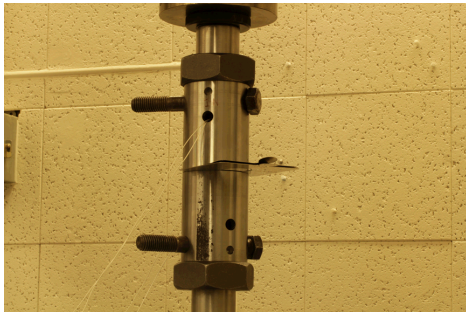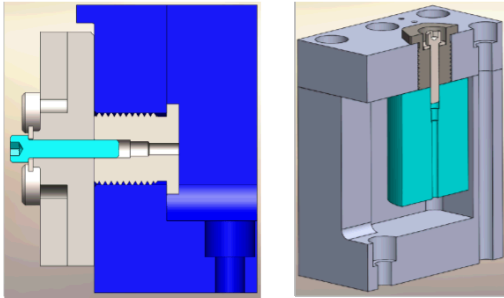# Evaluating the Process of Obtaining Reduced Order Finite Element Models of Threaded Fasteners

2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference

January 8-12, 2018, Kissimmee, Florida, United States

John P. Mersch[1], Jeffrey A. Smith[1],

Evan P. Johnson[2], Thomas Bosiljevac[3]

1: Component Science & Mechanics

2: Advanced Munitions & Mechanical Systems

3: Experimental Environmental Simulation

Motivation

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

- These complex structures can contain many fasteners, and the fasteners can be:
    - Different sizes
    - Subjected to diverse loadings
    - Loaded at various rates

- It thus becomes necessary to model fasteners with reduced order models yet still capture the global behavior of the joint.

Goal: Explore reduced order modeling techniques and identify sensitivities of the testing-calibration-modeling process.

Our Approach

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

- Calibrate reduced order modeling approaches to quasistatic test data.

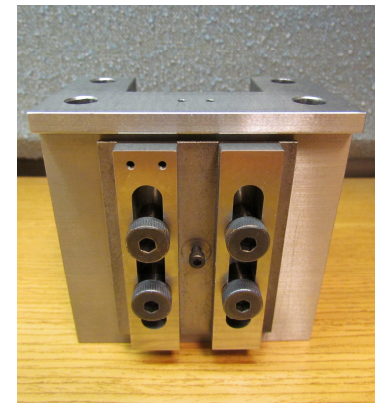- Assess calibrated models in other load and/or loading rate applications.
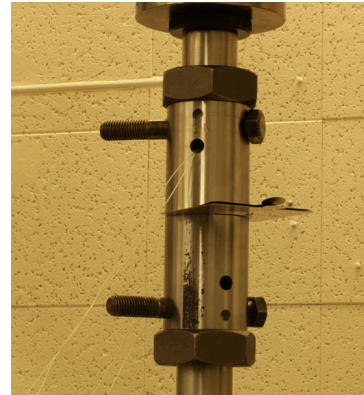
Quasistatic Tension Test Setup

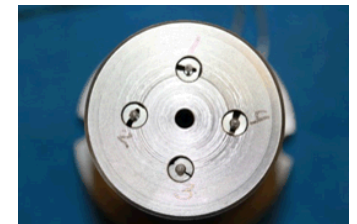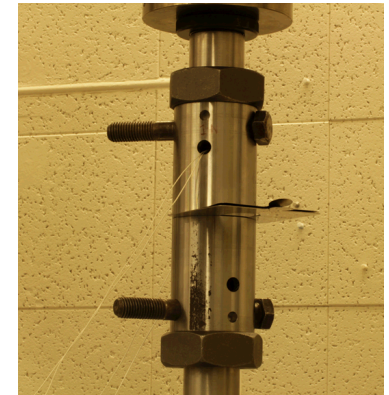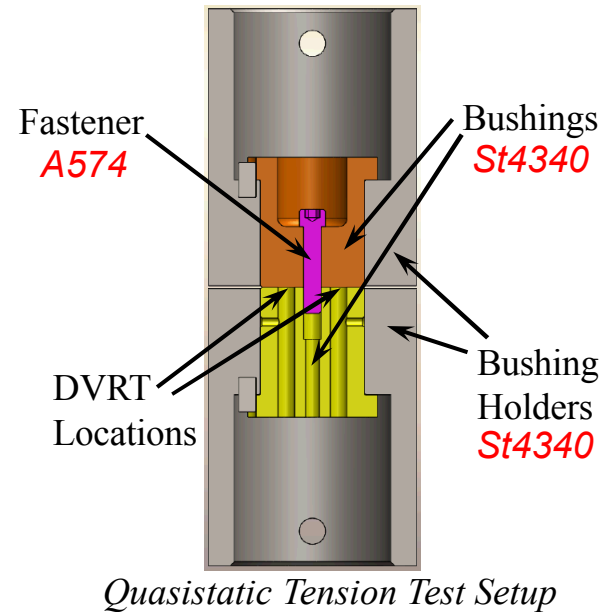*Quasistatic Shear Test Setup*

Dynamic Tension Test Setup

Dynamic Shear Test Setup

We will focus on quasistatic/dynamic tension and dynamic shear
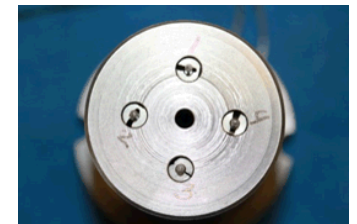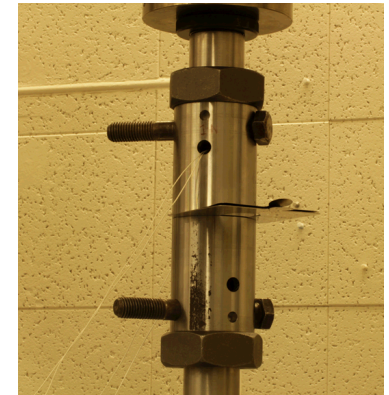
Quasistatic Testing

- Test fixtures made of 4340 steel.

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

- Data also collected from the stroke of the test machine.

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

Fastener
A574

Bushings
St4340

DVRT Locations

Bushing Holders
St4340

Quasistatic Tension Test Setup

Quasistatic Tension Test Setup

NAS1352-06-6P Fastener

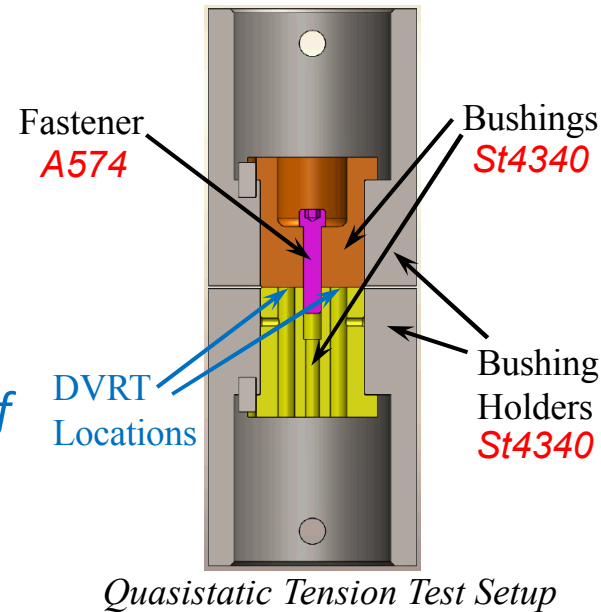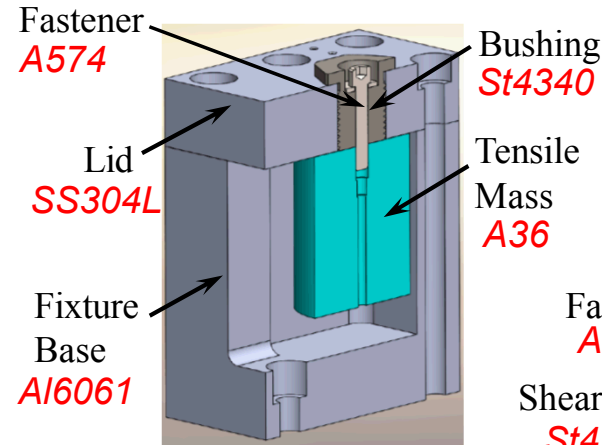*DVRT Locations in Bushing*

Quasistatic Testing

- Test fixtures made of 4340 steel.

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

- Data also collected from the stroke of the test machine.

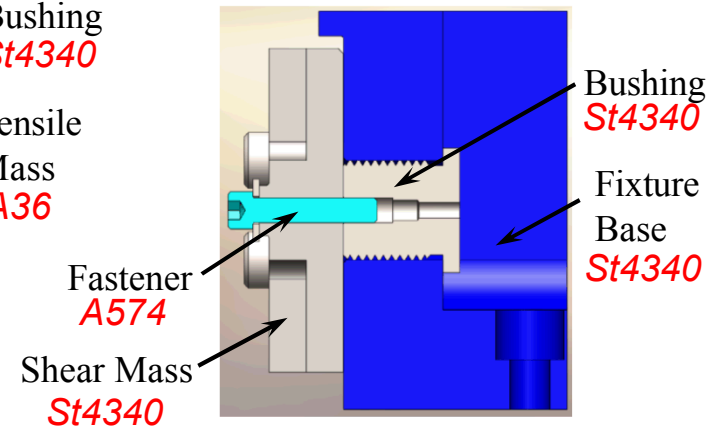- Tests performed on both preloaded (20 in-lb) and hand-tightened fasteners.

Fastener
A574

Bushings
St4340

DVRT
Locations

Bushing
Holders
St4340

Quasistatic Tension Test Setup

Quasistatic Tension Test Setup

NAS1352-06-6P Fastener

DVRT Locations in Bushing

Dynamic Testing

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

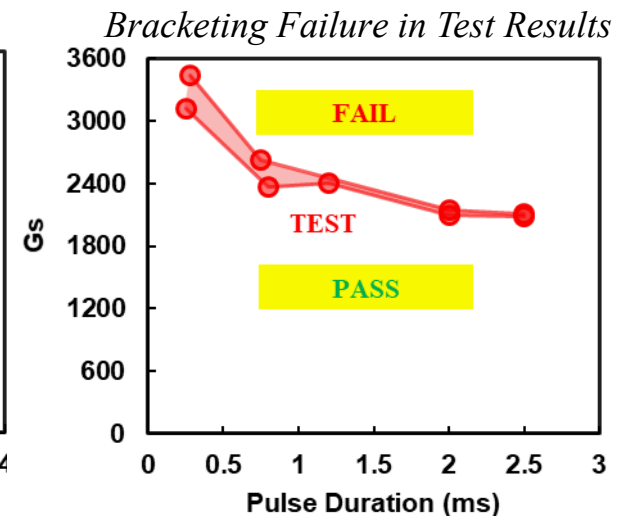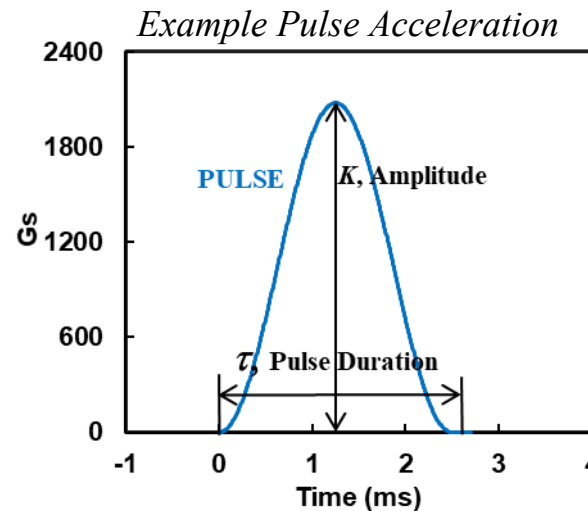- Tensile mass and shear mass transmit dynamic loads to fastener.

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

Fastener *A574*

Bushing *St4340*

Lid *SS304L*

Tensile Mass *A36*

Fixture Base *Al6061*

Dynamic Tension Test Fixture

Bushing *St4340*

Fixture Base *St4340*

Fastener *A574*

Shear Mass *St4340*

Dynamic Shear Test Fixture

Example Pulse Acceleration

PULSE

K, Amplitude

τ, Pulse Duration

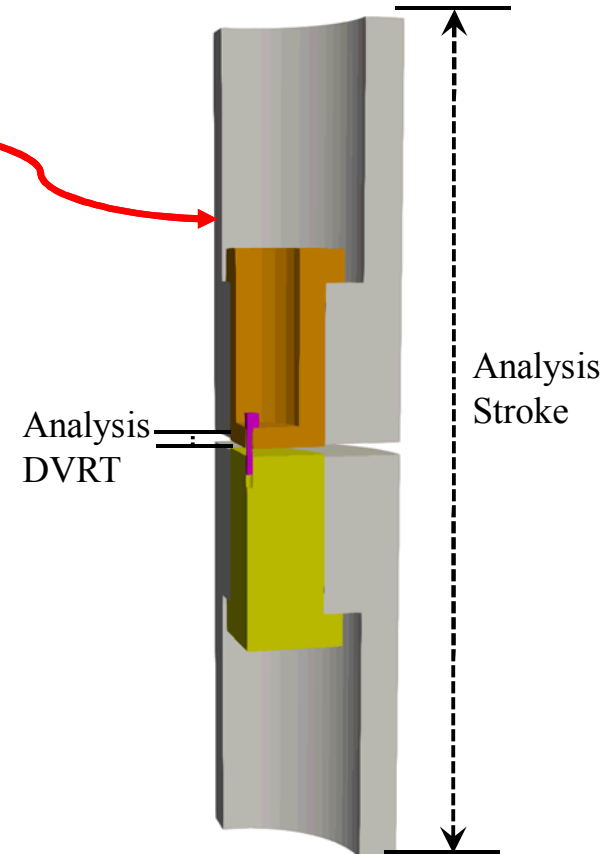*Bracketing Failure in Test Results*

FAIL

TEST

PASS

Quasistatic Analysis Models

- One-quarter of the quasistatic test setup modeled utilizing symmetry

- Measurements analytically reproduced for DVRT and stroke in analysis model.

*Quasistatic Tension **Test Setup***
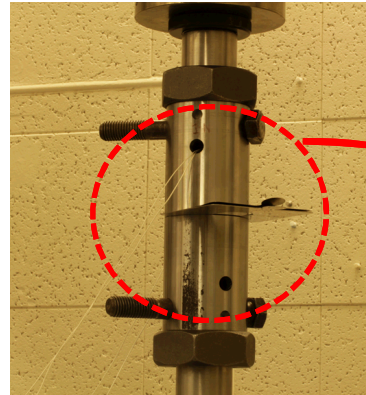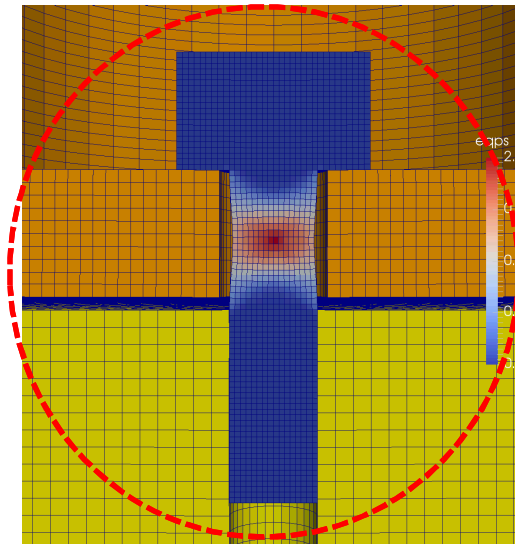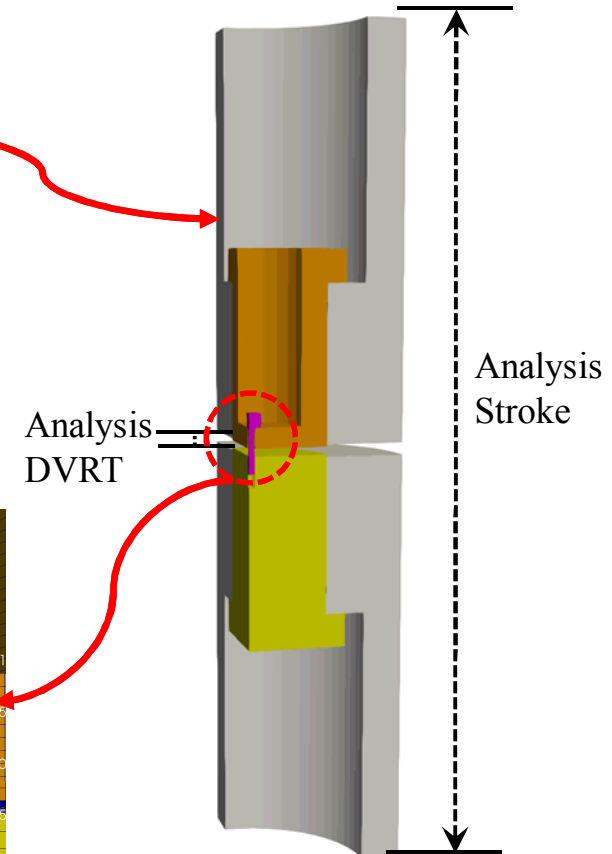
Analysis DVRT

Analysis Stroke

*Quasistatic Tension **Analysis Model***

Quasistatic Analysis Models

- One-quarter of the quasistatic test setup modeled utilizing symmetry

- Measurements analytically reproduced for DVRT and stroke in analysis model.

- Using a "plug" fastener modeling approach.
  - Hex elements
  - Elastic-plastic constitutive model
  - Piecewise-linear hardening
  - EQPS death criterion
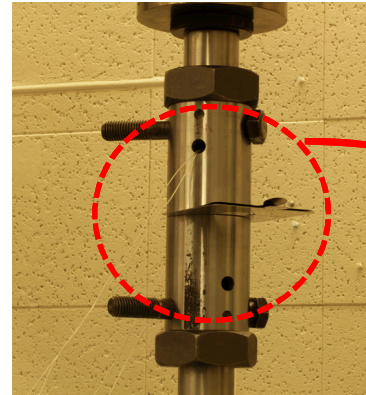
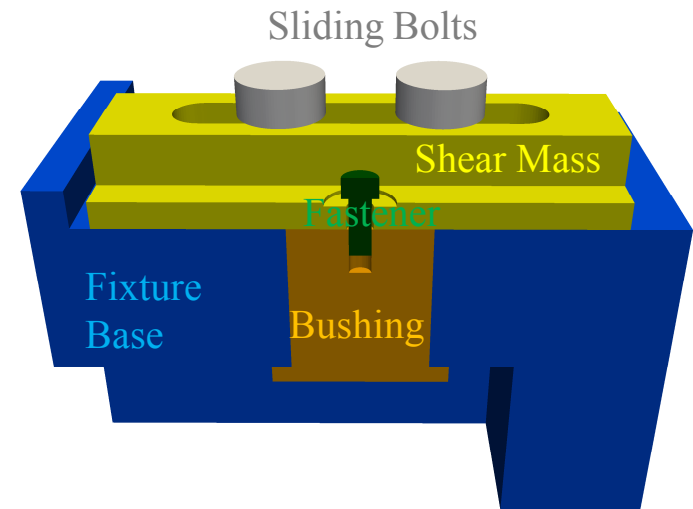*Quasistatic Tension **Test Setup***

Plug Modeling Approach

Analysis DVRT

Analysis Stroke
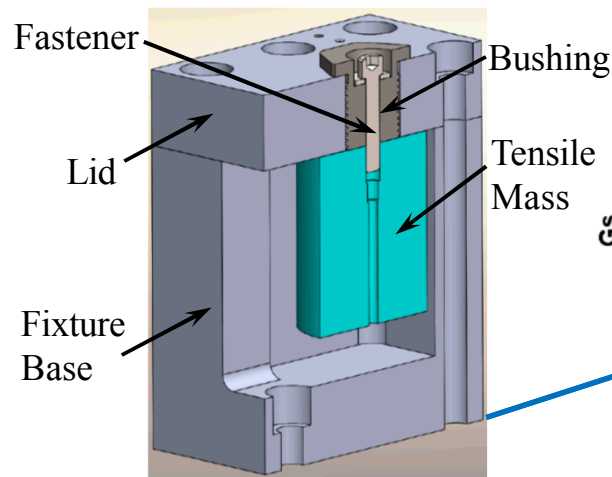
*Quasistatic Tension **Analysis Model***
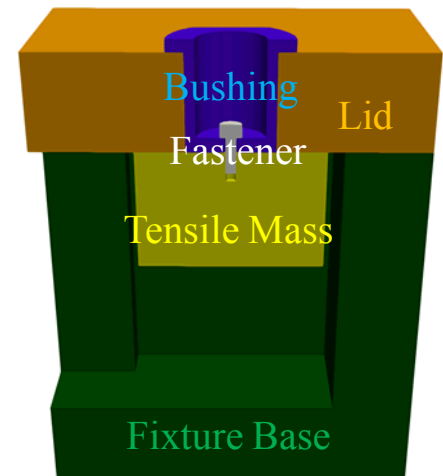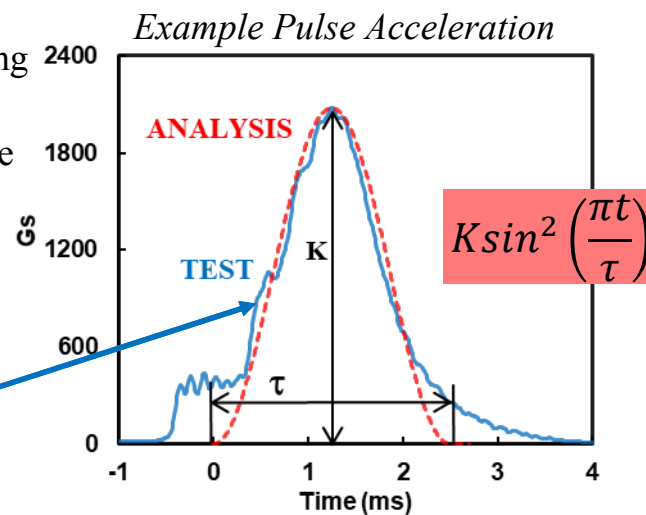
Dynamic Analysis Models

- One-half of the dynamic test setups were modeled utilizing symmetry.

- Analysis pulses take the form of a haversine function.
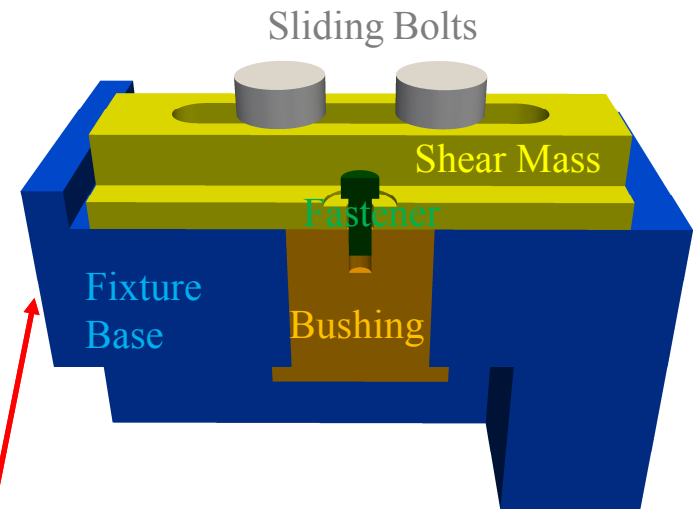

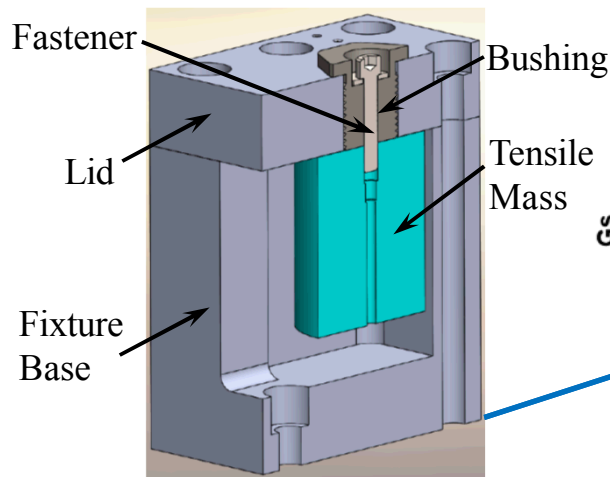*Dynamic Shear Analysis Model*

Dynamic Tension Test Fixture

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

Example Pulse Acceleration

Dynamic Tension Analysis Model
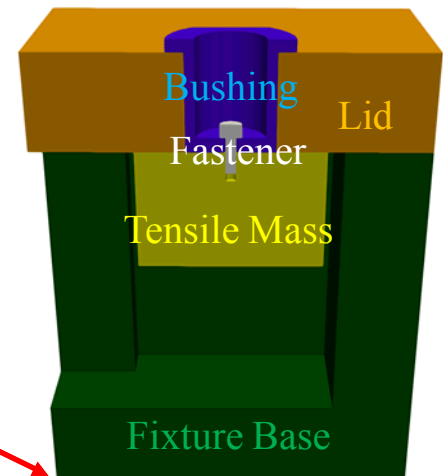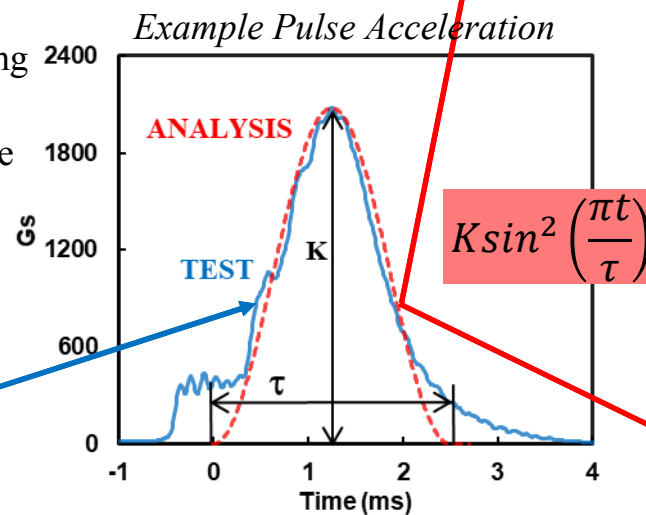
9

Dynamic Analysis Models

- One-half of the dynamic test setups were modeled utilizing symmetry.

- Analysis pulses take the form of a haversine function.

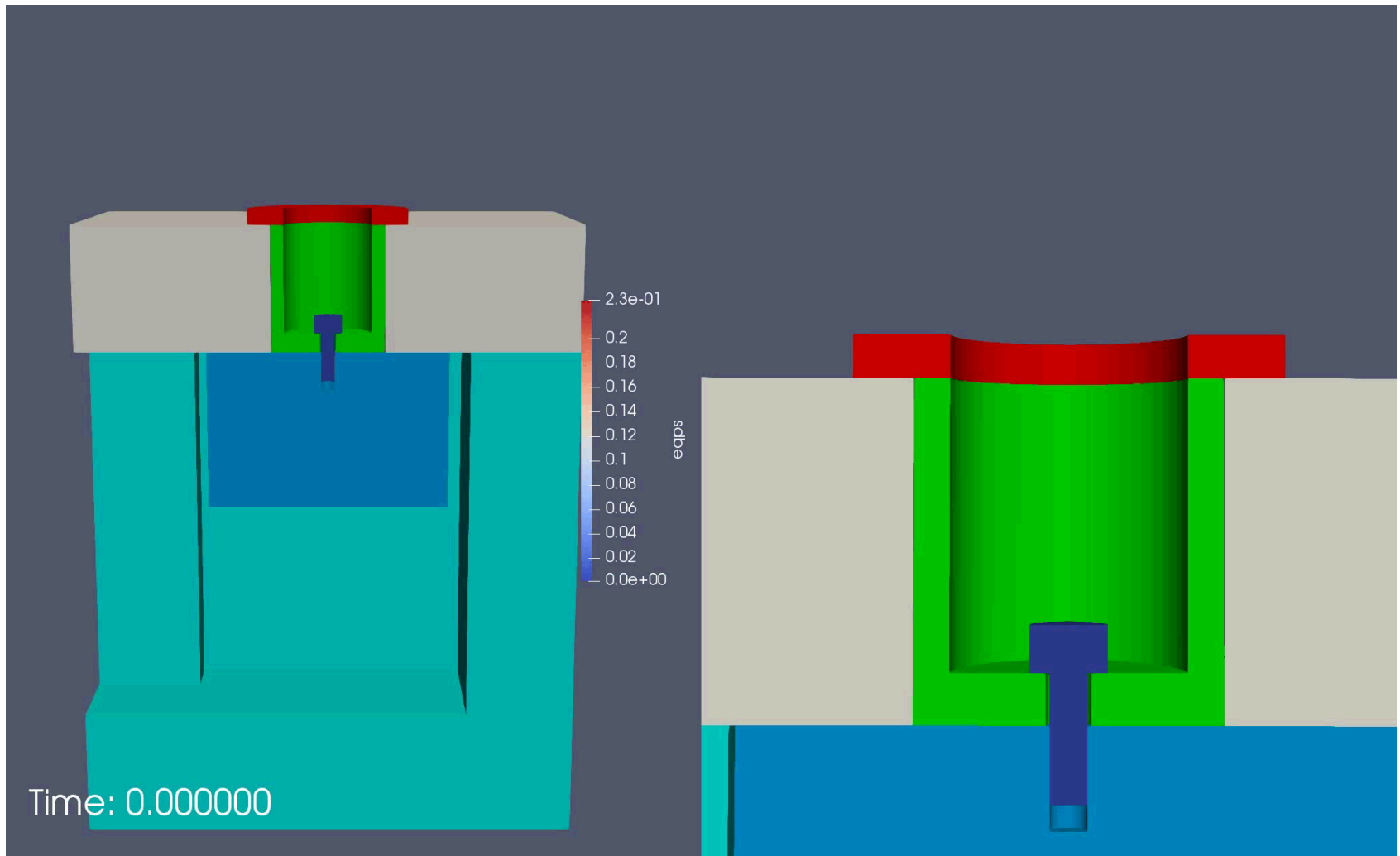- *Applied to a location representative of testing.*

Sliding Bolts

Shear Mass

Fastener

Fixture Base

Bushing

Dynamic Shear Analysis Model

Fastener

Bushing

Lid

Tensile Mass

Fixture Base

Dynamic Tension Test Fixture

Example Pulse Acceleration

ANALYSIS

TEST

K

τ

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

Bushing

Lid

Fastener

Tensile Mass

Fixture Base
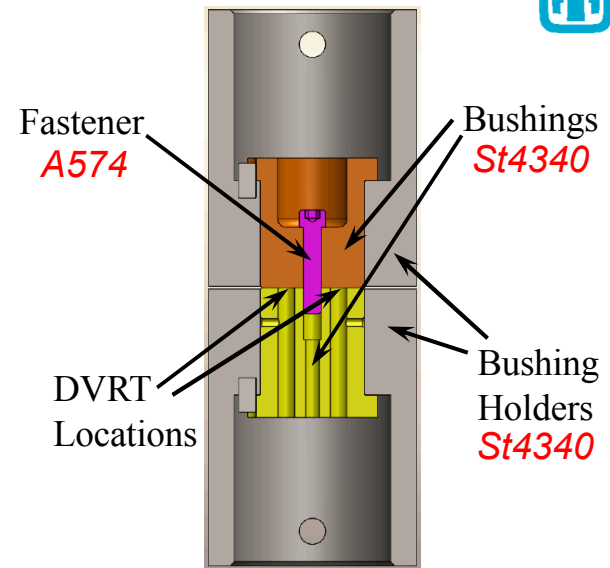
Dynamic Tension Analysis Model
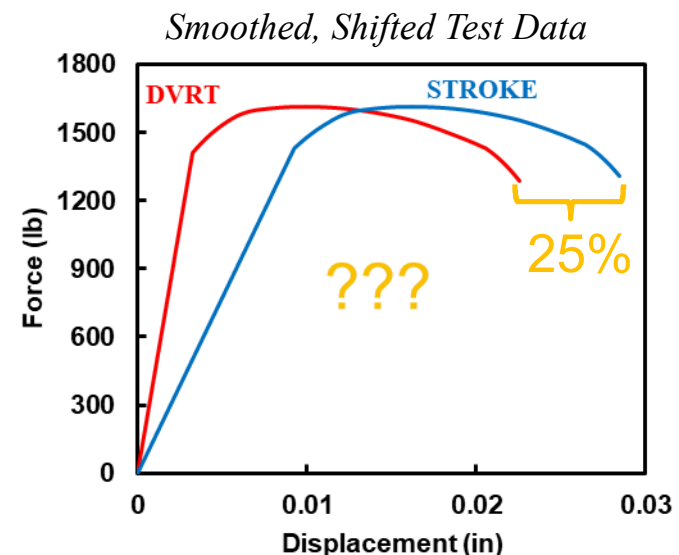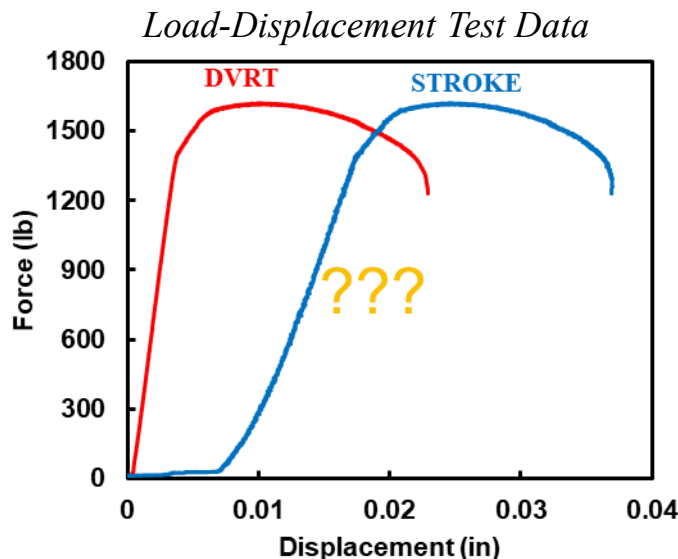
Dynamic Analysis Example

Quasistatic Test Results

- Displacement measurements from stroke and DVRTs were very different.

- Compliance significantly contributes to data acquisition.

- Where does this compliance come from?

Fastener *A574*

Bushings *St4340*

DVRT Locations

Bushing Holders *St4340*

Quasistatic Tension Test Setup

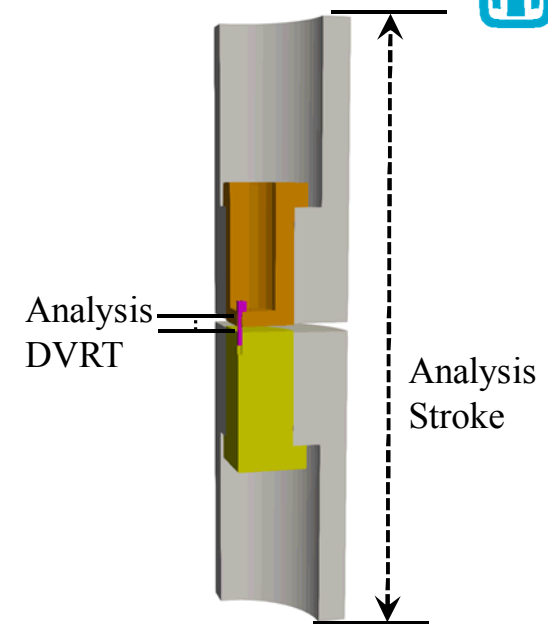*Load-Displacement Test Data*

Smoothed, Shifted Test Data

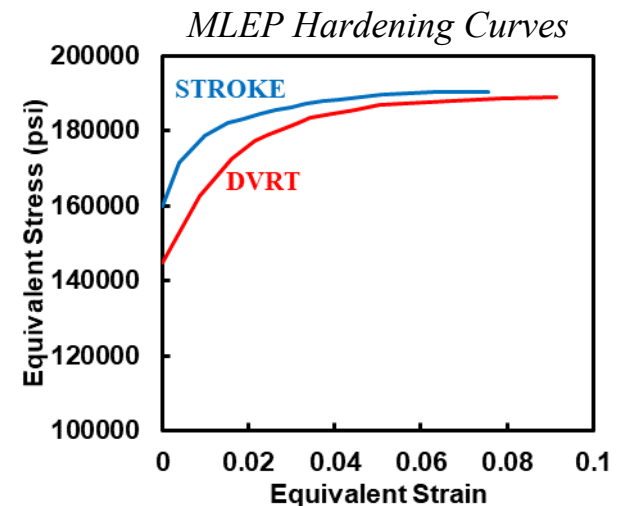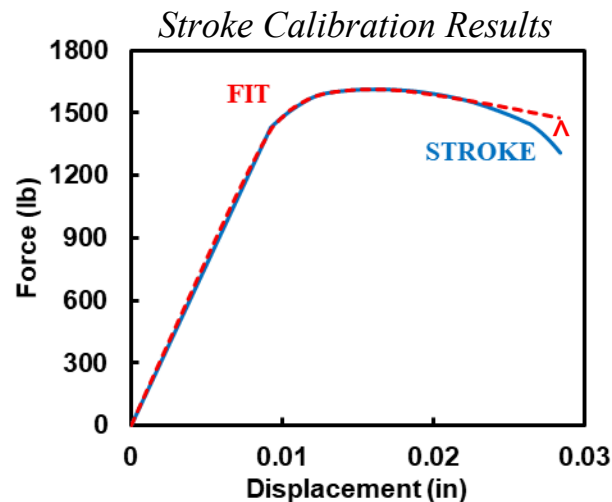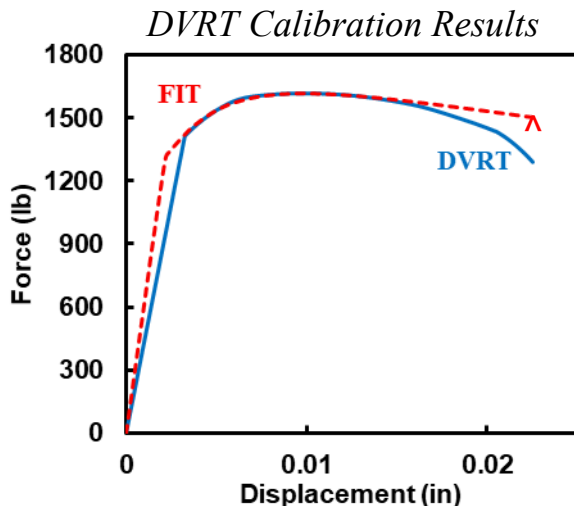Which set of data should we use to calibrate?

Calibration

- Performed calibrations for both the DVRT and stroke data.

- Used quasistatic tension load-displacement data to calibrate.

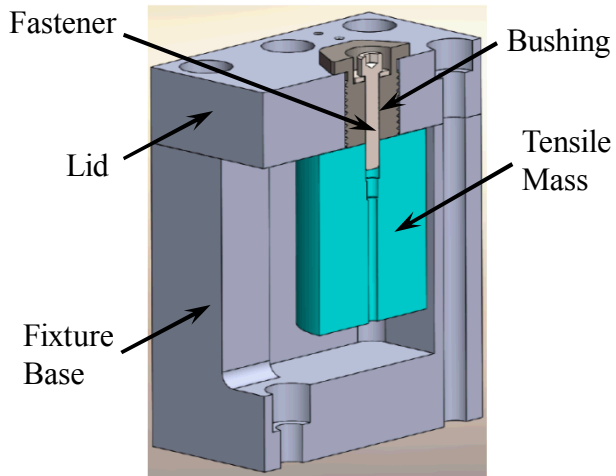- Fitted DVRT and Stroke test data with representative analysis measurement.

Analysis DVRT

Analysis Stroke

Quasistatic Tension Analysis Model

DVRT Calibration Results

Stroke Calibration Results

MLEP Hardening Curves

How well will these models perform when extended to other applications?

13

Model Extension – *Tension*
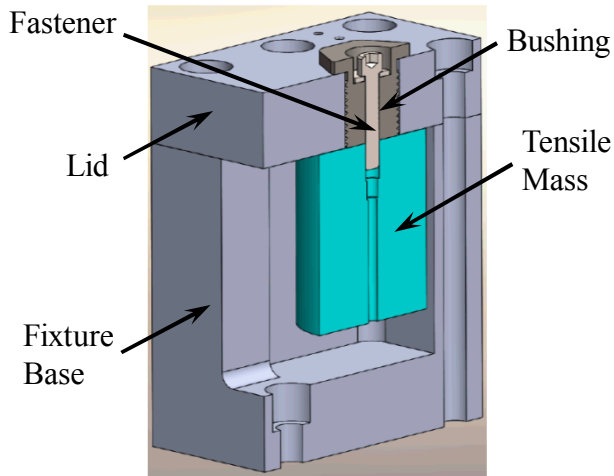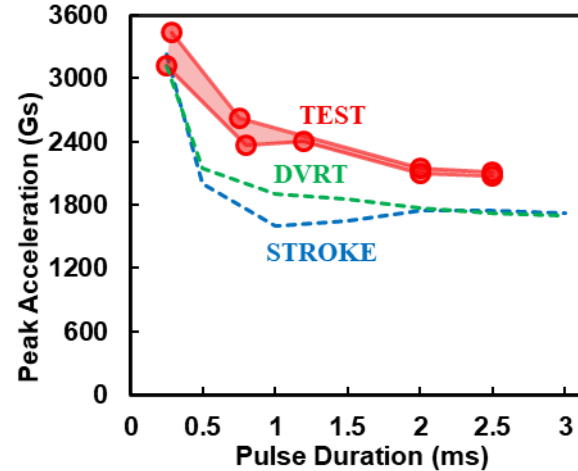

Dynamic Tension Test Fixture

Fastener

Lid

Fixture Base

Bushing

Tensile Mass

Common QoIs

- Failure Load
- Time to Failure
- Displacement at Failure

Model Extension – *Tension*

Fastener
Bushing
Lid
Tensile Mass
Fixture Base

Dynamic Tension Test Fixture

Failure Load Test-Analysis Comparison

TEST
DVRT
STROKE

Common QoIs

- **Failure Load**
- Time to Failure
- Displacement at Failure

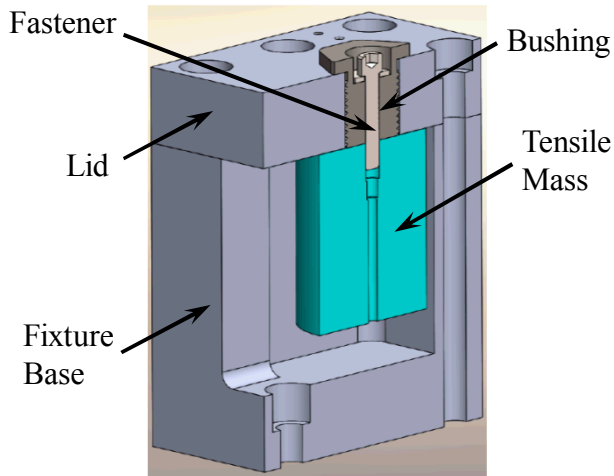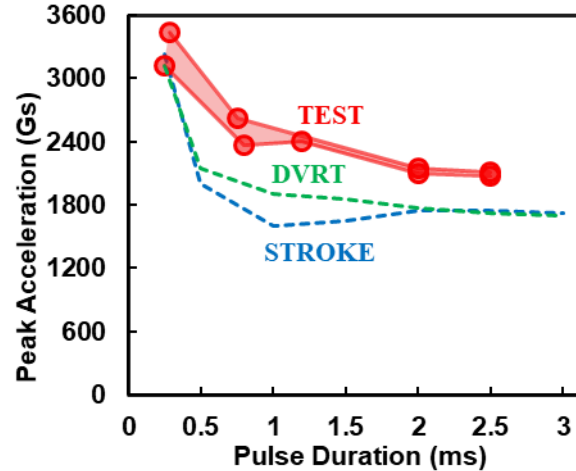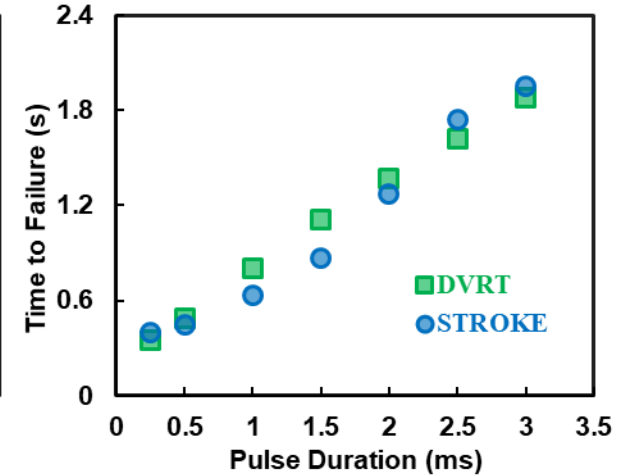# Model Extension – *Tension*

Dynamic Tension Test Fixture

Fastener
Bushing
Lid
Tensile Mass
Fixture Base

Failure Load Test-Analysis Comparison
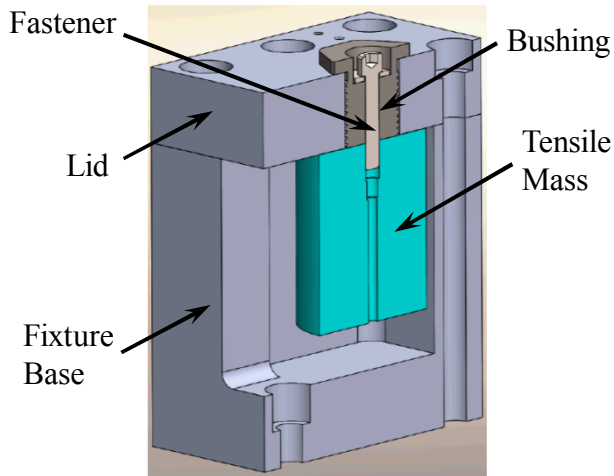
TEST
DVRT
STROKE

Analysis Time-to-Failure

DVRT
STROKE

Common QoIs

- Failure Load
- **Time to Failure**
- Displacement at Failure
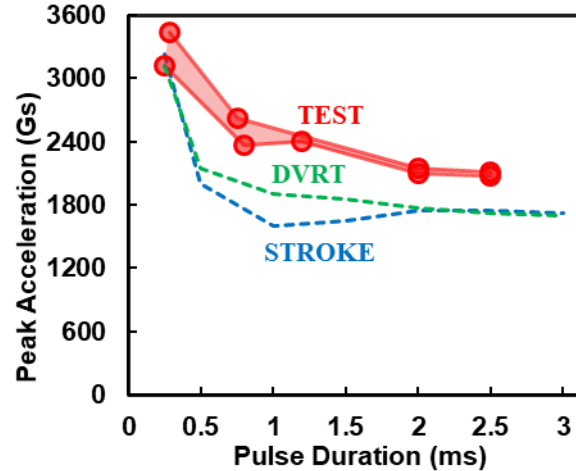
Note: Same Pulse Applied

Model Extension – *Tension*

Fastener

Bushing

Lid

Tensile Mass

Fixture Base

Dynamic Tension Test Fixture

Failure Load Test-Analysis Comparison

TEST

DVRT

STROKE

Analysis Time-to-Failure

DVRT

STROKE

Analysis Displacement-at-Failure

18% Difference

DVRT

STROKE

Common QoIs

- Failure Load
- Time to Failure
- **Displacement at Failure**

Note: Same Pulse Applied

Model Extension – *Tension*

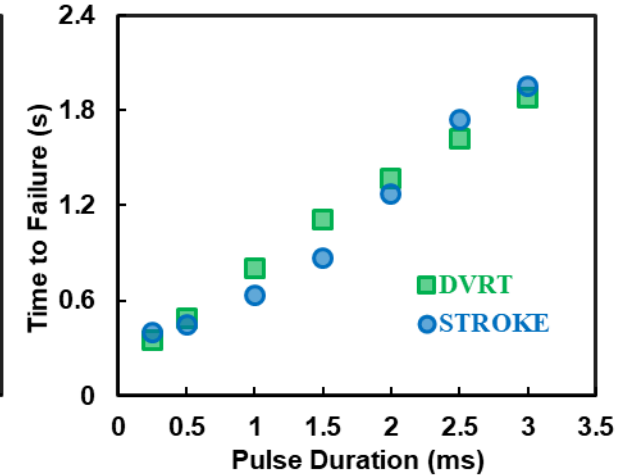*Dynamic Tension Test Fixture*

Fastener
Bushing
Lid
Tensile Mass
Fixture Base

Failure Load Test-Analysis Comparison

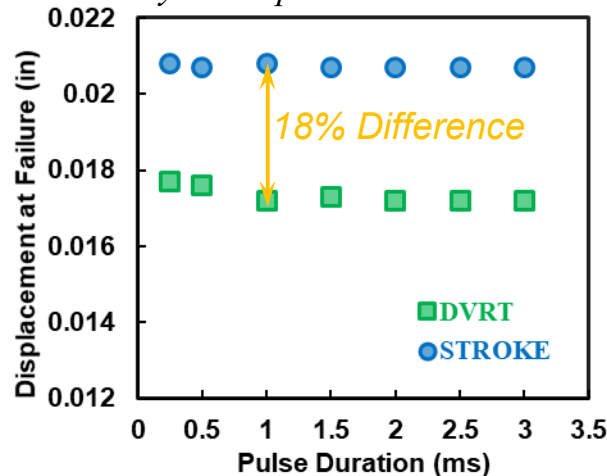TEST
DVRT
STROKE

Analysis Time-to-Failure

DVRT
STROKE

Common QoIs
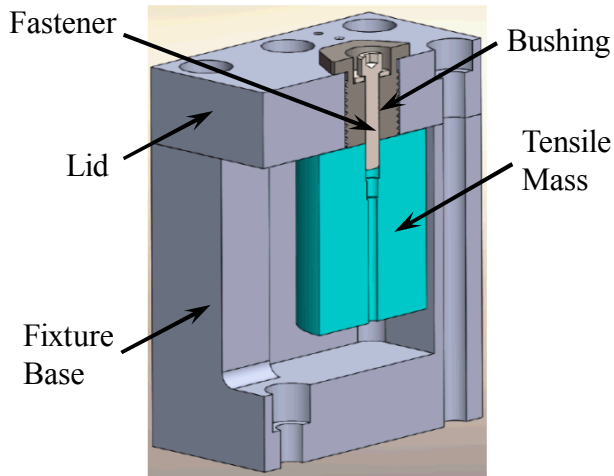
- Failure Load
- Time to Failure
- **Displacement at Failure**

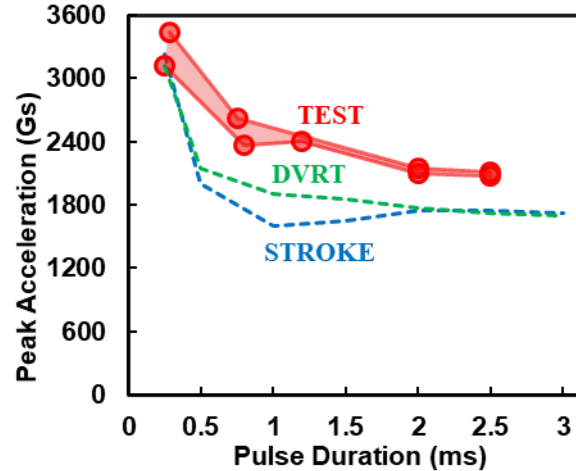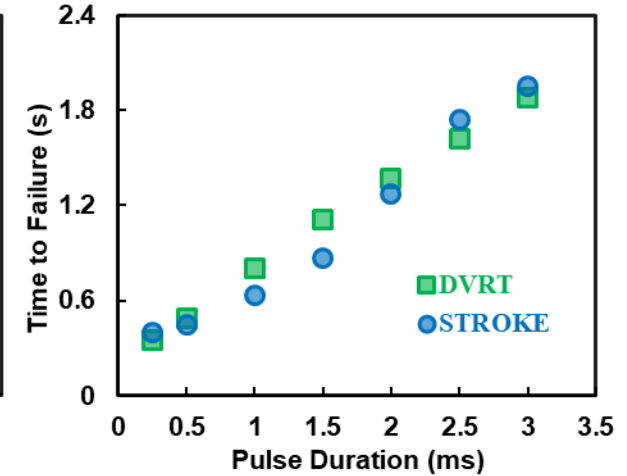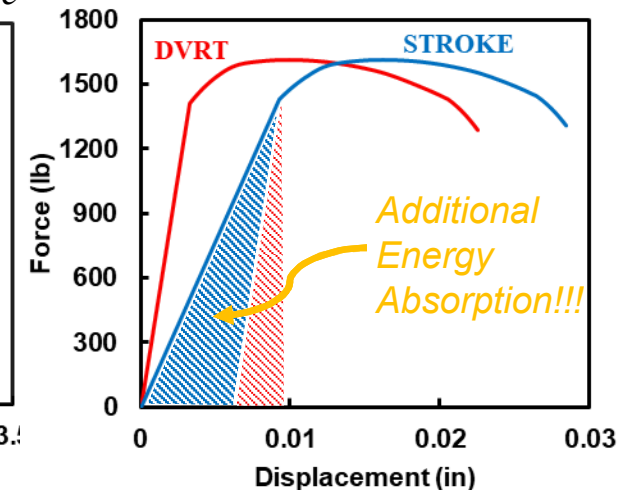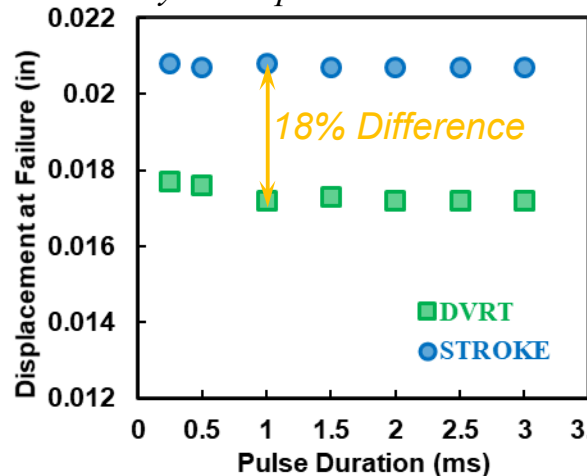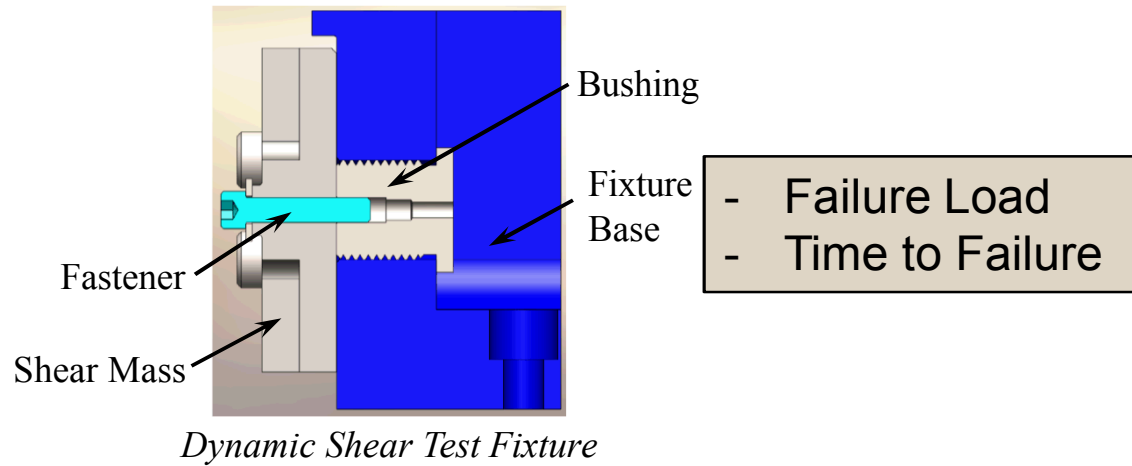*Note: Same Pulse Applied*

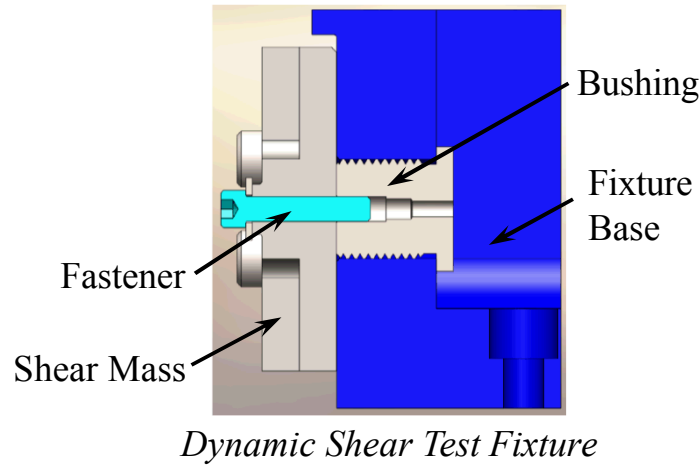
Analysis Displacement-at-Failure

18% Difference

DVRT
STROKE

DVRT
STROKE

Additional Energy Absorption!!!

Model Extension – *Shear*

Bushing

Fixture Base

Fastener

Shear Mass

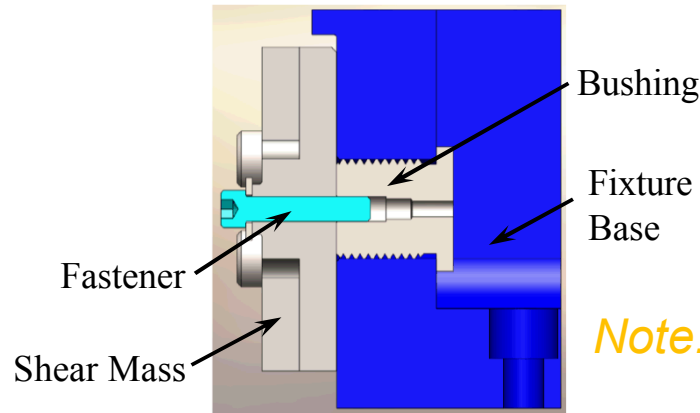*Dynamic Shear Test Fixture*

- Failure Load
- Time to Failure

Model Extension – *Shear*

Dynamic Shear Test Fixture

Labels: Bushing, Fixture Base, Fastener, Shear Mass

- **Failure Load**
- Time to Failure

Failure Load Test-Analysis Comparison

TEST

DVRT

STROKE

20+% Difference

Peak Acceleration (Gs)

Pulse Duration (ms)

Model Extension – *Shear*

Bushing

Fixture Base

Fastener

Shear Mass
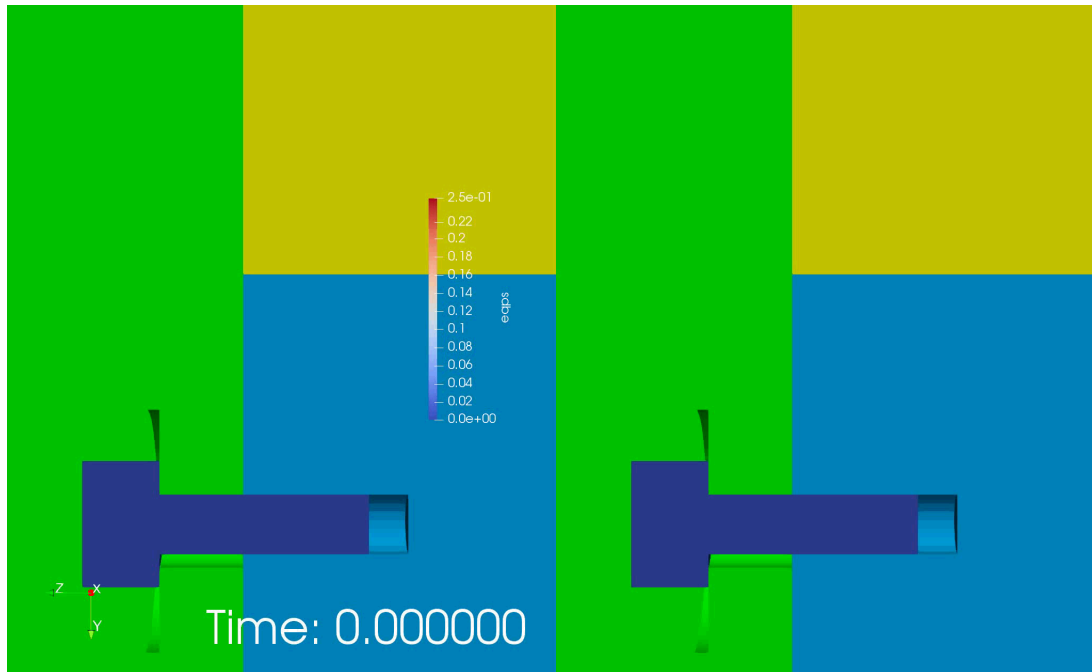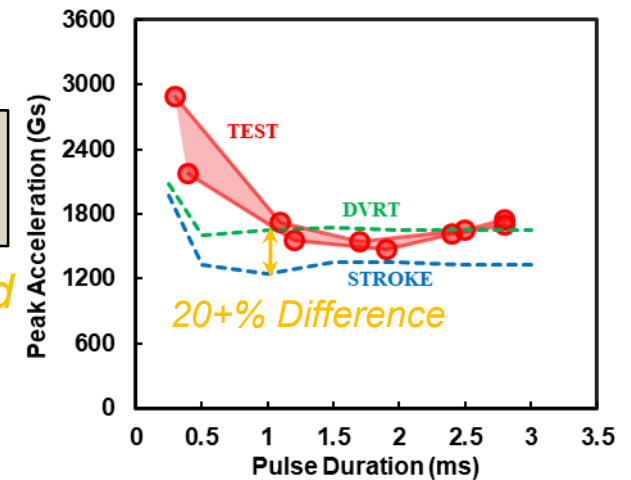
Dynamic Shear Test Fixture
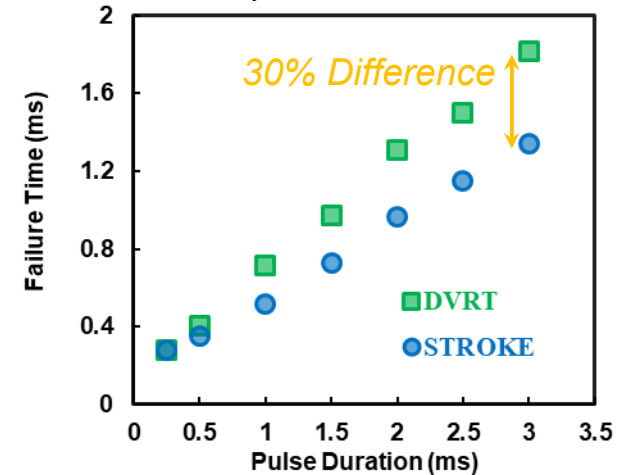
- Failure Load
- **Time to Failure**

Note: Same Pulse Applied

Failure Load Test-Analysis Comparison

20+% Difference

Analysis Time-to-Failure

30% Difference

Time: 0.000000

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Model Extension – Summary

Dynamic Tension Analysis Summary

Analysis Inputs		DVRT		Stroke		Percent Difference	
Duration (ms)	Accel Max (Gs)	Failure Time (ms)	Disp to Fail (in)	Failure Time (ms)	Disp to Fail (in)	Failure Time	Disp to Fail
0.25	3225	0.352	0.0177	0.4	0.0208	12.77%	16.10%
0.5	2150	0.489	0.0176	0.451	0.0207	8.09%	16.19%
1	1900	0.8	0.0172	0.632	0.0208	23.46%	18.95%
1.5	1850	1.11	0.0173	0.864	0.0207	24.92%	17.89%
2	1775	1.37	0.0172	1.27	0.0207	7.58%	18.47%
2.5	1750	1.62	0.0172	1.74	0.0207	7.14%	18.47%
3	1725	1.878	0.0172	1.95	0.0207	3.76%	18.47%

Dynamic Shear Analysis Summary

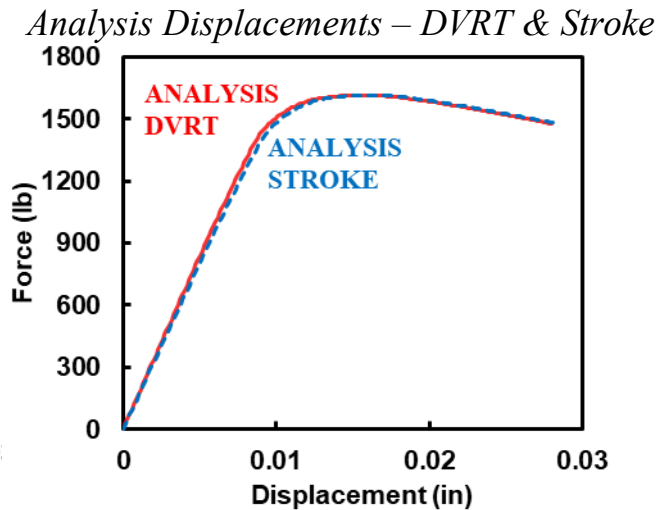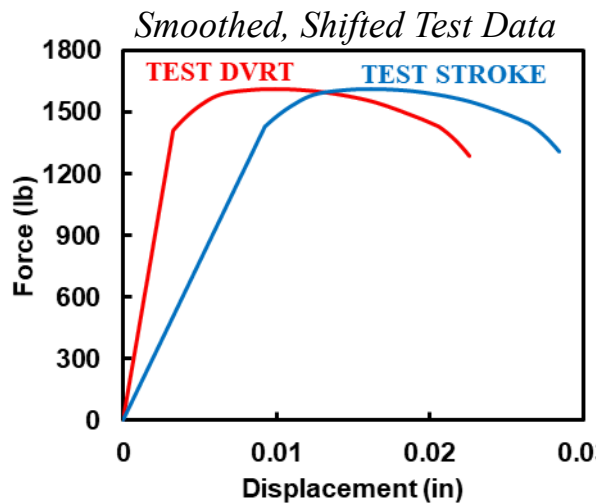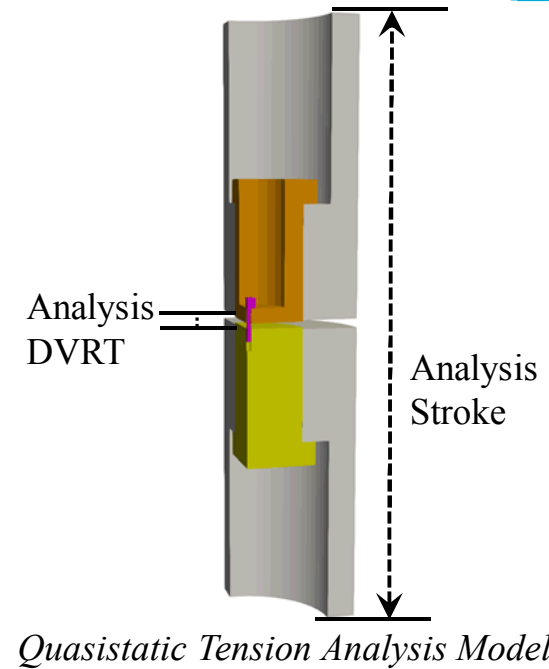| Duration (ms)	Peak Accel (Gs)	DVRT Failure Time (ms)	Stroke Failure Time (ms)	Percent Difference (%)
0.25	2075	0.276	0.281	1.80%
0.5	1600	0.406	0.354	13.68%
1	1650	0.712	0.513	32.49%
1.5	1675	0.972	0.728	28.71%
2	1650	1.31	0.965	30.33%
2.5	1650	1.5	1.15	26.42%
3	1650	1.82	1.34	30.38%

Nontrivial errors in important quantities of interest can result from these calibrated models
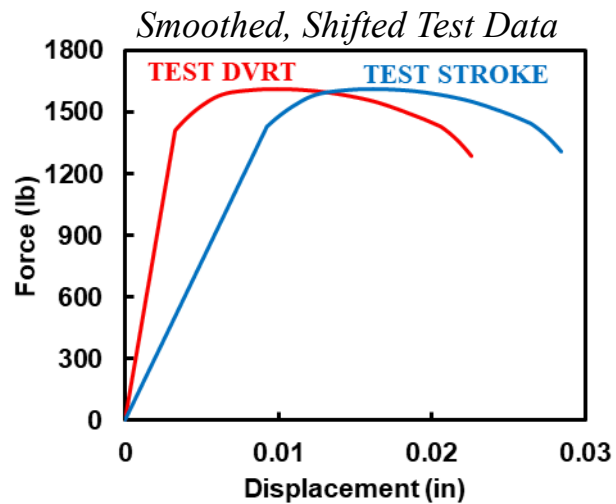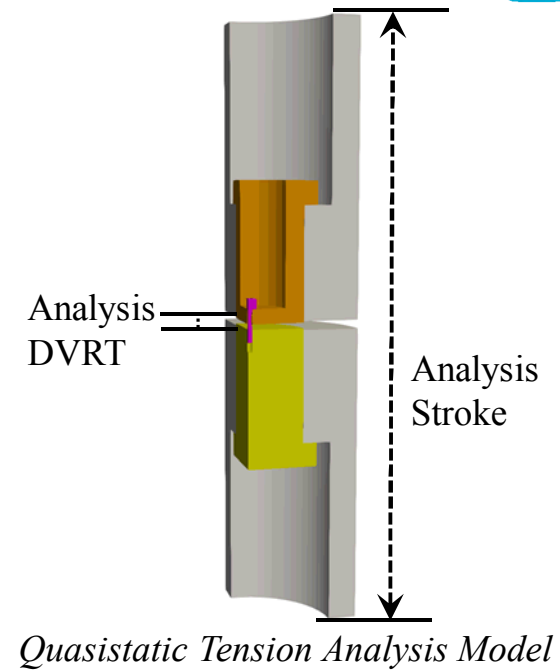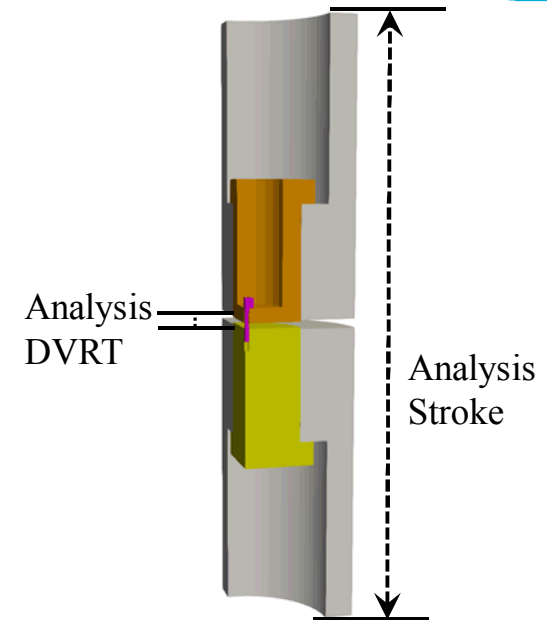
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What Happened?

Quasistatic Tension Analysis Model

Analysis DVRT

Analysis Stroke

Smoothed, Shifted Test Data

TEST DVRT   TEST STROKE

What Happened?

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

Quasistatic Tension Analysis Model

Analysis DVRT

Analysis Stroke

Smoothed, Shifted Test Data

Analysis Displacements – DVRT & Stroke

TEST DVRT   TEST STROKE
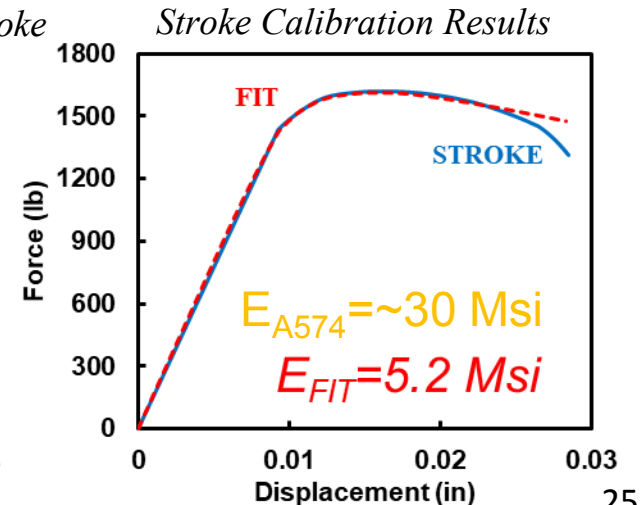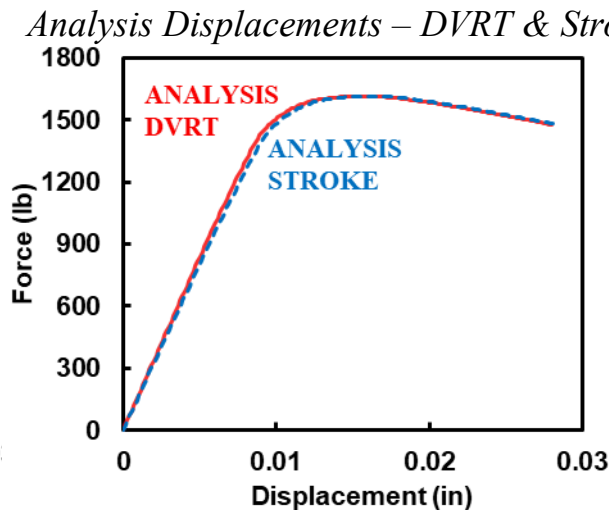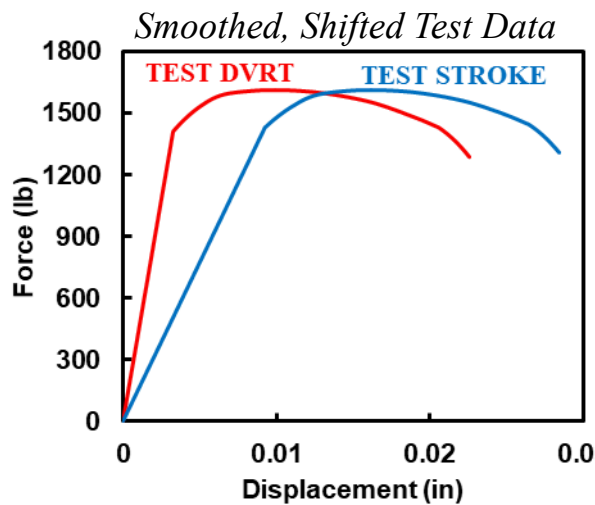
ANALYSIS DVRT   ANALYSIS STROKE

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.*
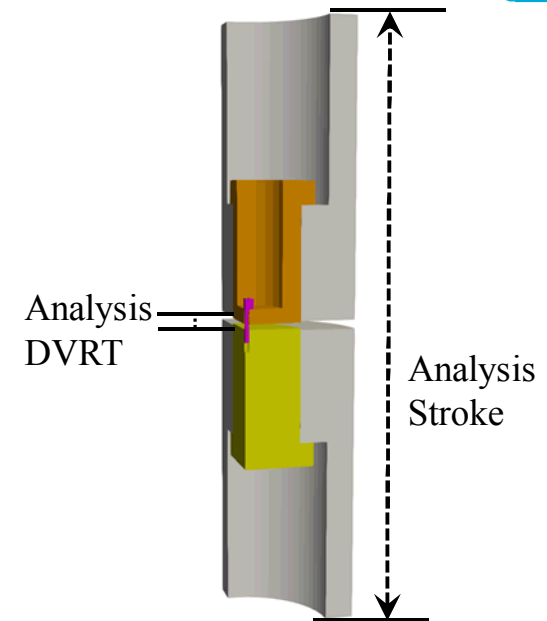
Analysis DVRT

Analysis Stroke

Quasistatic Tension Analysis Model

Smoothed, Shifted Test Data

TEST DVRT   TEST STROKE

Analysis Displacements – DVRT & Stroke

ANALYSIS DVRT

ANALYSIS STROKE

Stroke Calibration Results

FIT

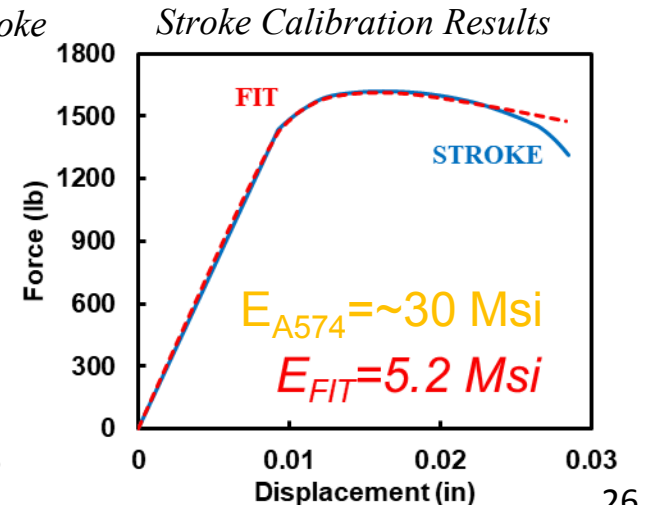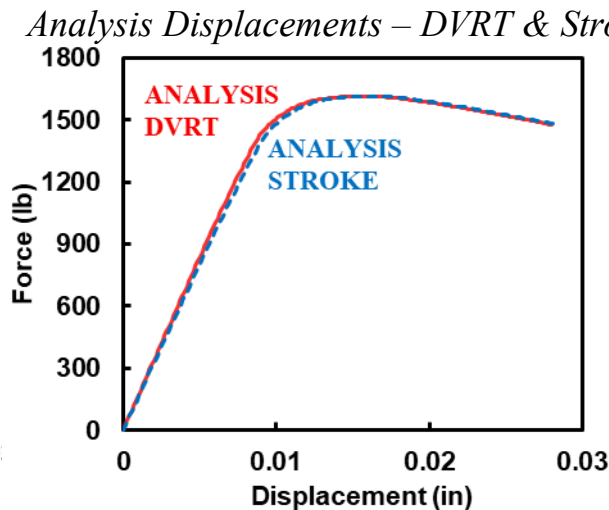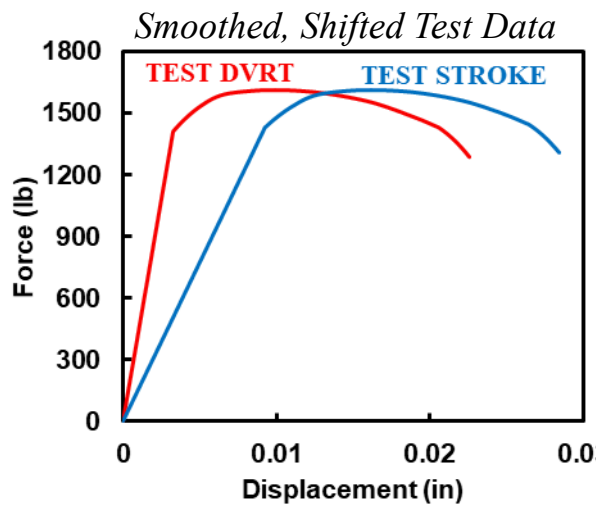STROKE

$E_{A574} = \sim30$ Msi

$E_{FIT} = 5.2$ Msi

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 might think:*
  - *Properties from literature*
  - *Only one source of displacement measurement*
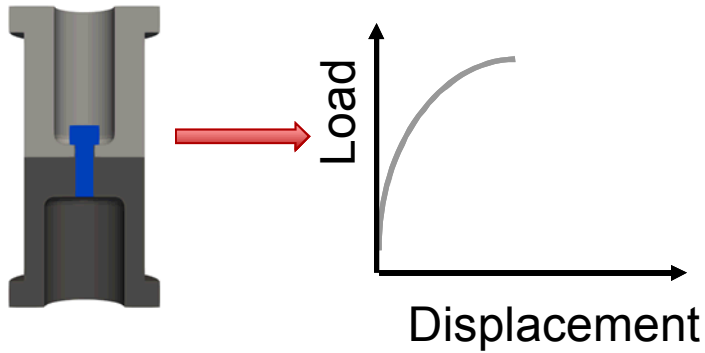 - *Tests are obtaining **joint** behavior, not fastener*

Quasistatic Tension Analysis Model

Smoothed, Shifted Test Data

Analysis Displacements – DVRT & Stroke

Stroke Calibration Results

E_{A574}=~30 Msi

E_{FIT}=5.2 Msi

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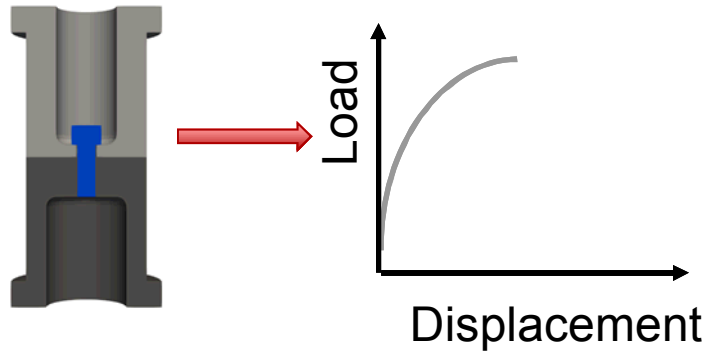What processes can be used to avoid these errors?

Idealistic Approach

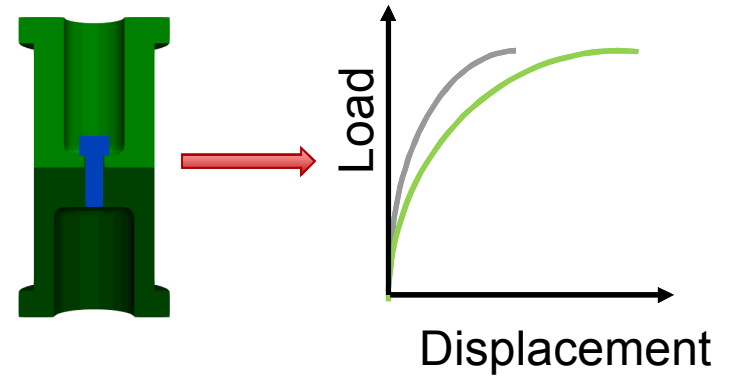① *Isolate fastener behavior with hardened steel bushings and local measurements.*

Idealistic Approach

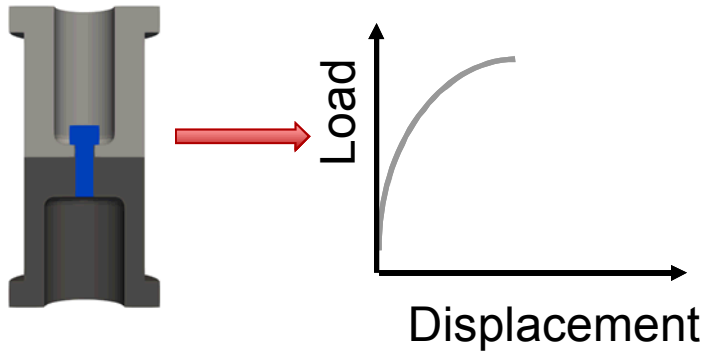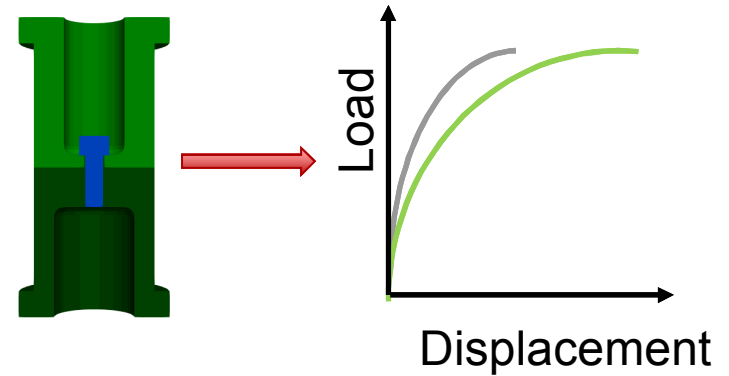① *Isolate fastener behavior with hardened steel bushings and local measurements.*

② *Predict behavior in application materials*

Idealistic Approach
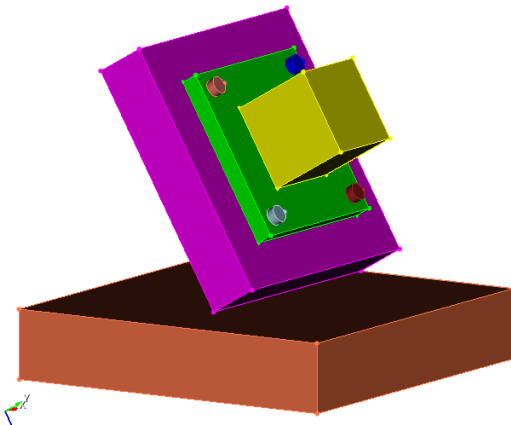
① *Isolate fastener behavior with hardened steel bushings and local measurements.*
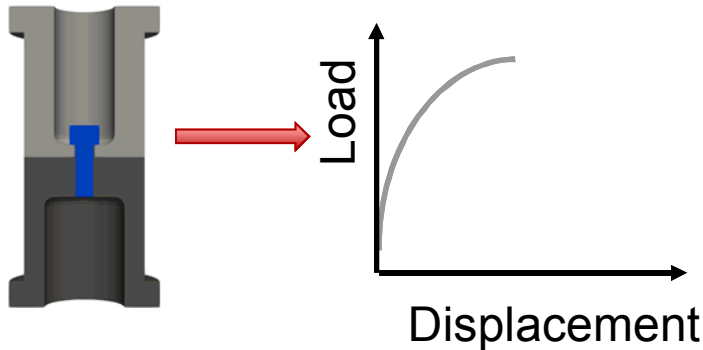
② *Predict behavior in application materials*
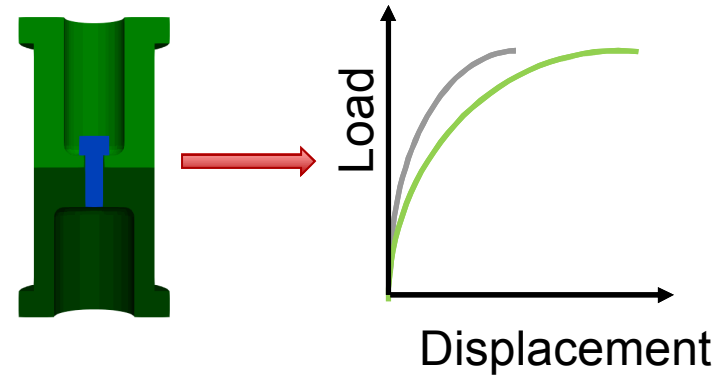
③ *Assess model in component-like test*

Idealistic Approach

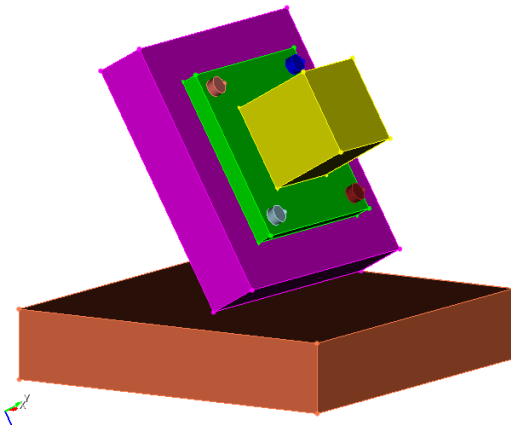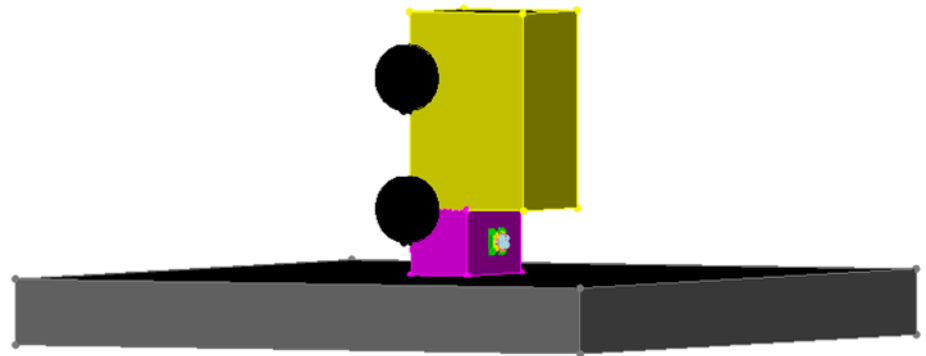① *Isolate fastener behavior with hardened steel bushings and local measurements.*

② *Predict behavior in application materials*
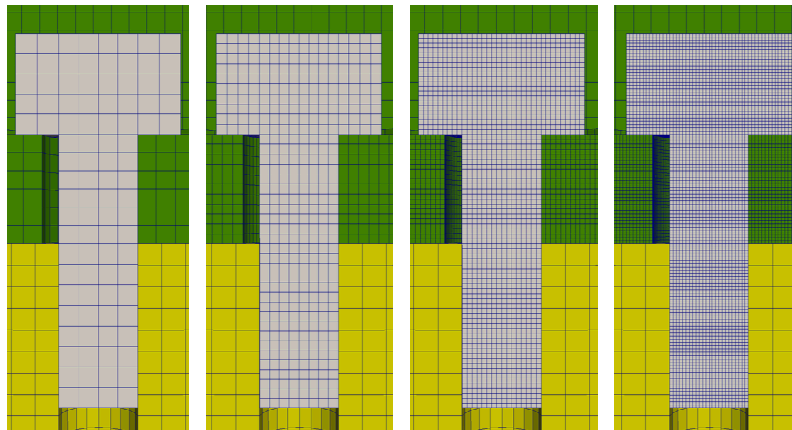

③ *Assess model in component-like test*
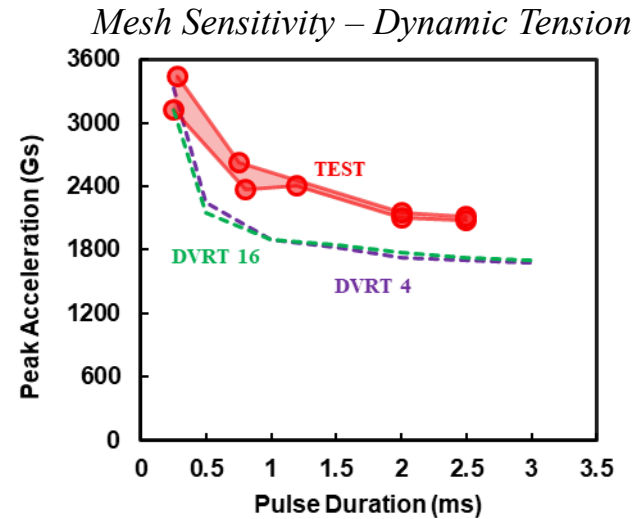

④ *Use modeling approach in system model!*

Mesh Sensitivity

- Mesh sensitivity was assessed in dynamic tension and shear models

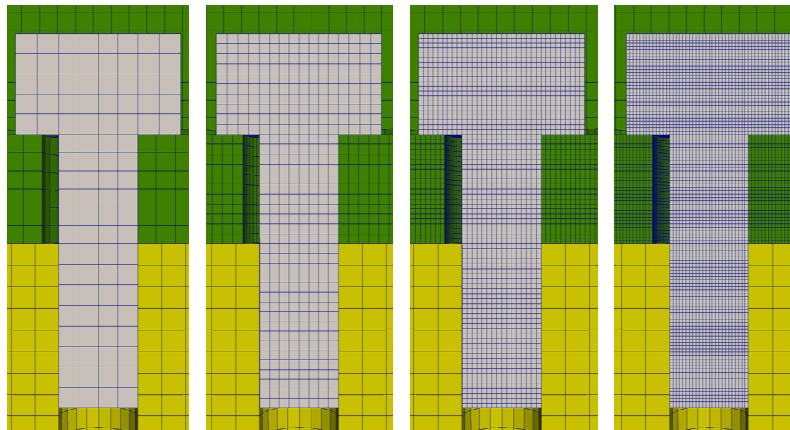- Tension analysis was insensitive to mesh

Mesh Sensitivity – Dynamic Tension

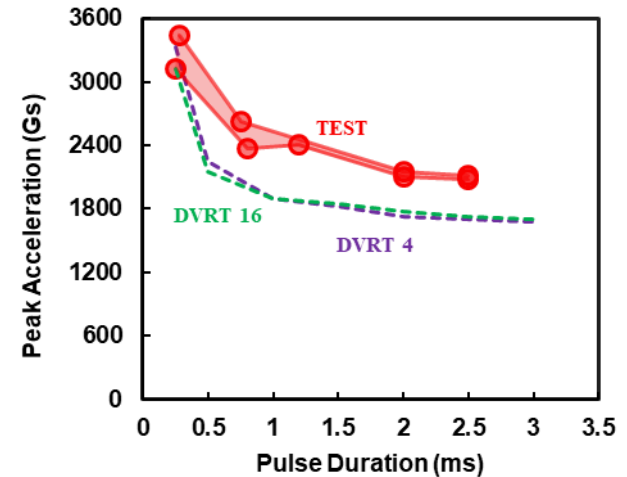*Meshes in Sensitivity Study (4, 8, 16, 24)*

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*
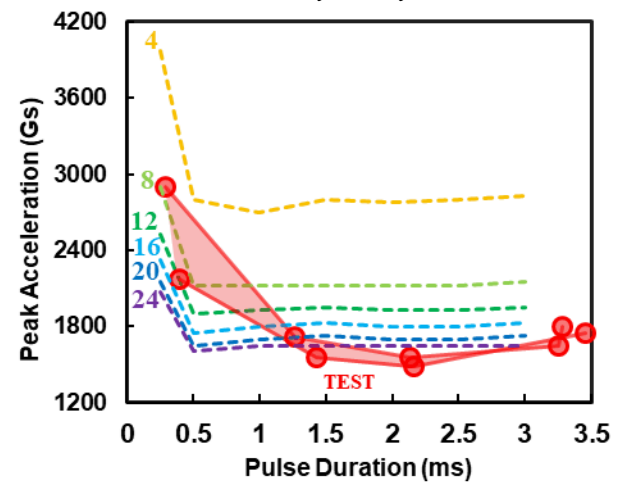
Mesh Sensitivity – Dynamic Tension

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

Mesh Sensitivity – Dynamic Shear

Relative difference in mesh sensitivity makes it difficult to model both types of loading accurately.
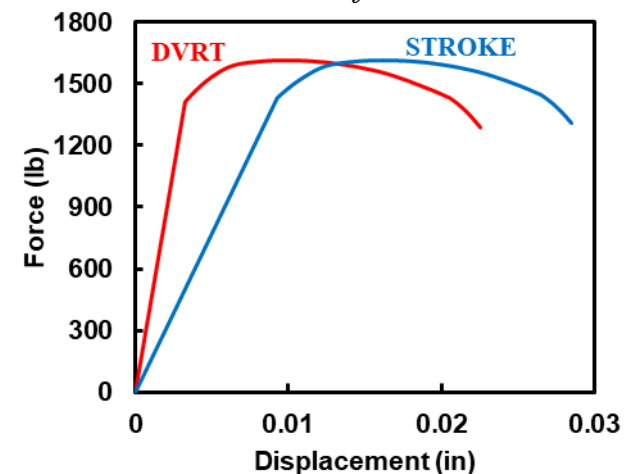
Conclusions

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

- Errors of 20-30% can manifest in common quantities of interest, such as failure load, time-to-failure, and displacement-at-failure when this data is not understood.

- The mesh sensitivity of shear applications makes obtaining robust, accurate reduced-order fastener models increasingly difficult.
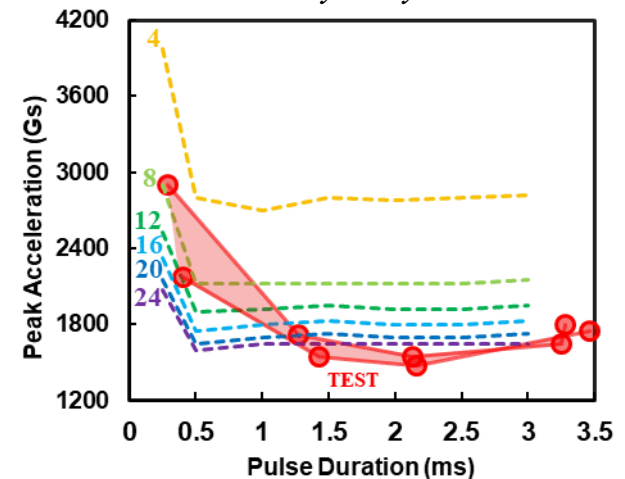
Smoothed, Shifted Test Data

Mesh Sensitivity – Dynamic Shear

Dynamic Shear Analysis Summary

Duration (ms)	Peak Accel (Gs)	DVRT Failure Time (ms)	Stroke Failure Time (ms)	Percent Difference (%)
0.25	2075	0.276	0.281	1.80%
0.5	1600	0.406	0.354	13.68%
1	1650	0.712	0.513	32.49%
1.5	1675	0.972	0.728	28.71%
2	1650	1.31	0.965	30.33%
2.5	1650	1.5	1.15	26.42%
3	1650	1.82	1.34	30.38%

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Reduced order fastener modeling is very difficult!!!

Future Work

- This study only investigated #6 fasteners. How well can constitutive models be extended to fasteners of different sizes?

- How much do our models improve if we include strain rate effects?

- Can we implement load-dependent failure (i.e. different death criterions for tension and shear)?

- Let's implement our ideal approach and see how we do!

QUESTIONS?