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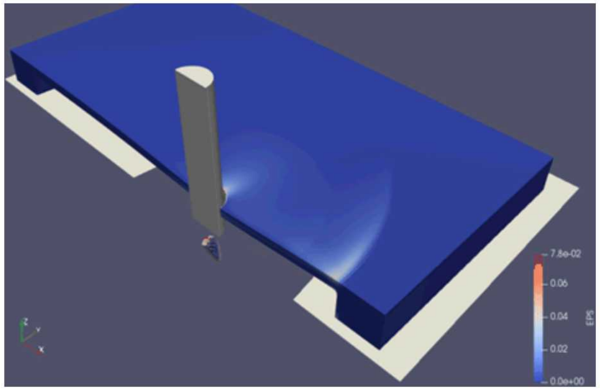

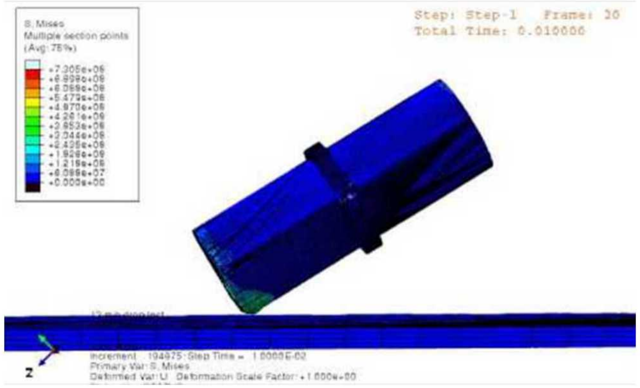

Sandia National Laboratories

Student Research Projects

1 November 2018

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Safety Engineering

Safe Process for High-Consequence Systems

- Modeling and Simulation
  - Make conservative assumptions to bound the correct answer
  - "All models are wrong, but some are useful." (George Box)
- Testing and Validation
  - Perform tests to ensure that the model captures the relevant physics
  - Test a simplified geometry and tune the model to match
- Design a Safe Process
  - Limit sources of energy at safe thresholds
  - Prevent severe consequences with high probability
  - Improve component and tool designs where needed

Student Projects

Internships

- Exclusion Region Barrier Analysis
- Puncture Analysis
- Model Communication Worksheet

Senior Design Projects

- Mechanical Impact Tests
- Mechanical Joint Analysis

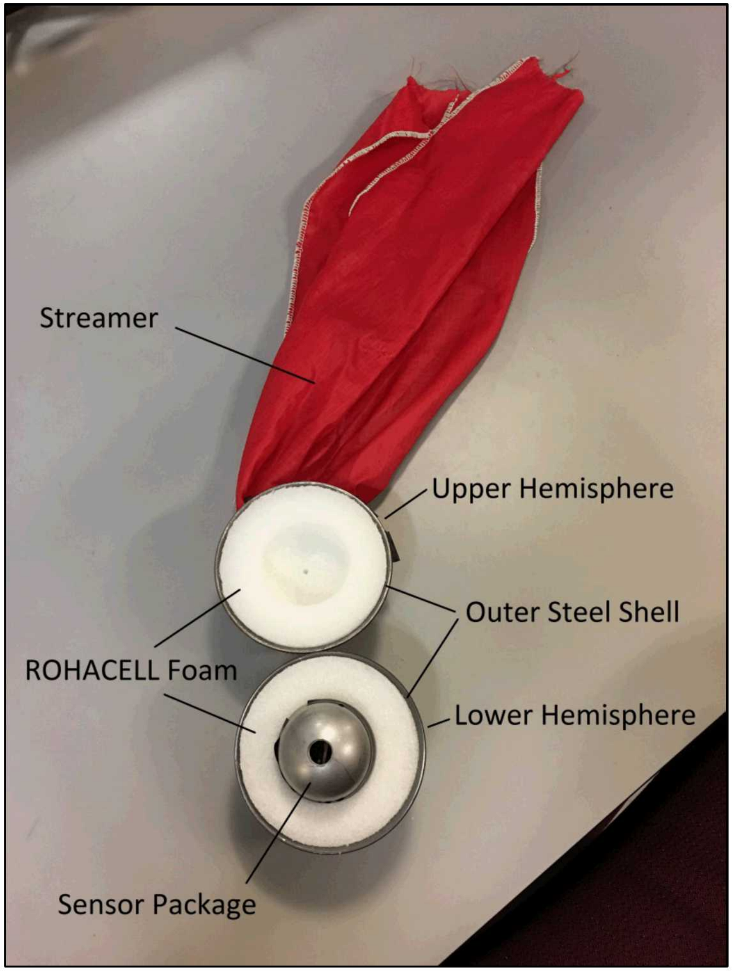
SHOCK ISOLATION

Drop Tests of Acceleration Sensor with or without Foam and Shell

Background

- For many problems we use a design principles approach to safety.
- This approach is used for systems which require extreme levels of certainty involving probabilities of one in a million or less.
- The safety design principles are called the three I’s
  - Isolation: Surround a critical component with a structure that blocks a form of energy.
  - Incompatibility
  - Inoperability

Shock Isolation



- **Need:**
Shock isolation of the sensor package from an external insult.

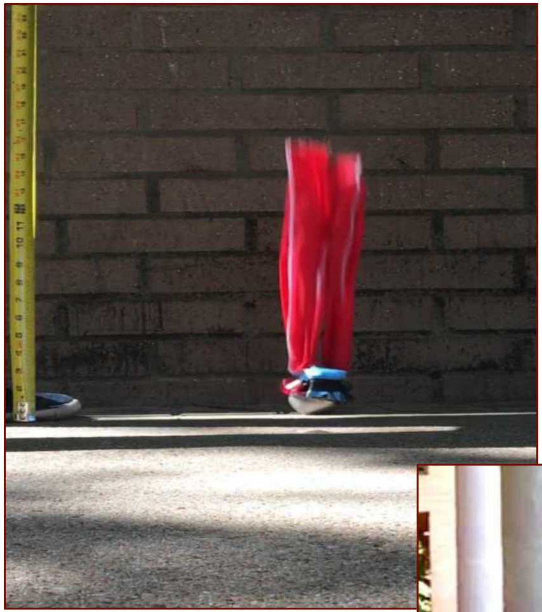
- **Constraints:**
Sensor and exterior volumes are bounded. The maximum allowable peak shock level at the sensor is 400 g's.

- **Problem:**
What migration material will produce the maximum level of shock isolation?

Shock Isolation

- Baseline tests:

Without mitigation, progressively drop the sensor at higher heights until 400 g's is reached.

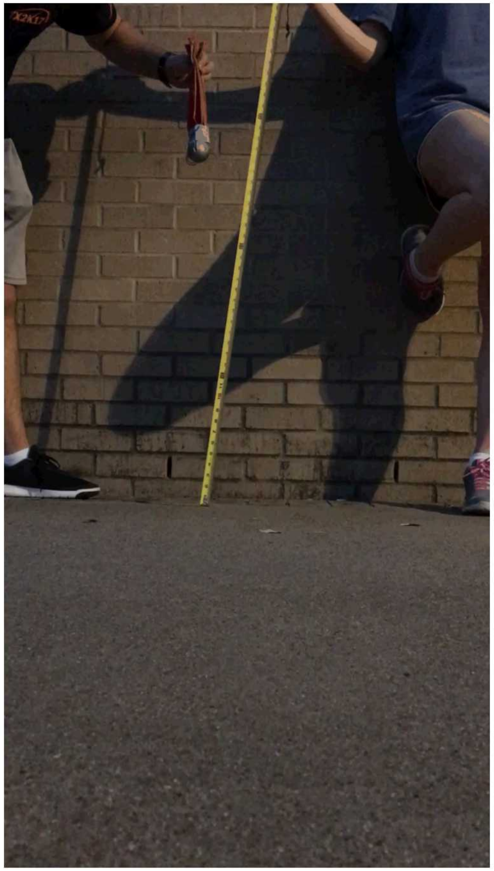


- Quantitative tests:

With mitigation, progressively drop the sensor at higher heights until 400 g's is reached.

Shock Isolation

- **Without mitigation:**
A drop from only 31 inches produced over 400 g's.



- **With mitigation:**
A drop from over 19 feet was required to produced over 400 g's.

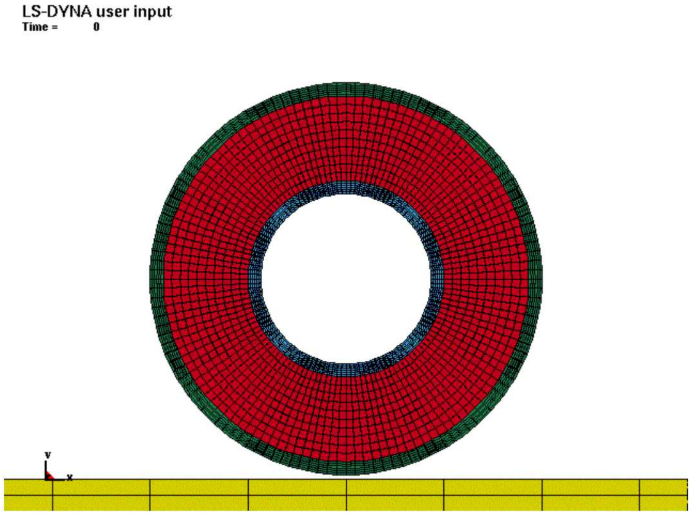
Shock Isolation

Post mortem

Most of the plastic deformation occurs within the foam.

Very little plastic deformation occurred in the shell

Modeling and experiment agreed.



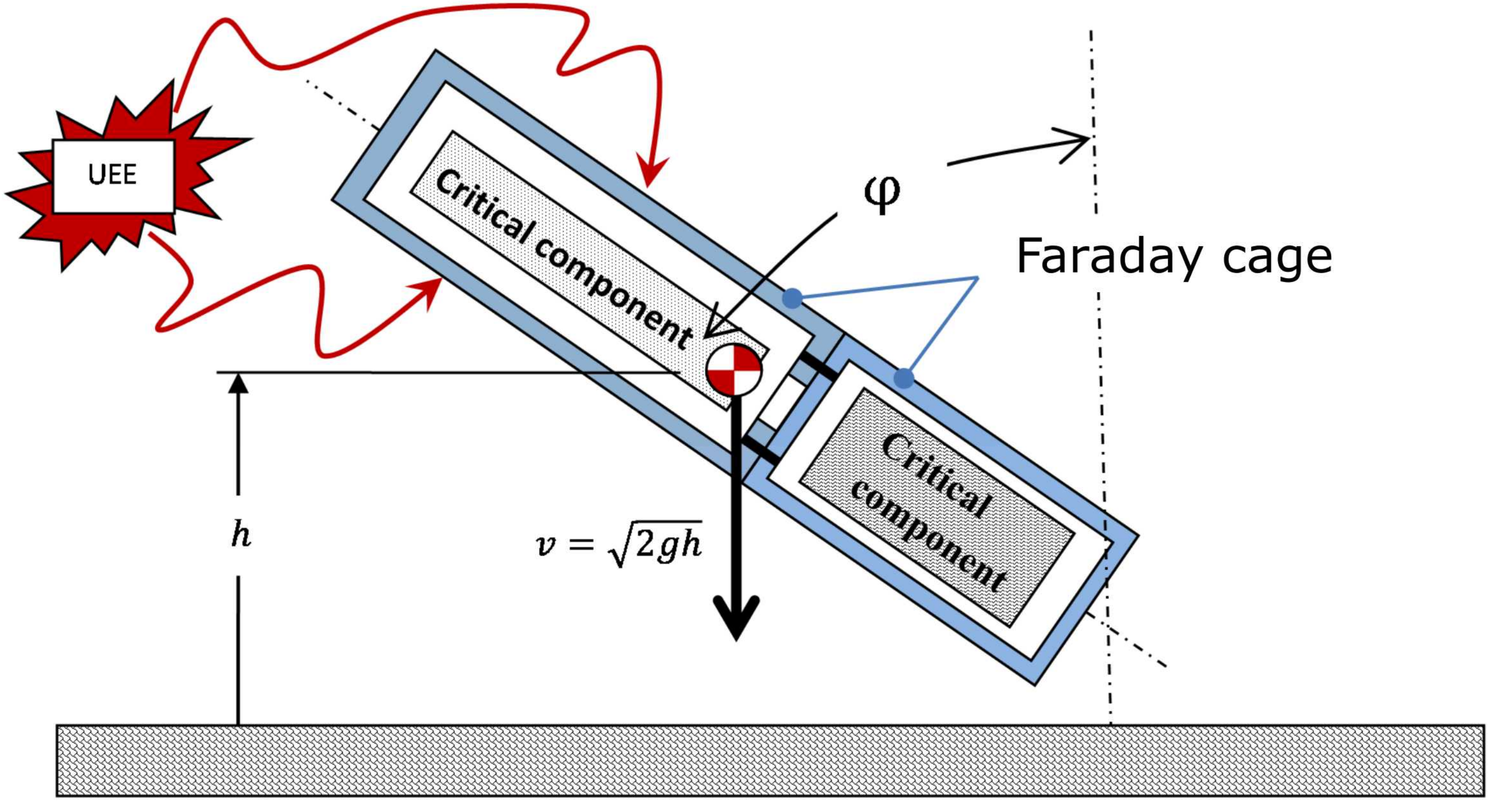
Only a portion of the foam was crushed.

ELECTRICAL ISOLATION

Design Study Optimizing Strength *vs.* Weight with Three Metals

Electrical Isolation

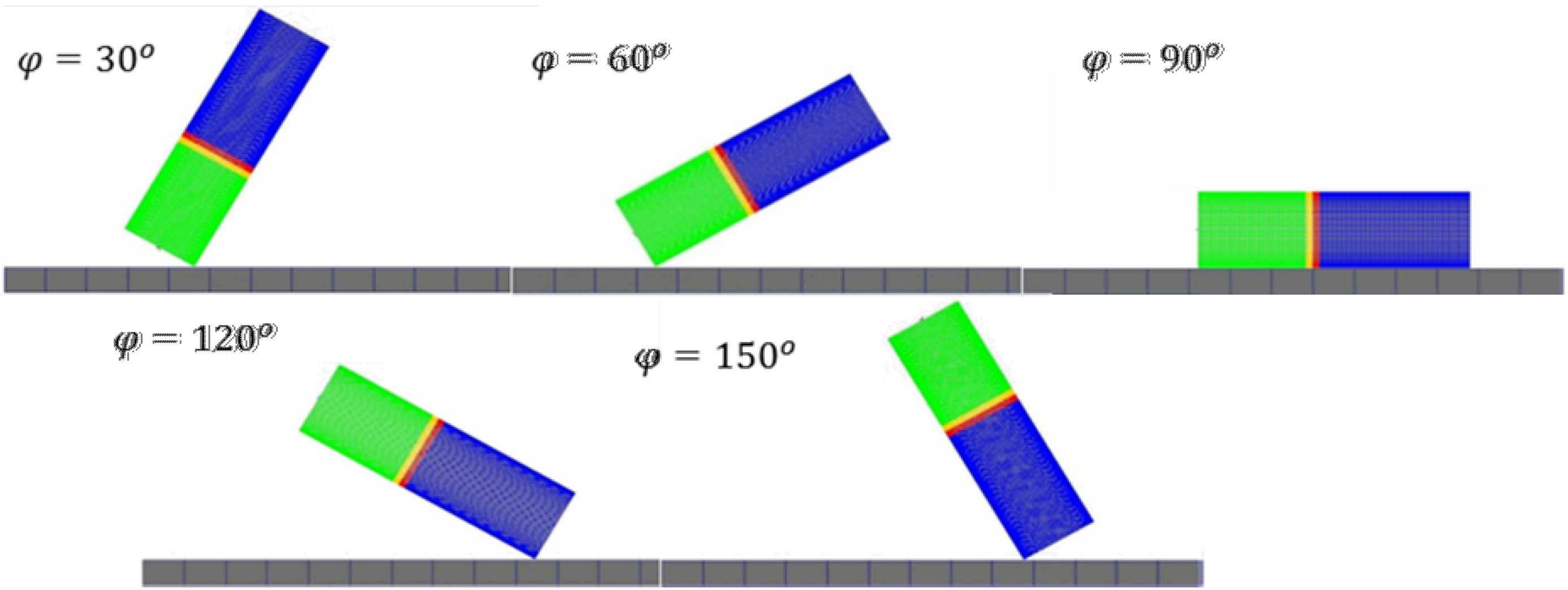
What is the best material to maintain a Faraday cage?



Electrical Isolation

Perform an Environmental Search

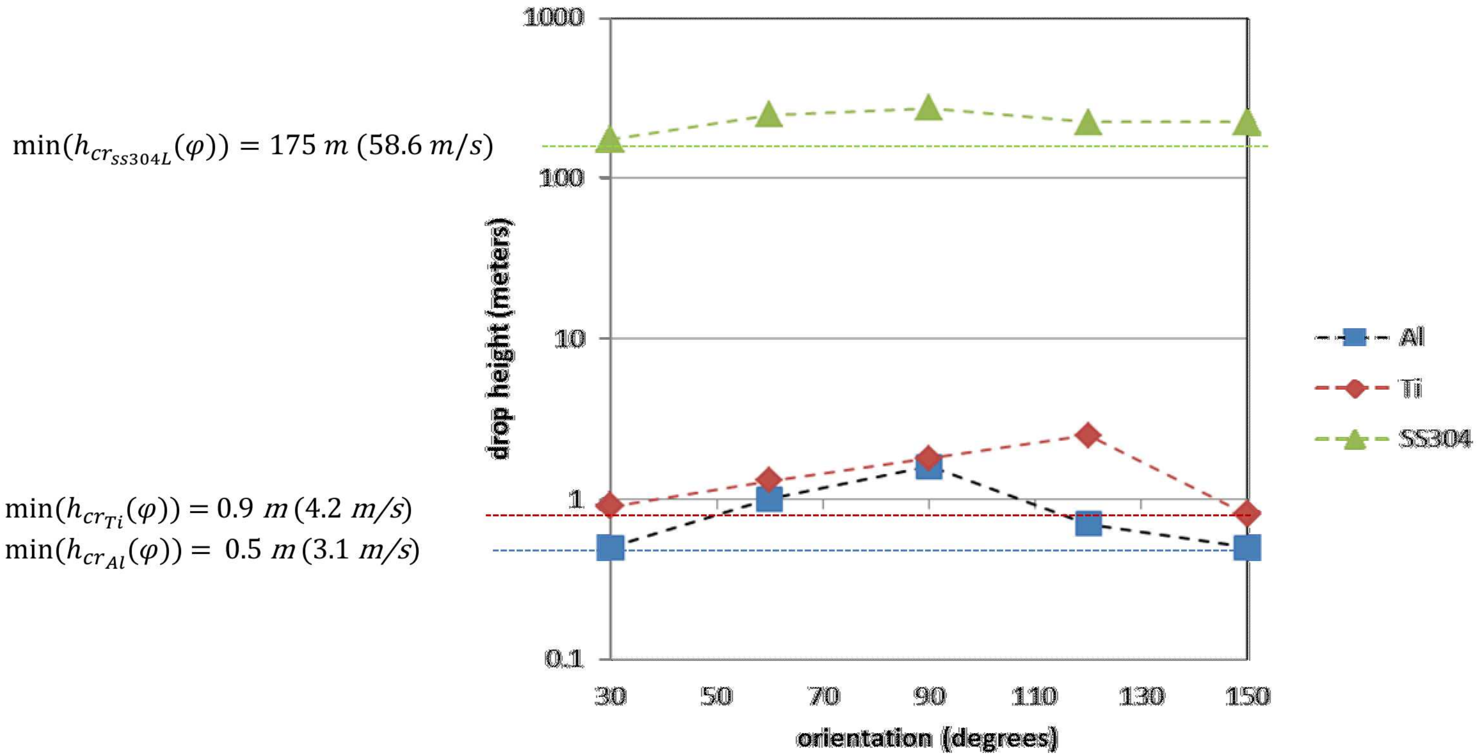
Simulations are performed for a distribution of insult orientations to determine the orientation that will produce material failure of the cage at the lowest drop height.



Electrical Isolation

What is the best material?

Aluminum, is the least effective material
Titanium was only marginally better than Aluminum
Steel, on the other hand, was by far the best option



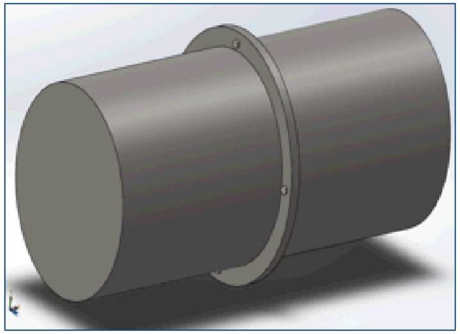
- We like ductile materials

MECHANICAL ISOLATION

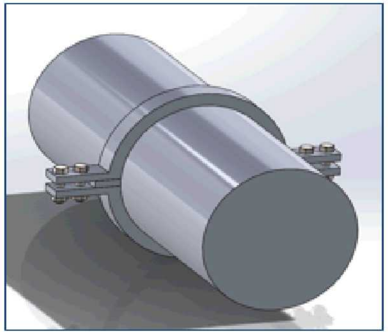
Design Study Maximizing Toughness with Three Means of Attachment

Mechanical Isolation

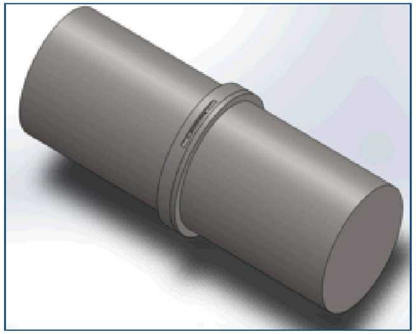
- What is the best joint design?



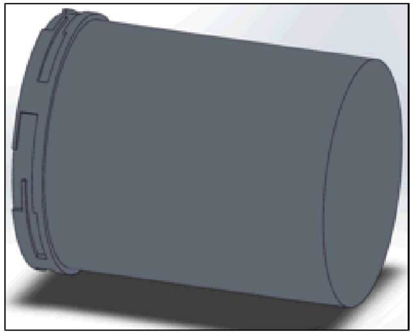
Bolted



Clamped



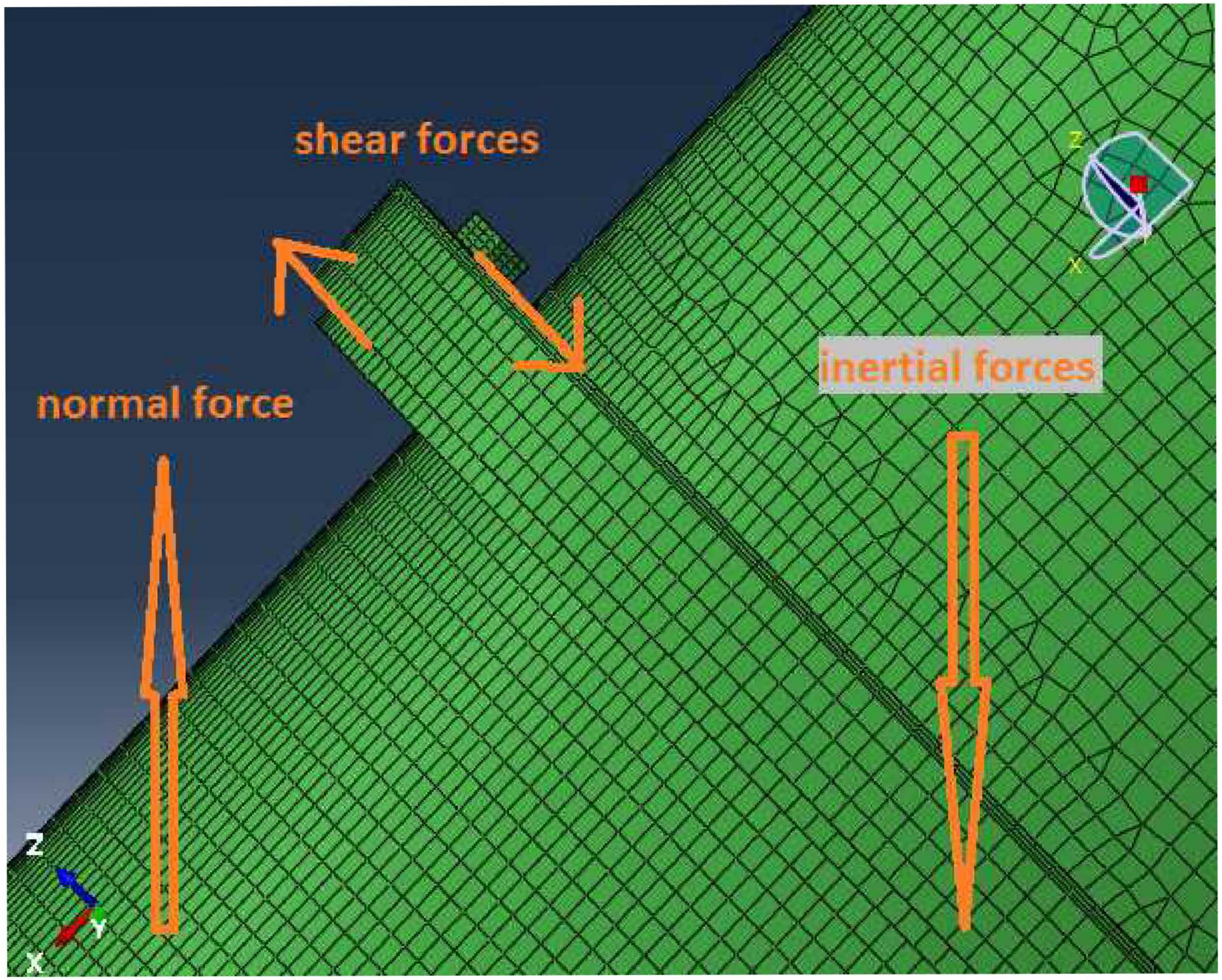
Tape Joint



J-Locked

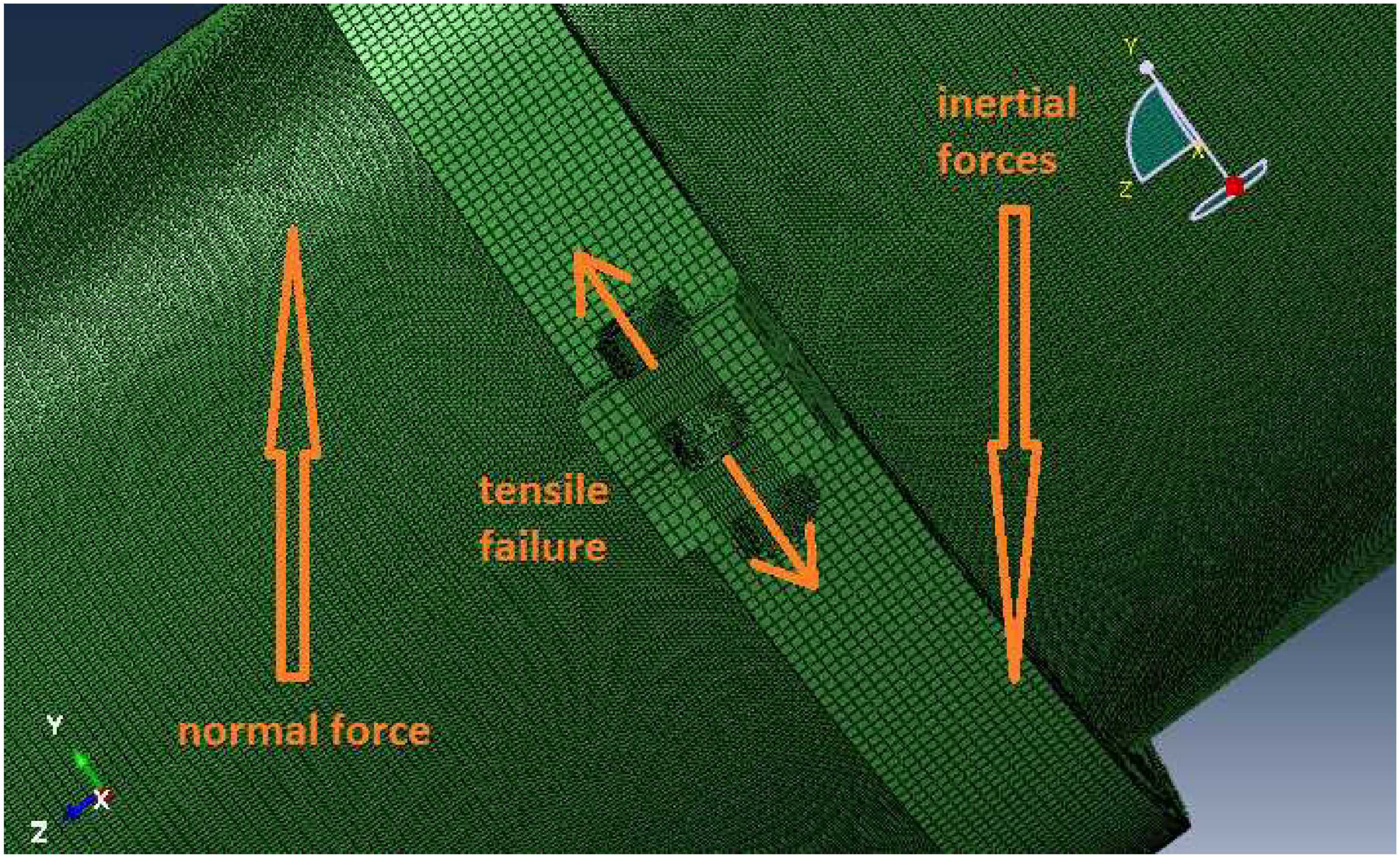
Mechanical Joints

Bolted Joint Model



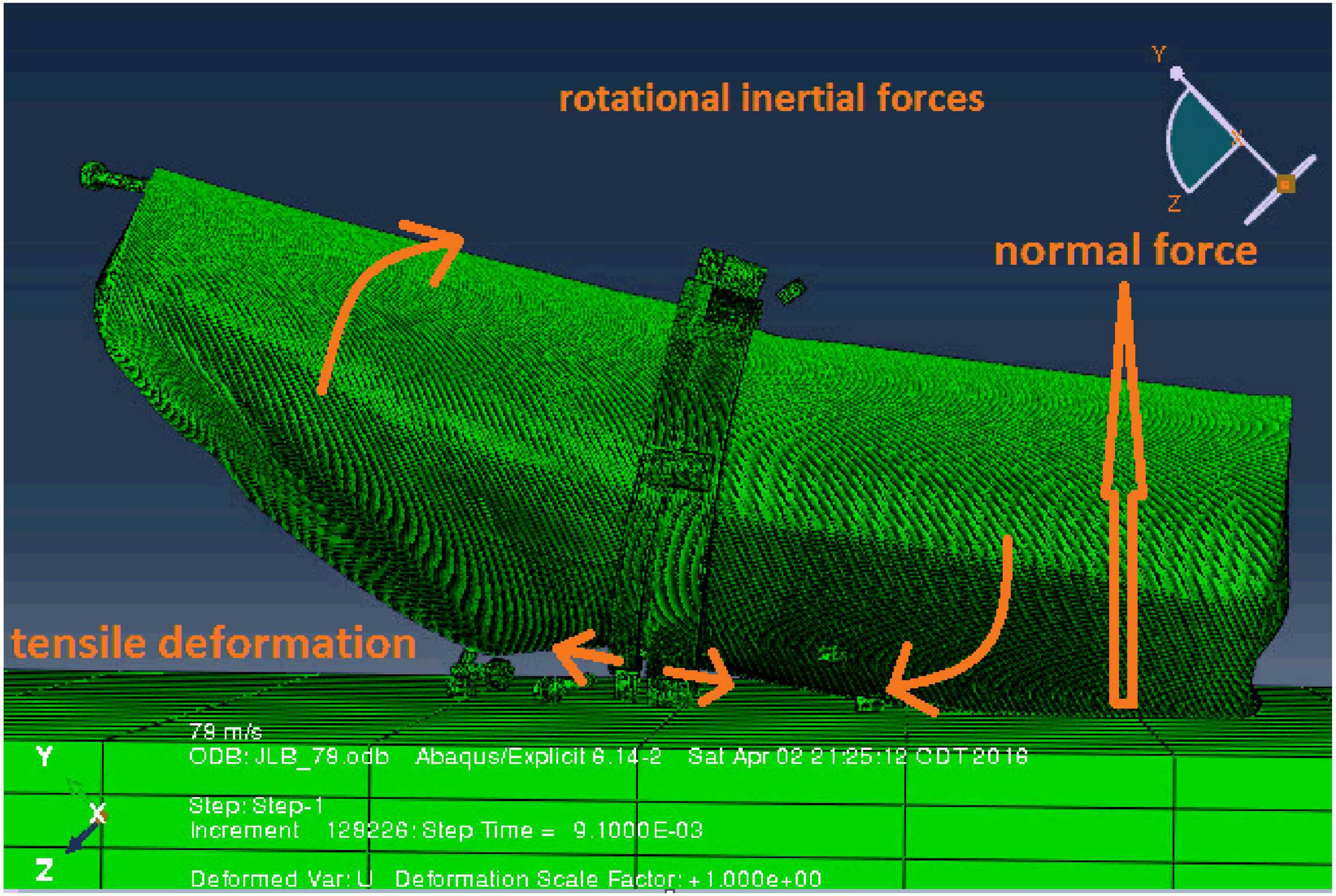
Mechanical Joints

Clamped Joint Model



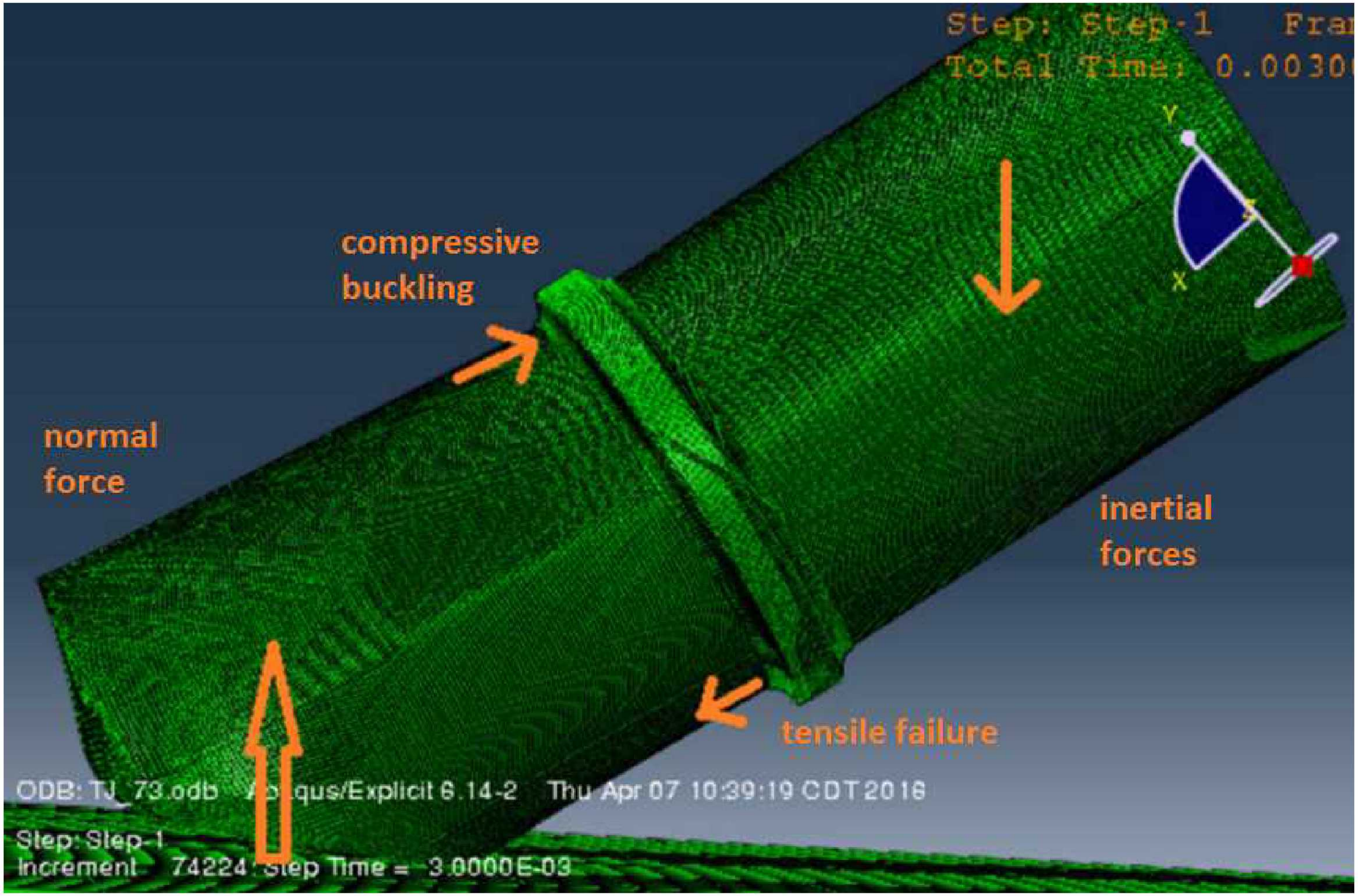
Mechanical Joints

Bolted J-Lock Joint Model



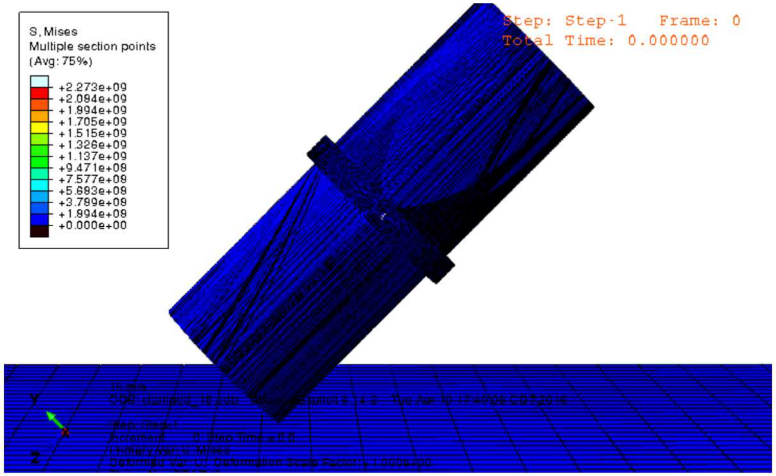
Mechanical Joints

Tape Joint Model

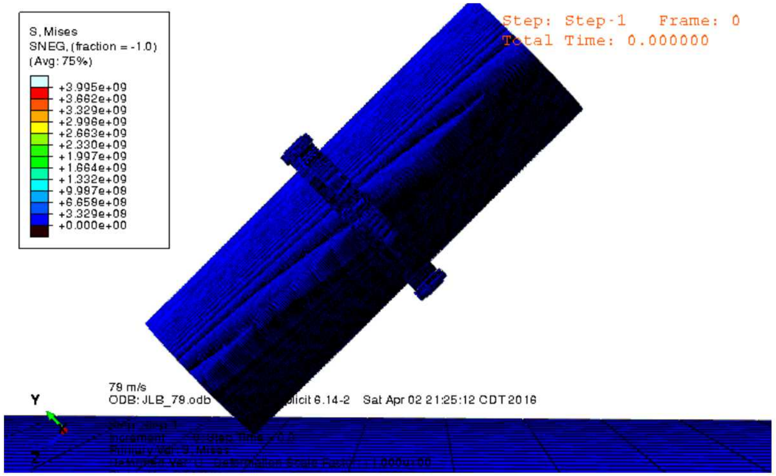


Mechanical Isolation

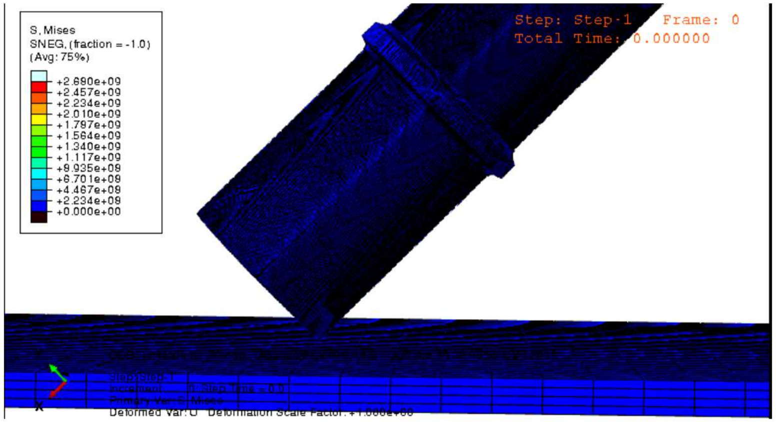
- Clamped



- J-lock



- Tape Joint



Mechanical Isolation

Simulation Results

Joint	Failure Velocity (m/s)	Energy Absorbed (J)
Bolted	12	1,152
Clamped	14	2,156
Bolted J-Lock	72	51,840
Tape Joint	72	53,136

- We do not like bolted interfaces

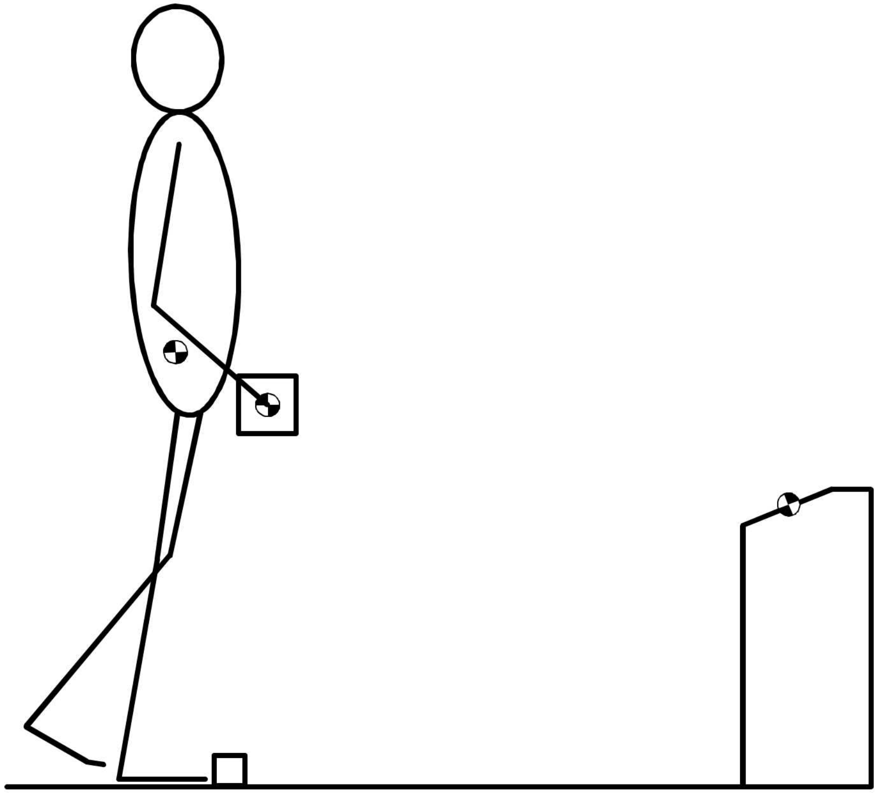
TRIP AND FALL HAZARD

Analysis of Impact Force and Energy in an Industrial Setting

Trip and Fall Hazard

Assumptions

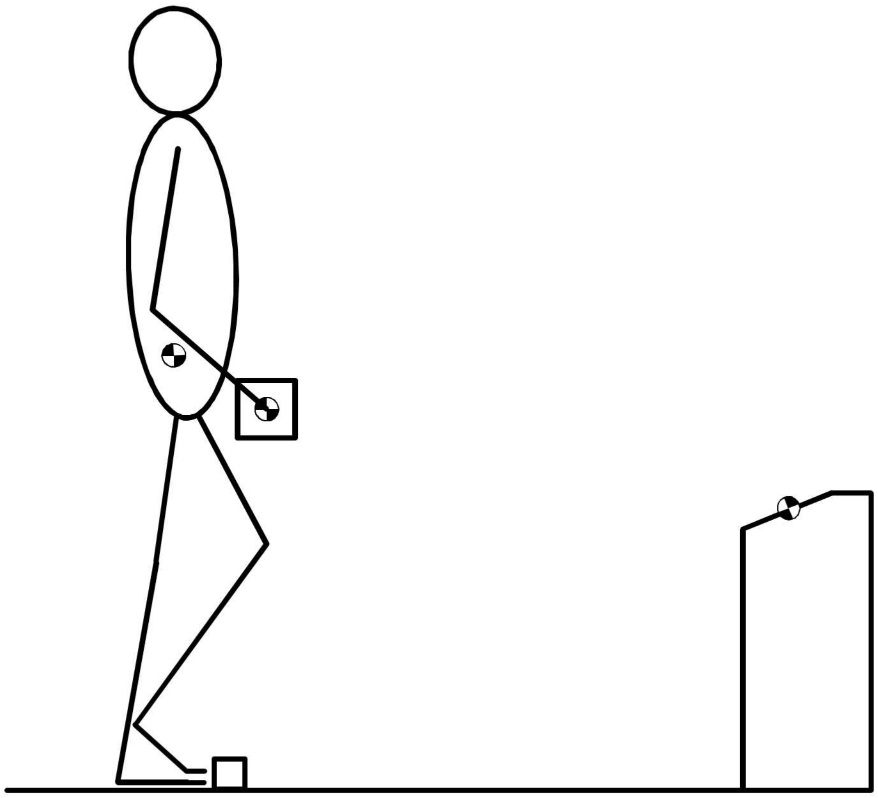
- Forward fall
  - No recovery or avoidance
- Two-dimensional
  - Load is held in both hands
  - No glancing blow
- Initial conditions
  - Walking toward sensitive target component
  - Carrying load in comfortable position



Trip and Fall Hazard

Trip Hazard

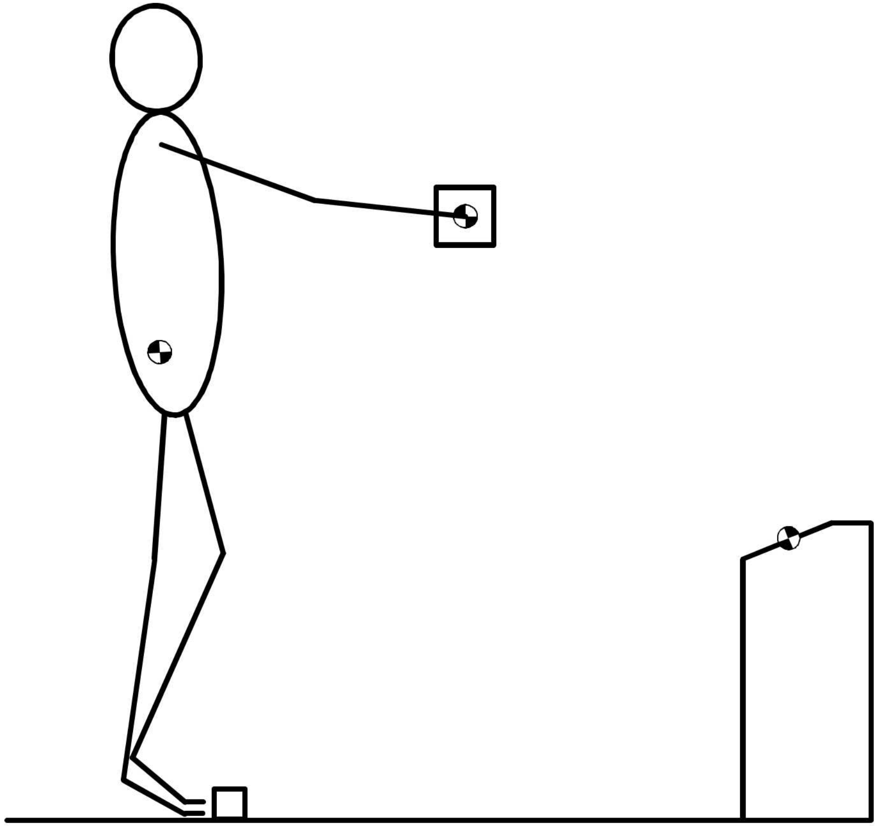
- Man trips on rigid obstacle
  - Both feet are trapped
  - Location results in load impacting critical component
- Trip analyzed with rigid-body dynamics
  - Momentum is conserved



Trip and Fall Hazard

Human Response

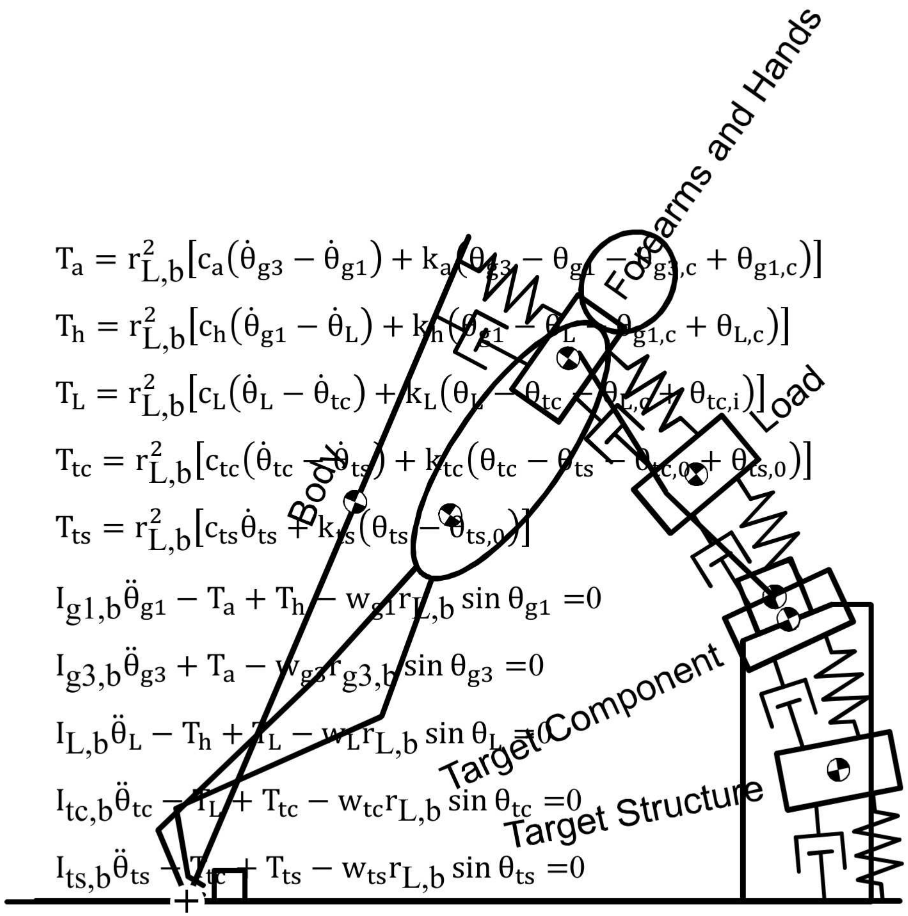
- Reaction observed in experiments
  - Flexion of ankle raises body and load
  - Man raises and extends arms
  - Man retains grip on load
- Muscle Action
  - Potential energy increases
  - Angular momentum is conserved
  - Angle to overall center of gravity is constant



Trip and Fall Hazard

Fall and Load Impact

- Fall analyzed with rigid-body dynamics
  - Man and load rotate together
  - Energy is conserved
- Load impact analysis
  - Coupled mass-spring-damper system
  - Arms flex until body contacts load



$$T_a = r_{L,b}^2\left[c_a\left(\dot{\theta}_{g3} - \dot{\theta}_{g1}\right) + k_a\left(\theta_{g3} - \theta_{g1} - \theta_{g3,c} + \theta_{g1,c}\right)\right]$$

$$T_h = r_{L,b}^2\left[c_h\left(\dot{\theta}_{g1} - \dot{\theta}_{L}\right) + k_h\left(\theta_{g1} - \theta_{L} - \theta_{g1,c} + \theta_{L,c}\right)\right]$$

$$T_L = r_{L,b}^2\left[c_L\left(\dot{\theta}_{L} - \dot{\theta}_{tc}\right) + k_L\left(\theta_{L} - \theta_{tc} - \theta_{L,c} + \theta_{tc,i}\right)\right]$$

$$T_{tc} = r_{L,b}^2\left[c_{tc}\left(\dot{\theta}_{tc} - \dot{\theta}_{ts}\right) + k_{tc}\left(\theta_{tc} - \theta_{ts} - \theta_{tc,0} + \theta_{ts,0}\right)\right]$$

$$T_{ts} = r_{L,b}^2\left[c_{ts}\dot{\theta}_{ts} + k_{ts}\left(\theta_{ts} - \theta_{ts,0}\right)\right]$$

$$I_{g1,b}\ddot{\theta}_{g1} - T_a + T_h - w_{g1} r_{L,b} \sin\theta_{g1} = 0$$

$$I_{g3,b}\ddot{\theta}_{g3} + T_a - w_{g3} r_{g3,b} \sin\theta_{g3} = 0$$

$$I_{L,b}\ddot{\theta}_{L} - T_h + T_L - w_{L} r_{L,b} \sin\theta_{L} = 0$$

$$I_{tc,b}\ddot{\theta}_{tc} - T_L + T_{tc} - w_{tc} r_{L,b} \sin\theta_{tc} = 0$$

$$I_{ts,b}\ddot{\theta}_{ts} - T_{tc} + T_{ts} - w_{ts} r_{L,b} \sin\theta_{ts} = 0$$

Trip and Fall Hazard

Body Impact

- Model transitions to new configuration
  - Arms lose strength
  - Hands retain grip on load
  - Body inertia reacted through chest
- Body impact analysis
  - Real-time coupling of masses in dynamic system
  - Springs and dampers apportion impact energy between target and person

$$T_b = \begin{cases} T_{b,1} & r_{L,b}\left(\theta_{g4} - \theta_{g2} - \theta_{g4,d} + \theta_{g2,d}\right) \le \delta_{b,t} \\ T_{b,2} & r_{L,b}\left(\theta_{g4} - \theta_{g2} - \theta_{g4,d} + \theta_{g2,d}\right) > \delta_{b,t} \end{cases}$$

$$T_{b,1} = r_{L,b}^2\left[c_b\left(\dot\theta_{g4} - \dot\theta_{g2}\right) + k_{b,1}\left(\theta_{g4} - \theta_{g2} - \theta_{g4,d} + \theta_{g2,d}\right)\right]$$

$$T_{b,2} = r_{L,b}^2\left[c_b\left(\dot\theta_{g4} - \dot\theta_{g2}\right) + k_{b,2}\left(\theta_{g4} - \theta_{g2} - \theta_{g4,d} + \theta_{g2,d}\right)\right] + r_{L,b}\left(k_{b,1} - k_{b,2}\right)\delta_{b,t}$$

$$c_b = \begin{cases} c_{b,c} & \dot\theta_{g2} \le \dot\theta_{g4} \\ c_{b,e} & \dot\theta_{g2} > \dot\theta_{g4} \end{cases}$$

$$T_s = r_{L,b}^2\left[c_s\left(\dot\theta_{g2} - \dot\theta_L\right) + k_s\left(\theta_{g2} - \theta_L - \theta_{g2,d} + \theta_{L,d}\right)\right]$$

$$T_h = r_{L,b}^2\left[c_h\left(\dot\theta_{g1} - \dot\theta_L\right) + k_h\left(\theta_{g1} - \theta_L - \theta_{g1,c} + \theta_{L,c}\right)\right]$$

$$T_L = r_{L,b}^2\left[c_L\left(\dot\theta_L - \dot\theta_{tc}\right) + k_L\left(\theta_L - \theta_{tc} - \theta_{L,c} + \theta_{tc,c}\right)\right]$$

$$T_{tc} = r_{L,b}^2\left[c_{tc}\left(\dot\theta_{tc} - \dot\theta_{ts}\right) + k_{tc}\left(\theta_{tc} - \theta_{ts} - \theta_{tc,0} + \theta_{ts,0}\right)\right]$$

$$T_{ts} = r_{L,b}^2\left[c_{ts}\dot\theta_{ts} + k_{ts}\left(\theta_{ts} - \theta_{ts,0}\right)\right]$$

$$I_{g1,b}\ddot\theta_{g1} + T_h - w_{g1}r_{L,b}\sin\theta_{g1} = 0$$

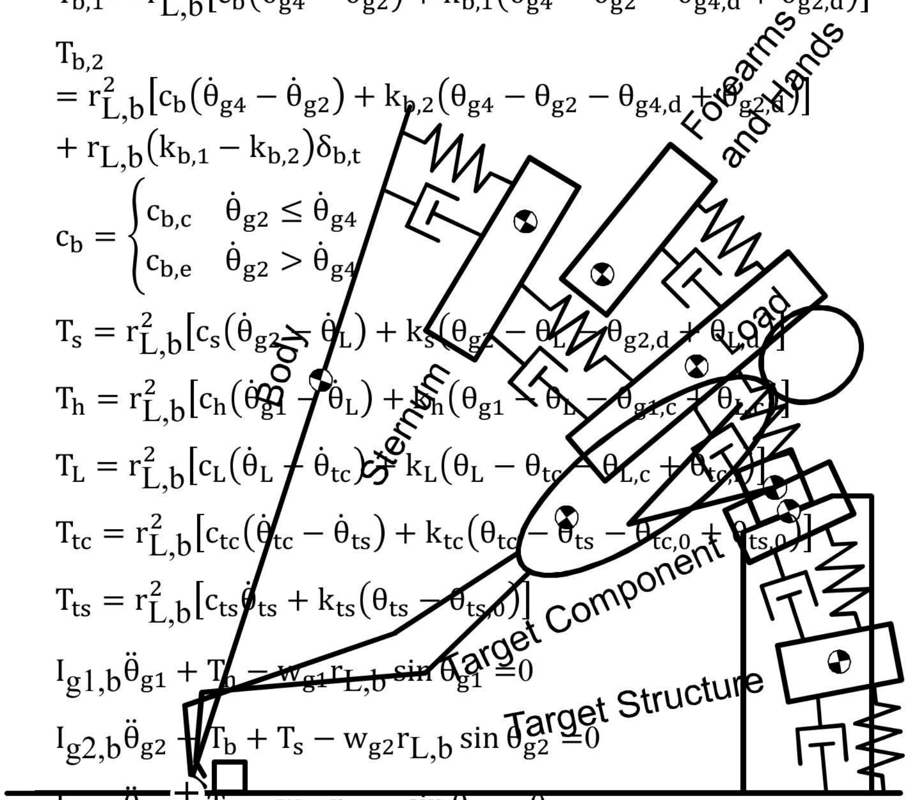
$$I_{g2,b}\ddot\theta_{g2} - T_b + T_s - w_{g2}r_{L,b}\sin\theta_{g2} = 0$$

$$I_{g4,b}\ddot\theta_{g4} + T_b - w_{g4}r_{g4,b}\sin\theta_{g4} = 0$$

$$I_{L,b}\ddot\theta_L - T_s - T_h + T_L - w_L r_{L,b}\sin\theta_L = 0$$

$$I_{tc,b}\ddot\theta_{tc} - T_L + T_{tc} - w_{tc}r_{L,b}\sin\theta_{tc} = 0$$

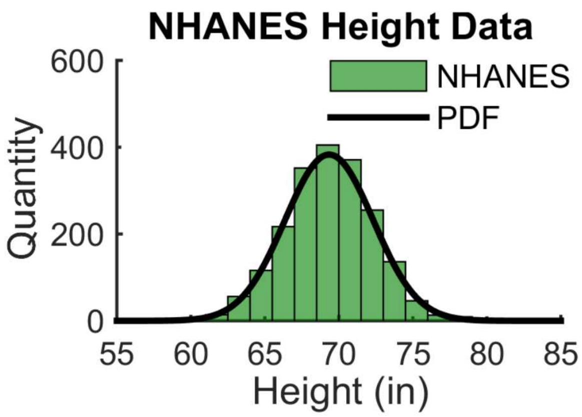
$$I_{ts,b}\ddot\theta_{ts} - T_{tc} + T_{ts} - w_{ts}r_{L,b}\sin\theta_{ts} = 0$$

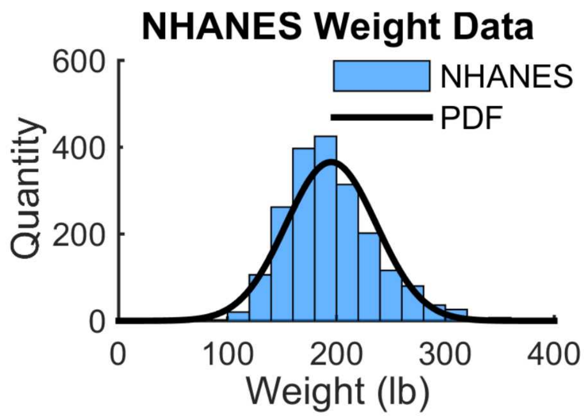


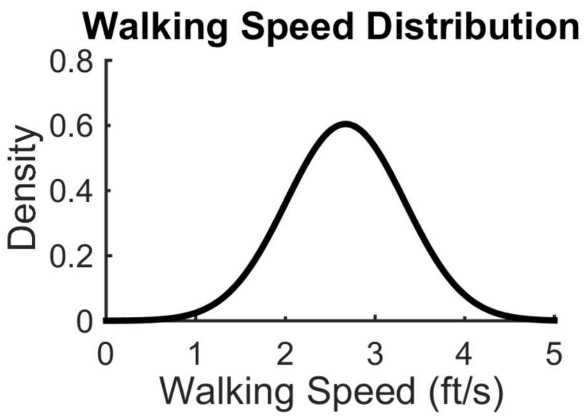
Trip and Fall Hazard

Inputs

- Weight of load
- Dynamic properties of mass-spring-dampers
- Height of target
- Probability of bounding real hazard
- Correlated height and weight of man
- Walking speed



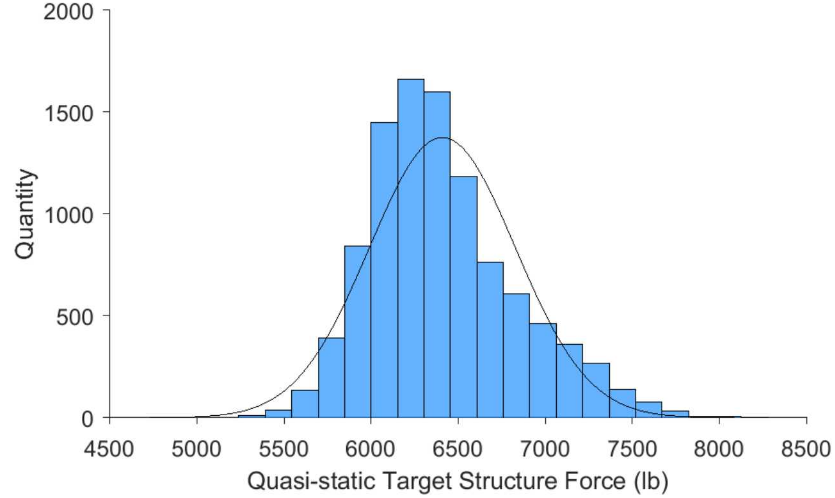


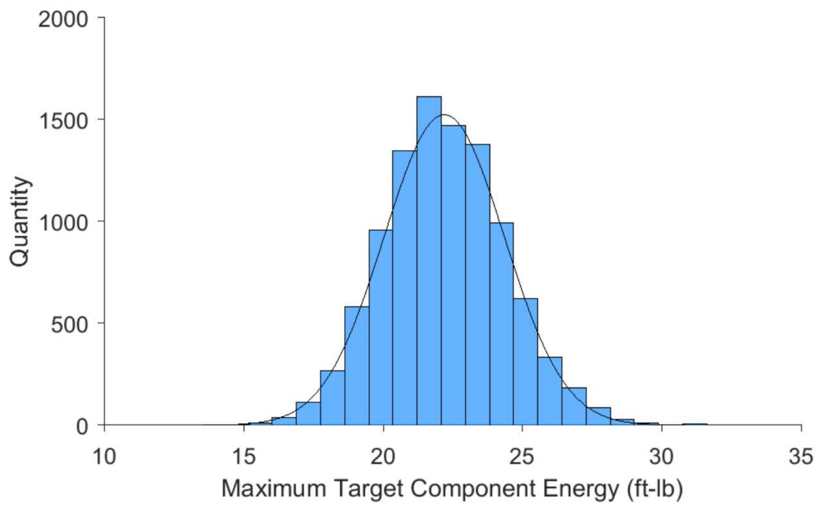


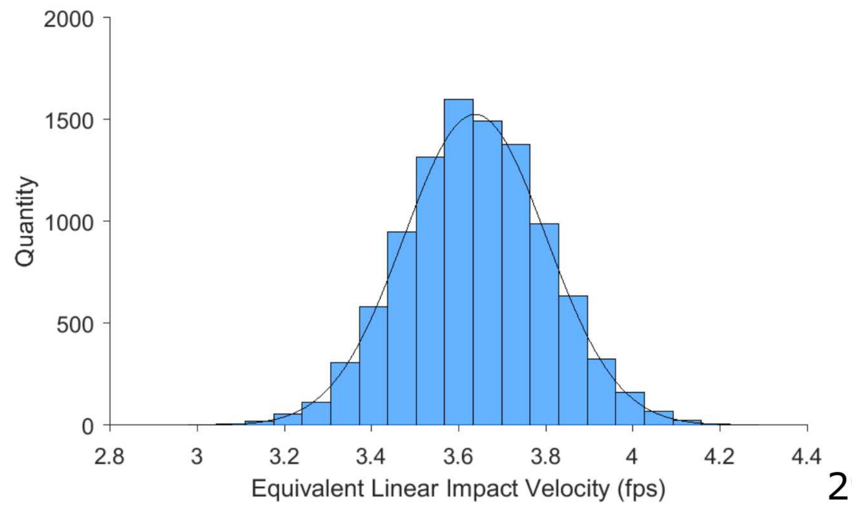
Trip and Fall Hazard

Output for a Single Scenario

- Load weighs 5 lb
- Target 25 in high
- Thin target component
- Stiff target structure
- 10,000 random men

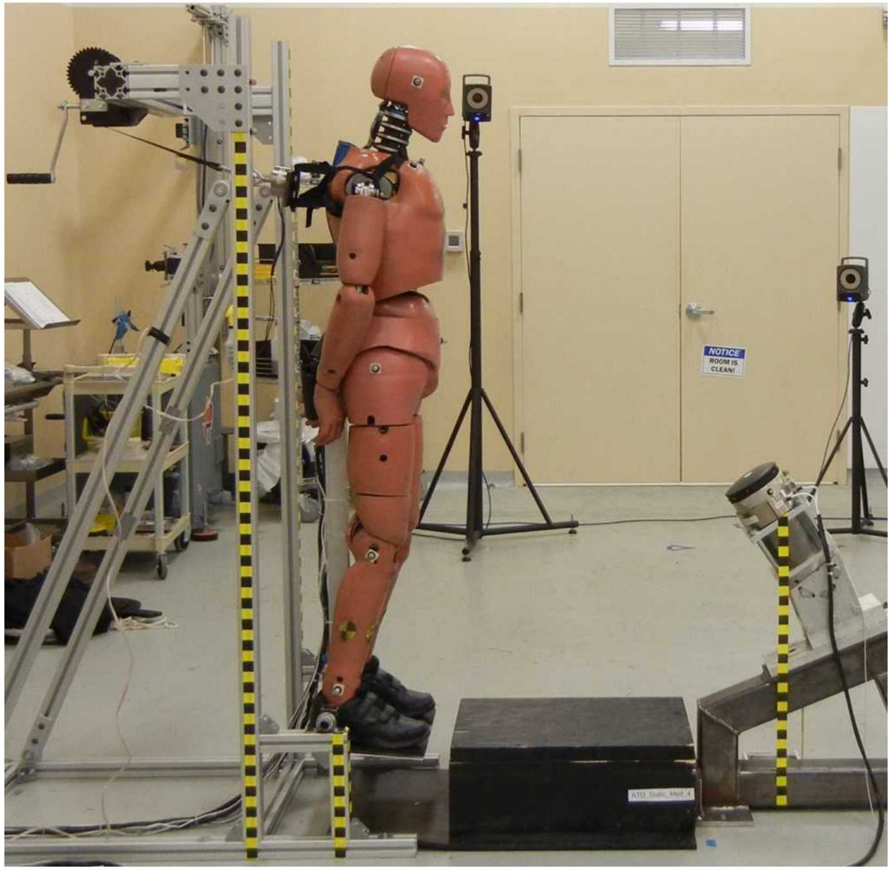




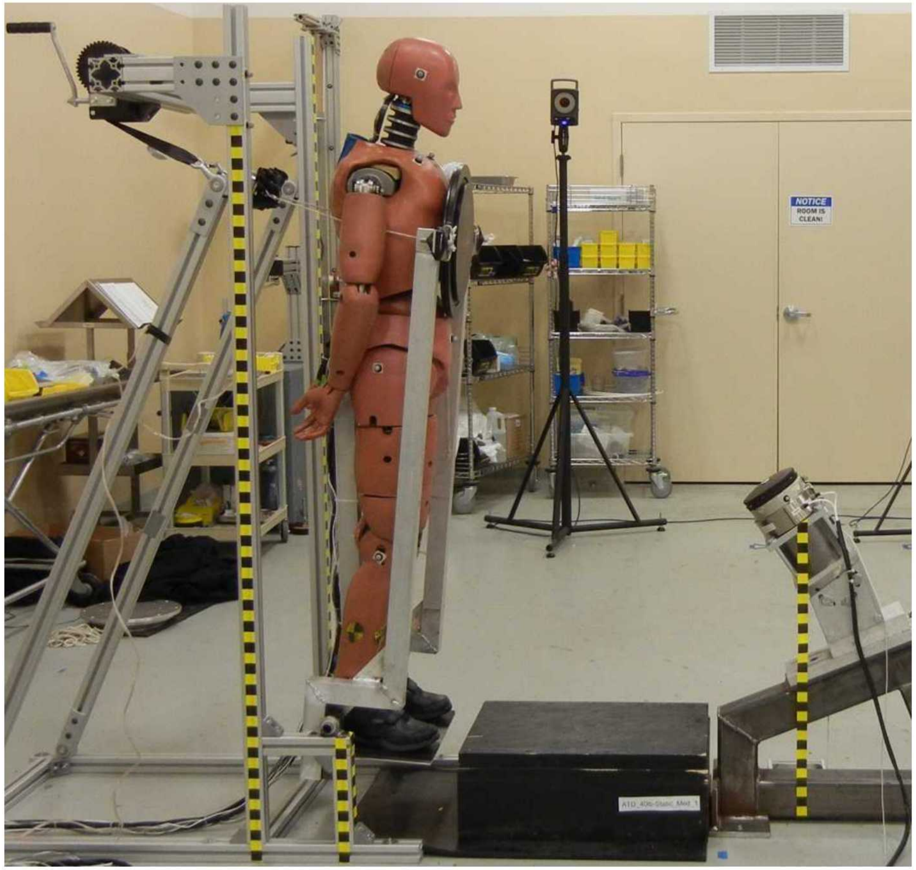


Trip and Fall Hazard

Anthropomorphic Test Device (ATD)



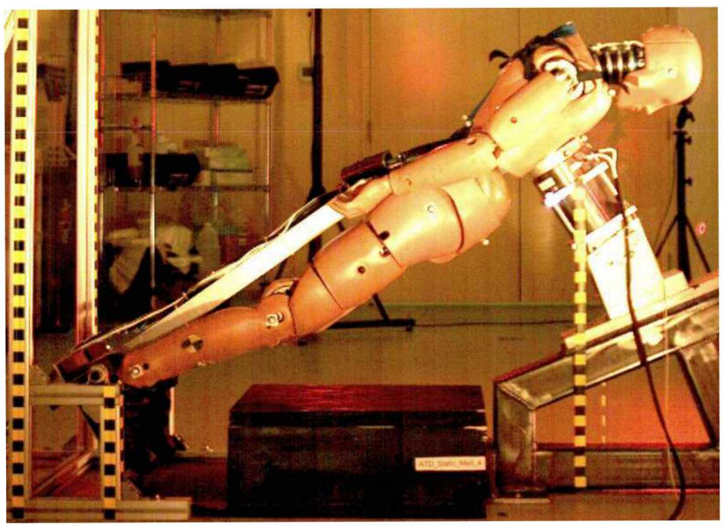
ATD Only



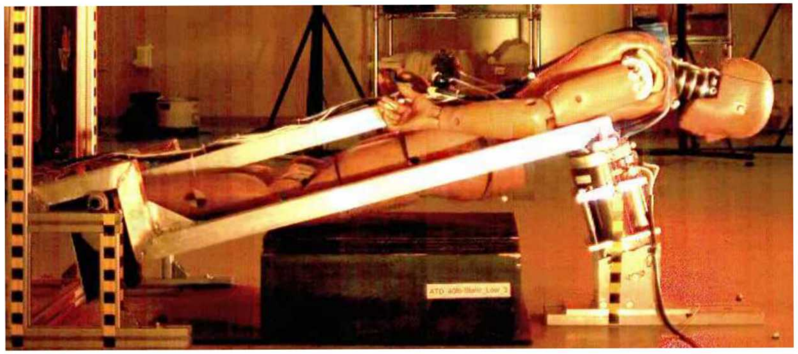
ATD with 40-lb Load

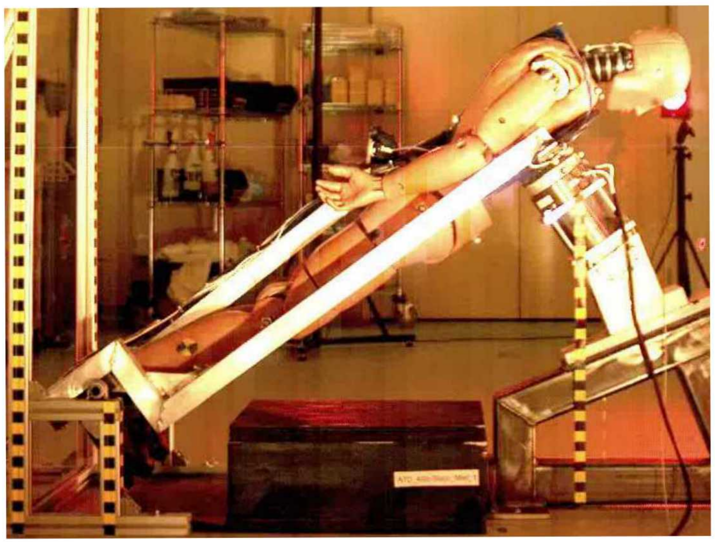
Trip and Fall Hazard

Anthropomorphic Test Device (ATD)



ATD Only



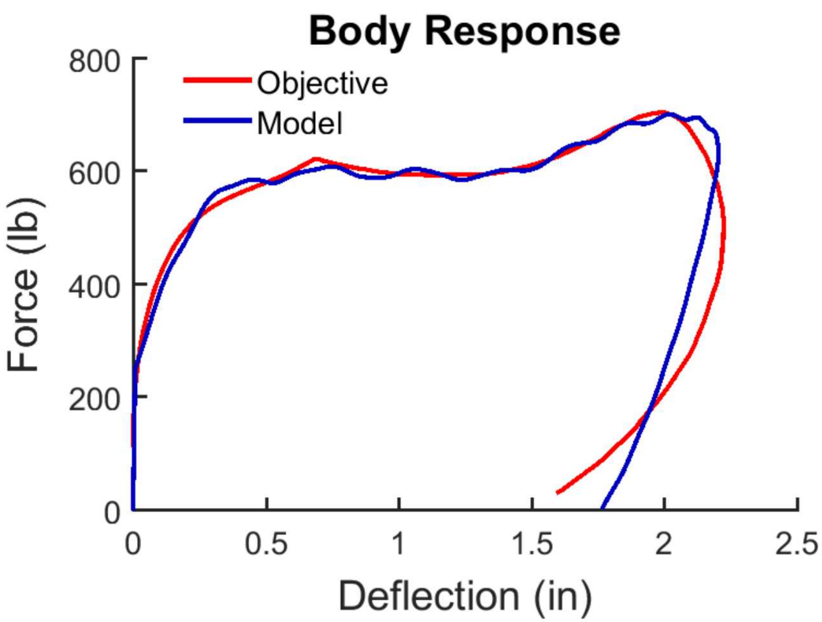


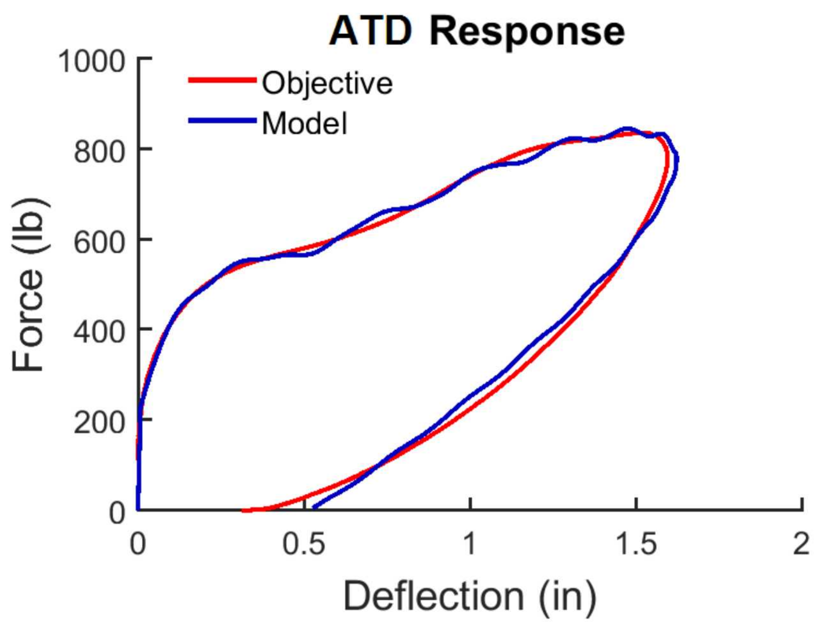
ATD with 40-lb Load

Trip and Fall Hazard

Model Correlation

- Correlated body response to combined response from ATD and cadaver tests
- Optimized properties to ATD response for validation of model





Trip and Fall Hazard

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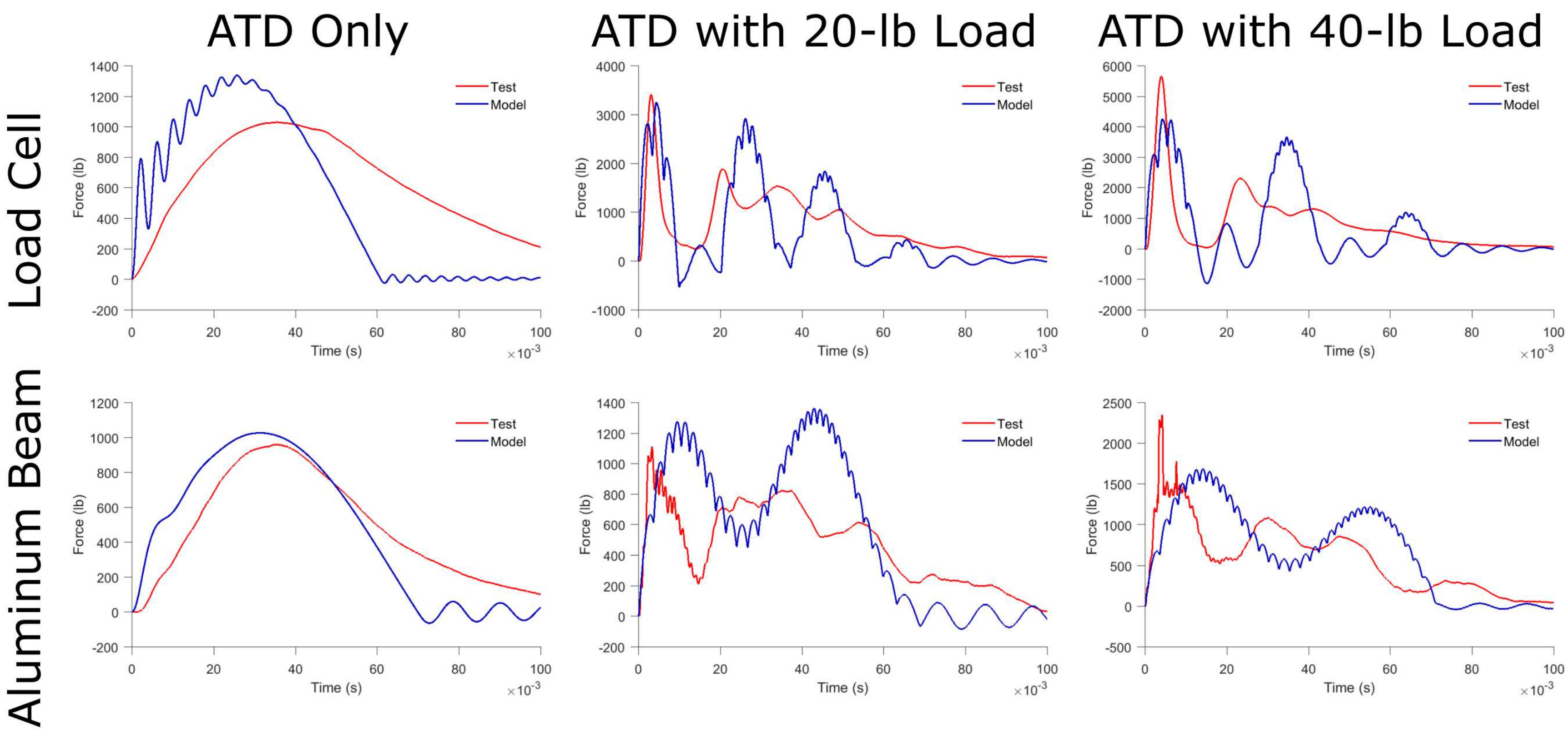
Model Validation



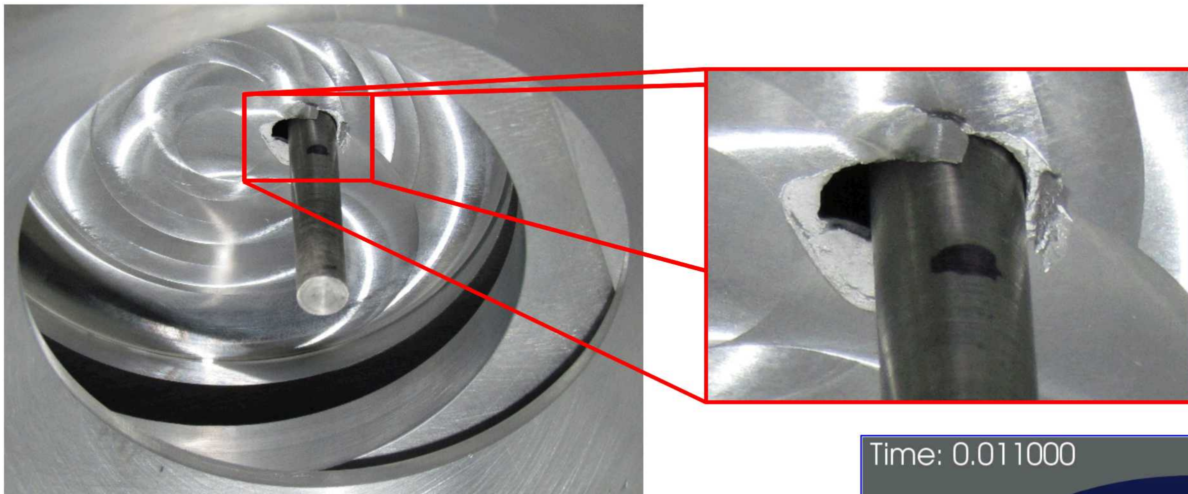
PROBE PUNCTURE SIMULATIONS

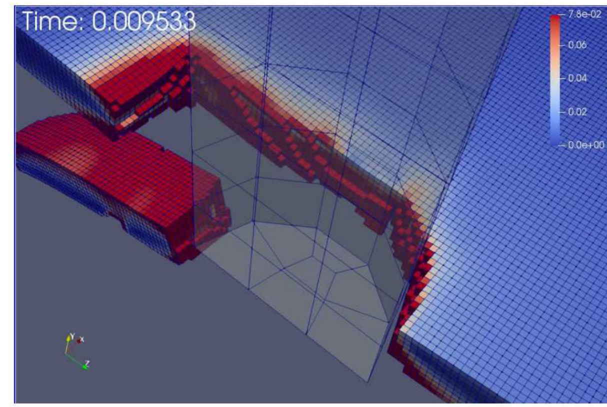
Validation of Constitutive Models and Failure Criteria

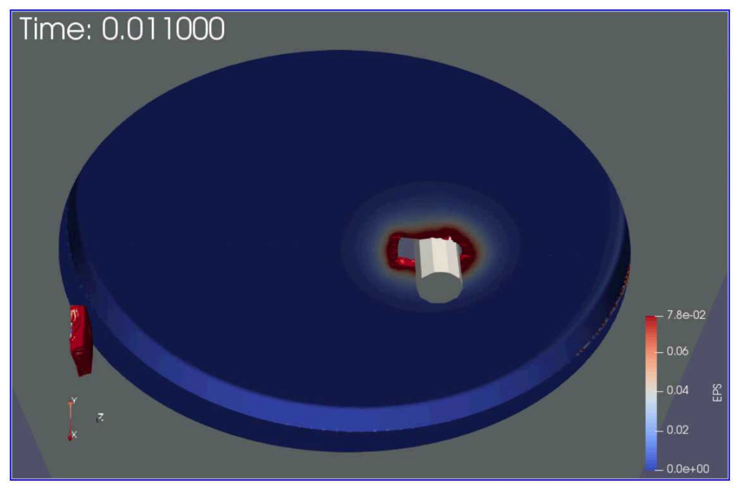
Probe Puncture Simulations

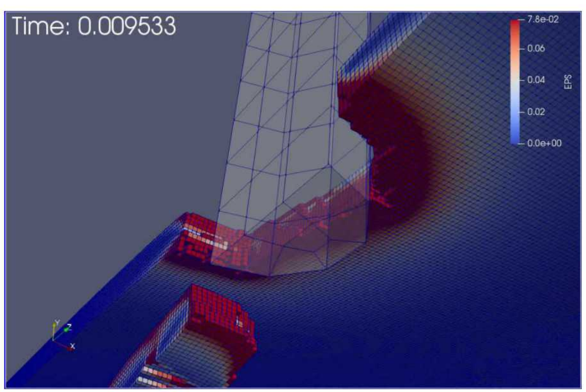
Small Probe with Flat End

Johnson-Cook Model with Strain Energy Density Failure Criterion





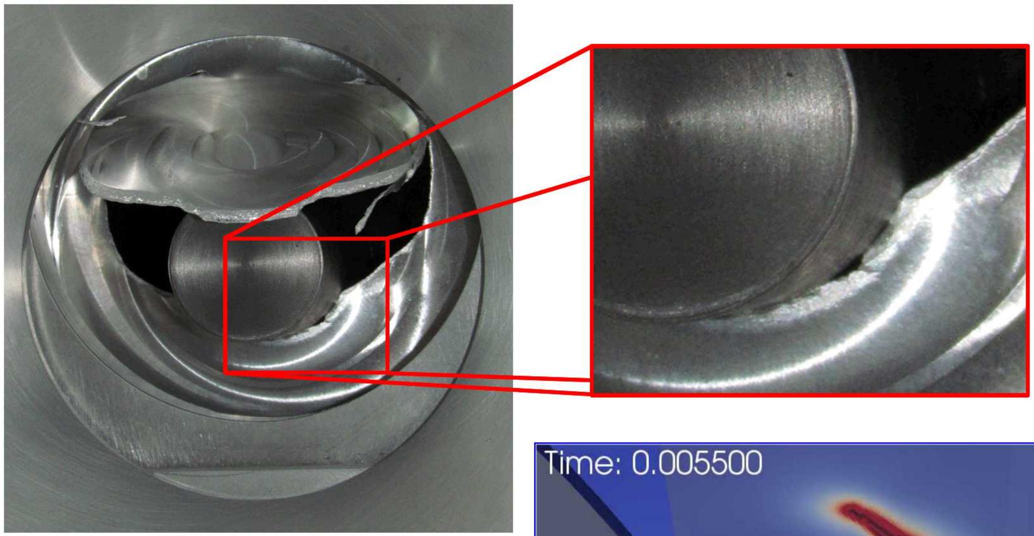


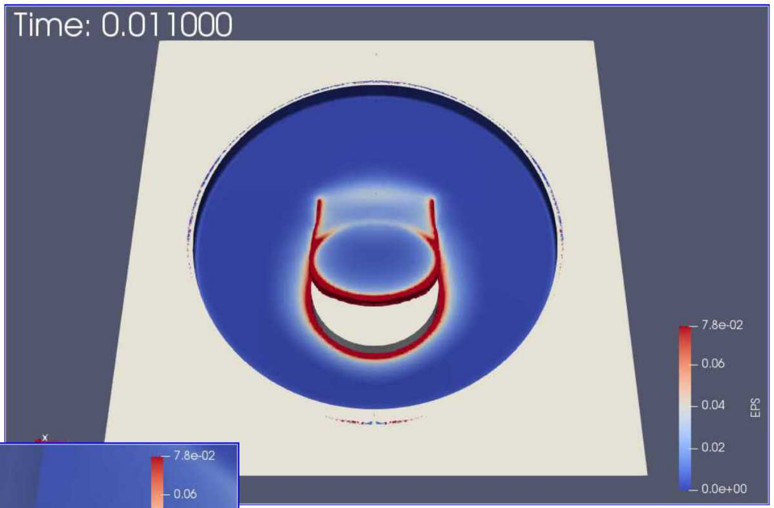


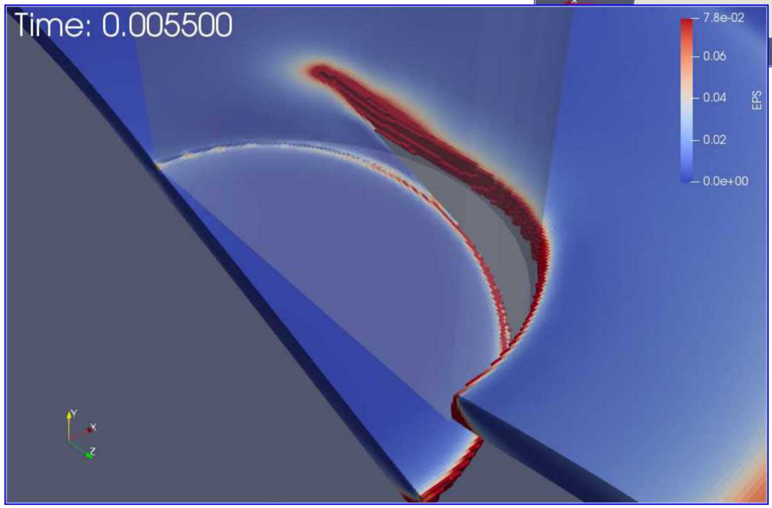
Probe Puncture Simulations

Large Probe with Flat End

Johnson-Cook Model with Strain Energy Density Failure Criterion



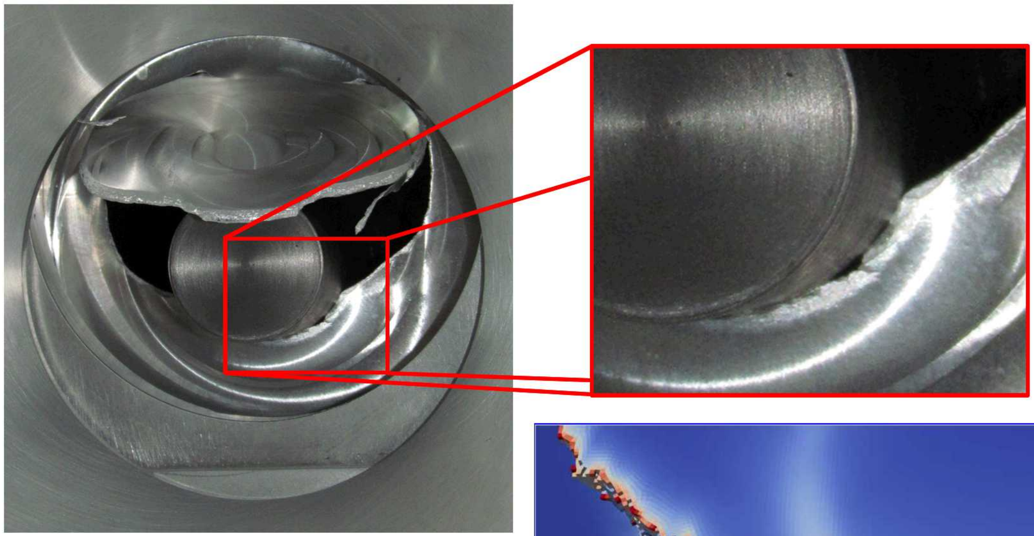


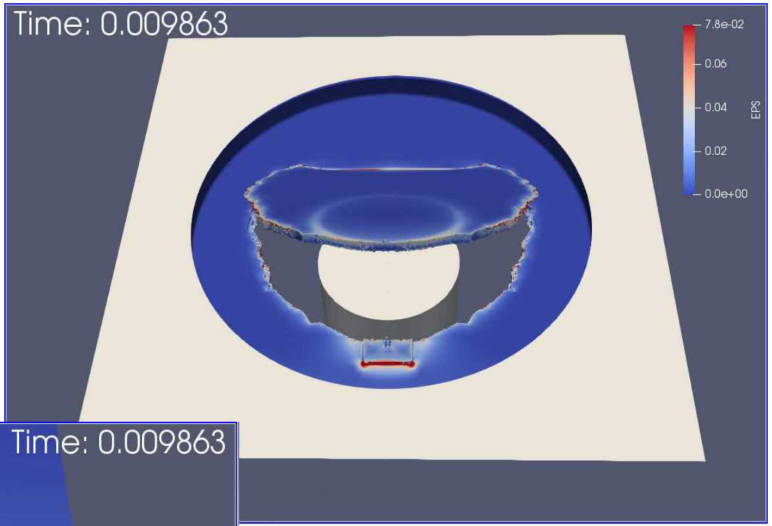


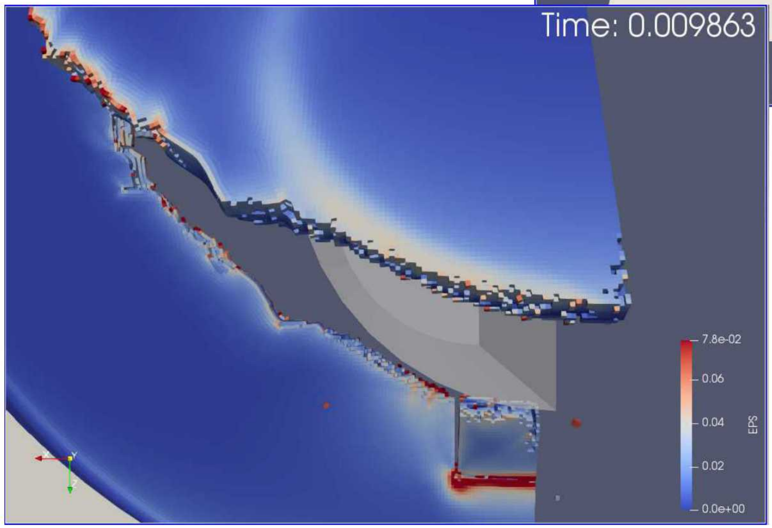
Probe Puncture Simulations

Large Probe with Flat End

Johnson-Cook Model with Wellman Failure Criterion



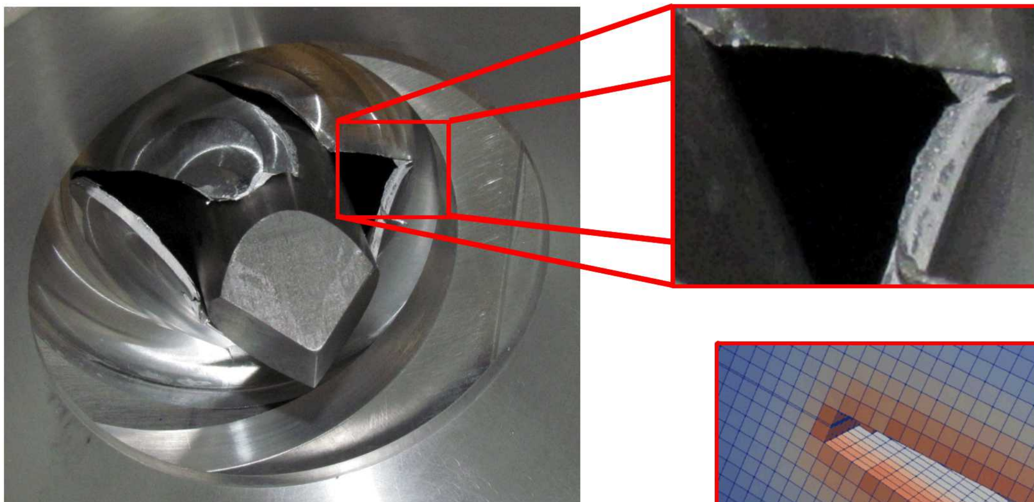


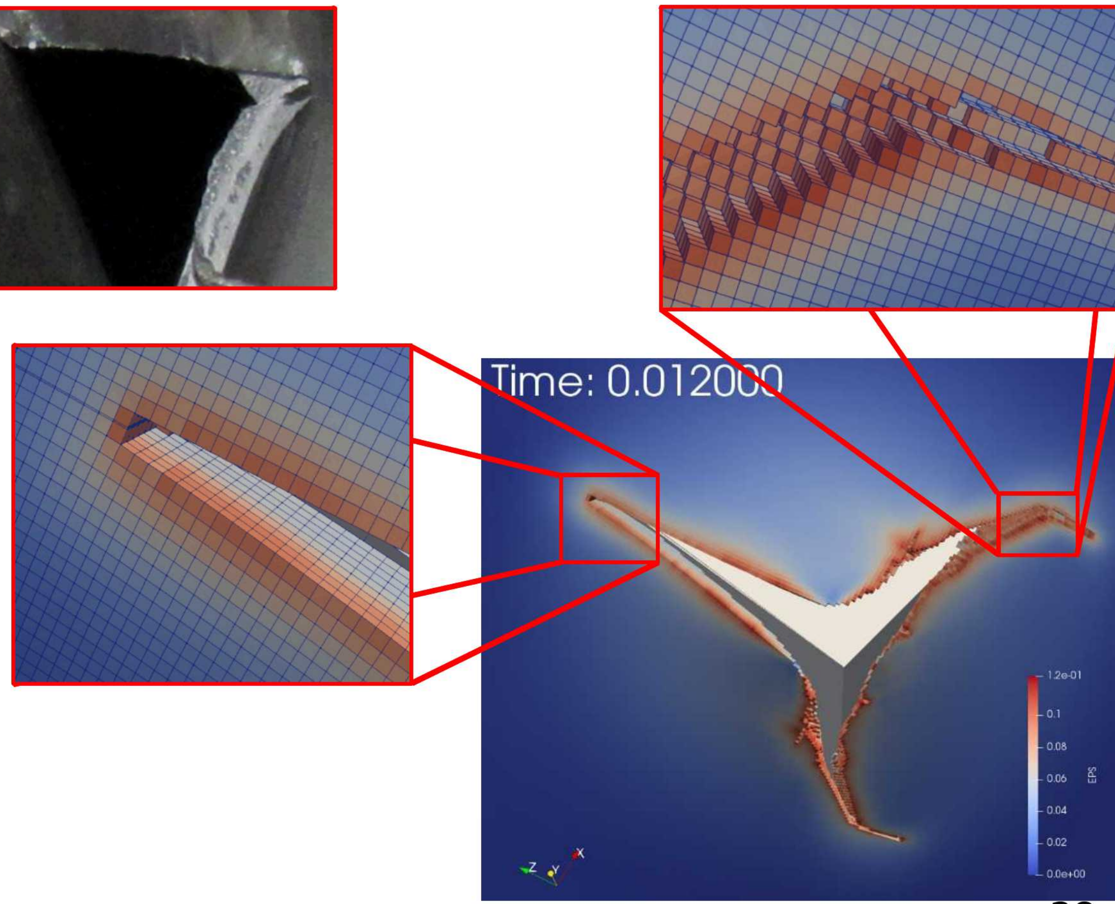


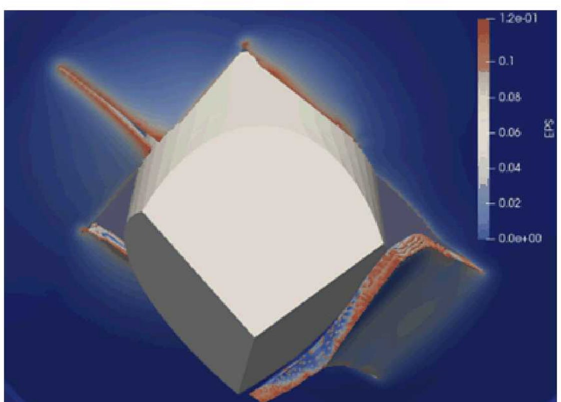
Probe Puncture Simulations

Large Probe with Sharp Corner

Johnson-Cook Model with Critical Stress Failure Criterion

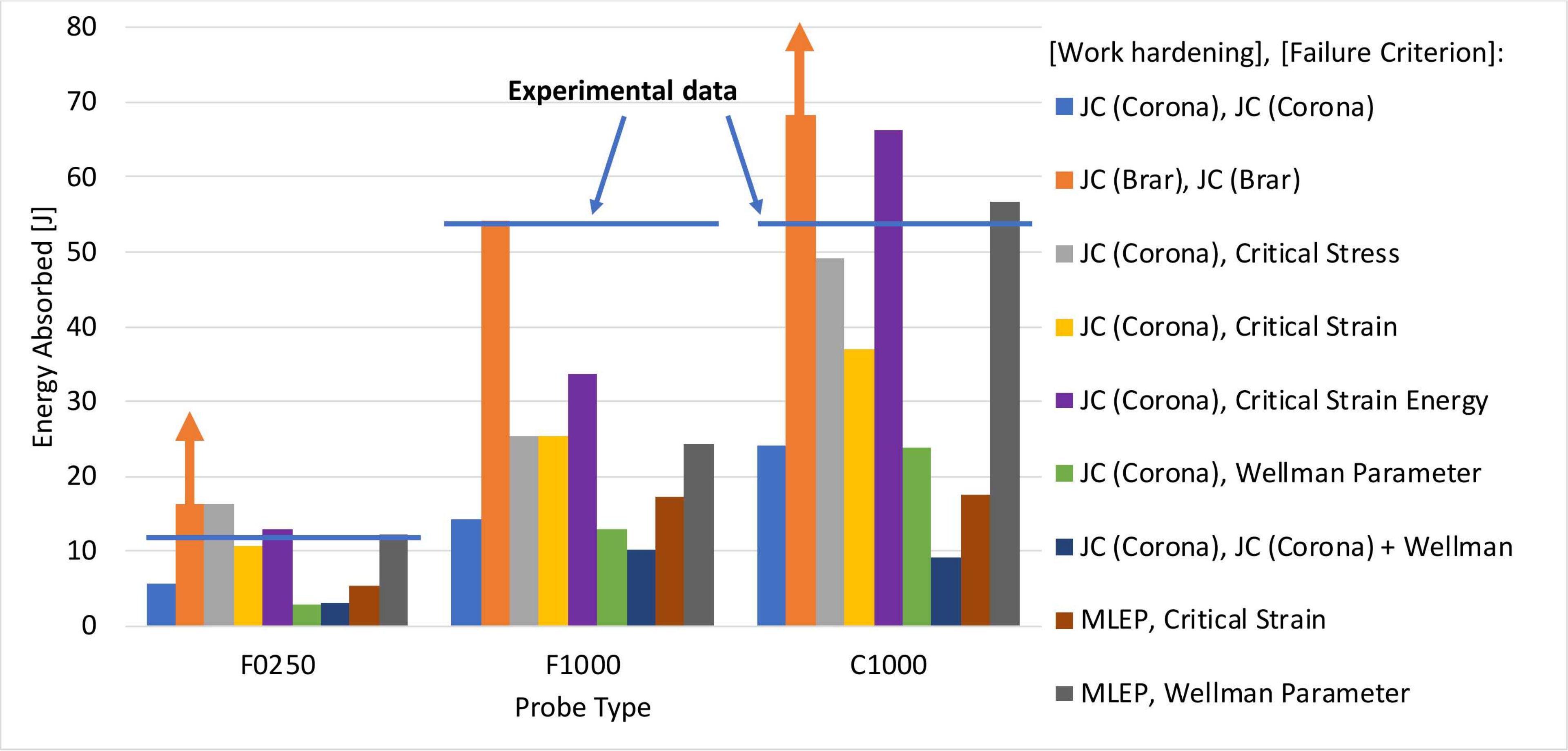






Probe Puncture Simulations

Results



PROPERTIES OF SYNTACTIC FOAM

Testing and Model Correlation

Properties of Syntactic Foam

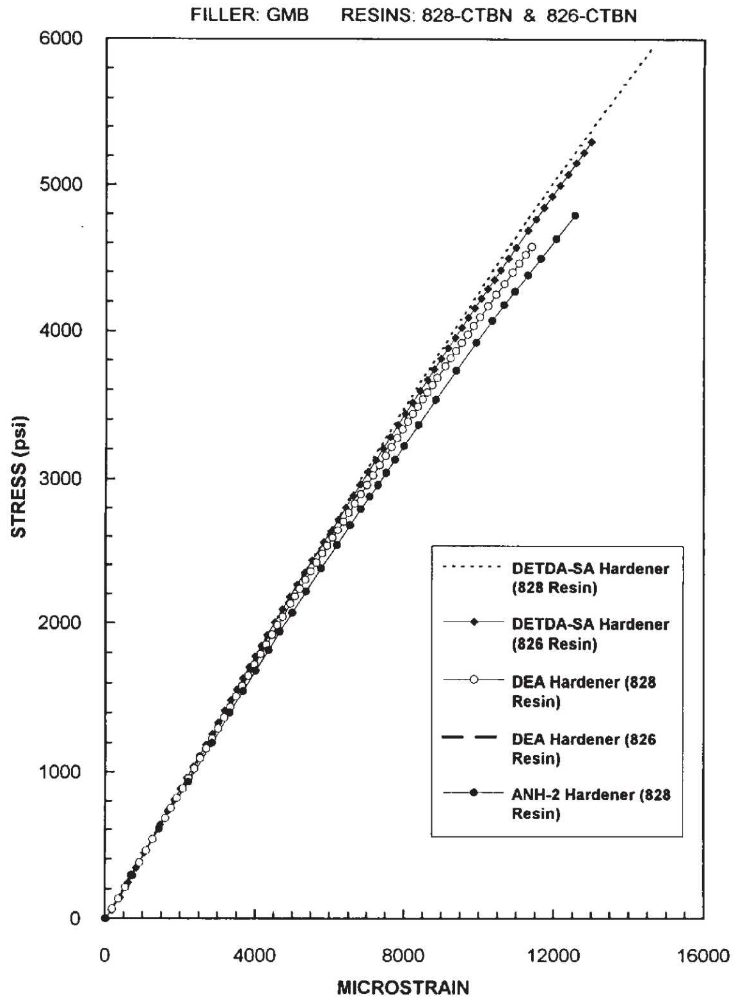
Simulation of Cylinder in Tension

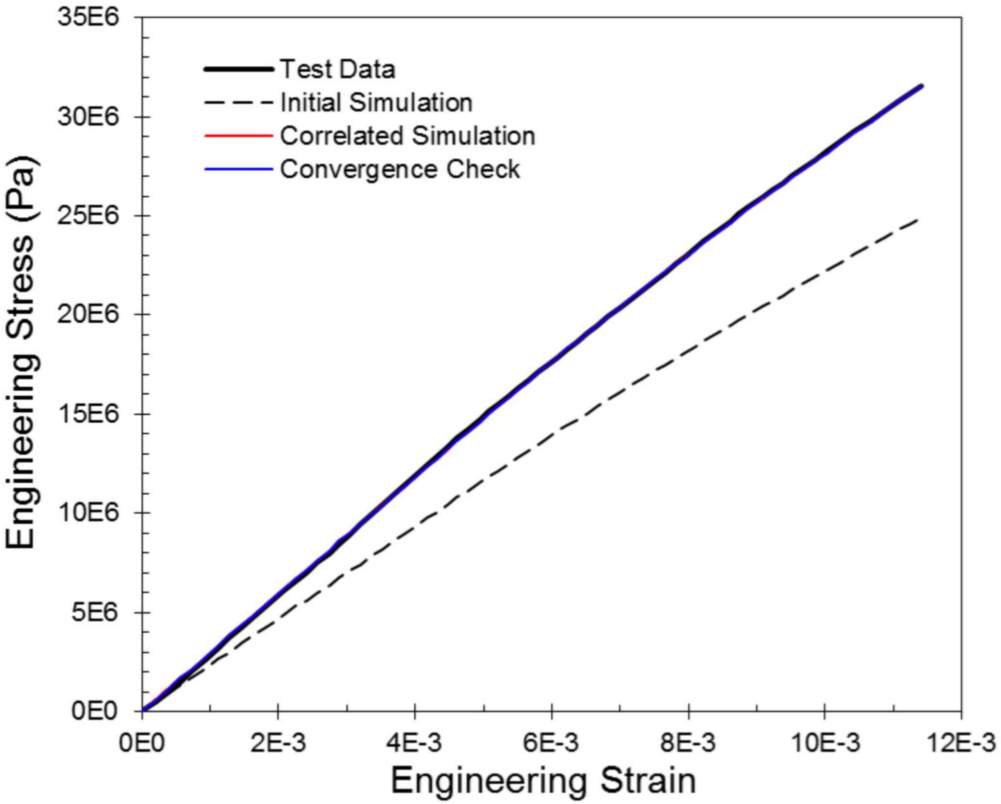
Coarse Mesh

Fine Mesh

Properties of Syntactic Foam

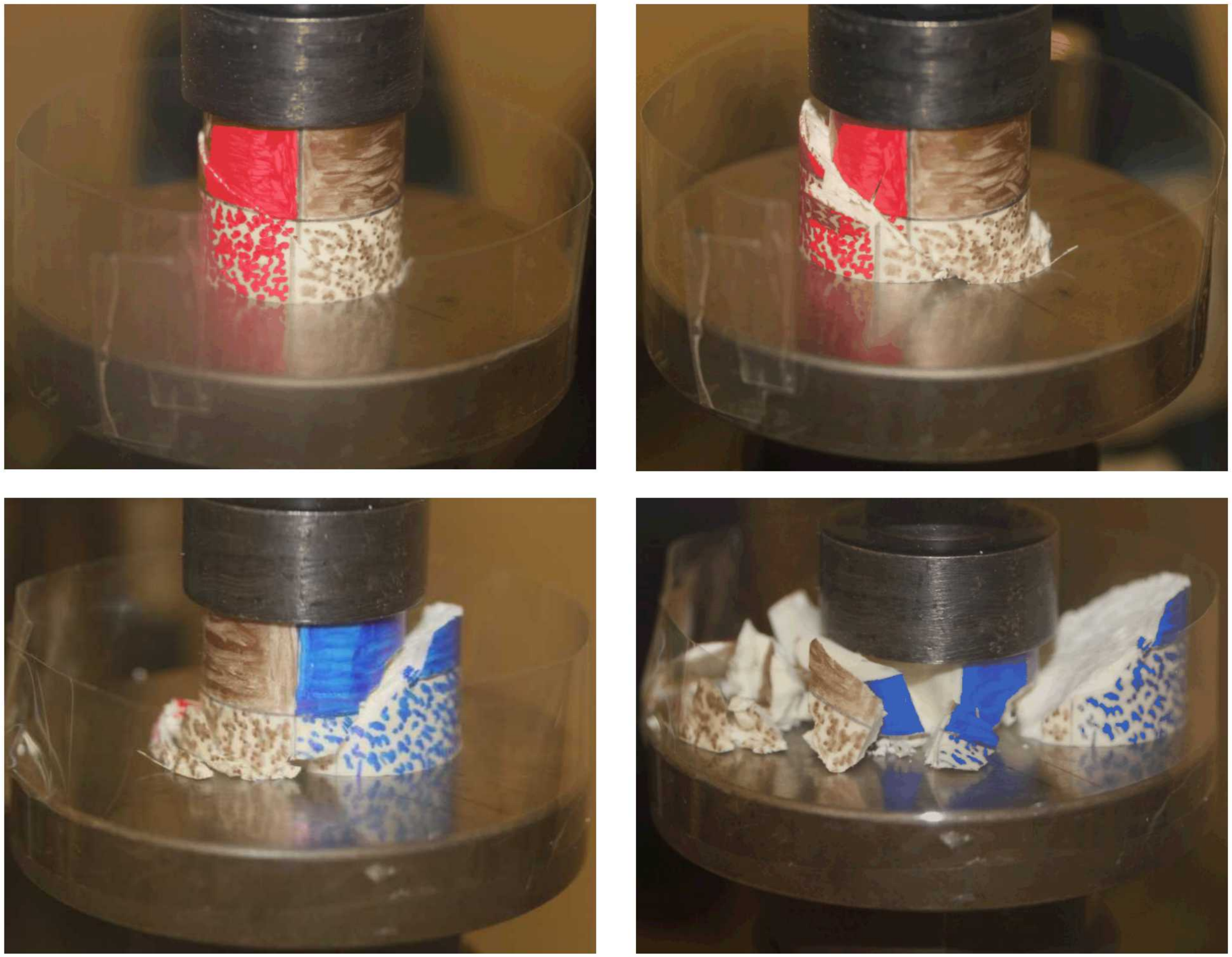
Correlation to Published Test Results





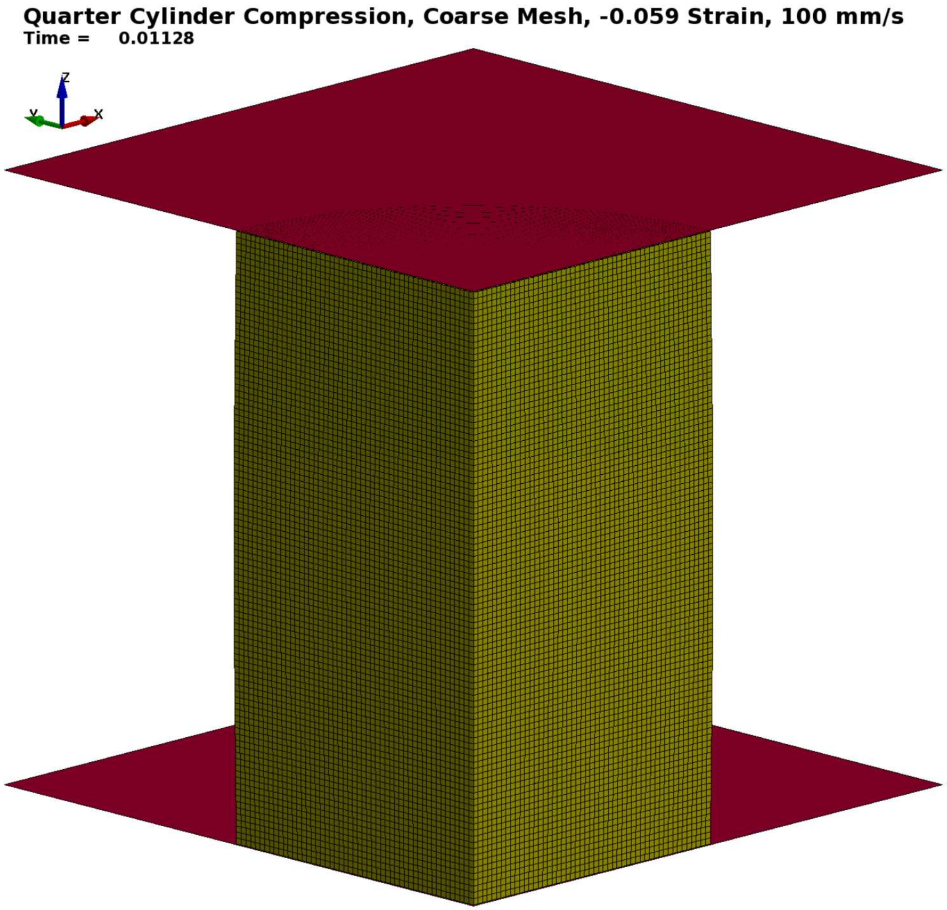
Properties of Syntactic Foam

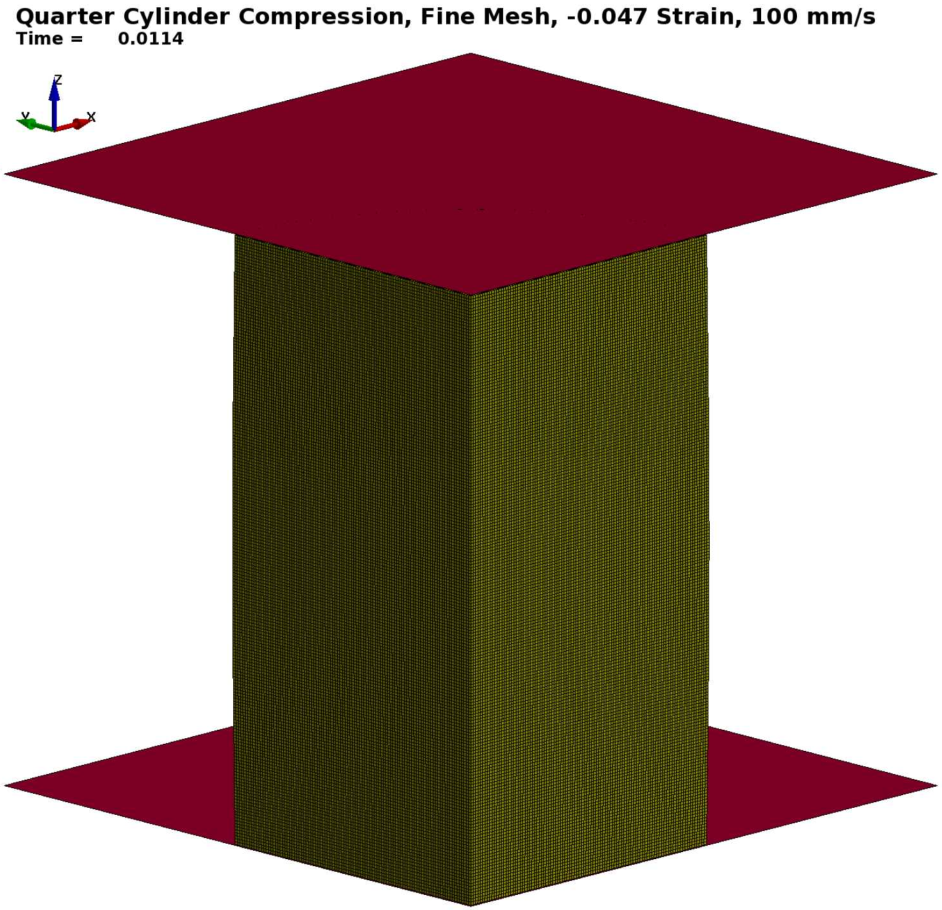
Tests of Cylinders in Compression



Properties of Syntactic Foam

Simulation of Cylinder in Compression



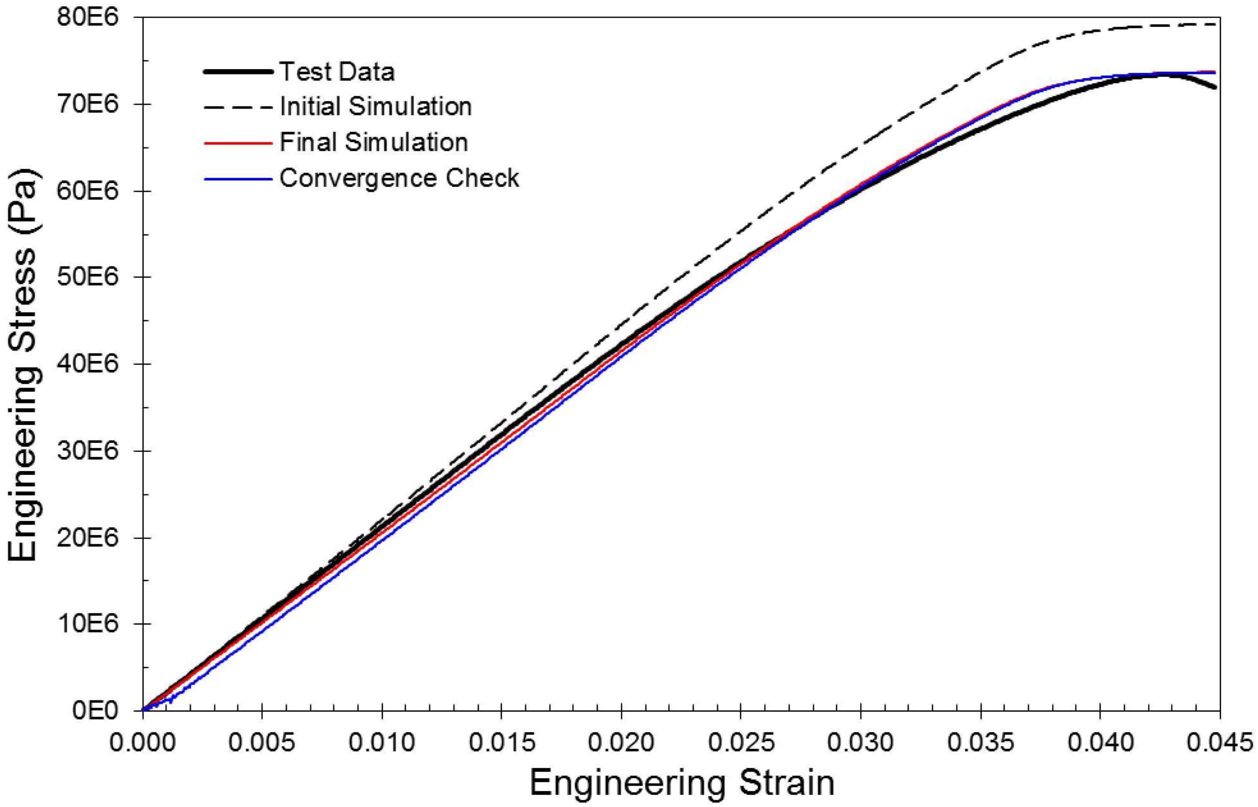


Coarse Mesh

Fine Mesh

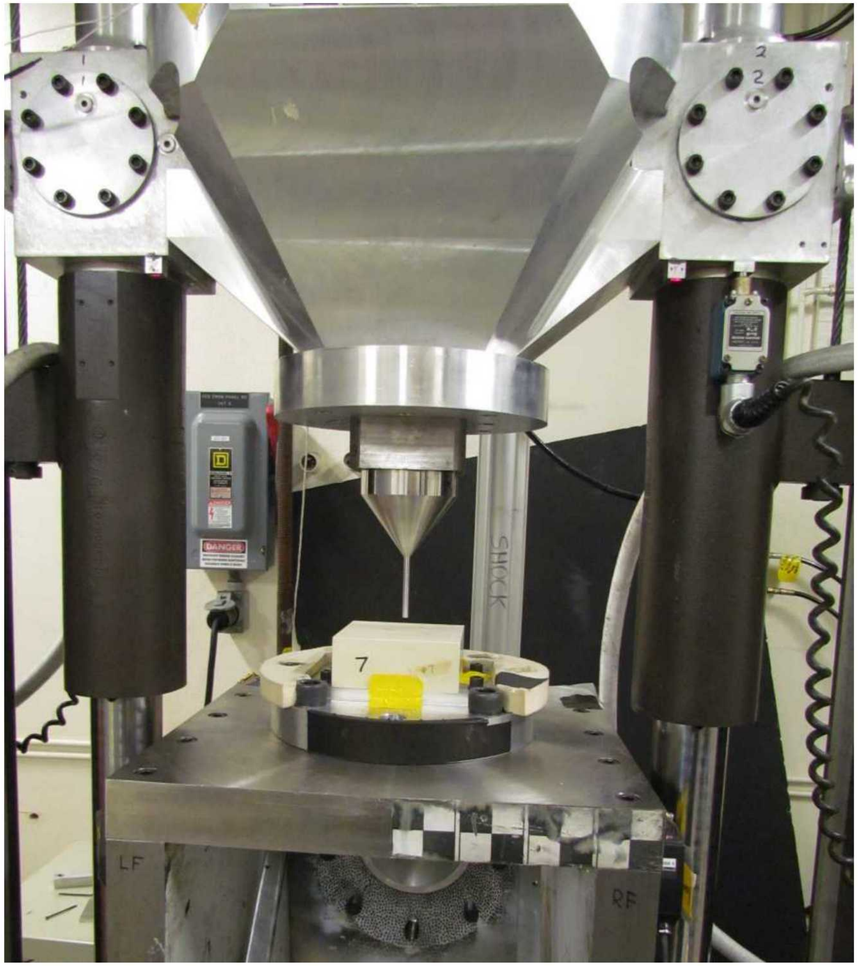
Properties of Syntactic Foam

Correlation to Test Results



Properties of Syntactic Foam

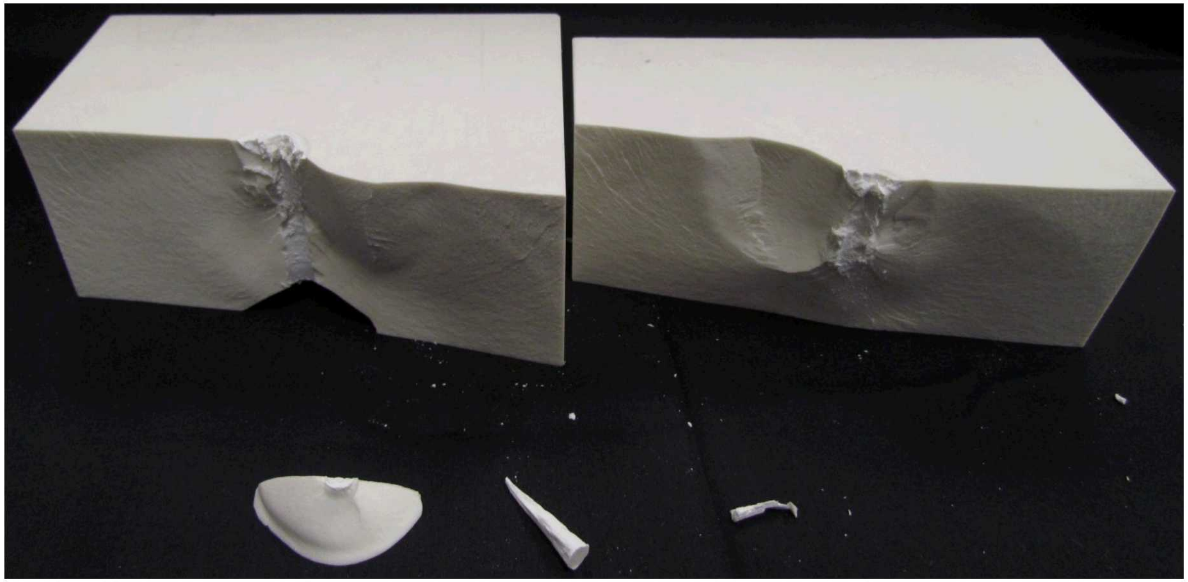
Test of Probe Penetrating Block



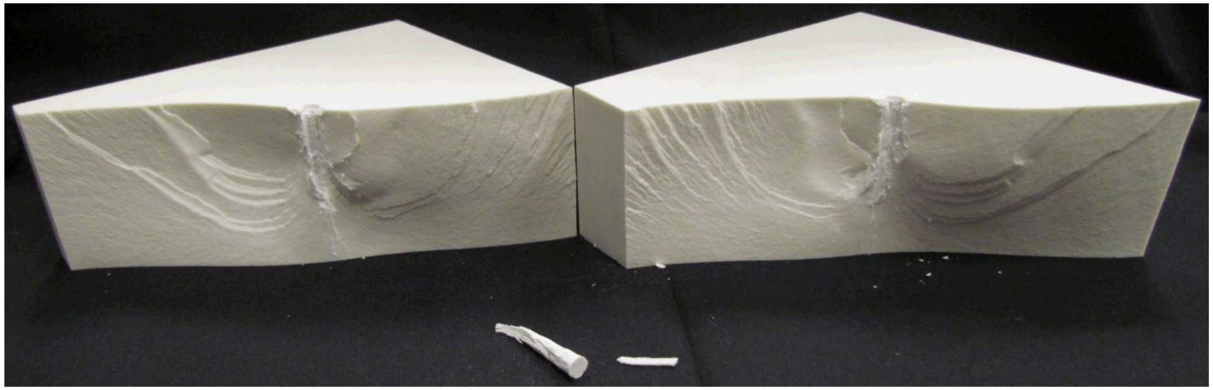
Properties of Syntactic Foam

Fractured Blocks

Sample 3



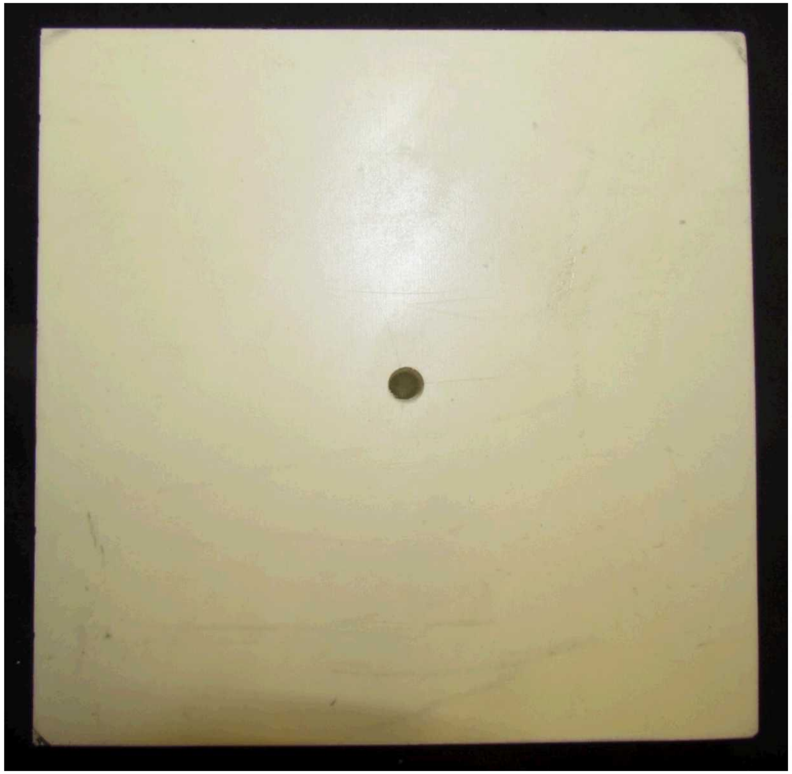
Sample 4



Properties of Syntactic Foam

Intact Blocks

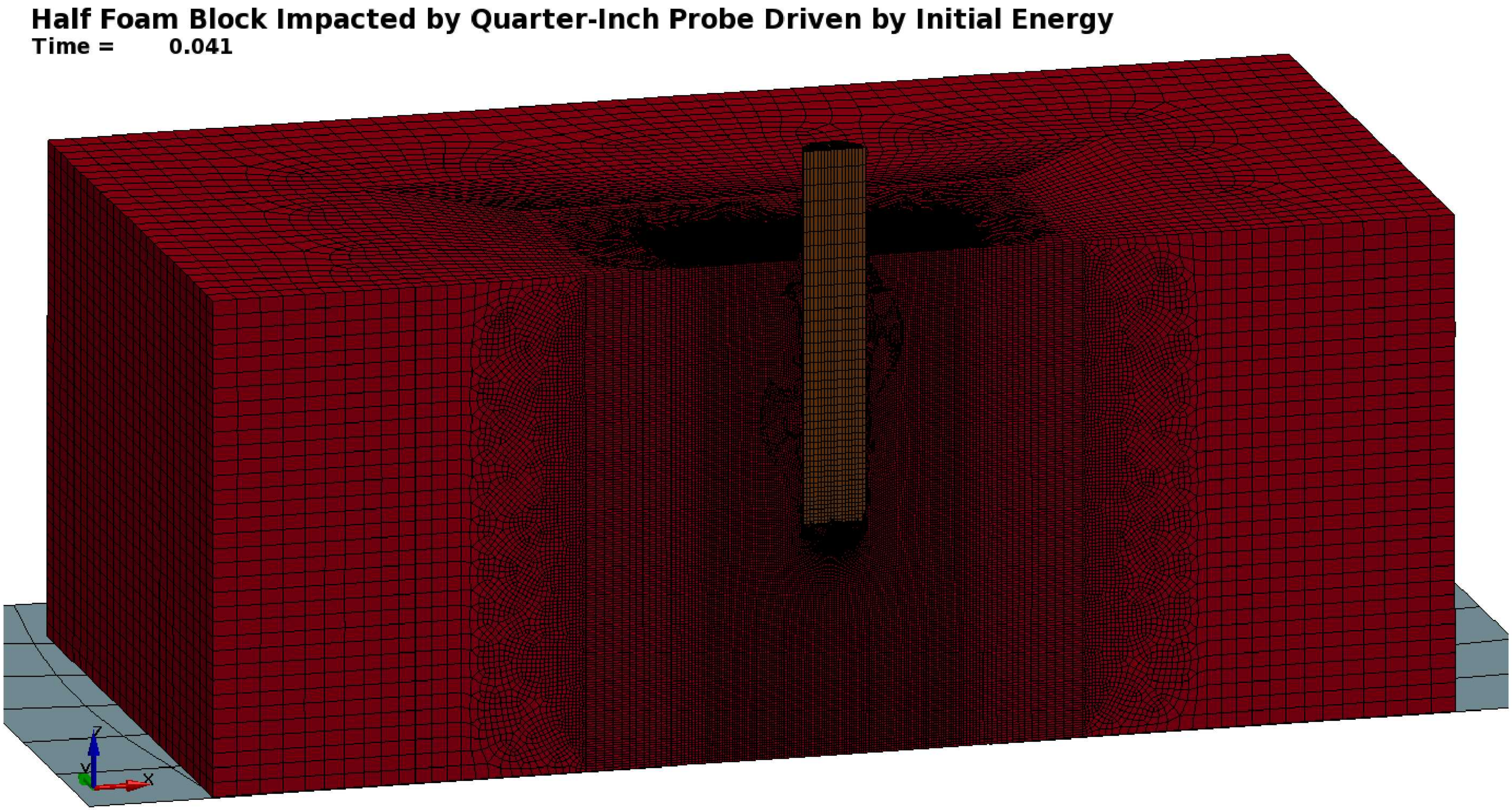
Sample 1



Sample 6

Properties of Syntactic Foam

Simulation of Probe Penetrating Block



Properties of Syntactic Foam

Test Results

Result	Condition	Value
Mean Penetration Depth	Fractured	27.1 mm
	Intact	20.9 mm
Energy at Mean Depth	Fractured	140 J
	Intact	143 J

Simulation Results

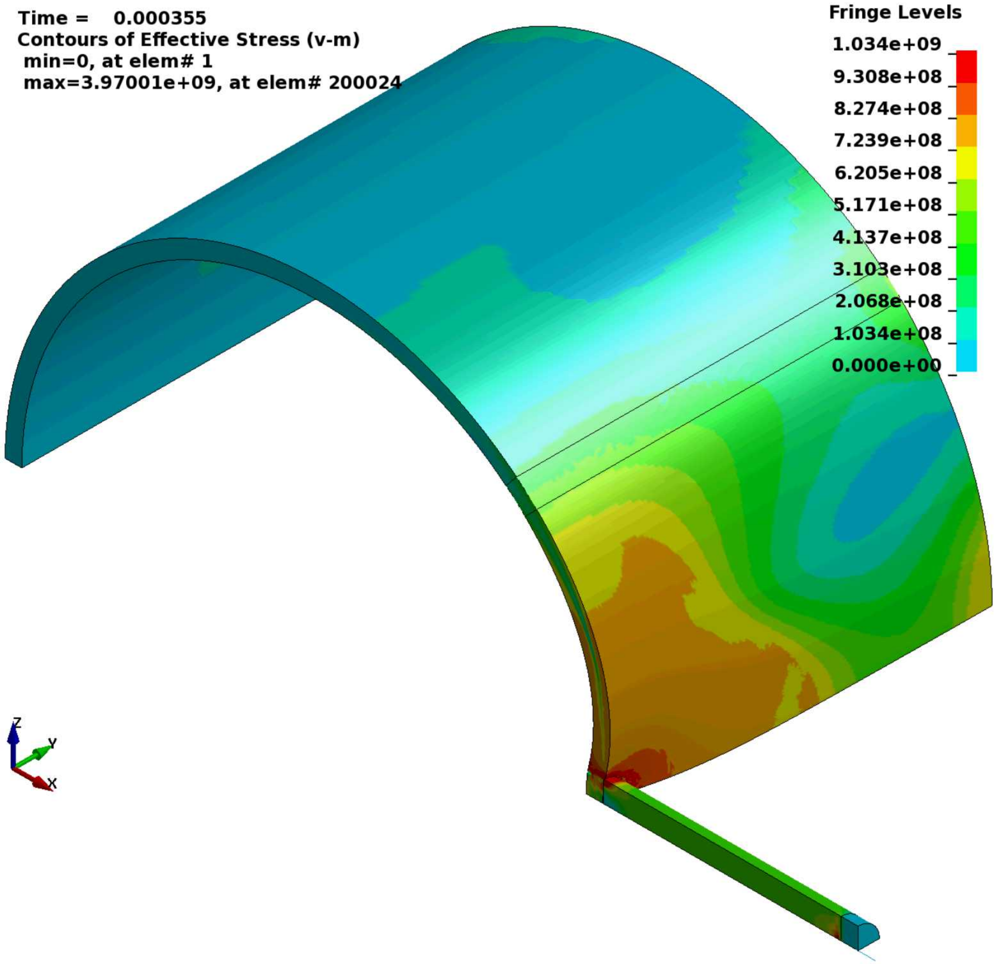
Result	Value	Fraction of Test Result
Time	40.9 ms	
Displacement	27.3 mm	131%
Initial Kinetic Energy	124 J	
Potential Energy	25 J	
Energy Absorbed	149 J	104%

MESH CONVERGENCE

Determine Mesh Size Prior to Meshing Complex Geometry

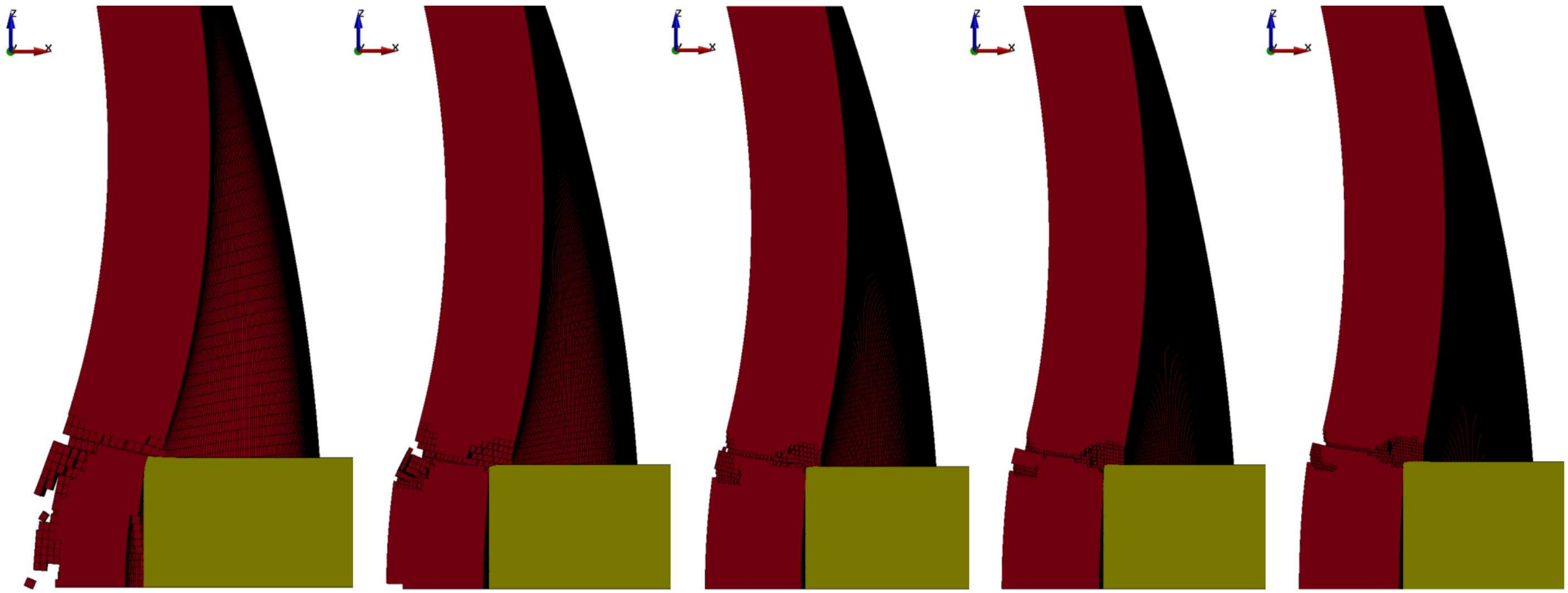
Mesh Convergence

One-Quarter-Inch Flat Probe



Mesh Convergence

One-Quarter-Inch Flat Probe

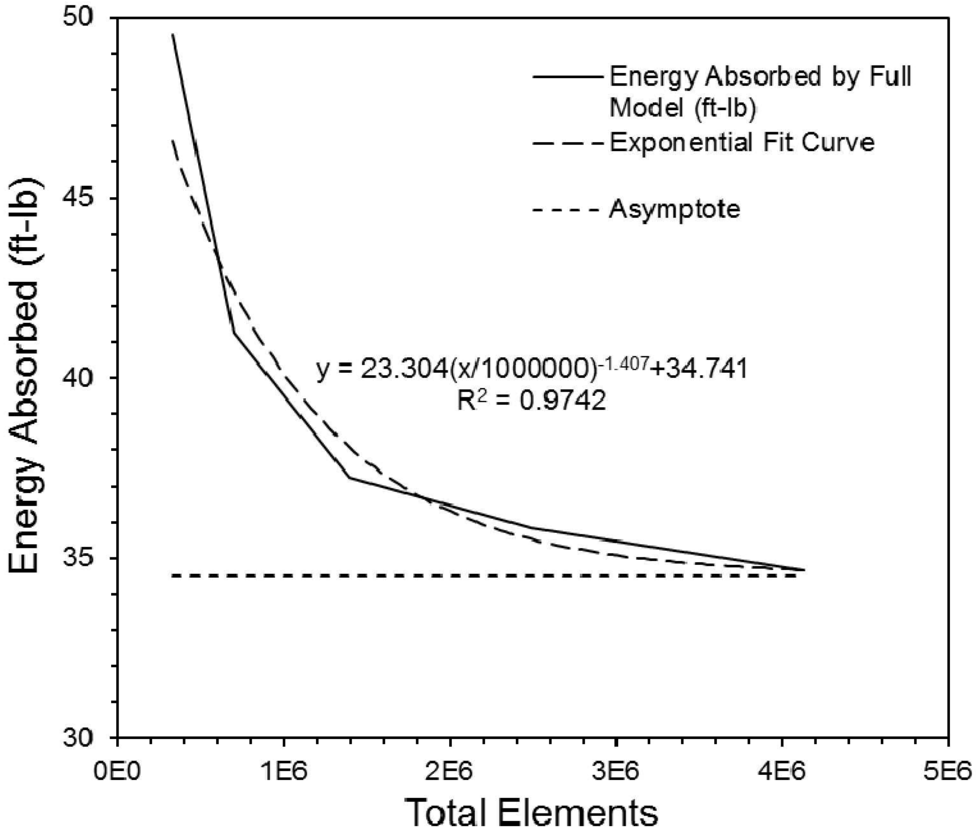


14 21 28 35 42

Number of Elements Through the Thickness

Mesh Convergence

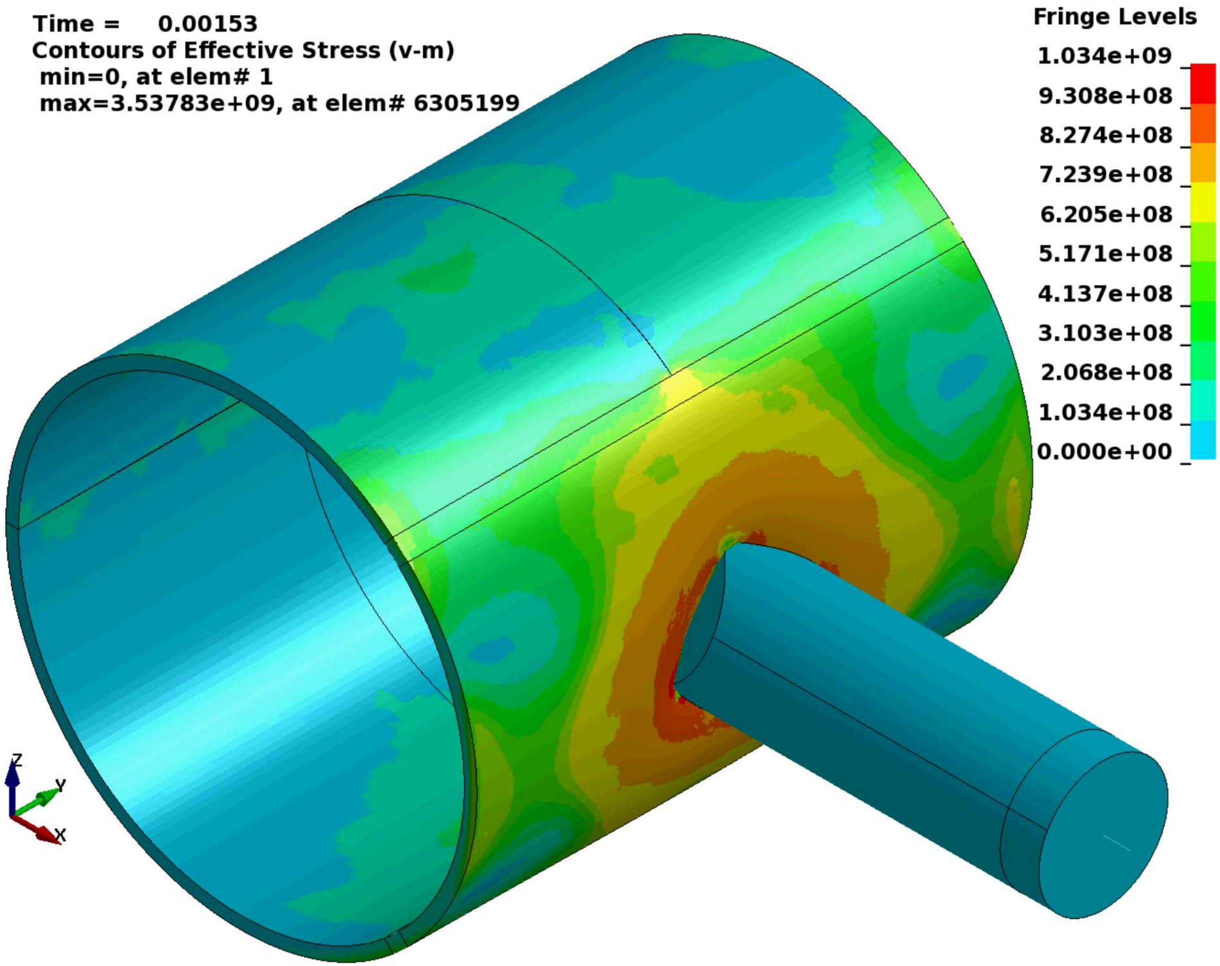
One-Quarter-Inch Flat Probe



Asymptotic Convergence

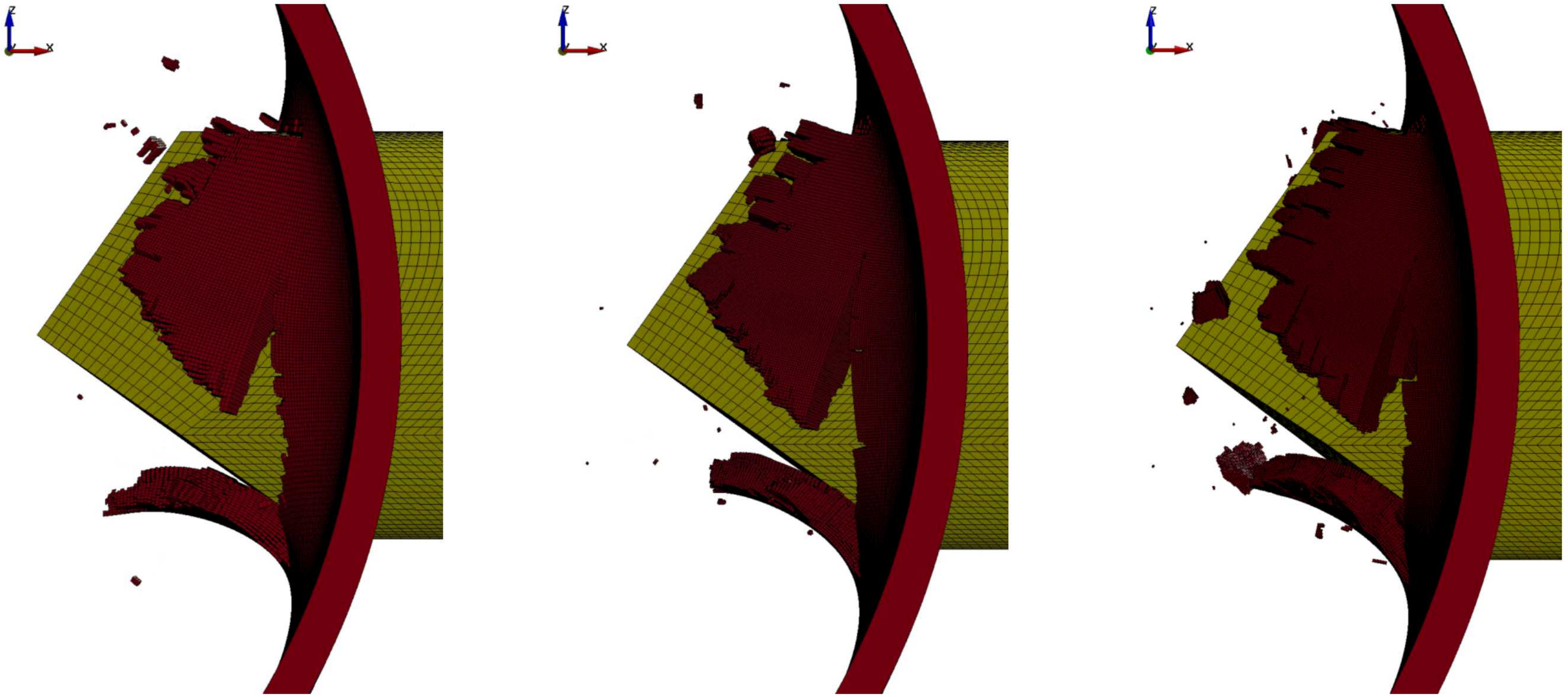
Mesh Convergence

One-Inch Corner Probe



Mesh Convergence

One-Inch Corner Probe

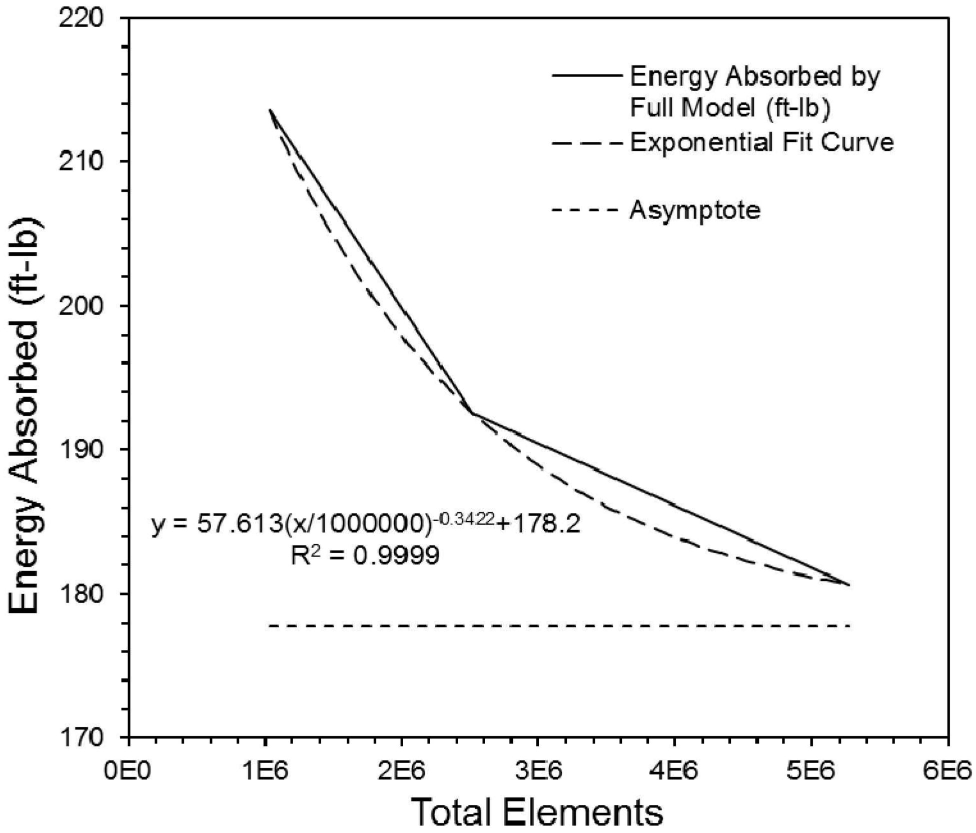


14 21 28

Number of Elements Through the Thickness

Mesh Convergence

One-Inch Corner Probe



Asymptotic Convergence

Safety Theme

Design Safe Processes for the Production of High-Consequence Systems

- Mitigate energy from mechanical impact hazards
- Exclude electrical energy by maintaining a Faraday cage
  - Design exclusion region barriers with ductile metals
  - Design strong, resilient joints
- Quantify hazards due to technicians falling
- Strengthen technical basis by improving accuracy of simulations
  - Test material properties
  - Correlate constitutive models and failure criteria
  - Verify convergence of finite element meshes

Conclusion

Safe Process for High-Consequence Systems

- Perform tests to establish first principles of physics
- Build conservative models to simulate reality
- Test simplified components if actual components are not available
- Validate models against test data
- Design components and tools for safety
- Limit sources of energy to prevent severe consequences

Questions?

What would you like to know about . . .

- Managing a senior design project
- Pursuing a graduate degree
- Interviewing for a job or internship
- Working at Sandia National Laboratories
- Living in Albuquerque, New Mexico