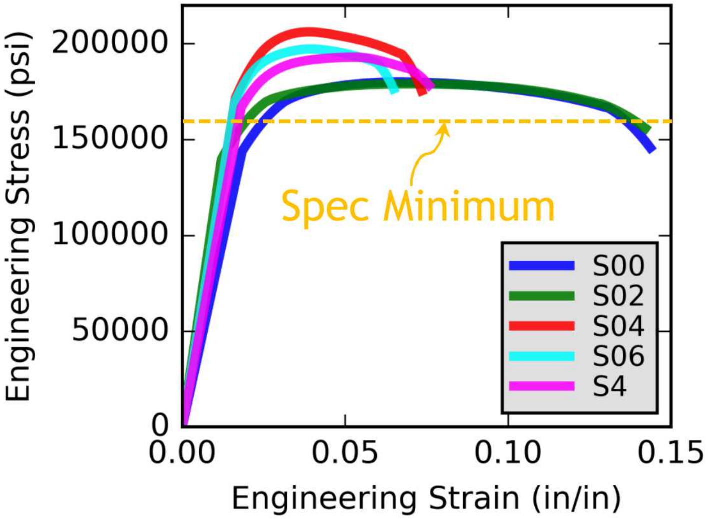
Load-displacement results reveal predictable failure load trends, but inconsistent failure displacements

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>

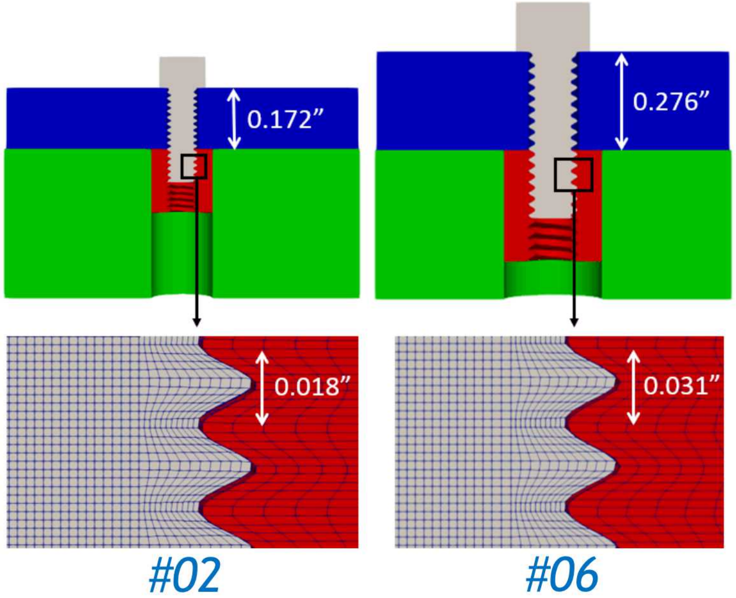
Build a high-fidelity fastener model to identify root cause of this behavior and investigate predictive capabilities.

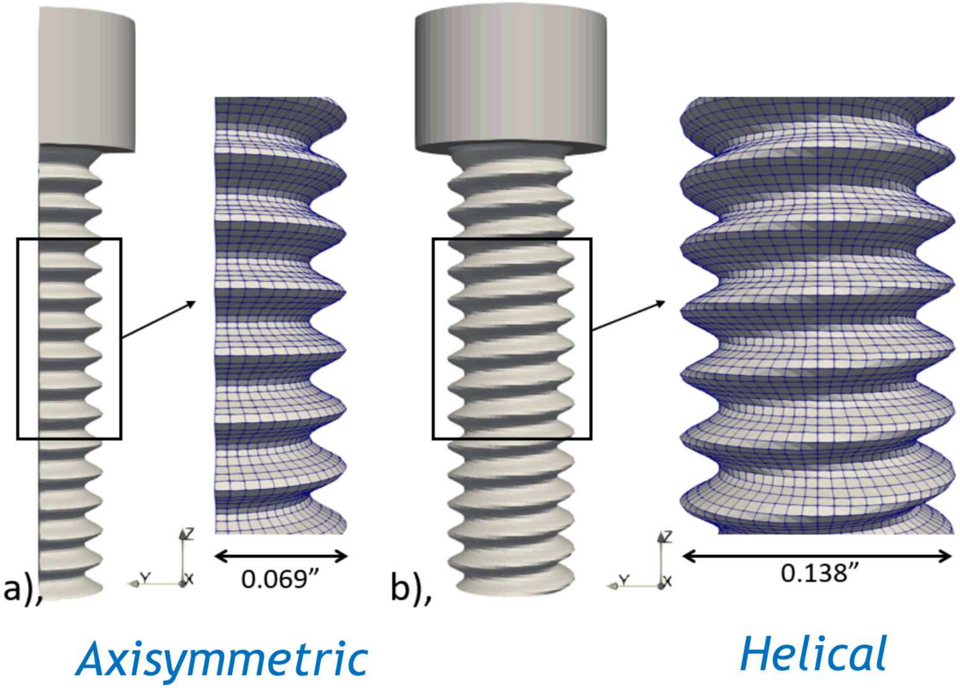
High-Fidelity Modeling

Constructed two high-fidelity models

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

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





Constitutive Model Hardening Function

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

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.

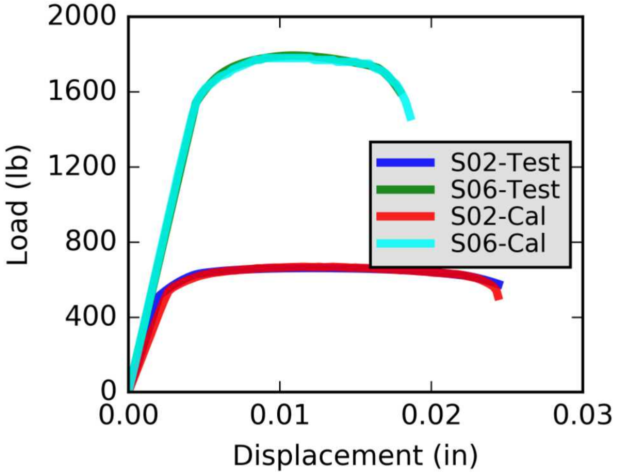
- #02: lower yield, larger $\epsilon_{p,crit}$
- #06: higher yield, smaller $\epsilon_{p,crit}$

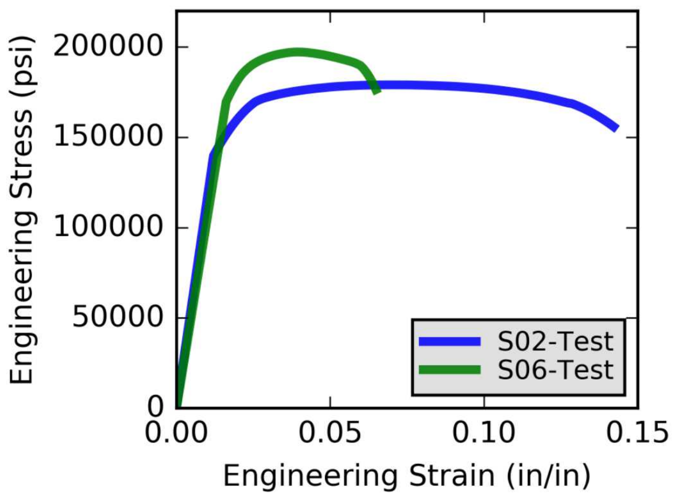
Calibrated an equivalent plastic strain (eqps) death criterion to capture displacement-to-failure.

Constitutive Model Hardening Function

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

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



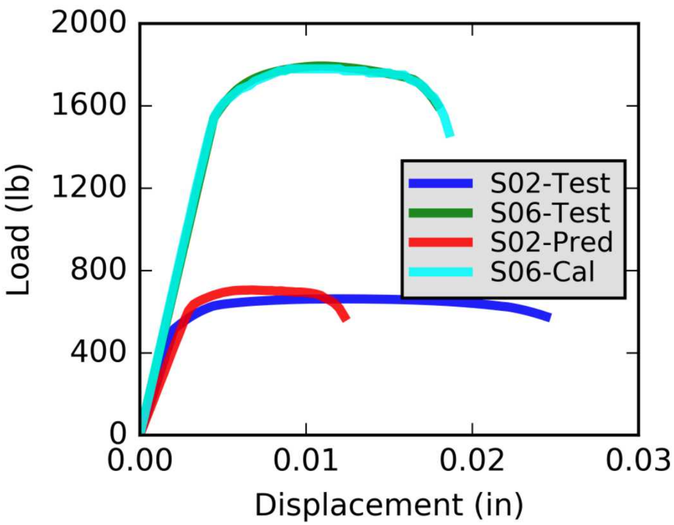


Material Parameter Extrapolation

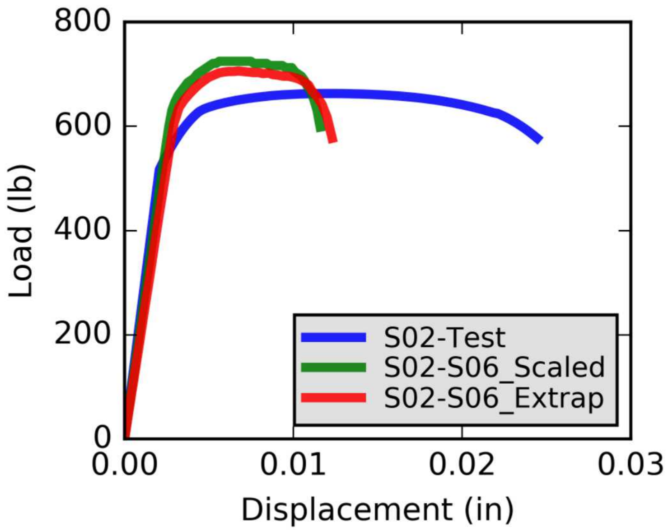
Applied calibrated #06 material properties to the #02 model.

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

<u>What happened???</u>



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

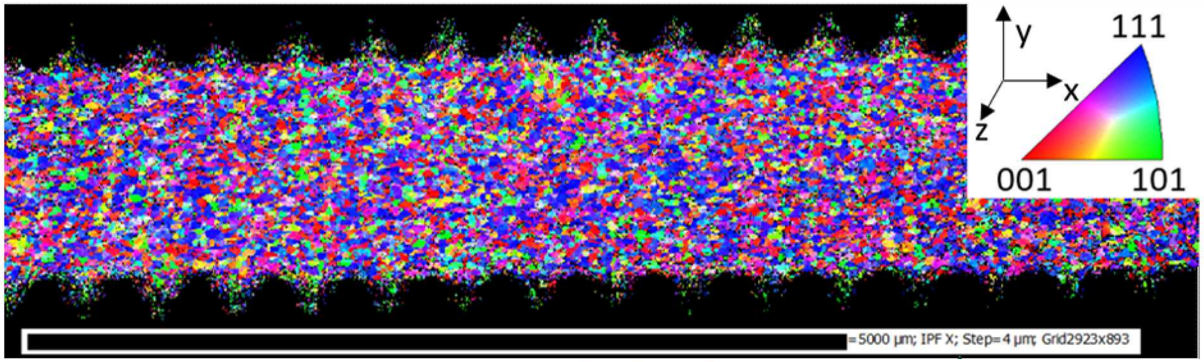
#02 Fastener:

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

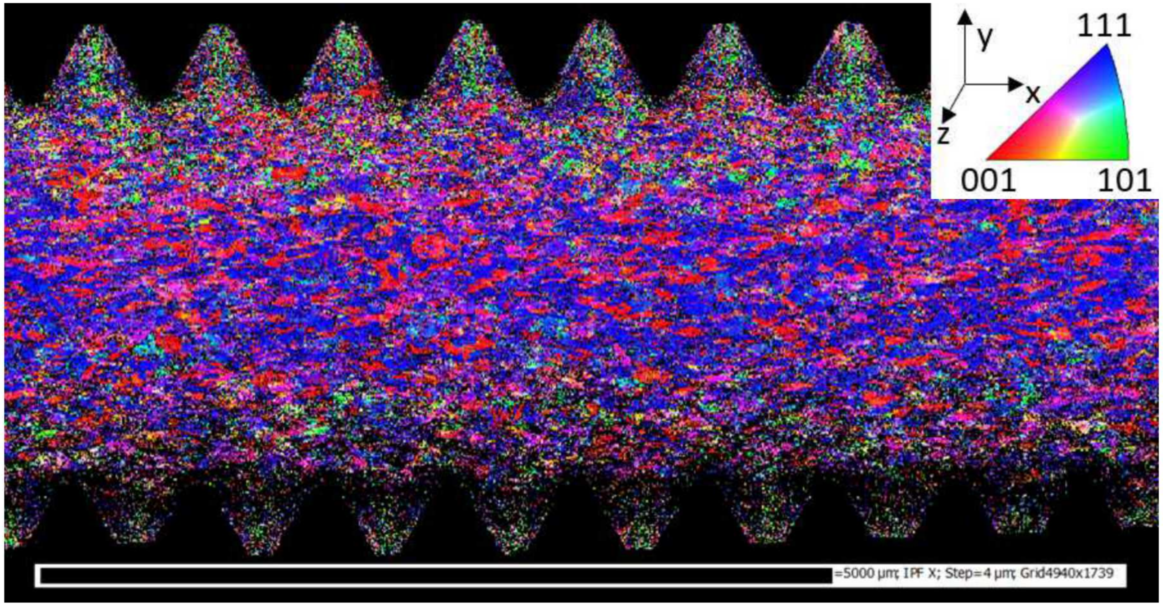
#06 Fastener:

- 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

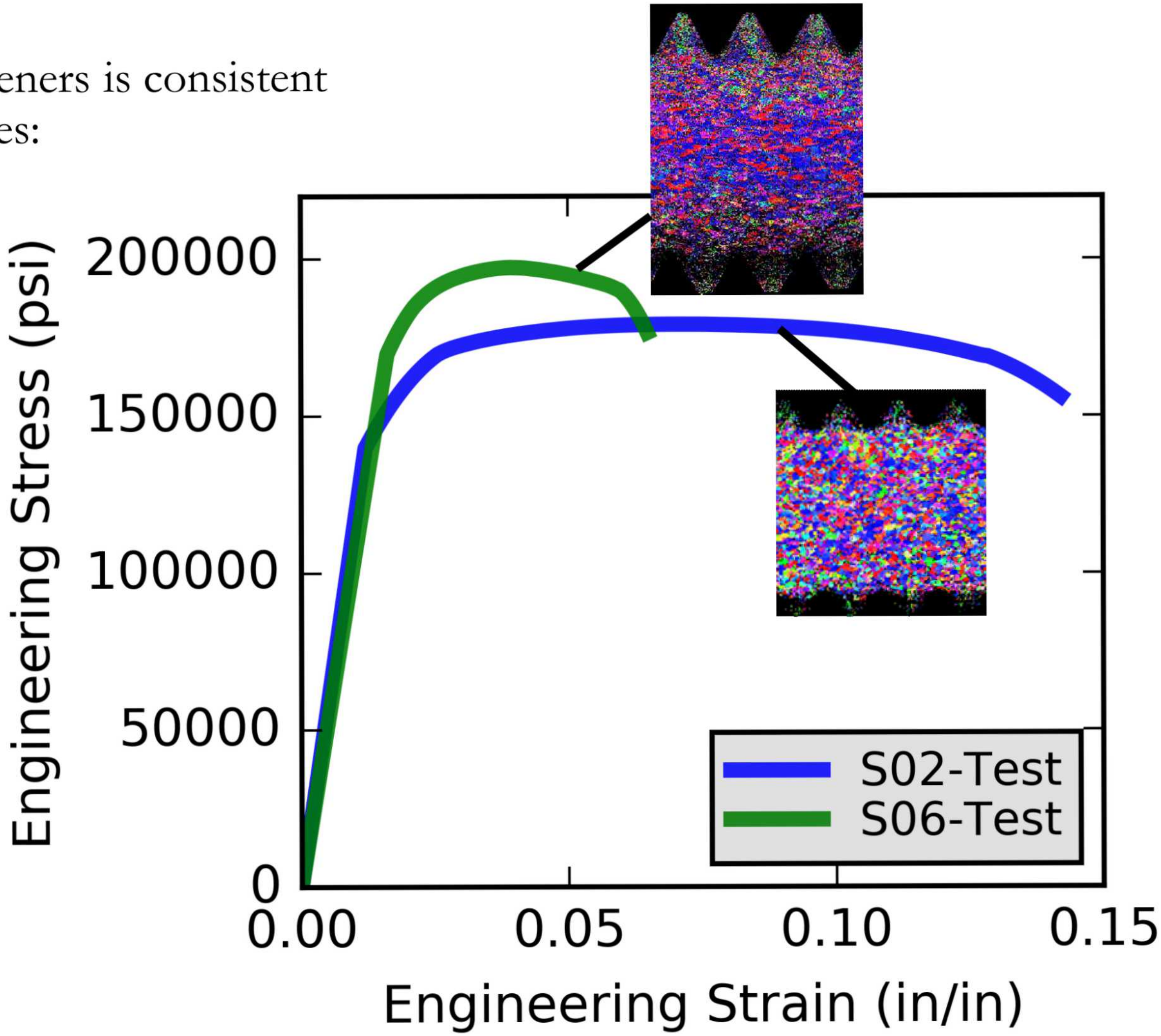
Microstructure and Stress-Strain Response

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

Cold Working↑ = Yield ↑

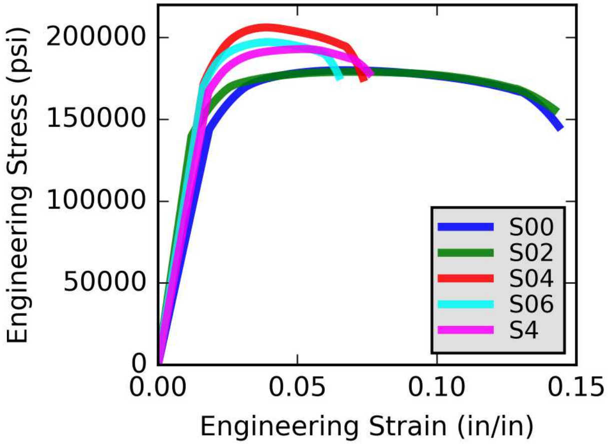
Cold Working↑ = Ultimate↑

Cold Working↑ = Ductility↓



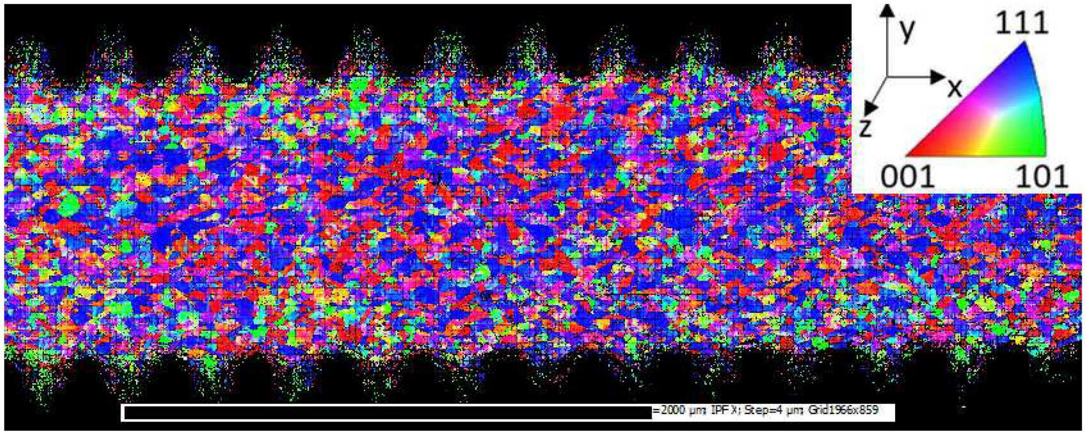
What will the microstructures of the #00 and #04 look like?

Microstructural Analysis



#00 Fastener:

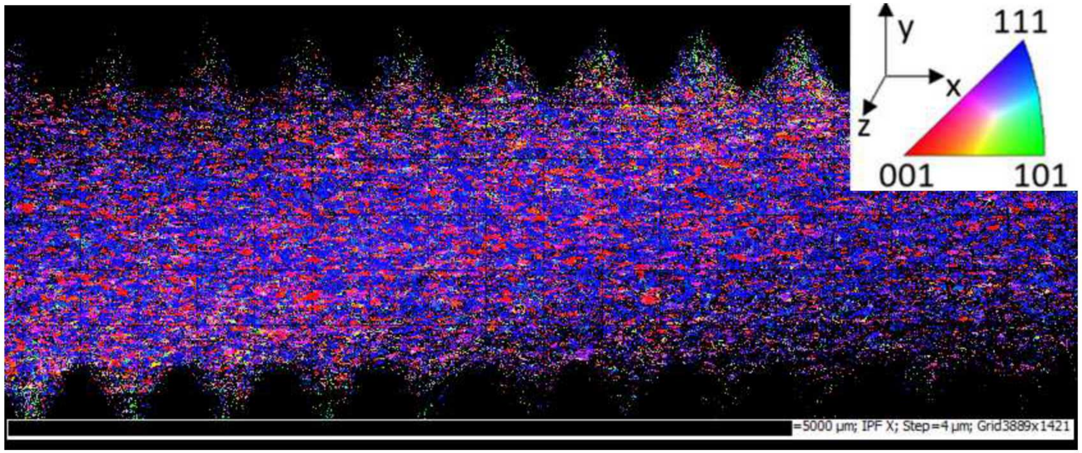
- Equiaxed Grains
- Balanced Color Distribution
- Evidence of Annealing



EBSD Map of #00 fastener

#04 Fastener:

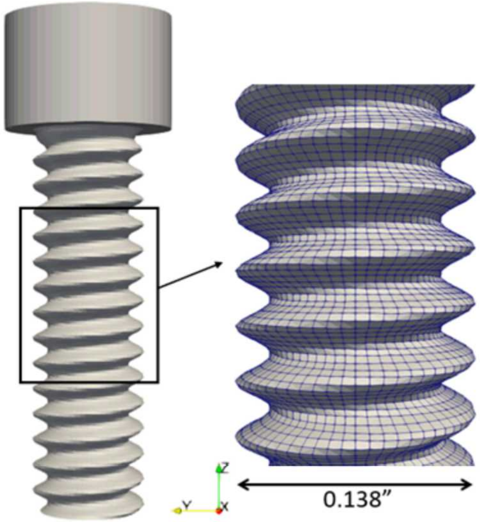
- Elongated Grains
- Affinity for Red, Blue
- Evidence of Cold Working



EBSD Map of #04 Fastener

Microstructures of all fasteners consistent with corresponding stress-strain response

Conclusions/Lessons Learned

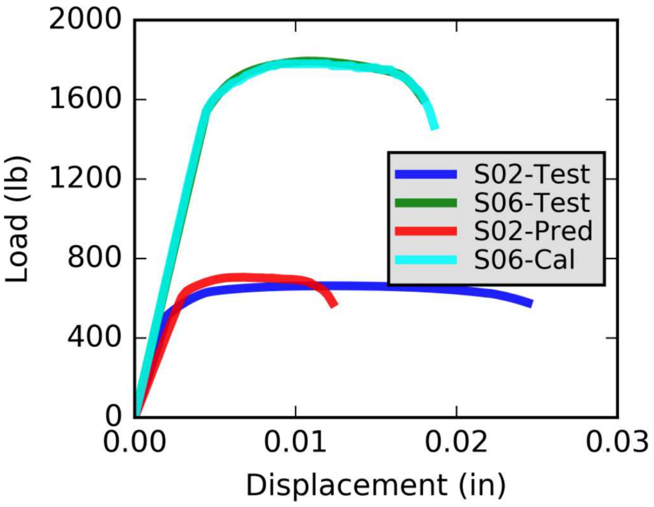


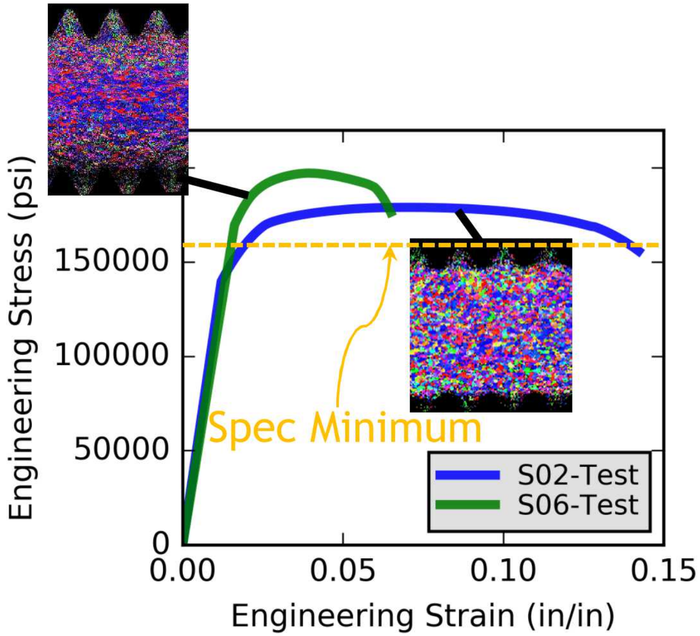
It is difficult to predict performance of fasteners without test data or material information!

- 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?

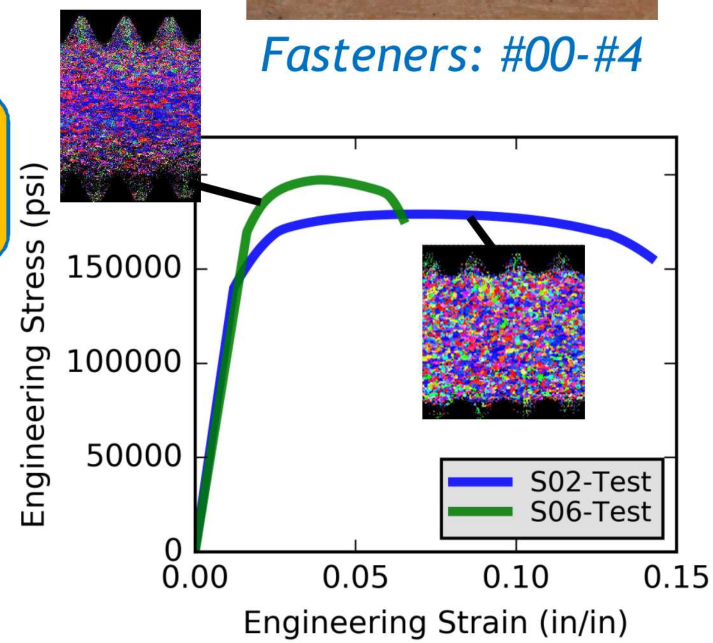
- NAFEMS World Congress
- Rate-dependent model

Thank You!

Normal environments response:

- Preload effects
- Dynamic environments (NOMAD 2019)

Fasteners: #00-#4



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Acknowledgements

- This effort is part of a larger collaborative study to explore best practices for the testing and modeling of threaded fasteners.

- John Emery, Bo Song, Brett Sanborn, Yuriy Veytskin, Tom Bosiljevac, Alejandro Mota, Jay Foulk, Jhana Gearhart, Doug Vangoethem, Steve Gomez, Sharlotte Kramer, Don Susan, Jeff Rodelas, David Lo, Eliot Fang, and Diane Peebles.