Model Validation of an Engineering Application at Los Alamos

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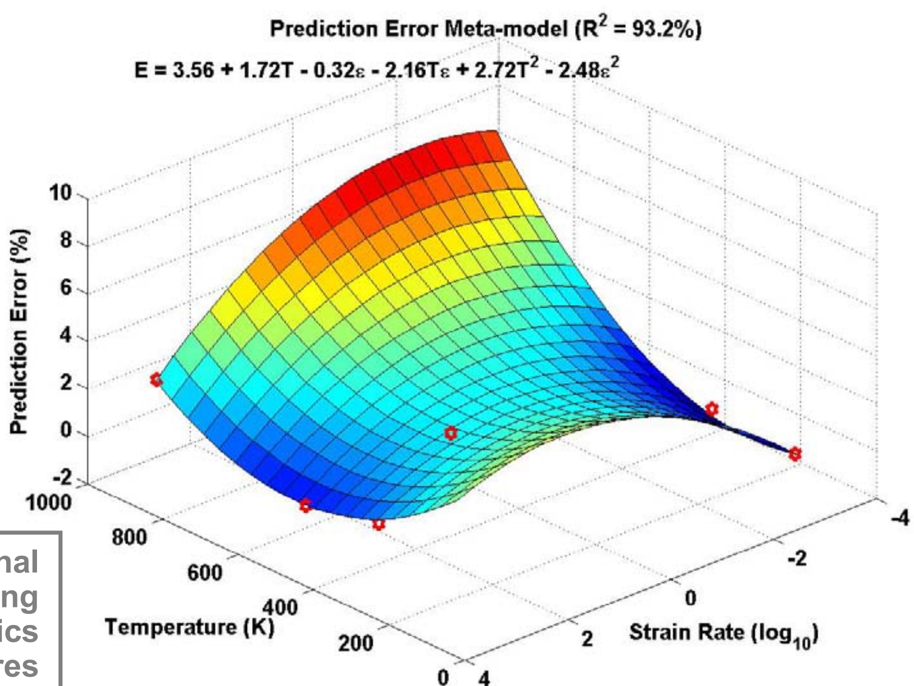
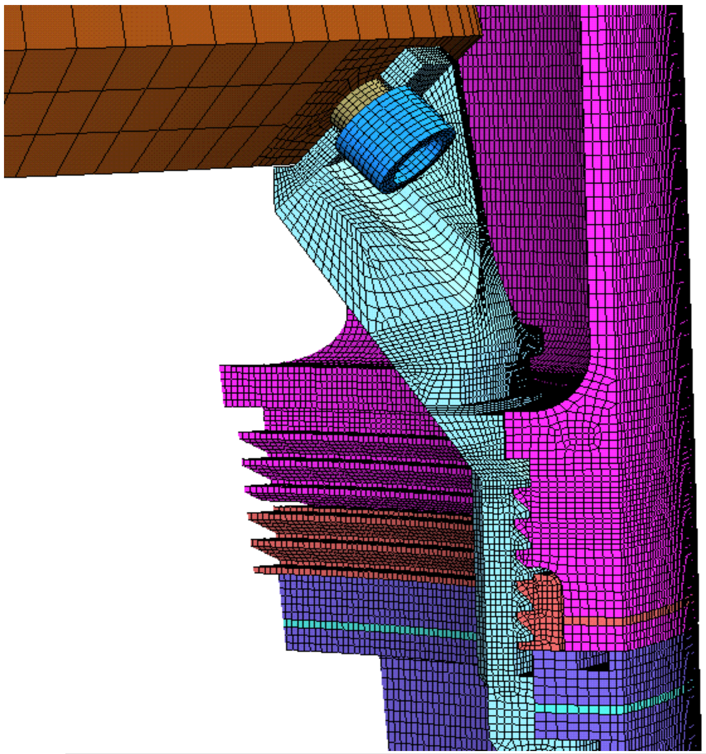
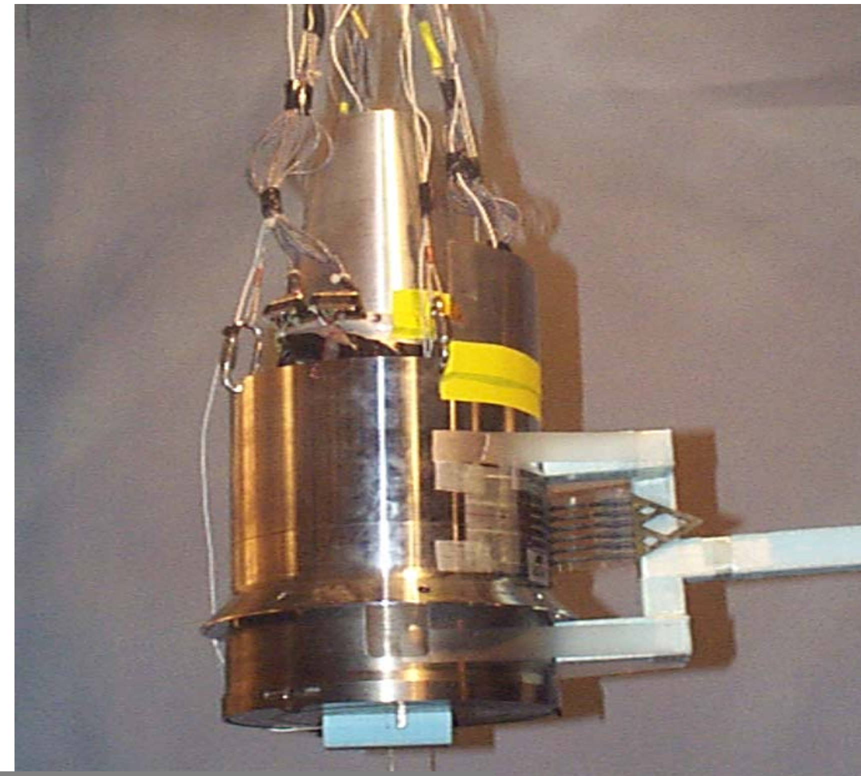
This presentation has been approved for unlimited, public release.
Date: January 4, 2008
Reference: LA-UR-07-8454
Level: Unclassified



An Engineering Application

- This application validates our ability to simulate the propagation of an explosive-driven mechanical shock through a complex threaded joint.(#)



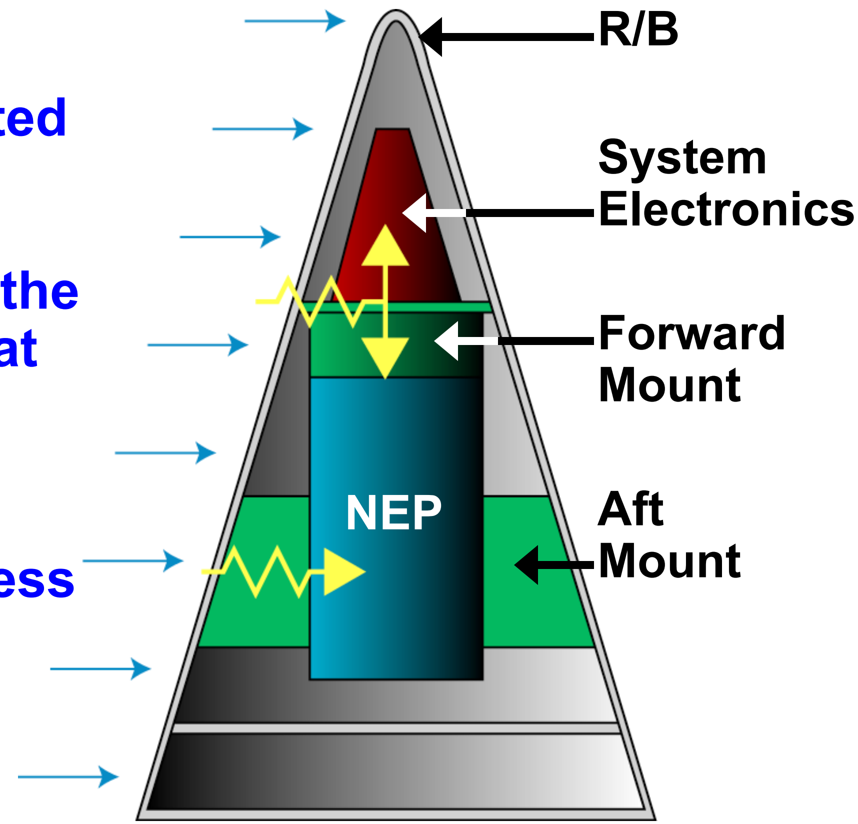


(#) References: Hylok, J.E., et al., "Validation of a Threaded Assembly Joint," *6th European Conference on Structural Dynamics*, Paris, France, September 5-7, 2005, LA-UR-05-6511, LA-UR-05-6735.

Background of this Application

- The background of this application is to demonstrate our ability to numerically simulate an environment to which one of our weapon systems may be subjected.

  - A Re-entry Body (R/B) is subjected to external impulsive loading.
  - The transmission paths include the forward mount and aft mount that connect the payload to the R/B.
  - Accurately predicting the shock transmission is essential to assess the response of the Nuclear Explosive Package (NEP).

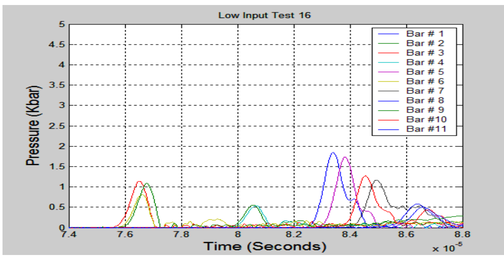


(Reference: LA-UR-09-4774.)

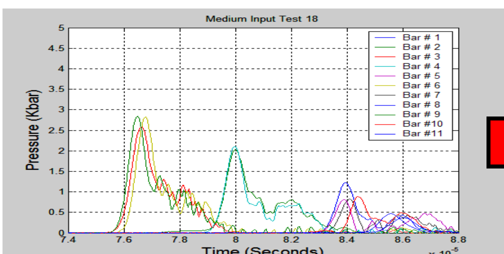
Impulse Testing Set-up

Impulse (Input)

Low Impulse

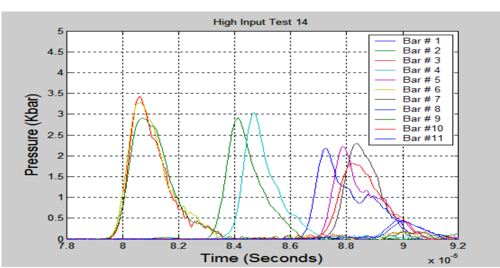


Medium Impulse

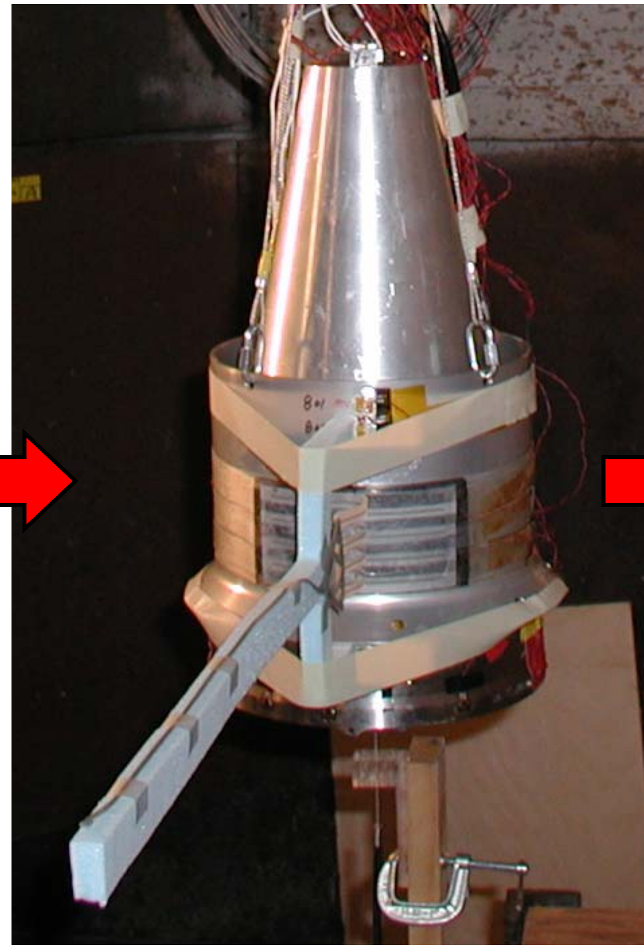


10^{-1} milli-second

High Impulse

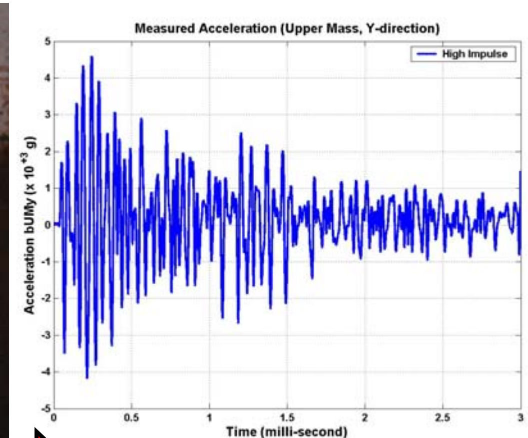


System

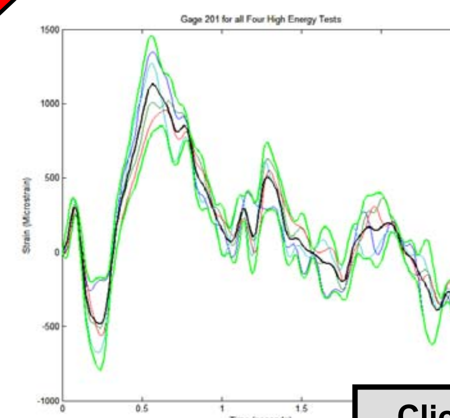


Response (Output)

Acceleration



Strain



Click > Movie

(Reference: LA-UR-05-6735.)

X DIVISION

Los Alamos NATIONAL LABORATORY

V&V Activities Deployed on This Study

Simulation
Testing

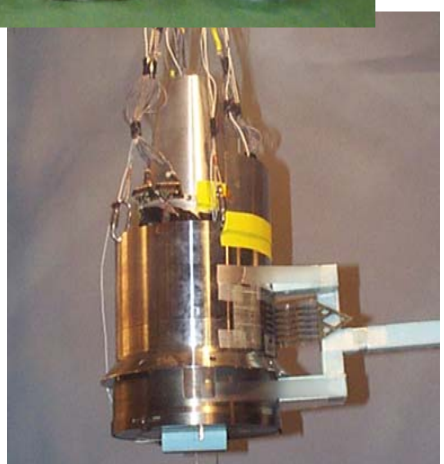
Approximate Timeline

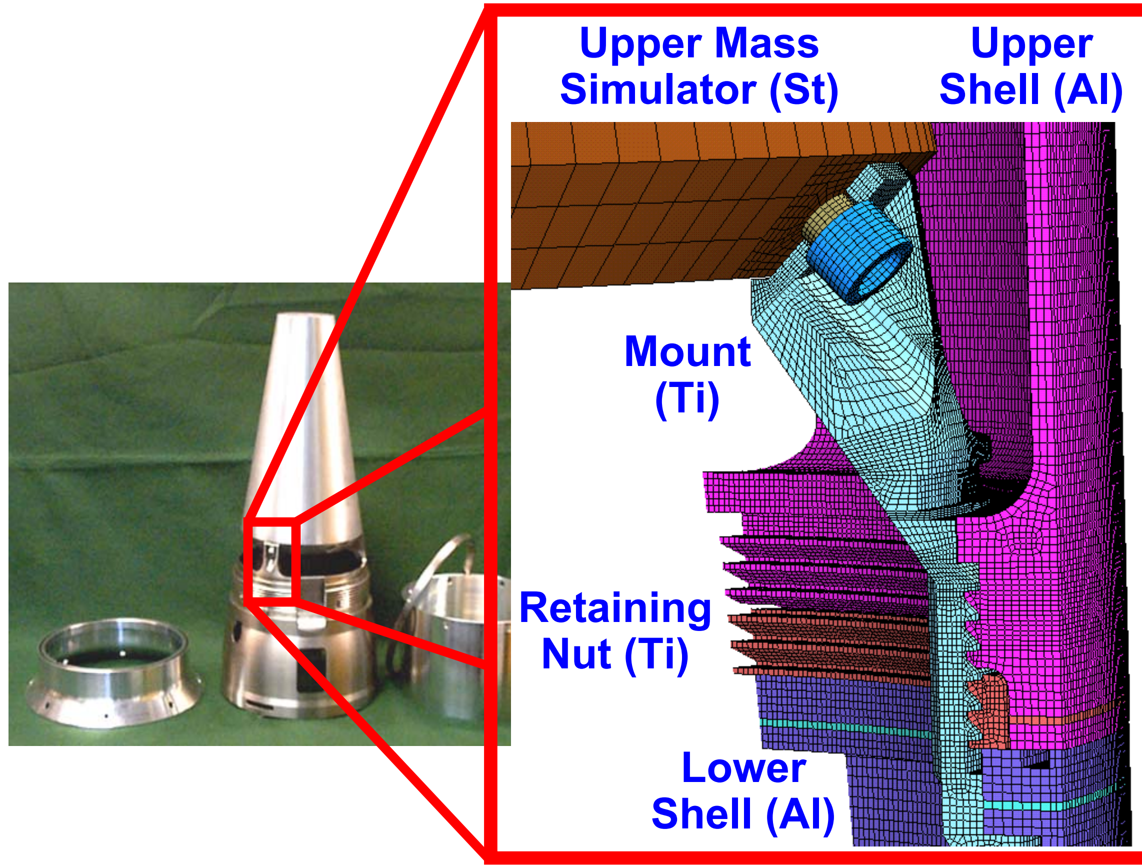
- Code verification activities
- Extraction of response features
- Asymptotic convergence of discrete solutions
- Phenomenon Identification and Ranking Table (PIRT)
- Design of computer experiments
- Design and execution of integral-effect experiments
- Global sensitivity (variance-based), effect screening
- Design and execution of separate-effect experiments
- Development of fast-running meta-models
- Uncertainty propagation and assessment
- Test-analysis correlation
- Assessment of prediction accuracy and uncertainty

Levels of Efforts of This Study

- A team of about 6 staff members at LANL worked on this project for one year, with each member at ½ time. (Budget of ~ 6 members x ½ FTE each ≈ $1M.)
- The experimental campaign for integral-effect testing, including explosive charge development and pre-test setup, lasted about 4 months. (Budget = 12 shots x $60k each ≈ $720k.)
- The experimental campaign for separate-effect testing lasted about two weeks and budget was insignificant.
- The simulation budget was ~ 300 runs performed over a 2-month period. The number of CPU hours burned was ~ 300,000 hours, which is 34 years of single-CPU run time! (Budget for 2 months x 1 analyst ≈ 50k.)
- Data processing took 1½ months. Documentation took about 1 month before the milestone was due.

Components of the Assembly

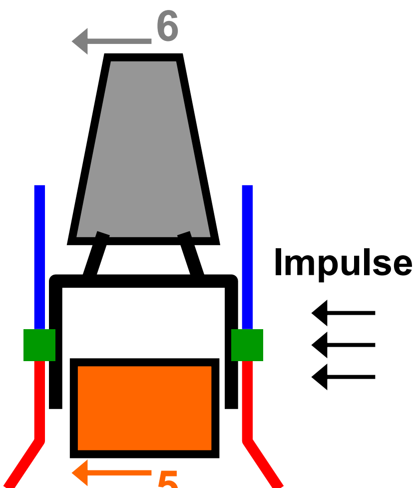




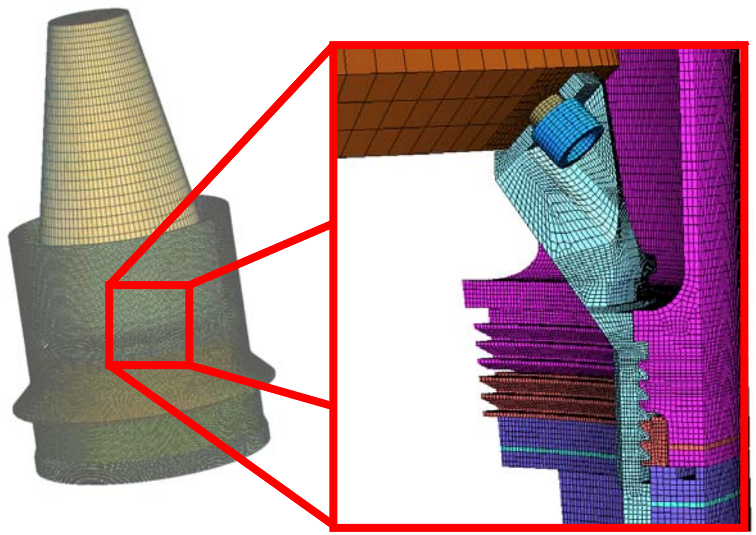
Click > Movie

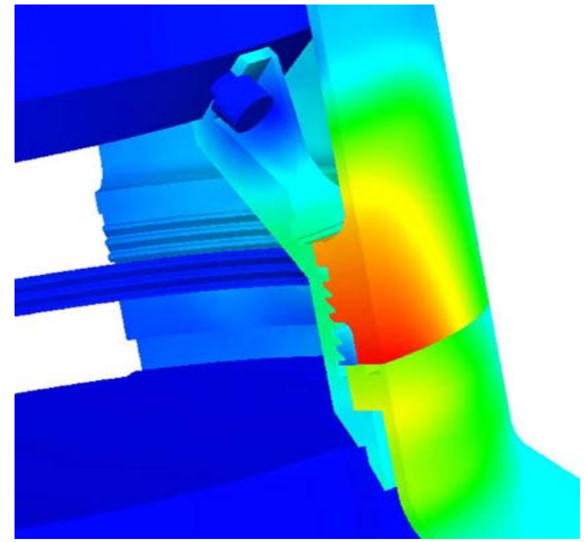
Threaded Joint Modeling

- The LLNL/ParaDyn explicit simulation implements 480 contact pairs, over 1.4 Million elements and 6 Million degrees-of-freedom. (This is for the 2004-2005 model.)



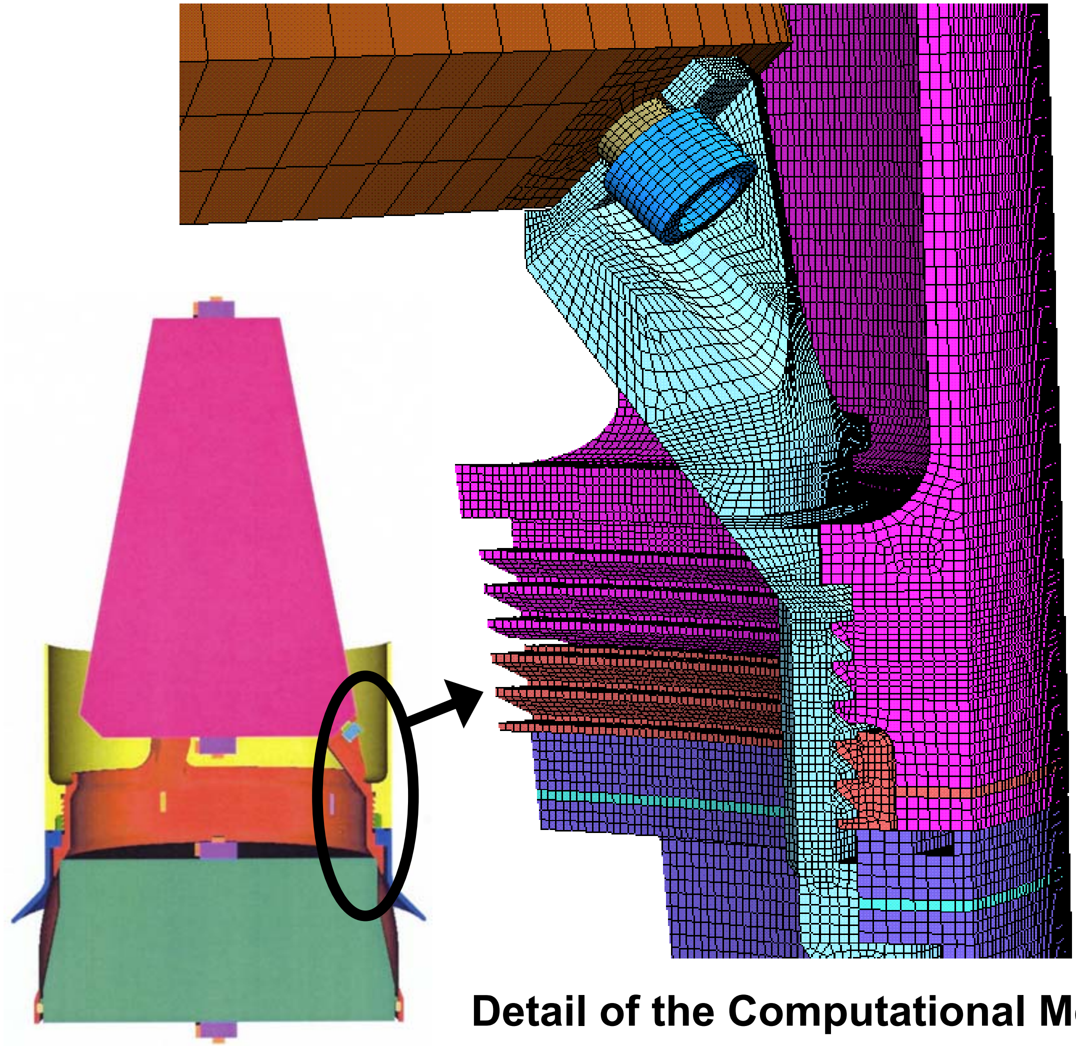
Sensors 5 & 6


Detail of the Computational Mesh

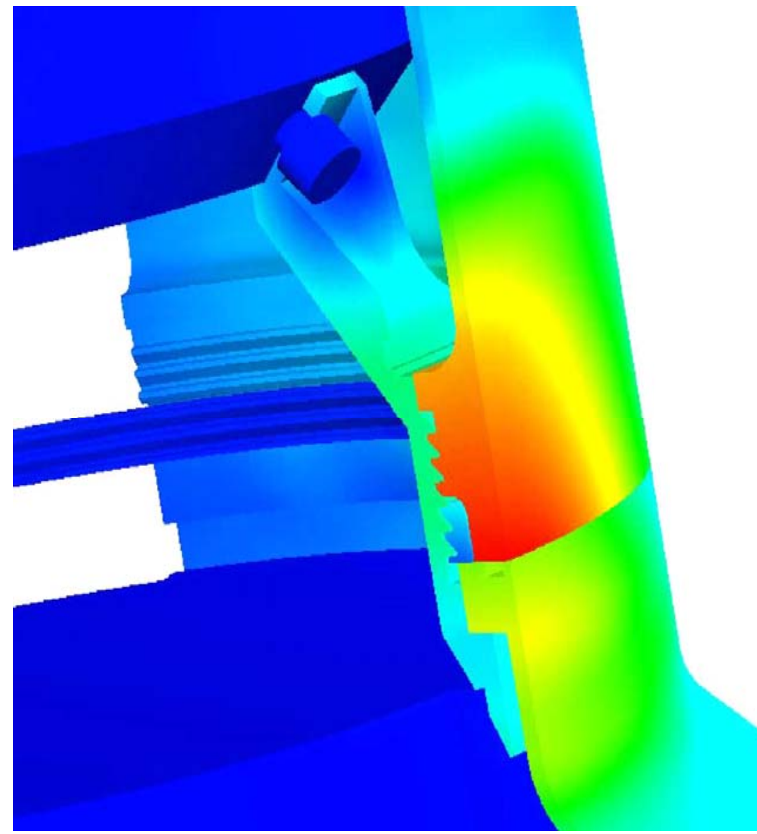

Displacement Contour

- Each run requires about one hour of computing time to simulate 10^{-3} sec. of response on 100 processors of the Q Machine. About 5 milliseconds of response are simulated for each run of the model.

Simulation Setup and Results



Detail of the Computational Mesh



Displacement Contour

(Reference: LA-UR-05-6735.)

Extraction of Response Features

- A significant effort was spent upfront to understand response quantities of interest to the customers. This involved a lot of discussion since customers did not have a clear appreciation for what they needed.

- We settled on:
  - Peak acceleration values (1)
  - Temporal moments (energy, E; centroid, τ; duration, D) of acceleration (3)
  - Moments (E; τ; D) of acceleration Power Spectral Density (PSD) functions (3)
  - Shock Response Spectrum (SRS) of acceleration
  - Dissipation rate of acceleration (1)
  - Secondary interest: peak values and times-of-arrival of strain responses (2)

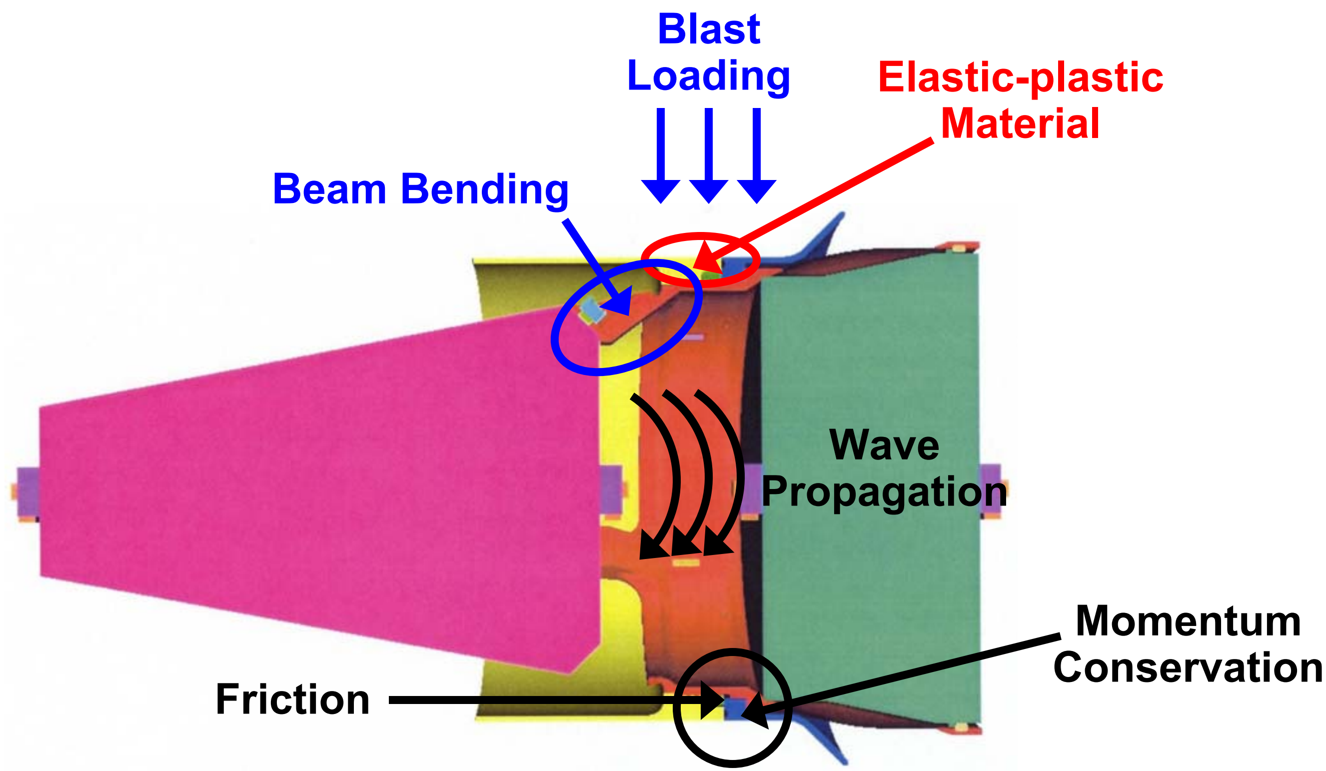
$$M_k = \int_{t_{Start}}^{t_{End}} t^k \cdot \left(y(t)\right)^2 \cdot dt$$

x 4 acceleration locations
x 2 orientations (Y; Z)
≥ 80 features to analyze!

Response of interest but too high-dimensional.

Verification Coverage of Key Physics

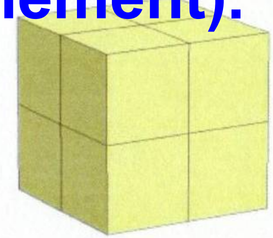
- The definition of test problems for code verification focuses on the main mechanics that the finite element code must be able to implement correctly.



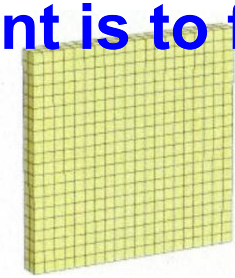
- These problems check for implementation mistakes.

Code Verification Test Problems

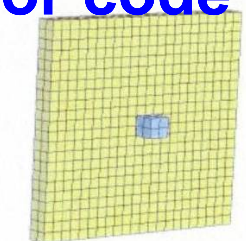
- These test problems possess *exact* solutions to which code predictions are compared (with or without mesh refinement). The point is to find major code mistakes.



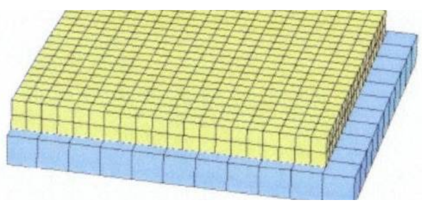
Elastic-plastic Material



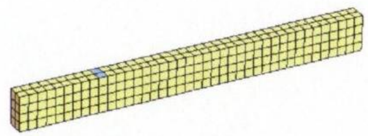
Blast Plate



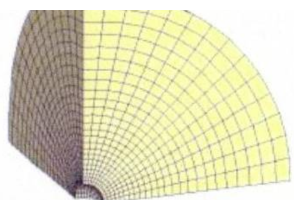
Momentum Conservation



Friction Pull-out



Beam Bending



Radial Wave Propagation

Table 19: Wave Propagation Model Results (Spatial + Tem

Relative Element Length (h)	Time Step (μs)	Numerical Solution (km/s)	Numerical Error (%)	GCI (%)
1	0.713	5.27	-8.9	18
1/2	0.320	5.44	-6.0	9.2
1/3	0.205	5.53	-4.6	9.2
1/4	0.150	5.59	-3.4	11
1/9	0.646	5.70	-1.6	4.6
1/12	0.048	5.71	-1.3	2.3
Exact Solution = 5.79 km/s				

Solution Convergence

- **A simplified geometry of the joint, that preserves the key mechanics of interest, is used to assess solution convergence through mesh refinement studies.**

As far as verifying the mechanics of the threads, these two meshes are equivalent!

?
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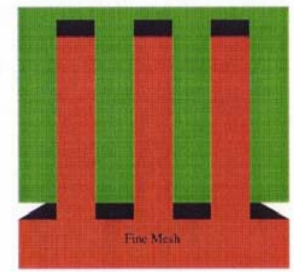
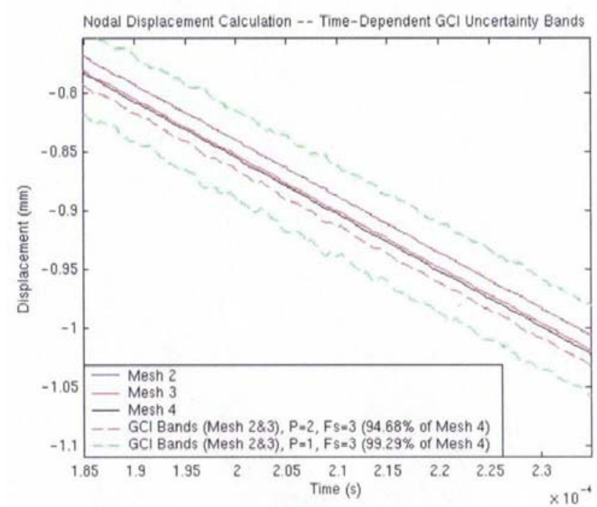


- Over twenty meshes were built and analyzed!
- The contact algorithm based on penalty coefficients (even though it is fast-running) was found to be deficient; it did not conserve total energy.
- Lagrange multipliers were used instead; they performed satisfactorily for the problem.



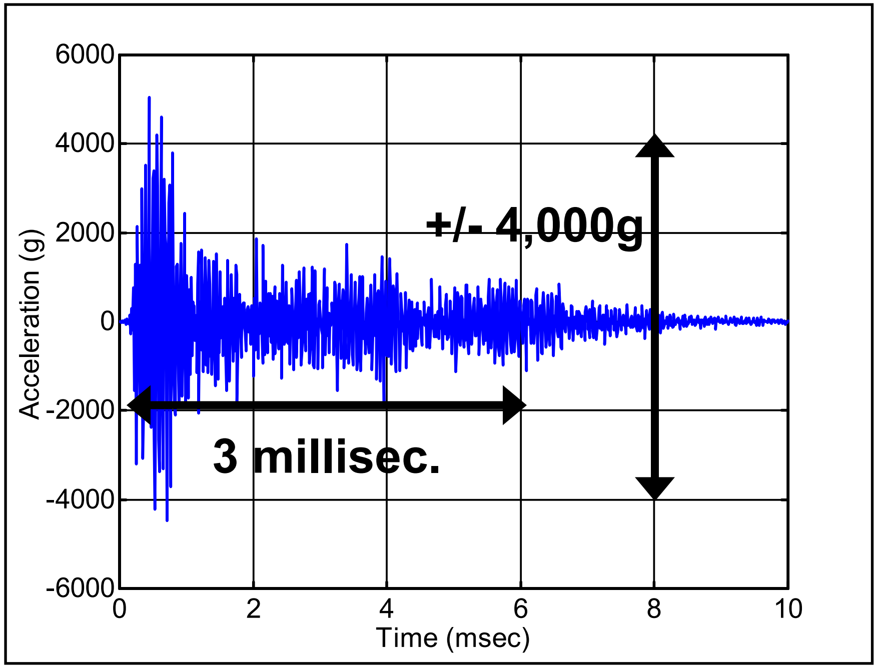
Design of Physical Experiments

- The domain of validation of 1D, defined by the level of applied impulse, and a 12-run design of experiments is defined with blocking and replication.

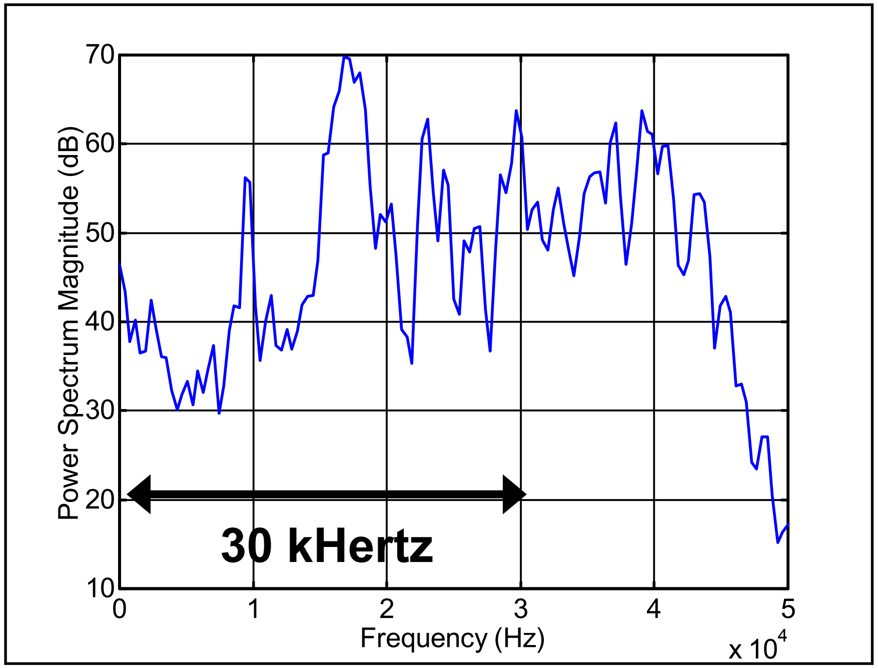
Test ID Number	Shell Set	Impulse Level	Velocity (cm/sec.)	Impulse (x 10^{+3} dyne-sec.)	
1	1	Low	2.57	71.00	3% Variability
4	2	Low	2.73	75.40	
7	3	Low	2.57	70.90	
10	4	Low	2.56	70.80	
2	1	Medium	3.00	82.85	6% Variability
5	2	Medium	3.31	91.30	
8	3	Medium	2.83	78.20	
11	4	Medium	3.09	85.40	
3	1	High	4.32	119.20	5% Variability
6	2	High	4.22	116.40	
9	3	High	3.88	107.20	
12	4	High	3.99	110.10	

Sample of Measured Acceleration

- The response of the structure to the applied impulse is a fast transient. Energy dissipates quickly through the threaded joint.



Time History



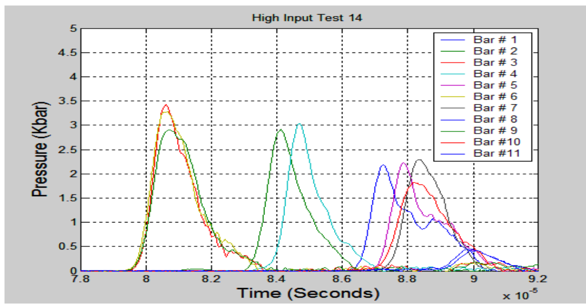
Power Spectrum Density (PSD)

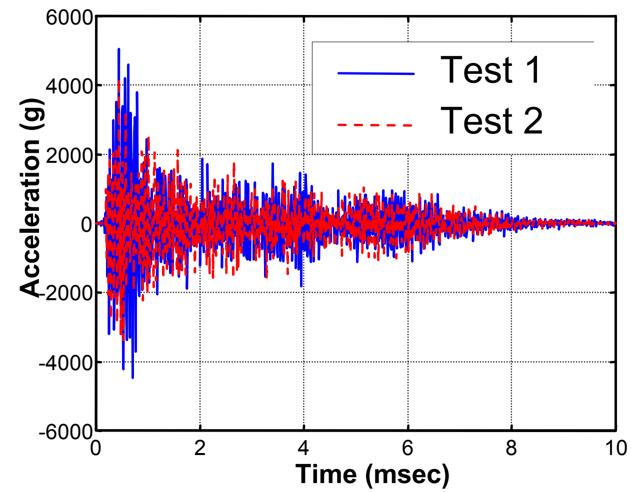
- The material response remains linear for the most part (no yielding, except maybe locally on the upper shell).

Test-to-test Repeatability

- **Test replication is used to estimate the experimental variability. The tests are reproducible given the levels of explosive charge and assembling variability.**

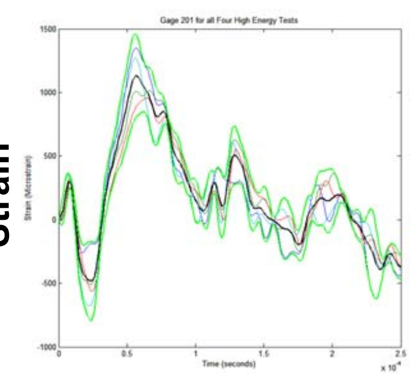
High Impulse





Descriptive Statistics of Acceleration Signals	Low Impulse	High Impulse
Mean, μ_A	0.00 g	0.00 g
Standard deviation, σ_A	627 g	641 g
Minimum, A_{Min}	-5,297 g	-17,314 g
Maximum, A_{Max}	5,542 g	11,57 g
Ratio σ_A/A_{Min}	-11.8%	-3.7%
Ratio σ_A/A_{Max}	11.3%	5.5%
Range $(\sigma_A/A_{Max}) - (\sigma_A/A_{Min})$	23.1%	9.2%

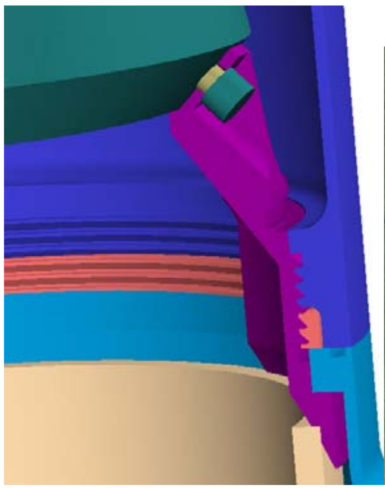
Strain

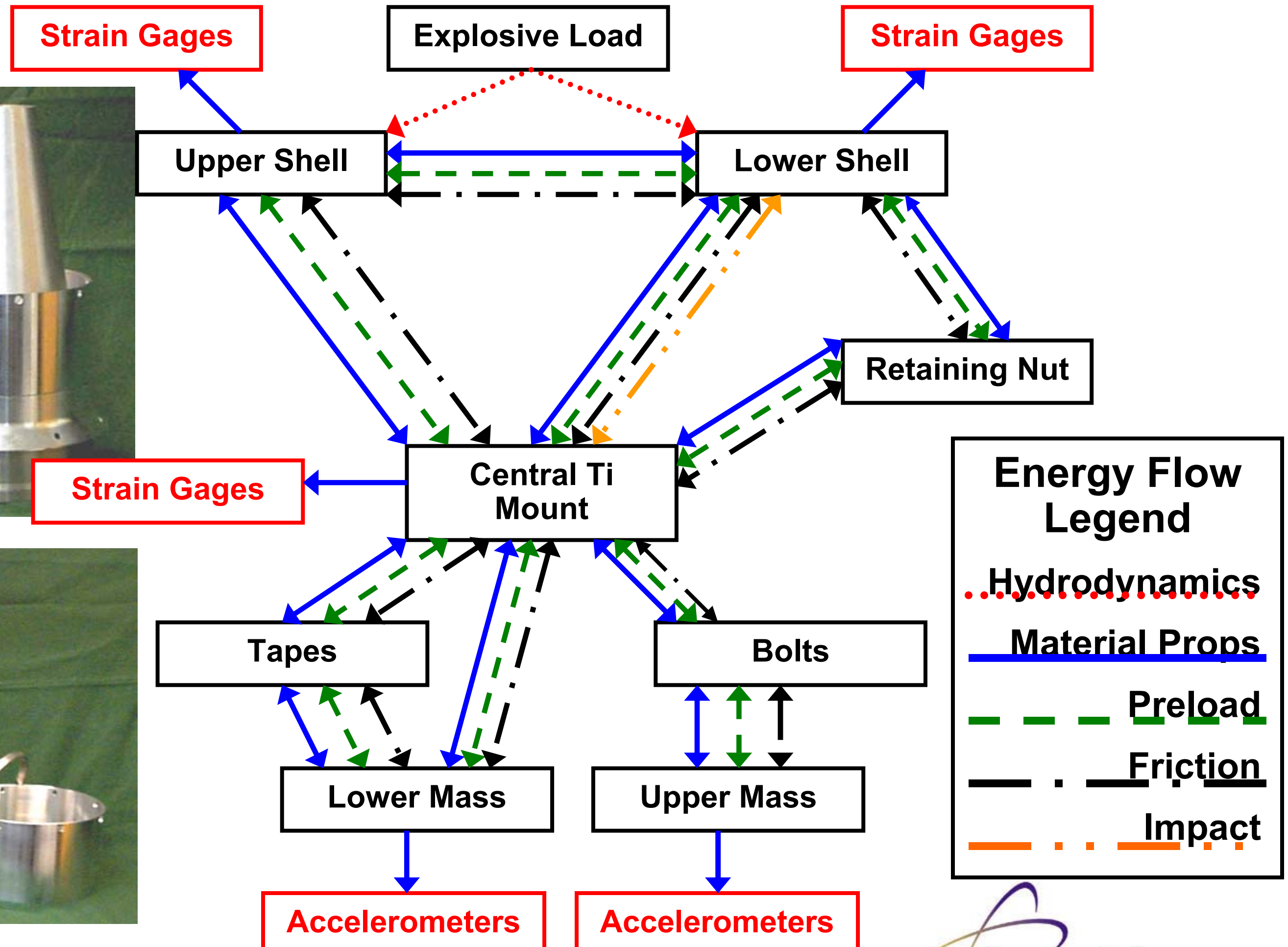


(Reference: LA-UR-05-8229.)

Energy Flow Diagram

- An energy flow diagram is defined to start writing the Phenomenon Identification and Ranking Table (PIRT).





Sample of Threaded Assembly PIRT

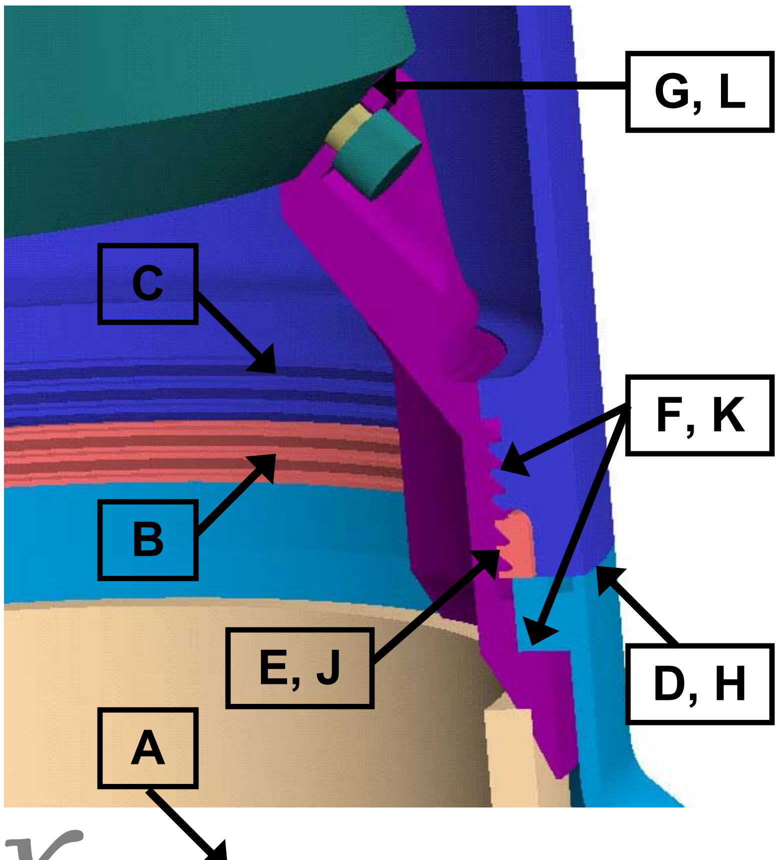
- **The PIRT developed included about 230 phenomena, down to the level of individual model variables.**

Phenomena	Master Phenomenon	Energy in/out	Min	Nom	Max	Importance	Mean Confidence	Dist confidence
Upper Shell Strain Gages								
Explosive load to upper shell	deta sheet load	E in		Low		High	Mid	Mid
				Mid		High	Mid	Mid
				High		High	Mid	Mid
Fraction of neoprene pad on upper shell	fabrication	E in (shape)		Low		High	High	Mid
				Mid		High	High	Mid
				High		High	High	Mid
Tolerance on the upper shell	fabrication	E in				Mid	High	High
Al/Al friction between shells	friction	E out				Mid-Low	Mid	Mid
Al/Ti thread friction	friction	E out				Mid-Low	Mid	Mid
Preload of Upper shell	preload	E out				Mid-Low	Mid	Mid
Modulus of Al 7075	mat prop	Mat resp to E				High	High	High
Density	mat prop	Mat resp to E				High	High	High
Poisson's Ratio	mat prop	Mat resp to E				High	High	High
Yield Stress	mat prop	Mat resp to E				Mid-Low	High	High

PIRT extracted from: Doebling, S., Anderson, M., Maupin, R., Hylok, J., Hemez, F., Rutherford, A., Salazar, I., Bement, M., Robertson, A., “Simulation of Engineering Shock Response of a Joint Surrogate Assembly: Verification and Validation Plan,” *Los Alamos Report* LA-CP-04-0232, Los Alamos National Laboratory, Los Alamos, New Mexico, February 2004, unclassified but limited distribution (OUO).

Parametric Studies

- The PIRT down-selected to a total of twelve individual phenomena (1 control parameter and 11 variables "θ") for parametric study and uncertainty quantification.



- Preloads:
  - tape joint (A)
  - retaining nut (B)
  - upper shell (C)
- Static coefficients of friction:
  - aluminum/aluminum (D)
  - titanium/titanium (E)
  - aluminum/titanium (F)
  - steel/titanium (G)
- Kinetic coefficients of friction:
  - aluminum/aluminum (H)
  - titanium/titanium (J)
  - aluminum/titanium (K)
  - steel/titanium (L)
- Impulse level (M) ← Control Parameter

Ancillary Variables (D–L, A–C)

Parameter Screening

- **Propagating uncertainty for 12 variables is still too high-dimensional. Statistical screening is performed first to identify which phenomena are truly important.**

- **Preloads:**
  - tape joint (A)
  - retaining nut (B)
  - upper shell (C)
- **Static coefficients of friction:**
  - aluminum/aluminum (D)
  - titanium/titanium (E)
  - aluminum/titanium (F)
  - steel/titanium (G)
- **Kinetic coefficients of friction:**
  - aluminum/aluminum (H)
  - titanium/titanium (J)
  - aluminum/titanium (K)
  - steel/titanium (L)
- **Impulse level (M)**

- Sensitivity analysis with high/low values for each of the 11 variables
- Yields 3 x 2^{11} = 6,144 possible combinations

Too many runs!

- Select a subset of these combinations using a Taguchi Orthogonal Array design
- 76 finite element runs performed

- Perform Analysis of Variance (ANOVA) to identify the most significant variables
- Perform down-screening of variables

Down-select to 5 variables.

Conduct small-scale validation experiments.

2nd Pass

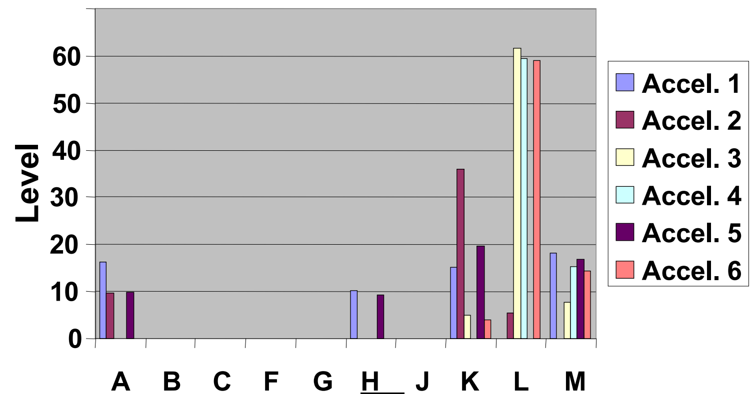
Results of Statistical Screening

- The sources of uncertainty that are found to exercise a significant effect on predictions are identified using analysis-of-variance (main effect analysis only).

- Preloads:
  - tape joint (A)
  - ~~retaining nut (B)~~
  - ~~upper shell (C)~~
- Static coefficients of friction:
  - ~~aluminum/aluminum (D)~~
  - ~~titanium/titanium (E)~~
  - ~~aluminum/titanium (F)~~
  - steel/titanium (G)
- Kinetic coefficients of friction:
  - aluminum/aluminum (H)
  - ~~titanium/titanium (J)~~
  - aluminum/titanium (K)
  - steel/titanium (L)
- Impulse level (M)

11 Sources of Uncertainty "θ"

Analysis-of-variance (ANOVA)

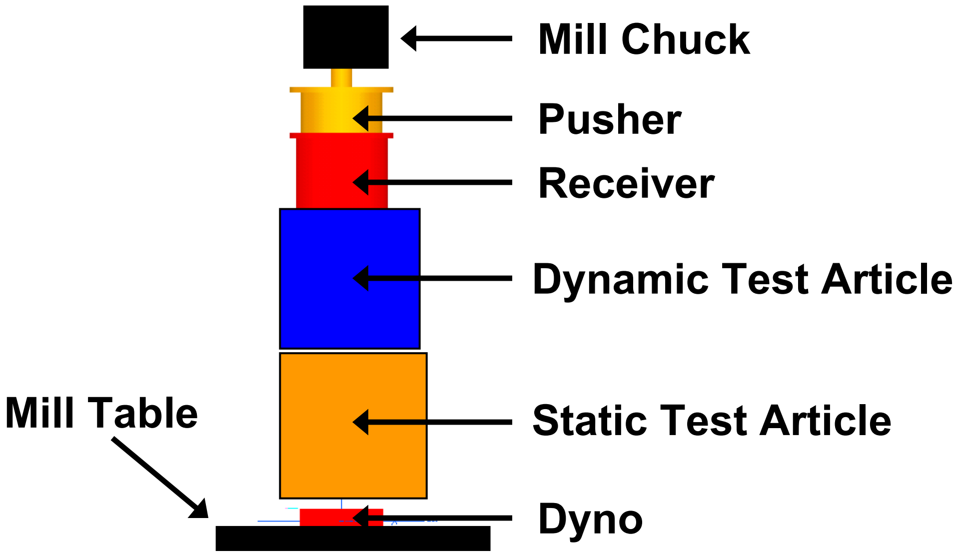


5 Sources of Uncertainty "θ"

Note that, after statistical screening, a full-factorial design with high/low values would require $3 \times 2^5 = 96$ runs only.

Separate-effect Validation Experiments

- **Friction testing is carried out on separate components to better estimate the statistics of friction coefficients.**



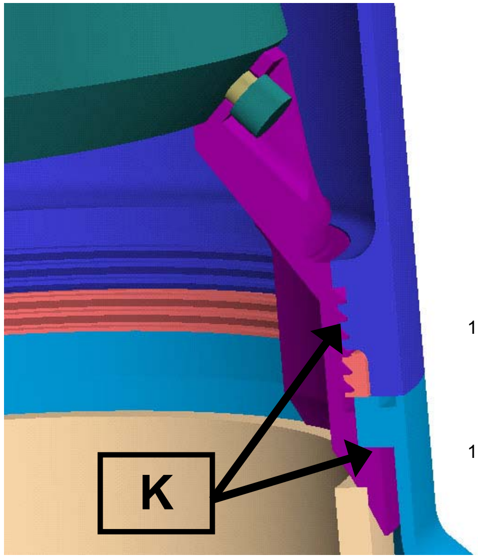
Amanda Rutherford of LANL operates the friction test apparatus (2005).

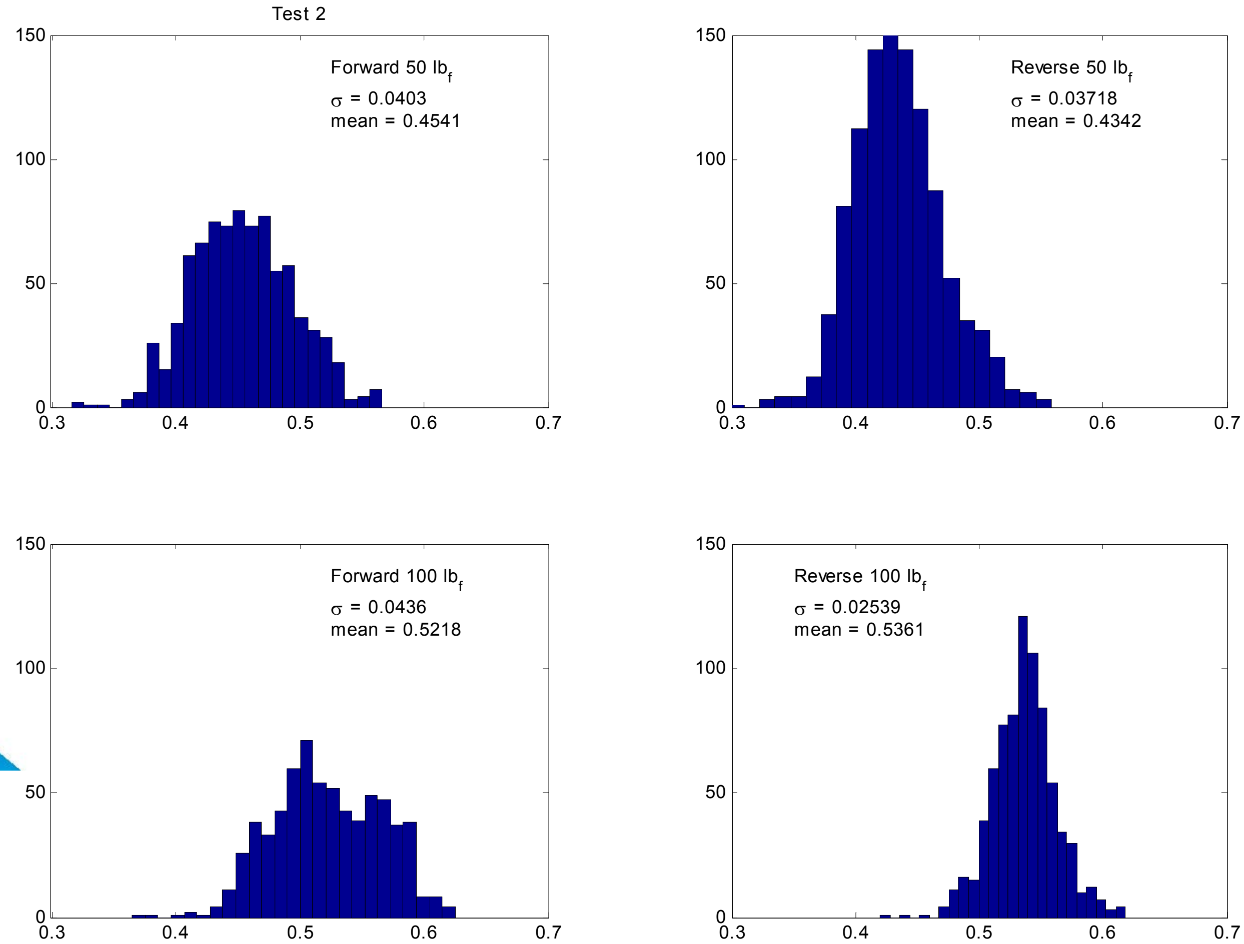
Experimental Procedure:

- Mill used to apply axial force to the assembly;
- One part is held fixed, the other is rotated by hand;
- Strain gage dynamometer provides six-axis measurements of forces and moments;
- Ratio of axial moment to axial force gives the friction coefficient.

Sample of Friction Measurements

- Distribution of friction coefficients for Al/Ti interface.





Statistics of Friction Coefficients

- One "surprise" is that we find significantly different coefficients for the Al/Ti interface whether contact and friction occur on the threads or along flat surfaces.

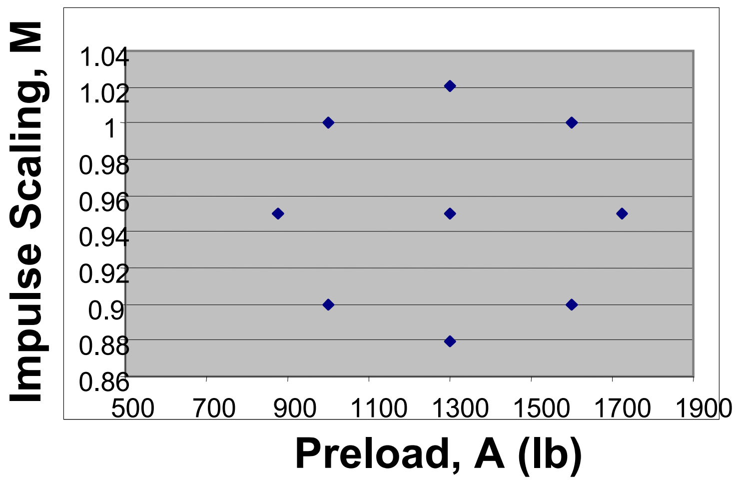
Kinetic Friction Coefficient	Nominal Range	Nominal Mean	Measured Value
Steel/Titanium (L)	0.225–0.975	0.6	0.443 ± 0.031
Aluminum/Titanium (K, edge)	0.325–1.675	1.0	0.47 ± 0.030
Aluminum/Titanium (K, thread)	0.325–1.675	1.0	0.77 ± 0.090
Aluminum/Aluminum (H)	0.525–1.275	0.9	0.52 ± 0.067
(The measured statistics are the mean value and +/- one standard deviation.)			

- Another surprise is that the nominal range used for the Al/Al interface almost missed the measured value!
- … This is a manifestation of *over-confidence*.

Meta-modeling

- **With the friction coefficients measured (G, H, K, L), all that is left is the tape joint pre-load (A) and magnitude of the impulse (M). Meta-models are developed in 2D.**

2D Central Composite Design



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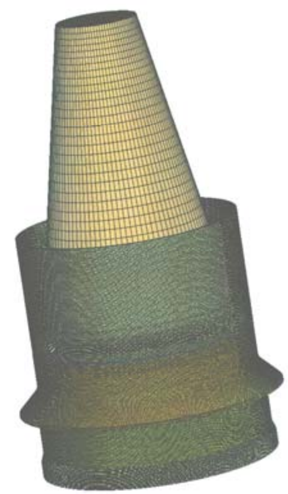
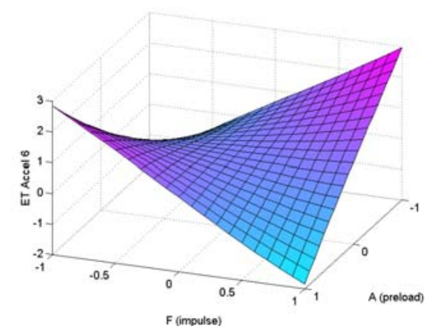
Independent Measurements of Friction Coefficients (G, H, K, L)

9 ParaDyn Runs



Generate a Meta-model Over (A; M)

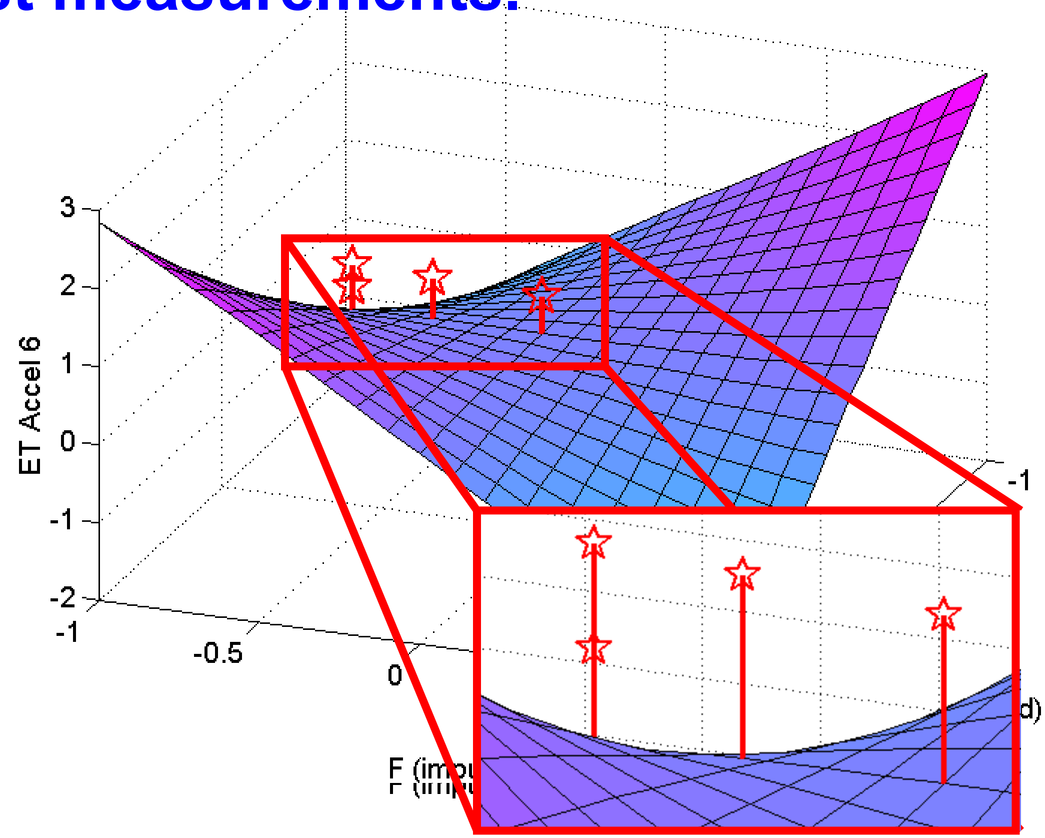


Use the response surface for uncertainty propagation and test-analysis correlation.

Test-analysis Correlation

- Predictions of a first 2D meta-model, developed with the *nominal* values of friction coefficients (G, H, K, L) are compared to test measurements.

- Preloads:
  - tape joint (A = nominal)
  - ~~retaining nut (B)~~
  - ~~upper shell (C)~~
- Static coefficients of friction:
  - ~~Al/Al (D)~~
  - ~~Ti/Ti (E)~~
  - ~~Al/Ti (F)~~
  - St/Ti (G = nominal)
- Kinetic coefficients of friction:
  - Al/Al (H = nominal)
  - ~~Ti/Ti (J)~~
  - Al/Ti (K = nominal)
  - St/Tim (L = nominal)
- Impulse level (M = controlled)

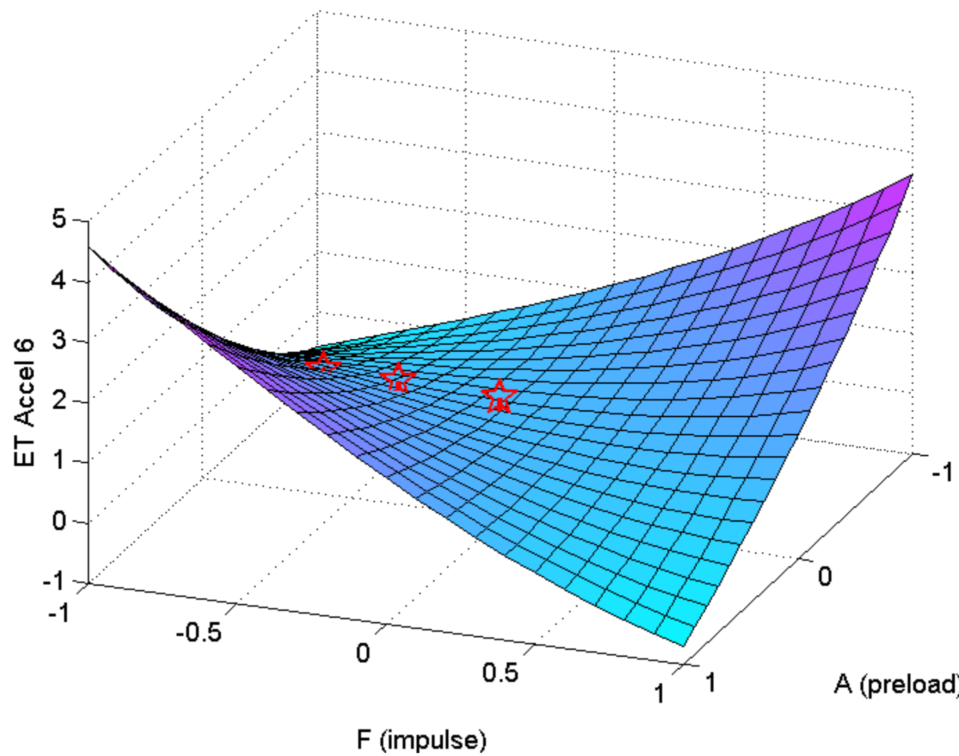


- The accuracy metric, $\varepsilon = ||y^{Test} - y||_2$, is equal to 0.93.

Improvement in Prediction Accuracy

- **Predictions of a second meta-model, developed with the *measured* values of friction coefficients (G, H, K, L), are compared to test measurements.**

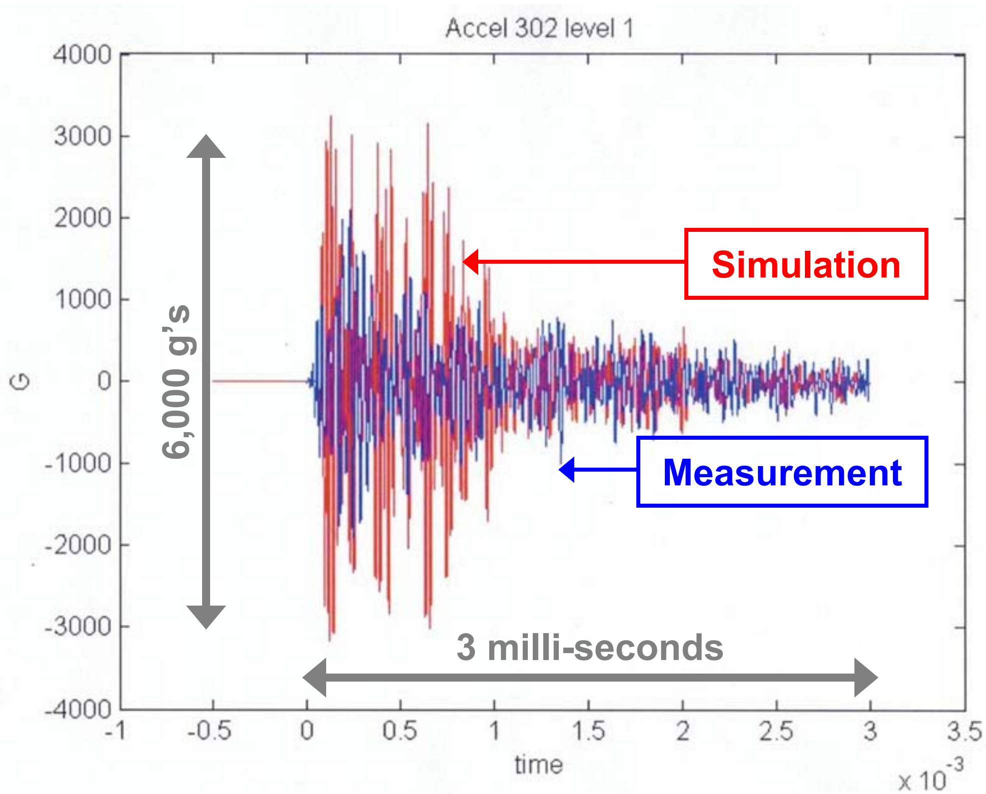
- **Preloads:**
  - tape joint (A = nominal)
  - ~~retaining nut (B)~~
  - ~~upper shell (C)~~
- **Static coefficients of friction:**
  - ~~Al/Al (D)~~
  - ~~Ti/Ti (E)~~
  - ~~Al/Ti (F)~~
  - St/Ti (G = measured)
- **Kinetic coefficients of friction:**
  - Al/Al (H = measured)
  - ~~Ti/Ti (J)~~
  - Al/Ti (K = measured)
  - St/Tim (L = measured)
- **Impulse level (M = controlled)**

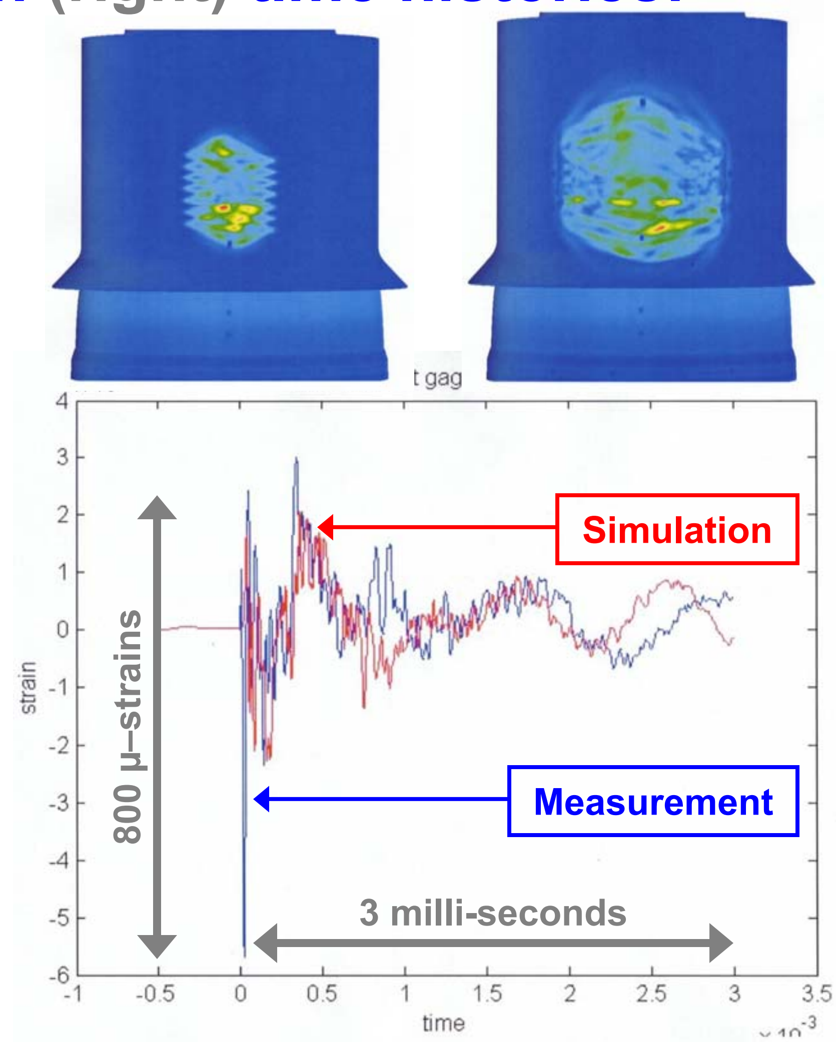


- **The improvement in prediction accuracy is significant, as observed with a metric ε = 0.39, down from 0.93.**

Test-analysis Comparison

- **Acceleration** (left) **and strain** (right) **time histories:**

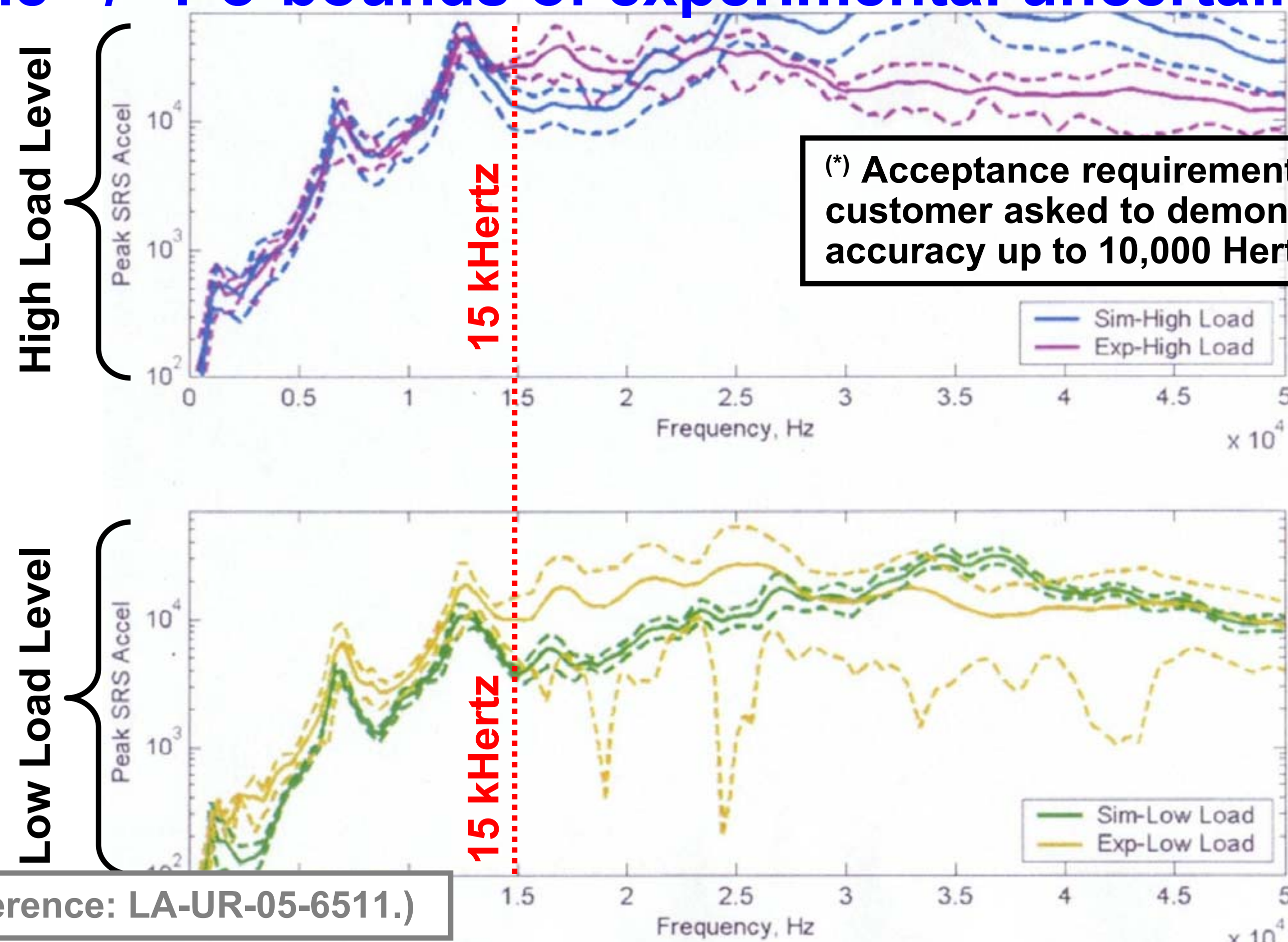




(Reference: LA-UR-05-6511.)

Frequency-domain Comparison

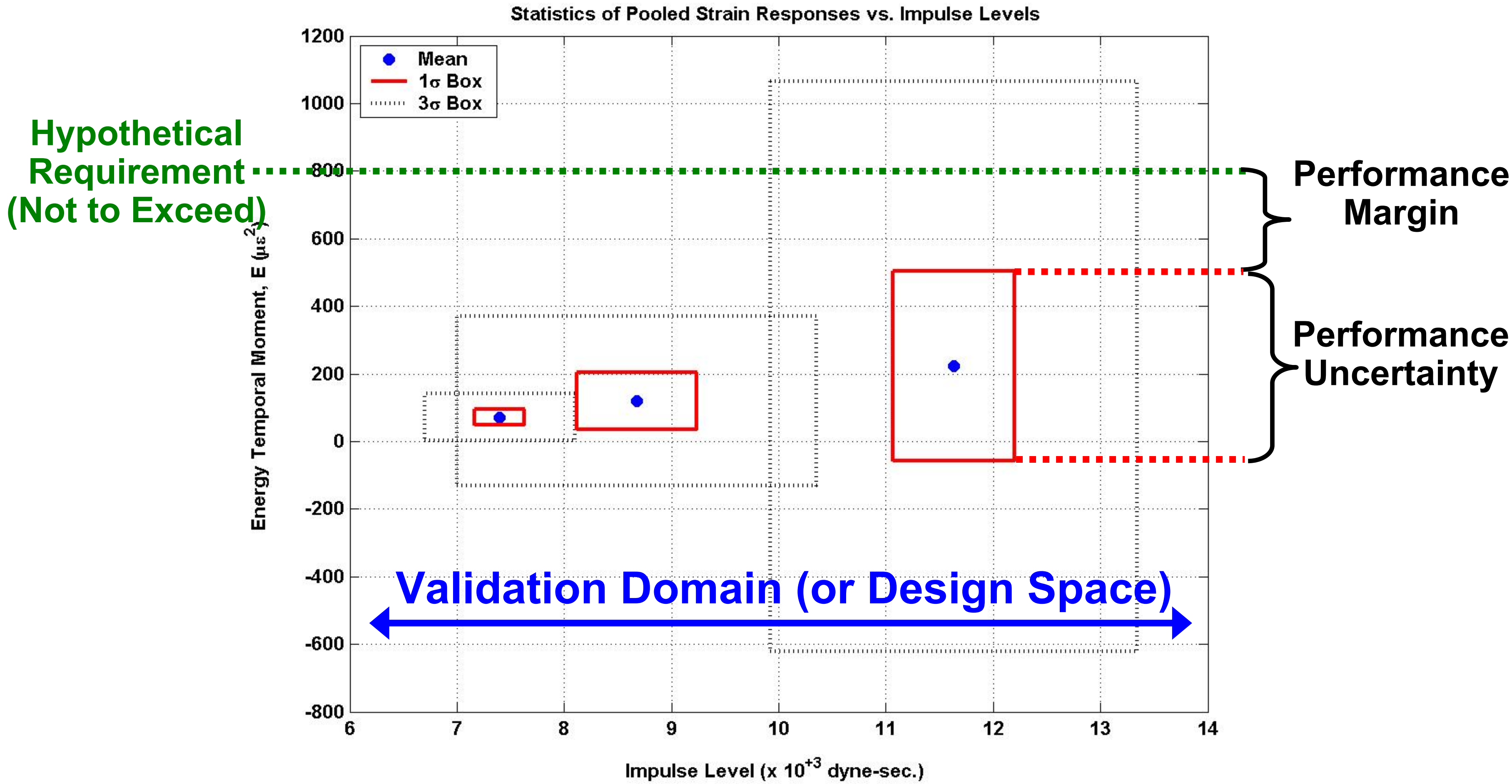
- **The measured and predicted shock response spectra agree remarkably well up to 15,000 Hertz, and within the +/- 1-σ bounds of experimental uncertainty.(*)**



(*) Acceptance requirements defined by the customer asked to demonstrate prediction accuracy up to 10,000 Hertz only.

(Reference: LA-UR-05-6511.)

Overall V&V Assessment



Reference: Hemez, F.M., Rutherford, A.C., Maupin, R.D., "Uncertainty Analysis of Test Data Shock Responses," *24th SEM International Modal Analysis Conference*, St. Louis, Missouri, January 30-February 2, 2006, LA-UR-05-8229.

Conclusion

- We delivered an assessment of prediction accuracy over the entire design space where the model needs to be exercised, not just in the neighborhood of a few test settings.
- We quantified the accuracy of our predictions and, more importantly, learned which sources of modeling uncertainty had the most influence on predictions.
- One short-coming of this study was the inability to thoroughly quantify the level of numerical uncertainty due to mesh discretization because, at the time, the tools needed to refine the mesh were not available.
- … This deficiency has since been addressed. In 2009, we demonstrated the capability to perform refinement and quantify the level of numerical uncertainty.