SAND2007-6850P

Challenges in Joint Modeling in Structural Dynamics

Vibration Damping and Shock Mitigation

Daniel J. Segalman

NSWC 1 November 2007

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Where We *Must* be Predictive -

Where correct answers are necessary and either experiments are just too expensive or are impossible

- **satellites**
- **next generation space telescopes**
- **jet engines and jet engine failure**
- **nuclear weapons systems (damping & shock)**

Predictive Modeling – Is that not what we already do?

- In general, engineers use simulation
  - To interpolate/extrapolate among experiments

    Note the tuned parameters
  - To help explain experiments
  - To help design experiments
  - To provide design guidance
  - To estimate factors of safely
- We generally do not try to predict with precision
  - Finer than the intrinsic variability of the problems
  - That which requires physics for which there are no models

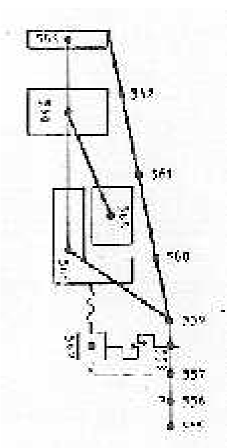
National Nuclear Security Administration

Sandia National Laboratories

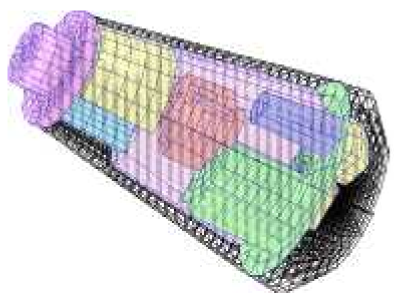
Traditional Barriers to Predictive Modeling

- **Discretization error**
- **Uncertainty in Material Properties**
- **Uncertainty in loads/boundary conditions**
- **Missing Physics - Interface Mechanics (Joints)**

Discretization Error: Less of an Issue Now Than in the Past

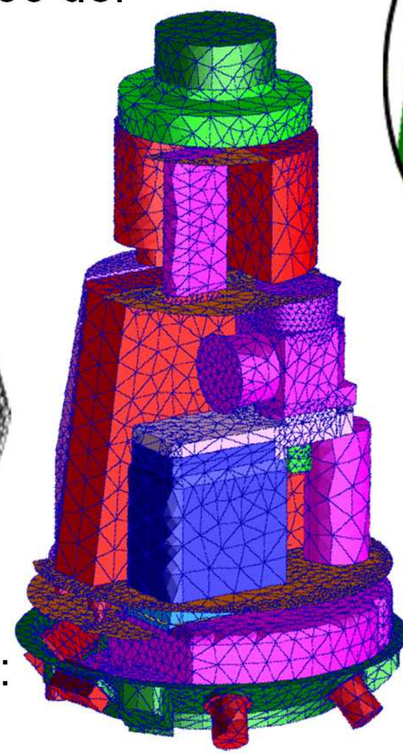


10 years ago:
Shellshock 2D
NASTRAN
200 dof

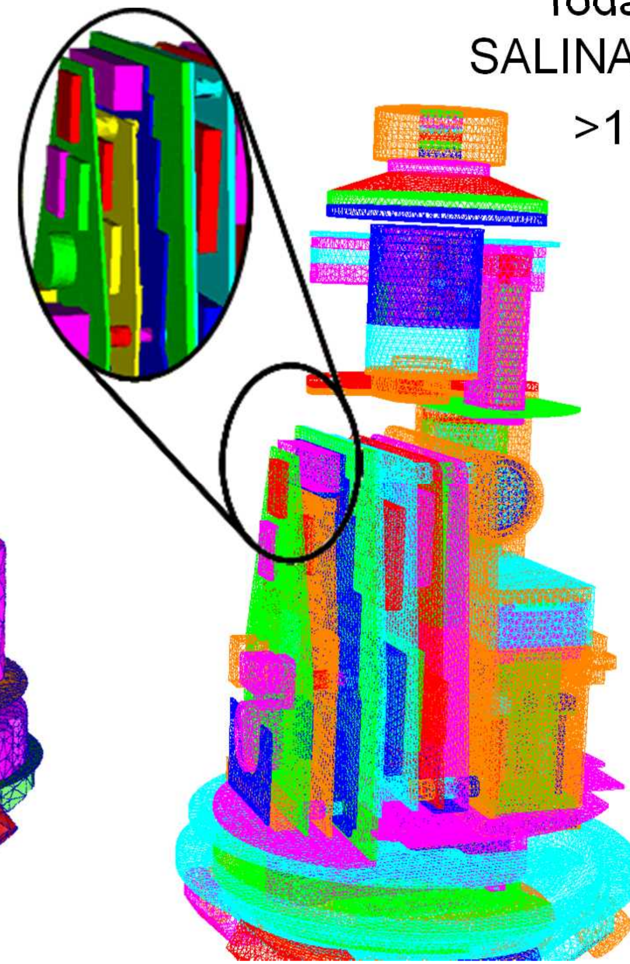


Recent Past:
NASTRAN
MC2912
30,000 dof

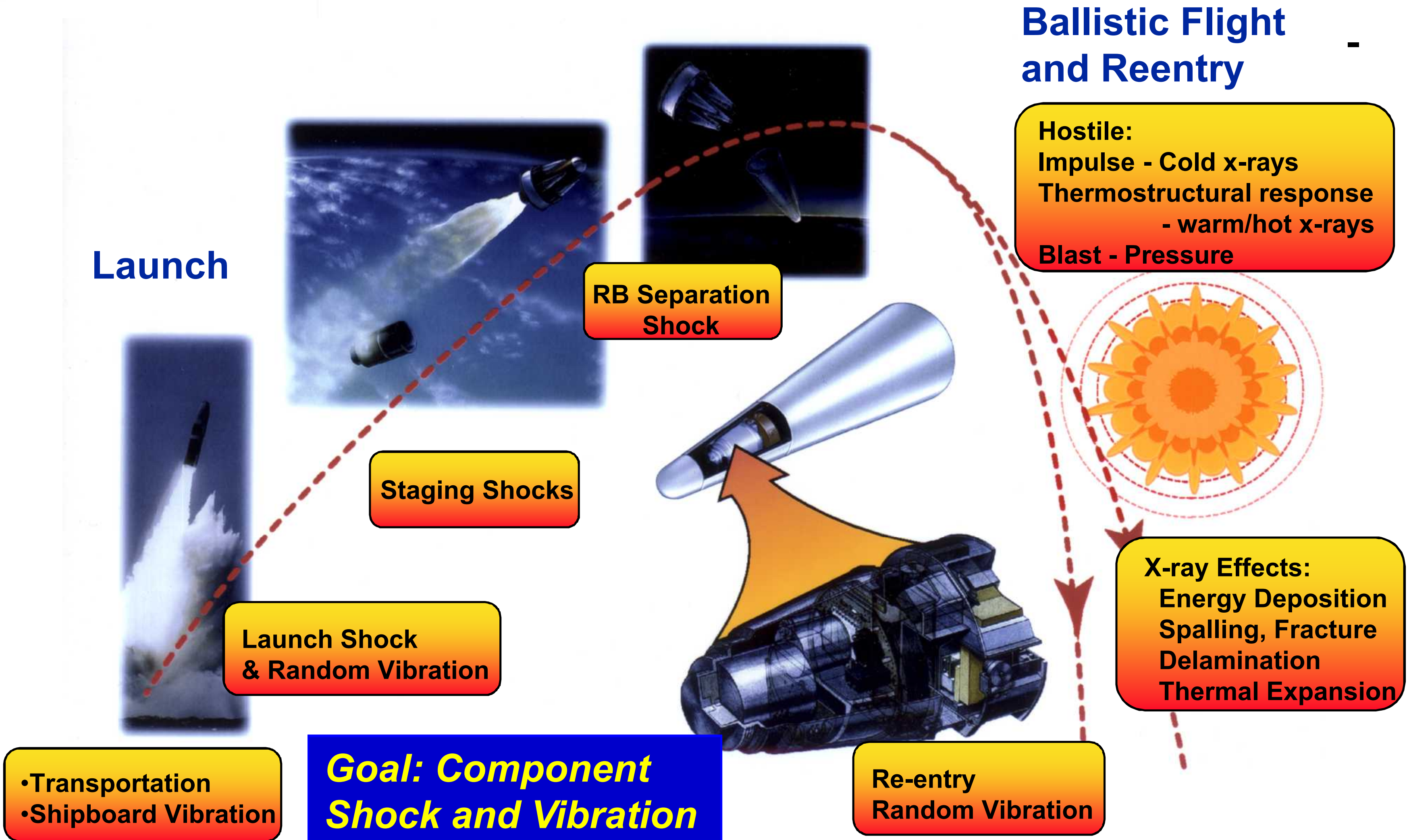
800,000 dof



Today:
SALINAS MP
>10M dof.



Stockpile Driver:
Structural Response of the W76-1

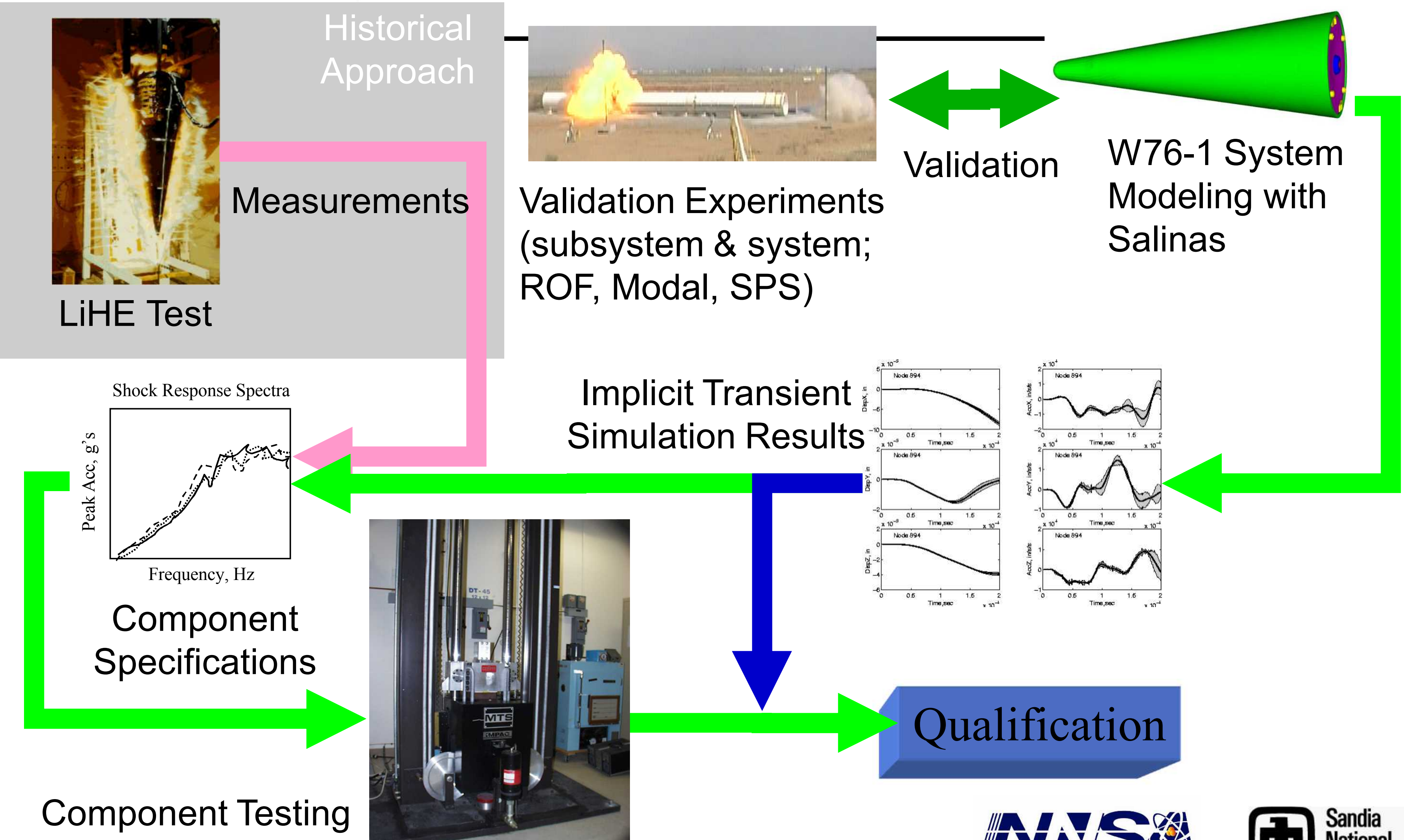


Goal: Component Shock and Vibration Specifications

NNSA National Nuclear Security Administration

Sandia National Laboratories

Simulation Based Approach to Hostile Qualification



Traditional Barriers to Predictive Modeling

- Discretization error
  - Mitigated substantially by MP technology
- Uncertainty in Material Properties
  - Subject of separate research efforts
- Uncertainty in loads/boundary conditions
  - Better measured, calculated, or bounded
- Missing Physics
  - Interface Mechanics (Joints)
  - The Tall Pole in the Tent
  - Topic of this talk

Topics include misfit, interference, and variability

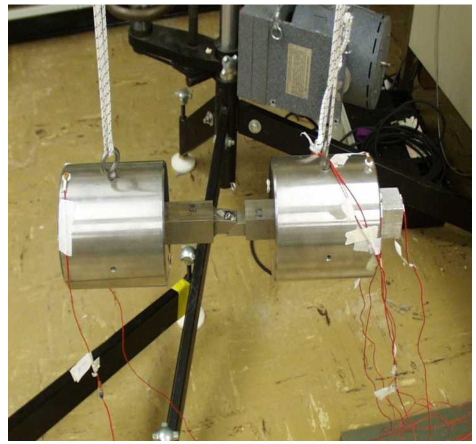
Significance of Joint Mechanics to Structural Dynamics

- **A (*the**) major source of vibration damping**
- **A (*the* *) major source of system non-linearity**
- **A (*the* *) major source of part-to-part variability**
- **A (*the* *) principle missing physics element of the simulation effort**

*depending on configuration and load

Major Experiments on Joints

Base Excitation at Resonance



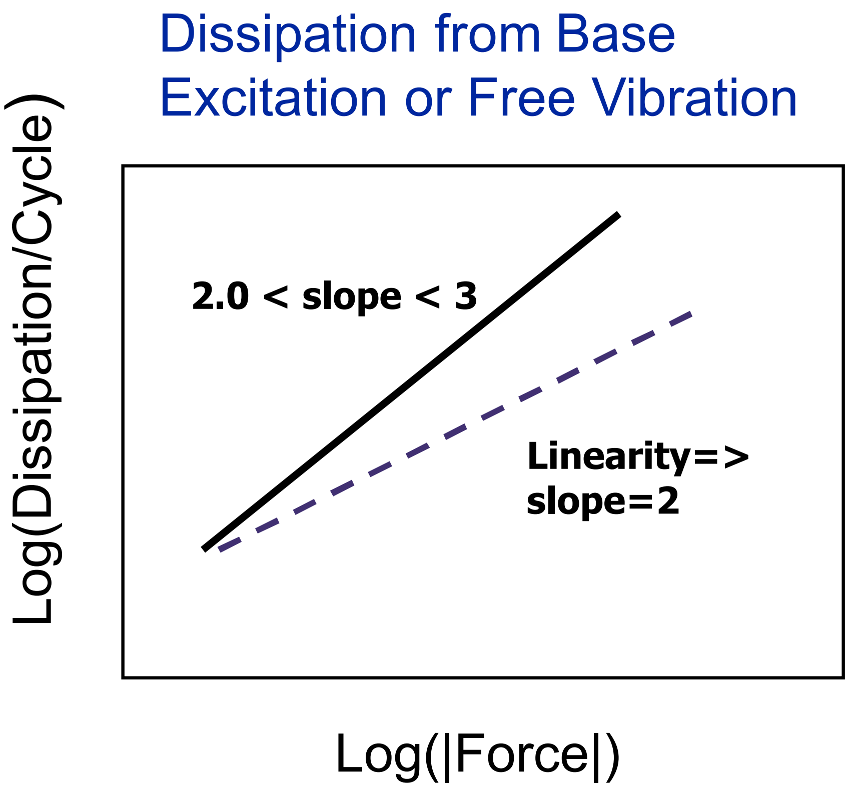
Ring-Down of Free Vibration

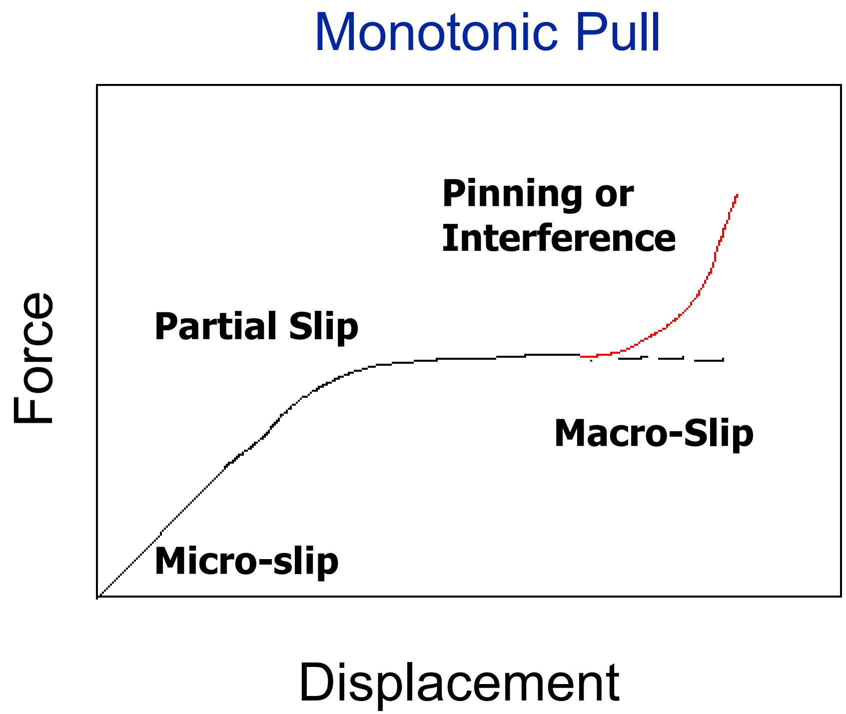
Quasi-Static Pull

Intrinsic difficulty of joint testing – the key physics is in a hidden interface

- The necessity of complementary joint-less specimens
- The limitations of quasi-static pull

Empirical Nonlinearity of Joints

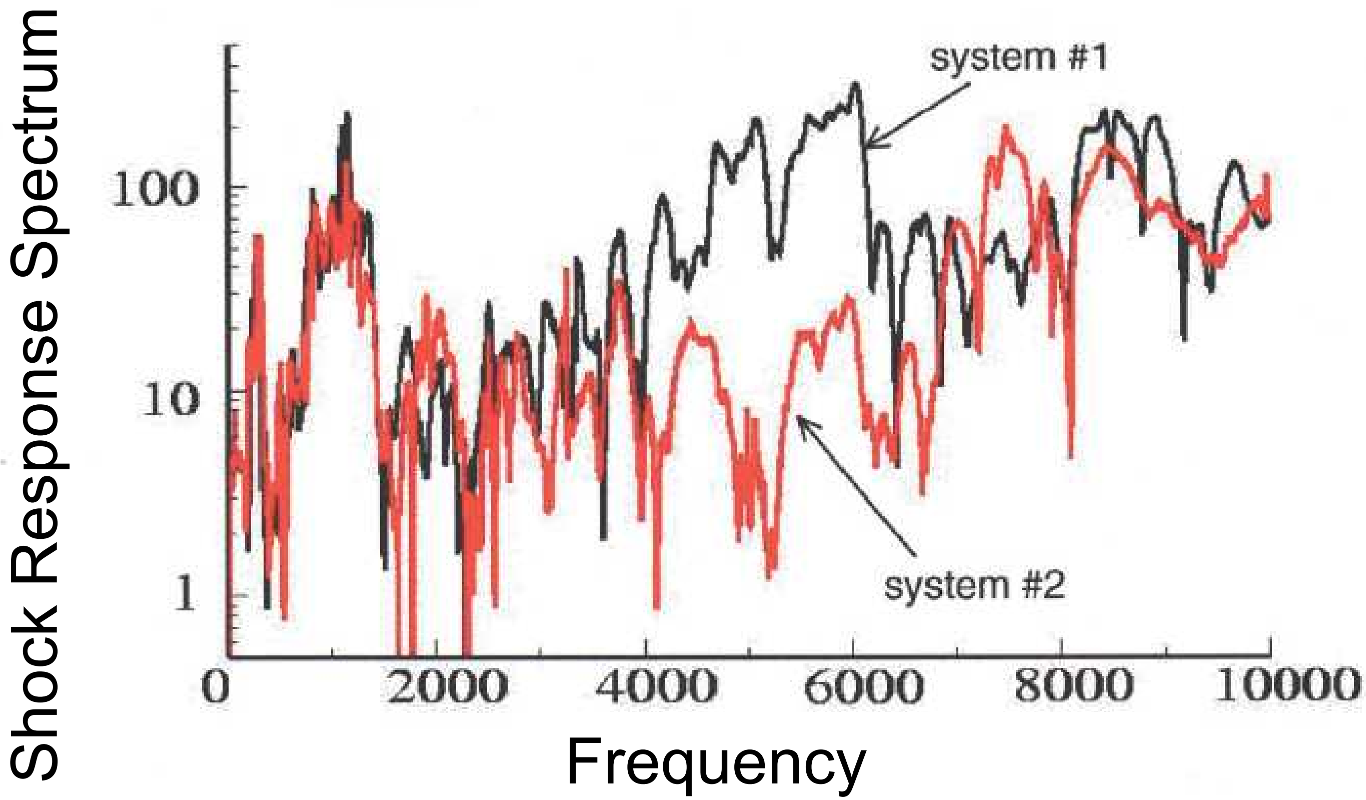




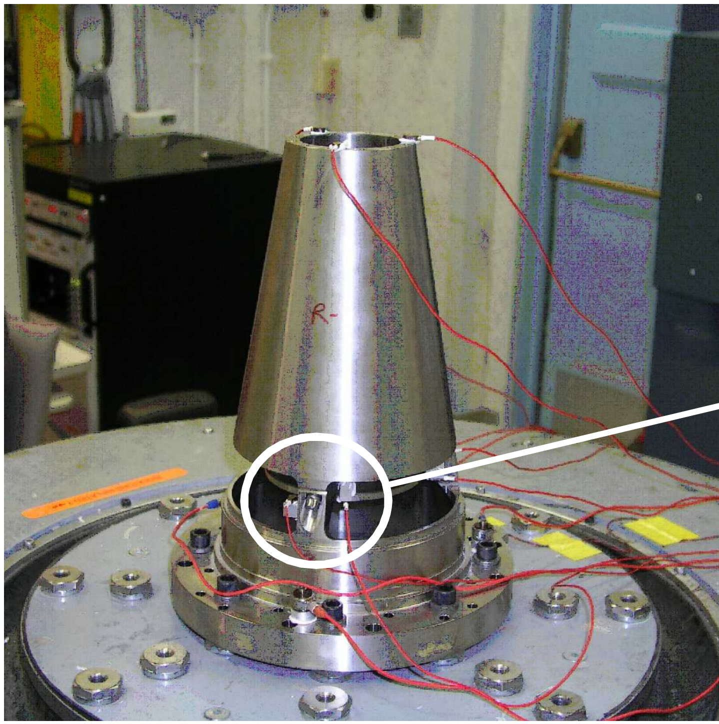
Nonlinearities even at Small Displacement

Large Displacement

Example of Variability Due to Joints



Example of Nonlinearity Due to Joints

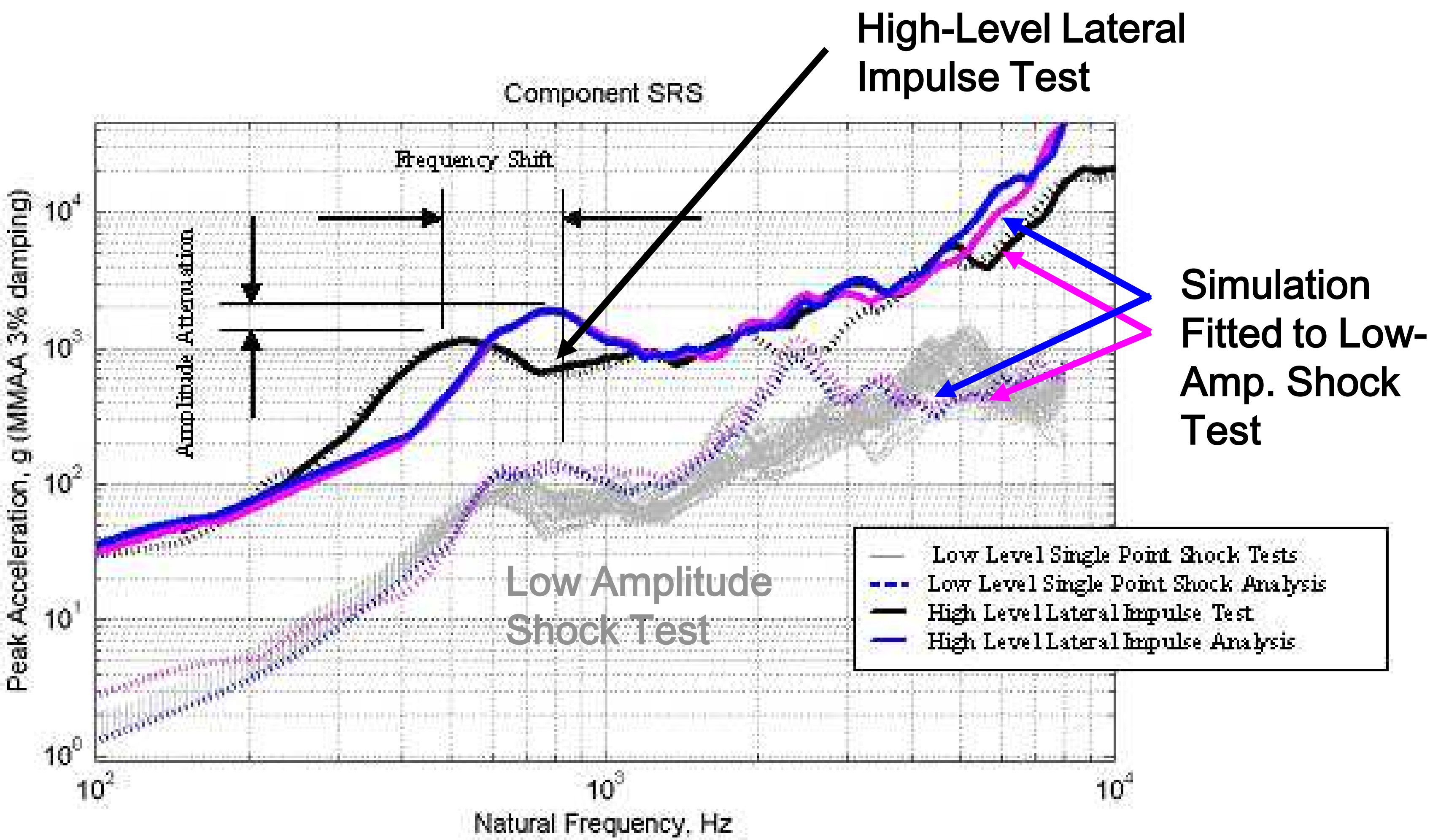


Mock sub-structure of a generic built-up assembly

Subject to various levels of transient lateral base excitation.

wah1

Nonlinearities Indicated by Shock Response Spectra: Particularly Stiffness Nonlinearity



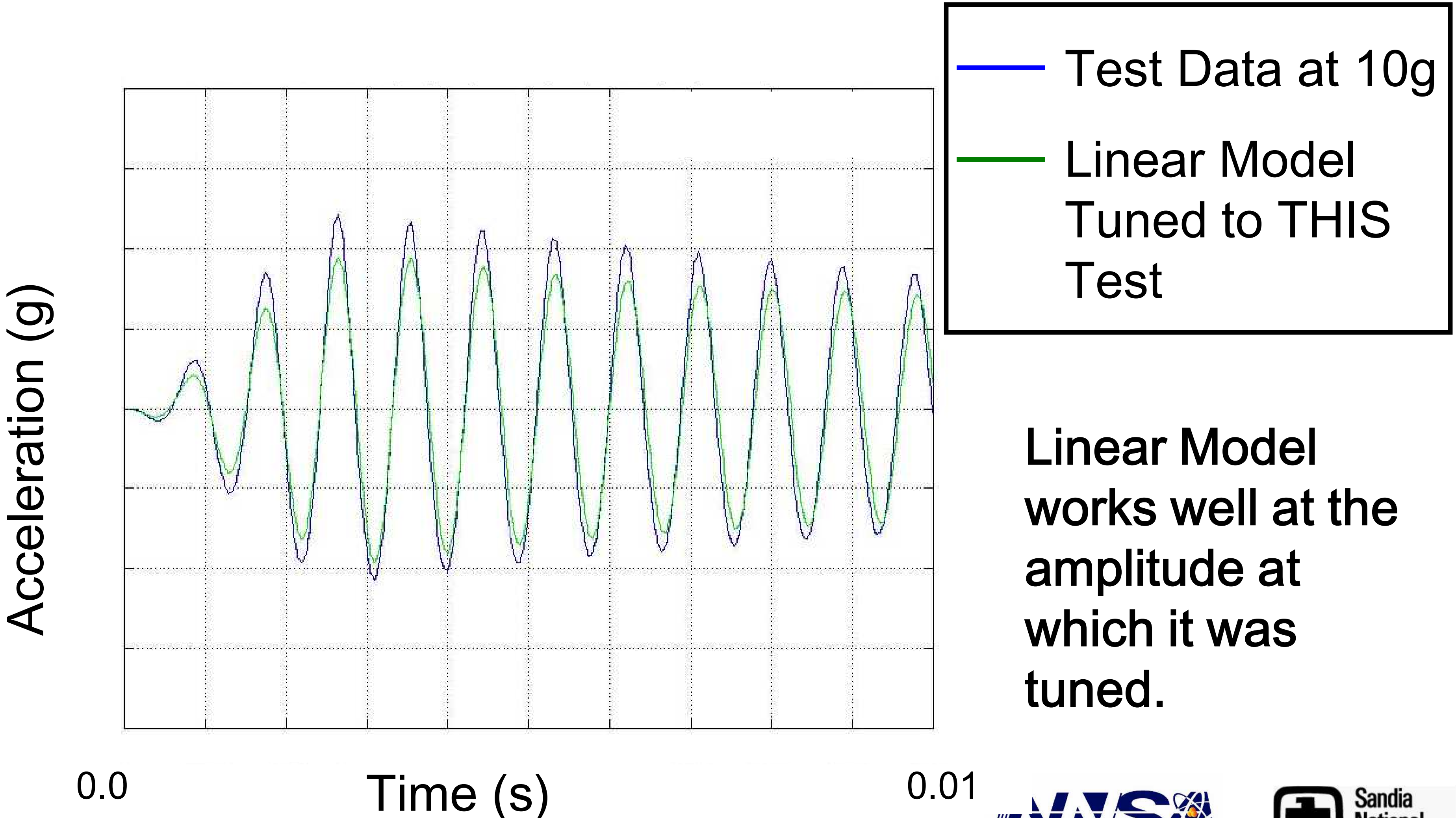
NNSA National Nuclear Security Administration

Sandia National Laboratories

Slide 14

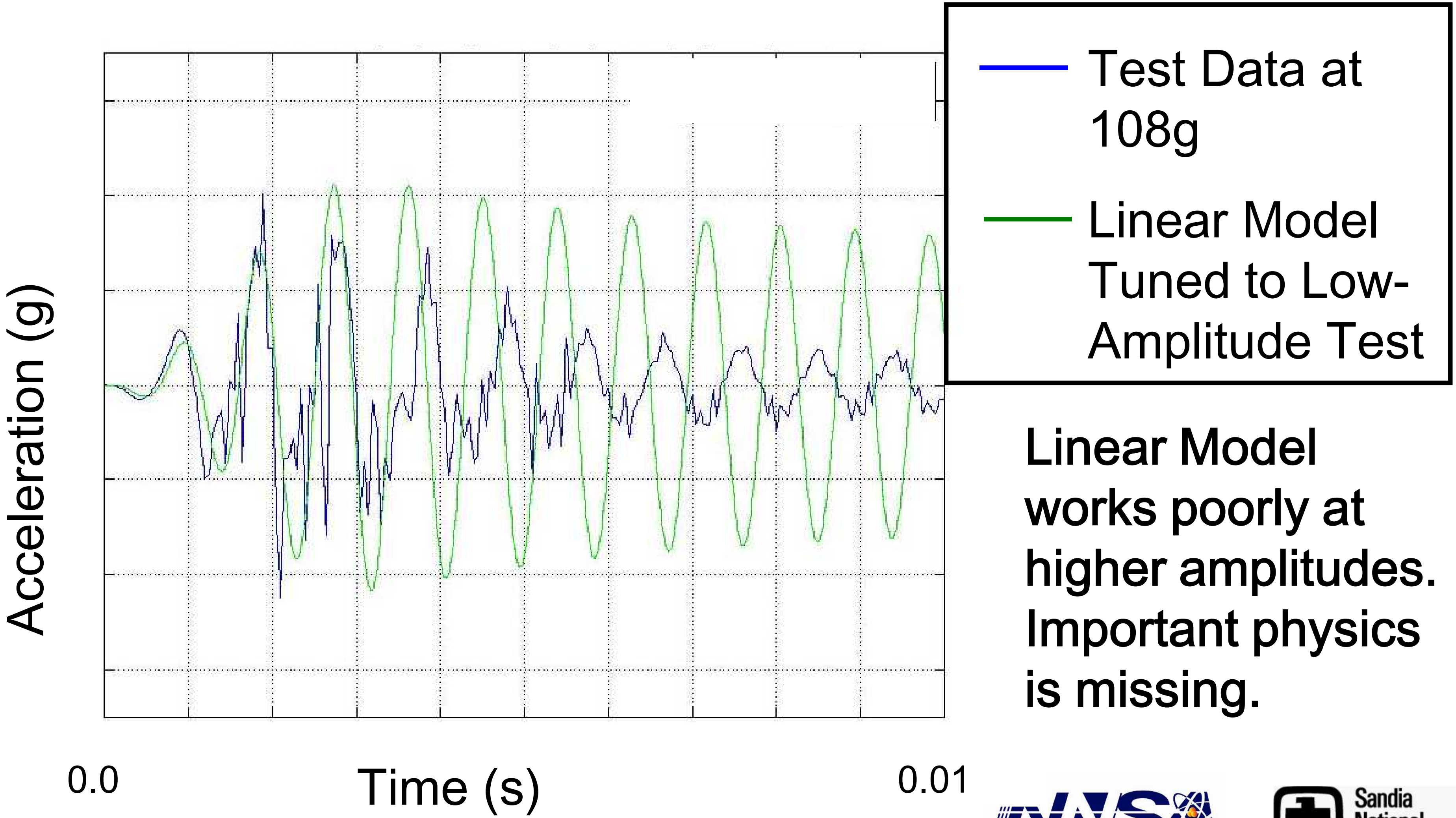
wah1 The upper blue and magenta curves correspond to simulation predictions (linear model) for high-level lateral impulse tests.
waholzm, 1/17/2005

How Well Does a Linear Model Do when Tuned to a Given Experiment?



Linear Model works well at the amplitude at which it was tuned.

How Well Does that Linear Model Do when Tested on a Different Experiment?



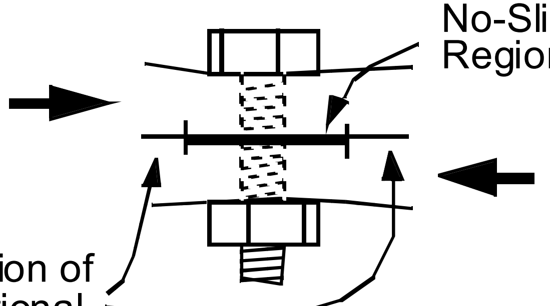
Linear Model works poorly at higher amplitudes. Important physics is missing.

Why Joint Modeling is So Difficult

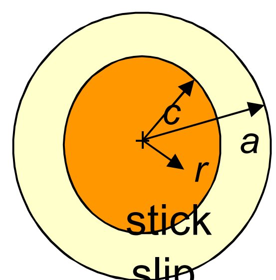
- **Moving boundaries**
- **Intrinsically multiscale**
- **Nonlocal**

Structure ~ meters

component ~ centimeters



"Slip"



Contact patch ~ cm

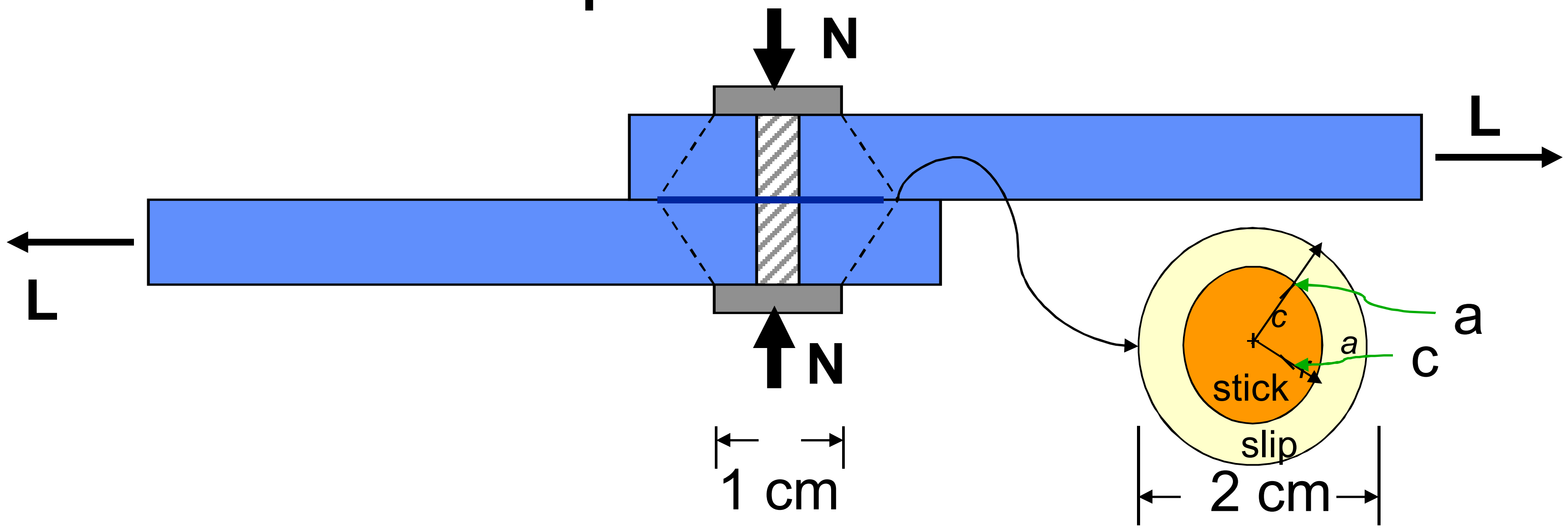
Slip zone ~100 µm

National Nuclear Security Administration

Sandia National Laboratories

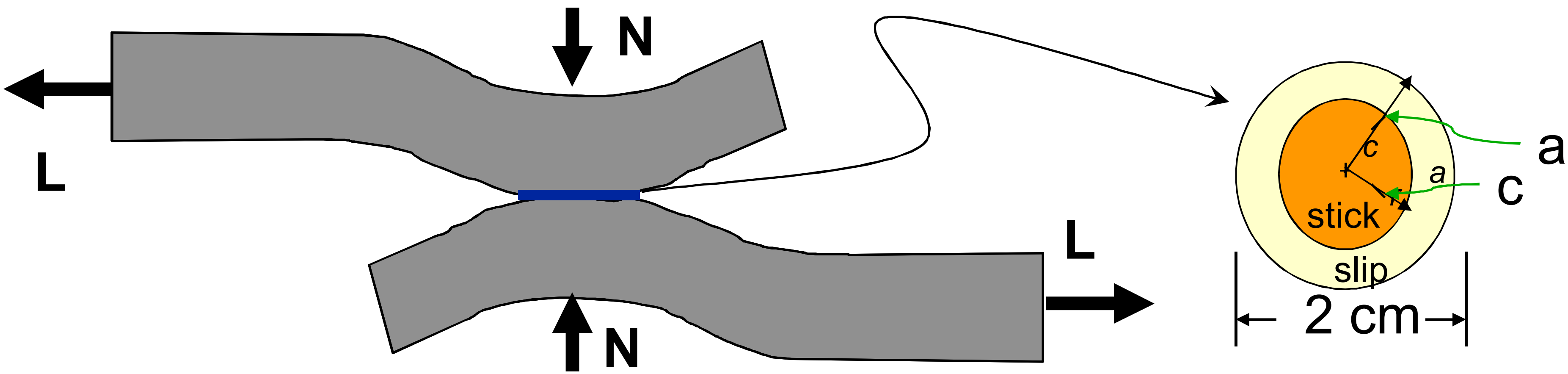
Illustration of Computational Difficulties

- Consider a lap joint with dimensions selected so that the contact patch is circular of radius a=1 cm



- Approximate the elastic contact problem with the Mindlin solution for two spheres.

Estimation of Interface Dimensions



- **Normal Load** $N = 4000\,\text{Newtons}$
- **Lateral Loads** $L \in \left(0.05\mu N, 0.8\mu N\right)$
- **Elasticity that of Steel**
- **Slip Zone:**

Say our interest in structural response is in 100Hz-3500Hz

$$\frac{c}{a} = \left[1 - \left(\frac{L}{\mu N}\right)\right]^{1/3} \Rightarrow \frac{c}{a} \in (0.58, 0.98) \Rightarrow \frac{a-c}{a} \in (0.02, 0.42)$$

Necessary Finite Element Scales
Courant Times

- **For case of small tangential loads** $L = 0.05\mu N$ **element dimension in slip zone necessary to capture dissipation is** $l = \frac{a-c}{10} = 20\mu m$ **and Courant time is 4 ns**
- **To simulate 10 ms (one cycle of 100 Hz vibration) requires 2.5E6 time steps.**

Compare this with 3E4 time steps if the problem were linear and solved implicitly

Even if This Problem is Solved Quasi-Statically

- **In each load cycle, the width of the slip zone twice spans from** $a-c=0$ to $a-c=0.42$
- **With characteristic element size in the contact patch**

$$l=\frac{a-c}{10}=20\mu m$$

- **Observing that quasi-static contact has difficulty changing stick-slip status of more than one node at a time and each time step required numerous iterations**
- **Approximately 800 steps per cycle are required, <u>each representing hundreds of iterations</u>.**

Conservation of Cussedness

Simply Employing More Elements is not the Solution

- **One cannot reasonably directly slave a micro-mechanics contact algorithm to a structural dynamics analysis.**
- **Tools are needed to cross the dimensions**

Interface Mechanics Involve More than Local Constitutive Behavior

- **The surface degrees of freedom on an elastic body are coupled through the elastic fields within the body.**

$$\tau(x) = \int_S G(x,y)\,u(y)\,dA$$

- **Displacement is solved subject to constraints**

$$\dot{u}(x)\left(\left|\tau(x)\right| - \mu\sigma_N\right) = 0 \text{ and } \left|\tau(x)\right| \le \mu\sigma_N$$

- **Refinement of the friction constitutive equation still leaves a difficult nonlinear system of equations to solve**

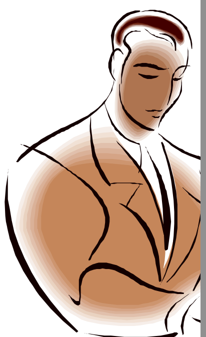
Refinement of frictional laws may be necessary to obtain better answers, but it cannot simplify the problem

National Nuclear Security Administration

Sandia National Laboratories

Standard Practice for Ignoring the Nonlinearity of Joints in Structural Dynamics

How … sis



t is
n
del

Elements of Process

- Assume system to be linear
- Represent each joint DOF as a linear spring
- Build and test a prototype structure
- Tune the spring stiffnesses to match frequencies
- Tune modal (or more complicated) damping to match damping of structure

Analyst c… coarse m… model pu… tunable s… interface… postulating proportional/modal damping

stiffness and modal damping to match test. He then makes prediction

Not Predictive for Real Systems

If you have to build the full structure in order to predict structural response, then you are not predictive.

The problem is fundamentally nonlinear and important phenomena cannot be captured by tuned linear models. (Silk purse/Sow's ear issue.)

The Beginning of an Approach to Accommodate Joint Nonlinearities

What would be the first step to bring more physics into the analysis?

- **Explicitly account for the joint nonlinearity**
- **Place a joint model at the location of the actual joint.**

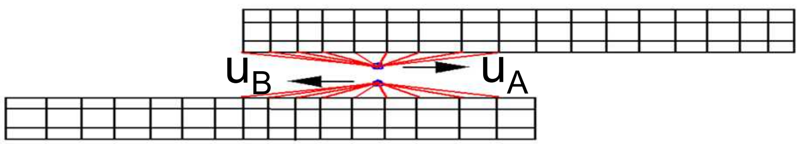
Strategy

- **Represent the <u>whole joint</u> with a small number of scalar constitutive models.**
- **Determine the parameters of these models either from micro-modeling or from experiments on individual joints.**

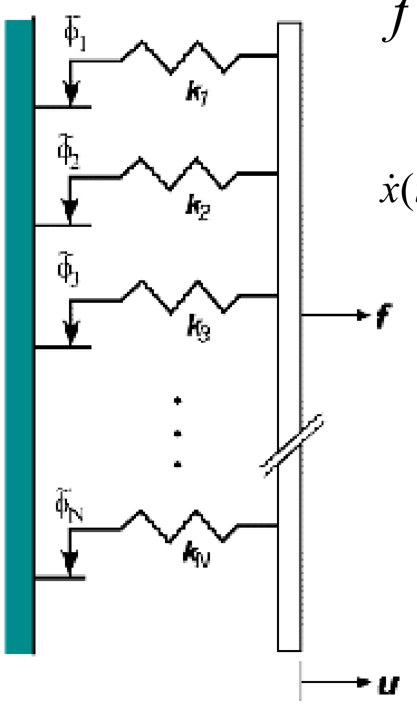
D.J. Segalman <u>ASME Journal of Applied Mechanics</u>, <u>V. 72</u>, 752 (2005)

D.J. Segalman, <u>Structural Control and Health Monitoring</u> <u>V. 13</u>, Issue 1, (2006)

The Whole-Joint Approximation and Iwan Models for Shear Joints

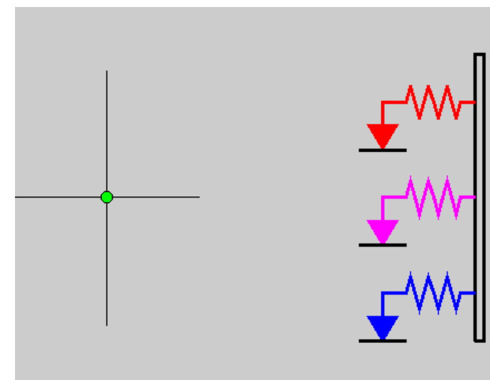


Whole-Joint approximation for interface



$$f(t) = \int_0^\infty \rho(\phi)[u(t) - x(t,\phi)]\, d\phi$$

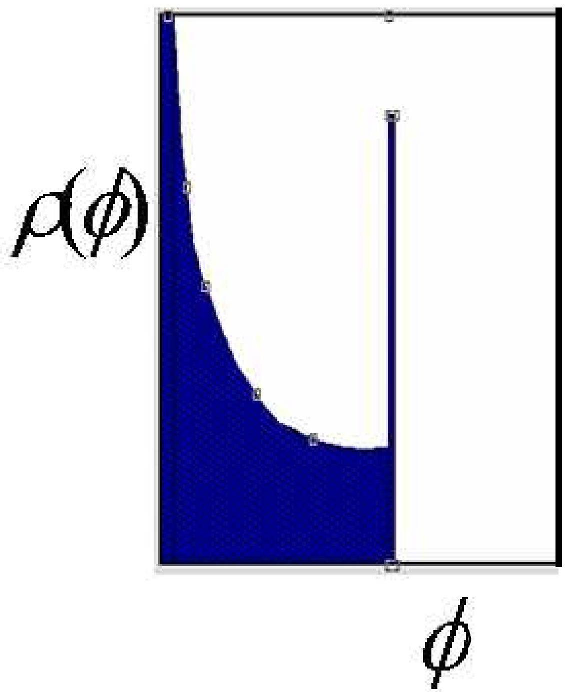
$$\dot{x}(t,\phi) = \begin{cases} \dot{u} & \text{if } |u - x(t,\phi)| = \phi \text{ and } \dot{u}\,(u - x(t,\phi)) > 0 \\ 0 & \text{otherwise} \end{cases}$$



The joint properties are characterized by $\rho(\phi)$

A Four-Parameter Iwan Distribution

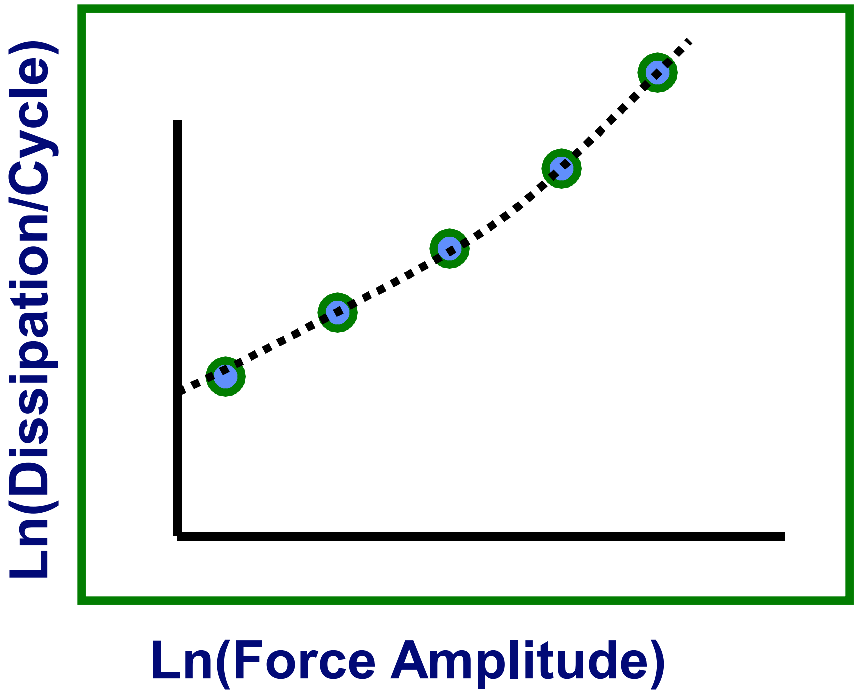
$$\rho(\phi) = R\phi^{\chi}\left(H(\phi) - H(\phi - \phi_{\max})\right) + S\delta(\phi - \phi_{\max})$$

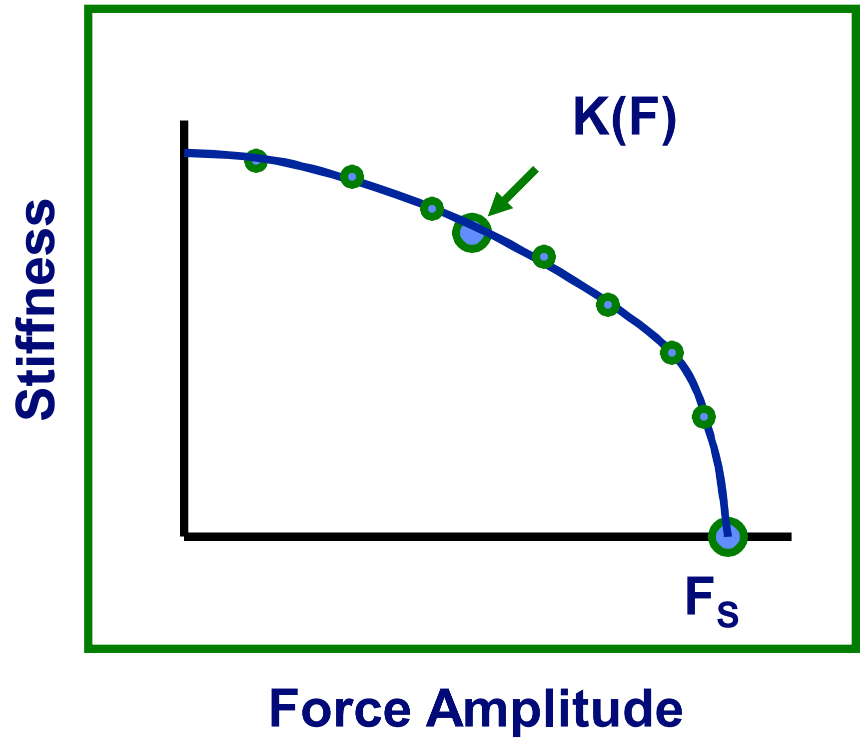


- Nearly linear behavior at low amplitude.
- Power-law energy dissipation
- Manifests micro- & macro-slip
- Physically reasonable
- Tractable

Parameters $R, S, \chi, \phi_{\max}$ map to some or more physical significance F_S, K_T, χ, β

Determining Joint Parameters: Measured Properties



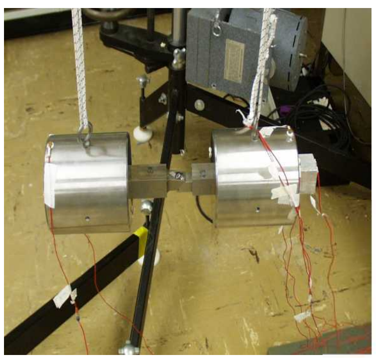


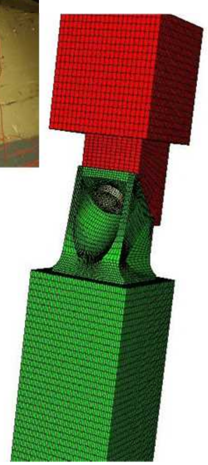
Experiments yield dissipation D(F) as a function of force amplitude, tangent stiffness K(F) at load, and yield force F_S.

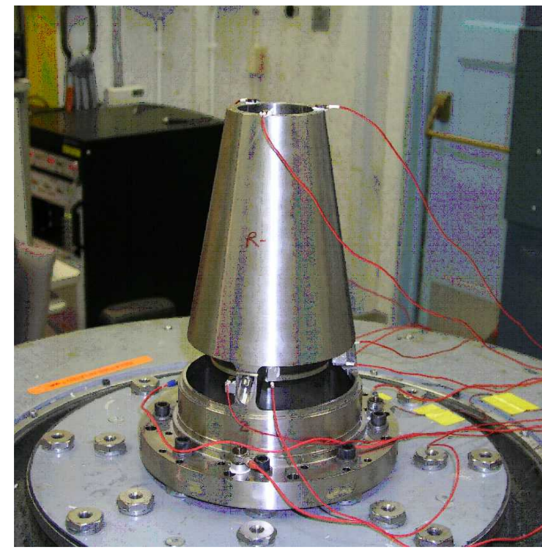
National Nuclear Security Administration

Sandia National Laboratories

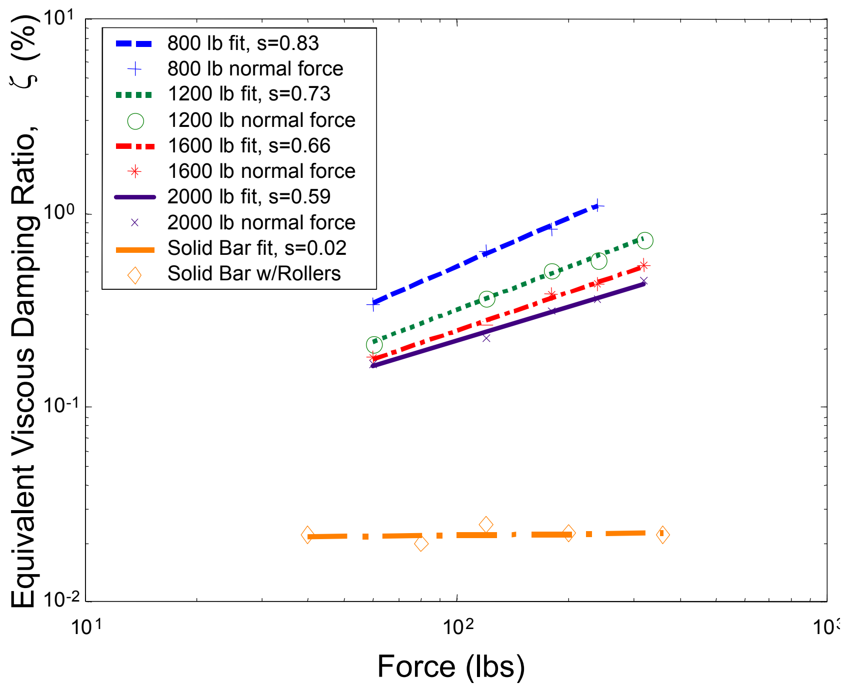
Calibration of Individual Joints to Predict Dynamics of 3-Legged Structure

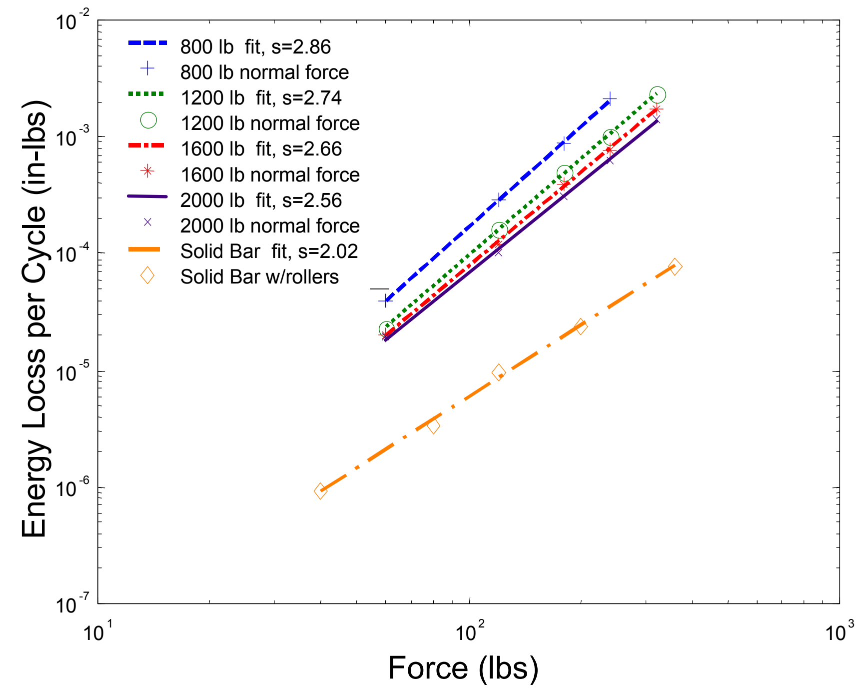






C6: Calibration of Individual Joints and Estimation of Part-to-Part Variability

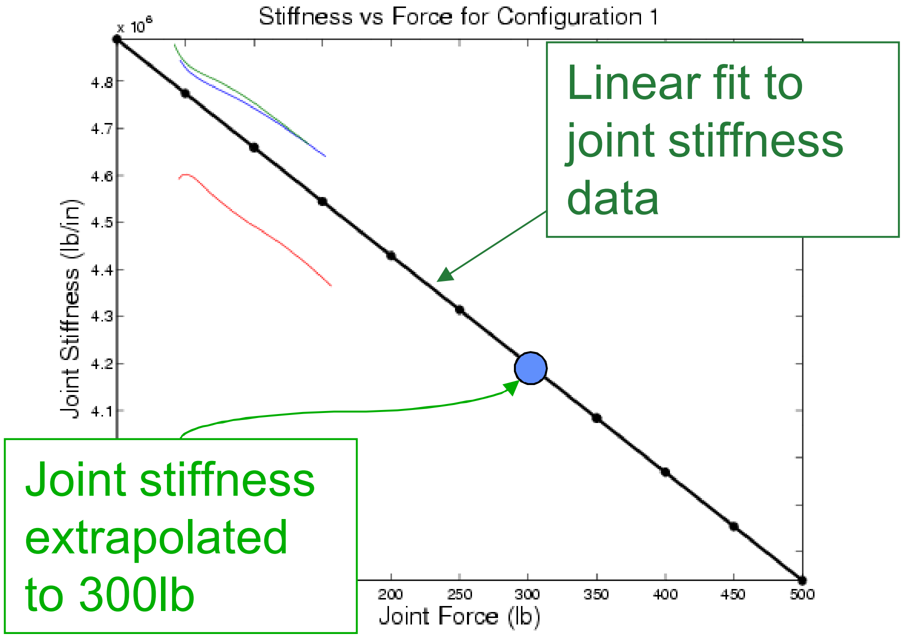




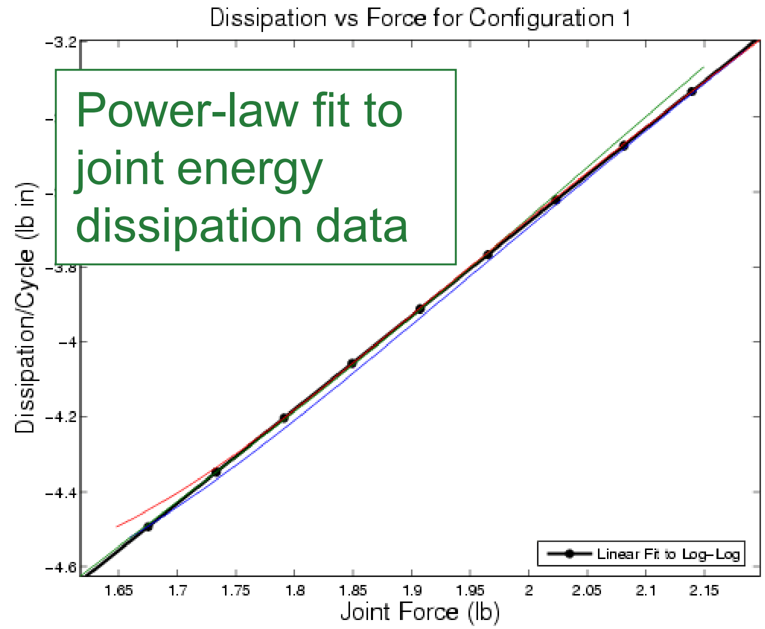
Slopes of Energy Dissipation Decrease with increasing normal force ---Seek relationship $E = K(n)F^{s(n)}$

Damping and Energy Loss per Cycle for Simple Lap Joint: C6

Plot Joint Stiffness and Dissipation as Functions of Joint Force



Joint Stiffness



Joint Dissipation

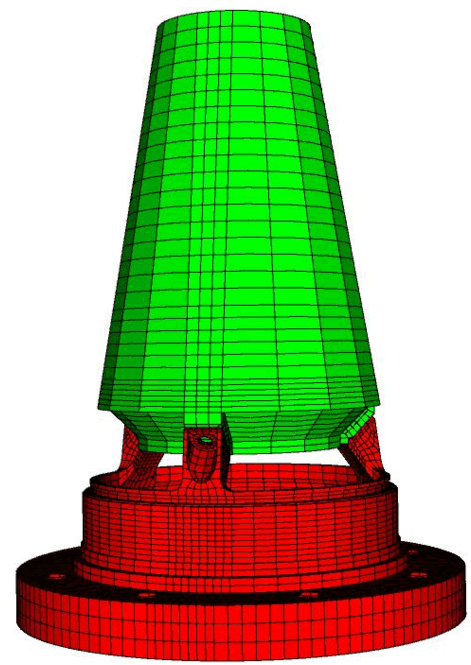
Model Parameters are selected to match the stiffness at 300lb force and to match the apparent power-law dissipation.

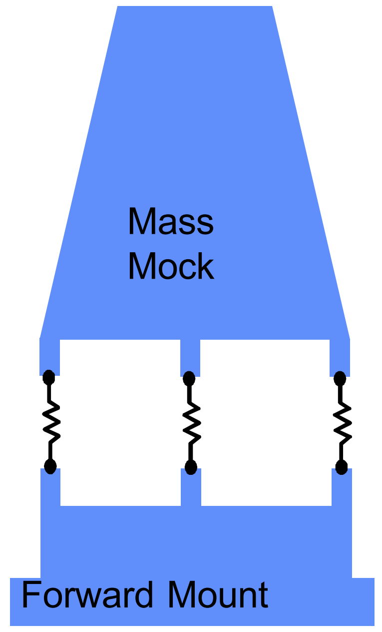
Analysis Code: *Salinas*

- Hostile simulations performed with Salinas
  - Massively parallel finite element code
  - Sandia developed (ASC)
  - Linear & nonlinear structural dynamics
  - Runs on all ASC platforms (required due to model size and complexity)
- Allows us to tailor code capabilities to unique RB/RV modeling needs
  - Thermostructural response loading
  - Mechanical joint behavior

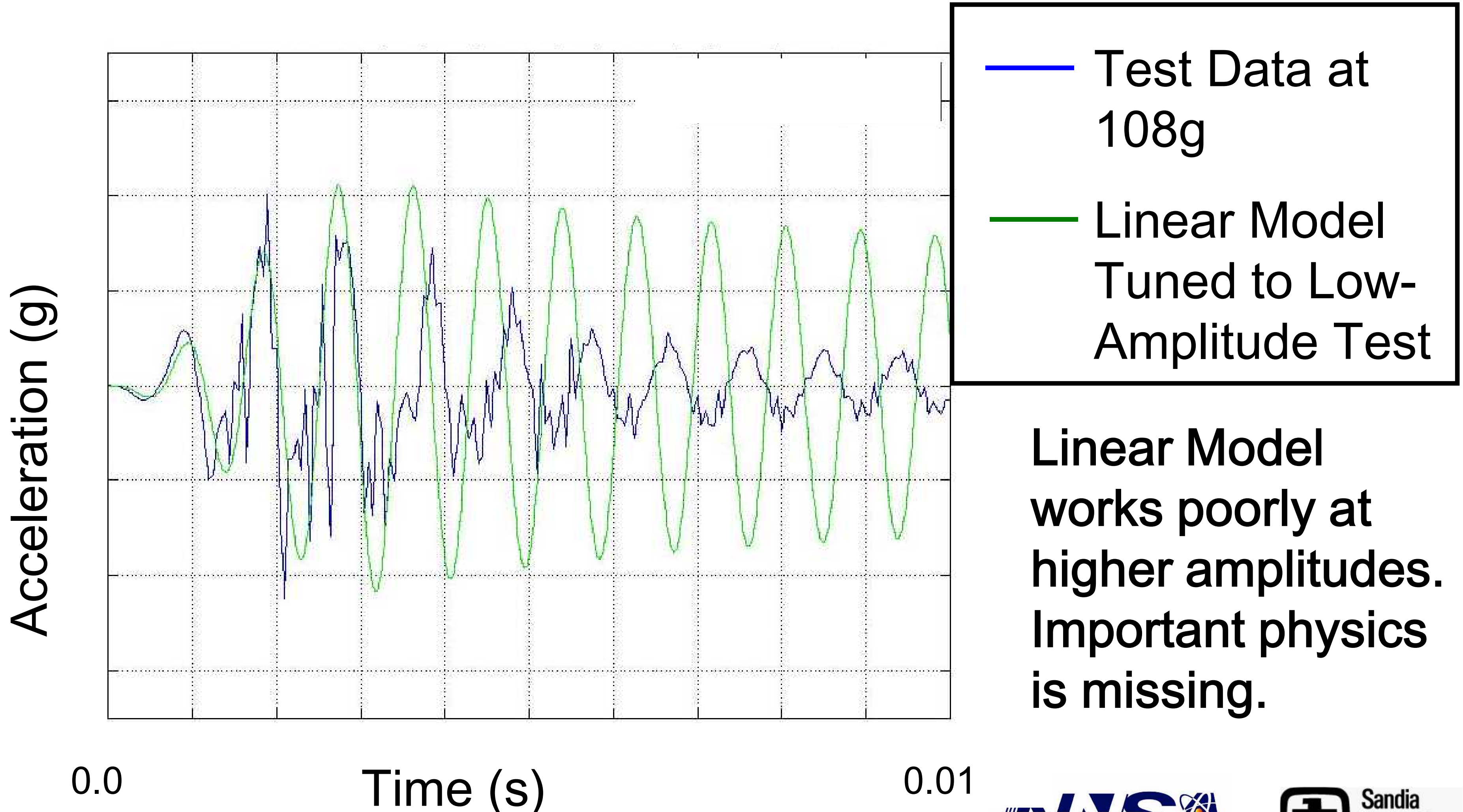
Predictions of Structural Dynamics Code (MP) Using a Joint Model

- Employ 4-parameter model at joint
- Represent the rest of the structure with linear finite elements
- Excite base sufficiently to cause macro-slip.





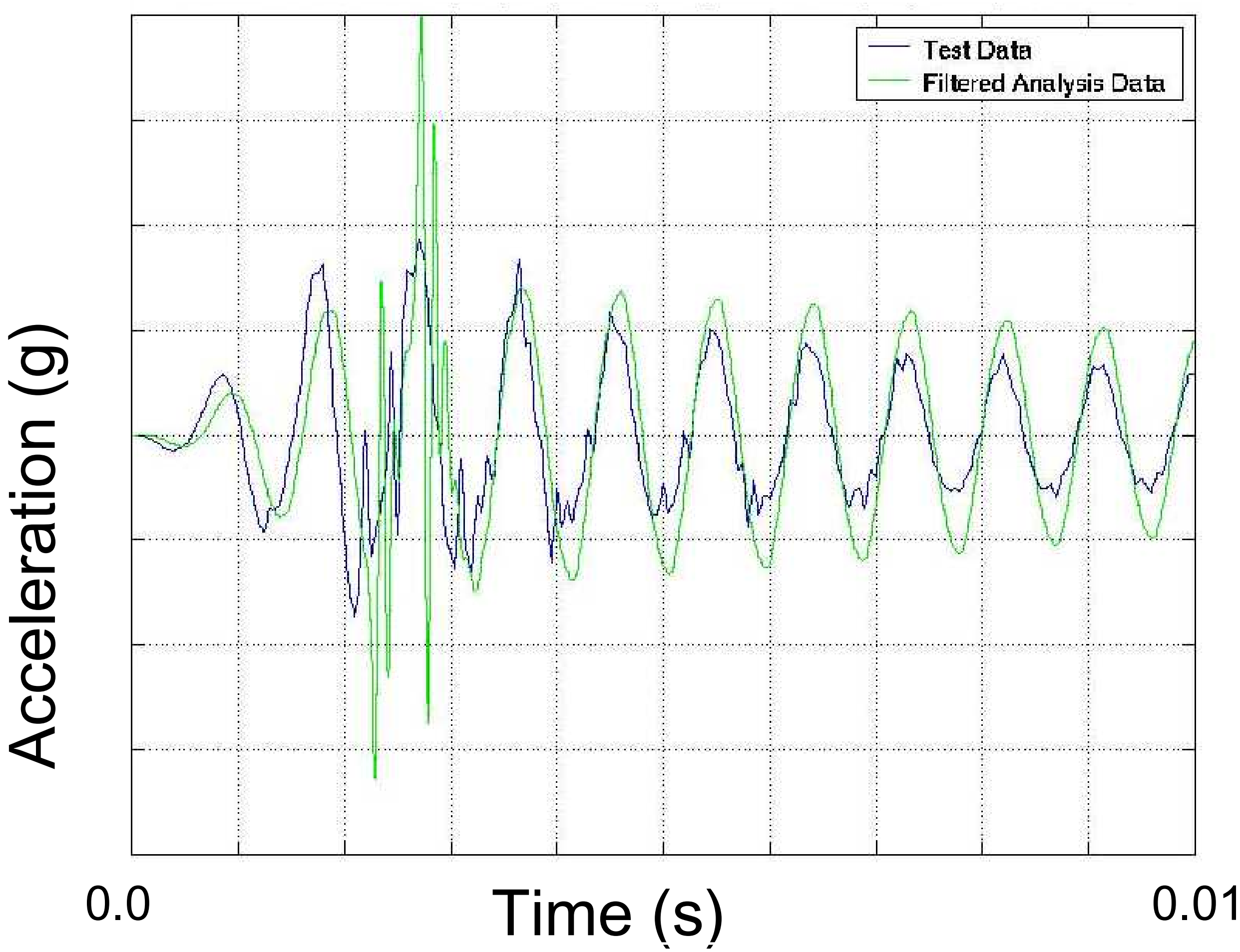
How Well Does that Linear Model Do when Tested on a Different Experiment?



Linear Model works poorly at higher amplitudes. Important physics is missing.

wah2

How Well Does This Model Do When Predicting 3-Legged Structure?



Test Data at 50g

4-Parameter Iwan Model. **No tuning for this structure.**

50g Axial Base Acceleration Case

National Nuclear Security Administration

Sandia National Laboratories

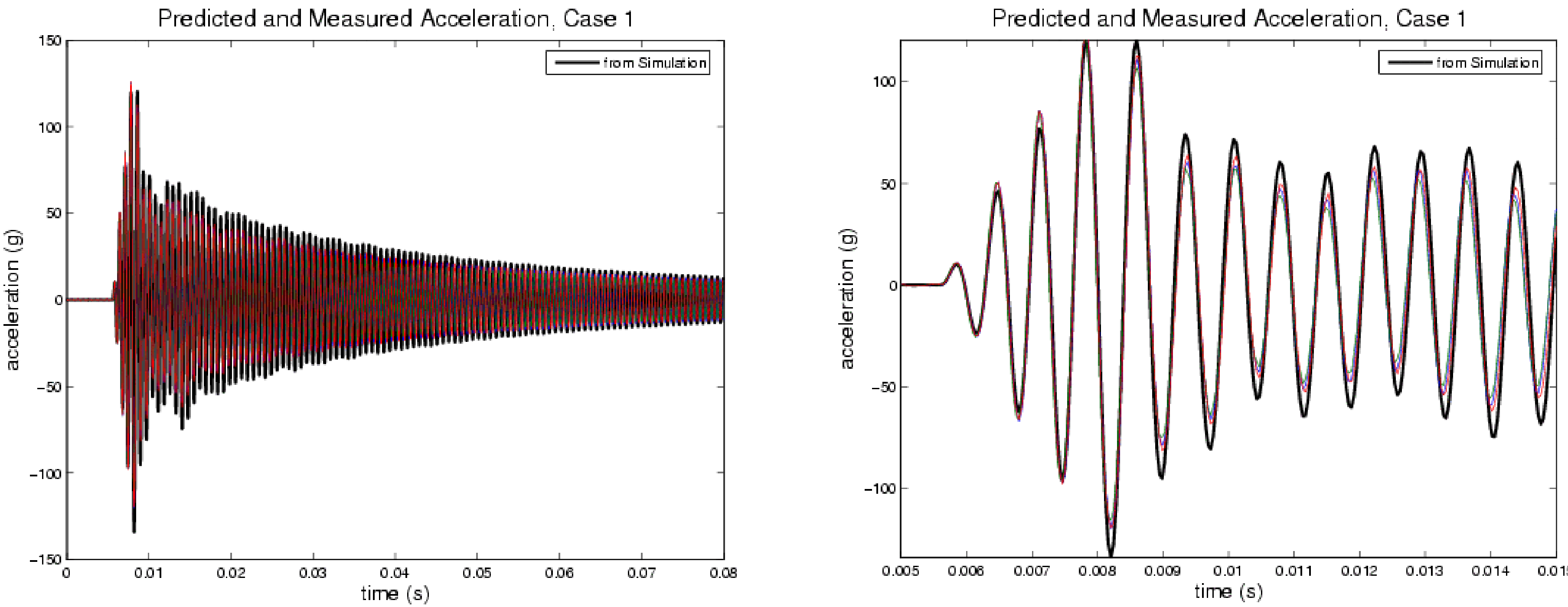
Slide 36

wah2 Change 3rd line of title to:

50g Axial Base Accleration Case

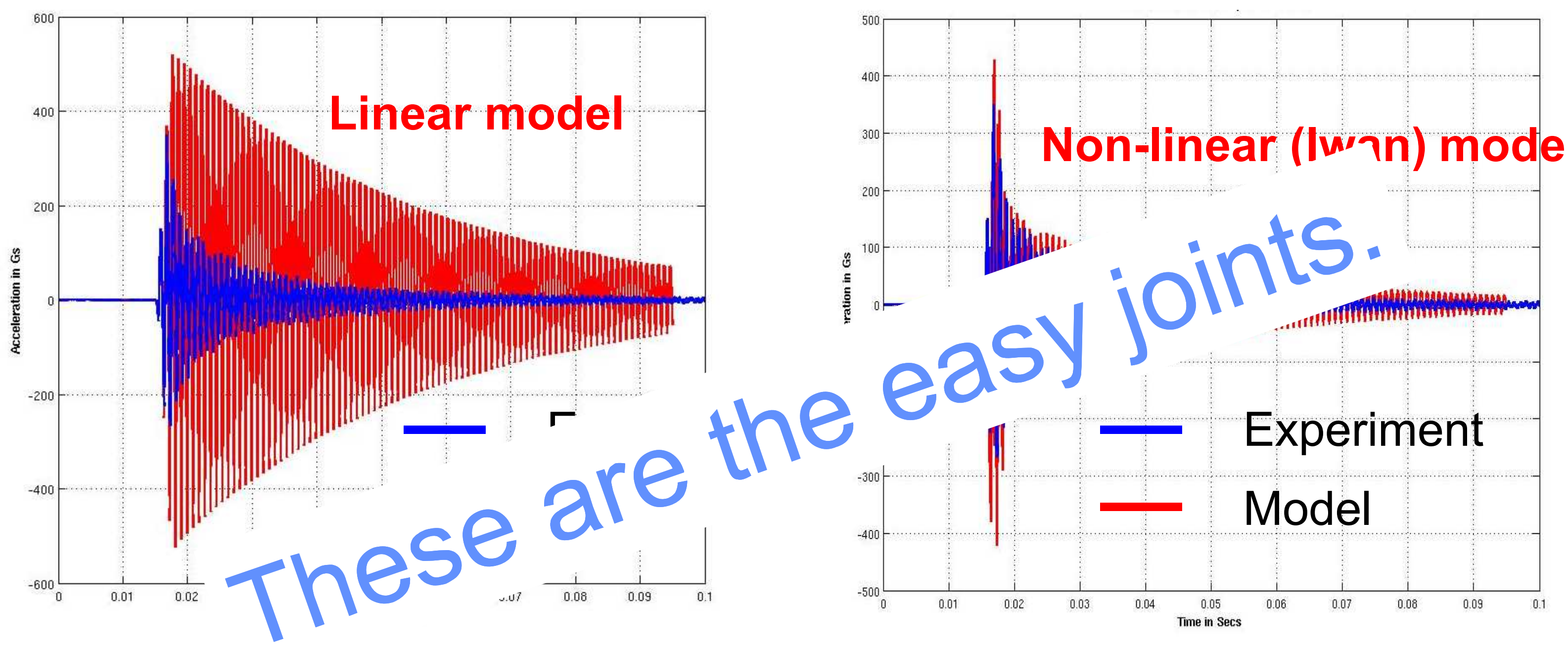
waholzm, 1/17/2005

Blast Simulation for Configuration 1



Explicit incorporation of a joint model can significantly improve the quality of predictions.

Predictions for Axial Base Excitation that Entails Macro-Slip



Explicit incorporation of a joint model can significantly improve the quality of predictions.

Other Challenges

- It is necessary to characterize every joint that is explicitly included in the structural dynamics calculation. What about distributed damping where hundreds or thousands of interfaces are involved?
- Particularly in shock, a realistic joint model in cause excitation of very high frequency harmonics that drive the computational time step down.

Distributed Damping

- It is plausible to incorporate explicitly a small number of joints along the major load paths.
- It is also plausible to consider explicitly the joints under specific critical components.
- Explicit consideration of all interfaces that contribute to the overall damping of the structure is not tractable.

This is a New Project

- We really do not know how we are going to do this.
- This problem is important enough that we are willing to take the risk.

Nonlinear Structural Model Reduction LDRD

One Part of a Two Part LDRD

- **Model reduction is necessary for rapid analysis of dynamics of structures with nonlinearities – essential at design stage.**
  - **Nonlinearities require nonlinear solutions – generally with embedded linear solutions. Each time step has substantially more burden than is the case for linear problems.**
  - **Sharp nonlinearities – such as are associated with joints – excite high frequency response.**
    - **Implicit solvers will not converge at large time step, necessitating many small time steps.**
    - **Even with convergence, there is often non-physical hash**
  - **Desire mathematical mapping that results in**
    - **Far fewer degrees of freedom**
    - **Larger time steps**

Why Galerkin with Modes of Reference Linear System Fails

- A standard approach to slightly nonlinear systems
  - Consider nonlinear system
  - Identify a reference linear system
  - Identify the eigen modes of that reference system
  - Employ assumed modes in a Galerkin solution for our nonlinear system
  - Solve resulting nonlinear system of equations for α_k
- Works best for distributed and very weak nonlinearities.
- Converges very poorly for strong, localized nonlinearity.

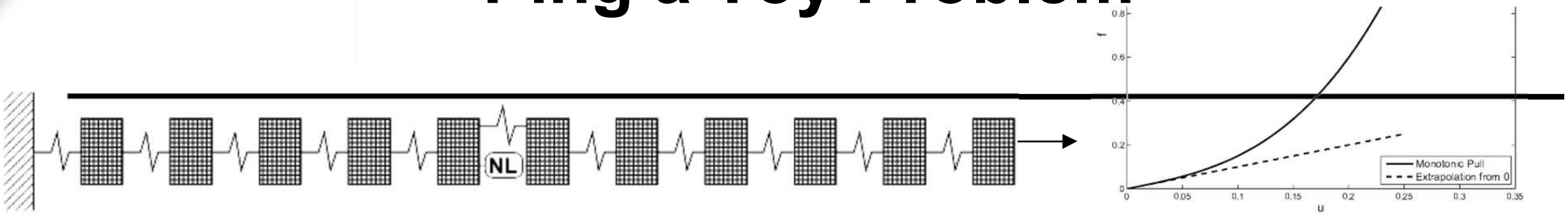
$$M\ddot{x} + C\dot{x} + Kx + \varepsilon N(\{x\}) = f(t)$$

$$M\ddot{x} + C\dot{x} + Kx = 0$$

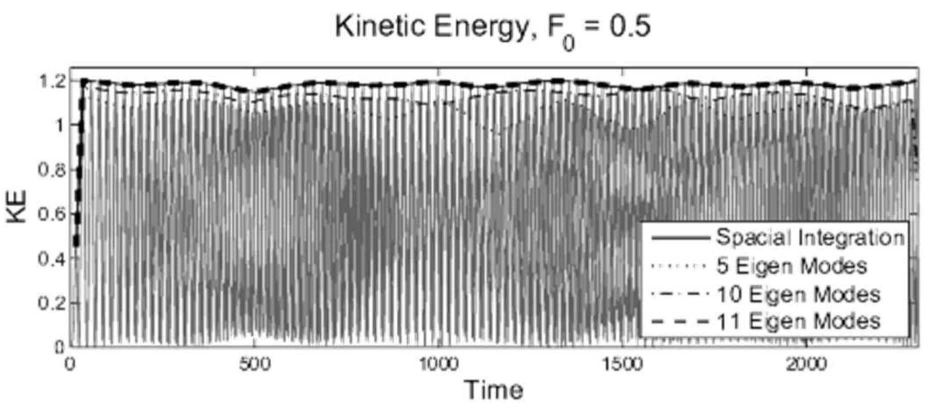
$$\omega_k^2 M y_k = K y_k$$

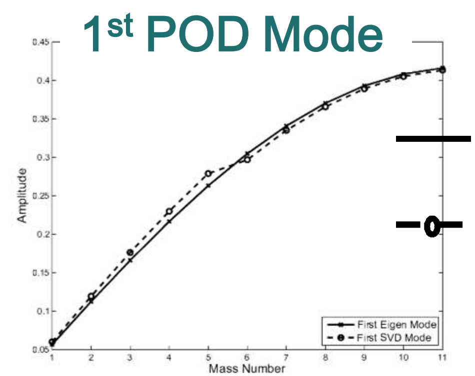
$$x(t) = \sum_1^N \alpha_k(t)\, y_k$$

Ping a Toy Problem



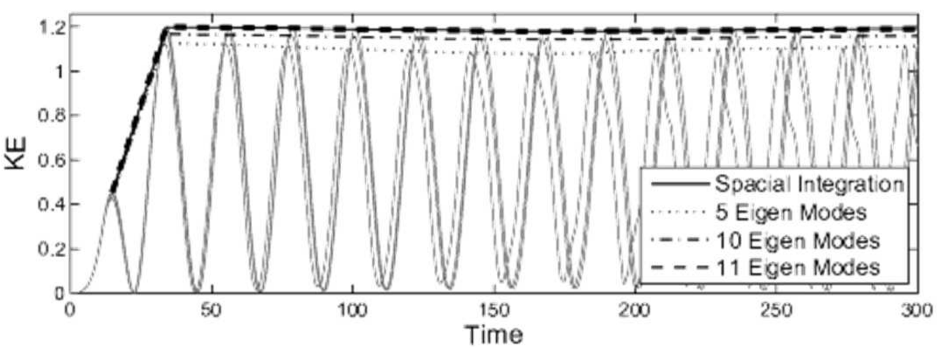
Cubic Nonlinearity





1st mode of reference linear system

1st POD mode



The configurations of the nonlinear response are not in the space spanned by any <u>proper</u> subset the linear modes.

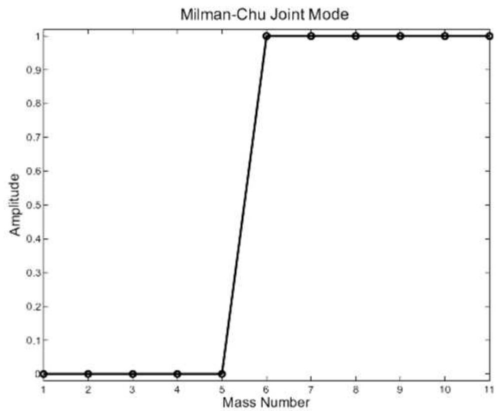
National Nuclear Security Administration

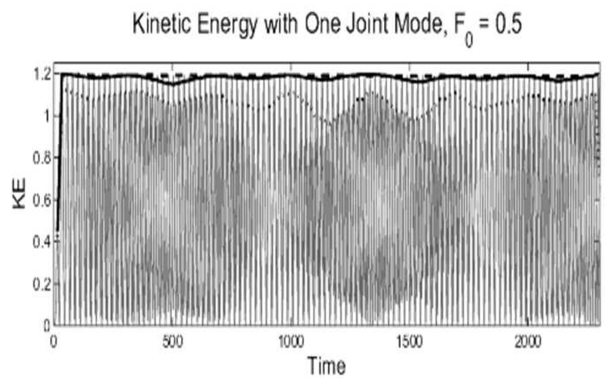
Sandia National Laboratories

Epiphany: If the Basis is Insufficient and the POD appears discontinuous …

Let's augment eigen modes with discontinuous basis functions.

Obtained by applying equal and opposite forces to the reference linear system at the joint locations. (Cheap)

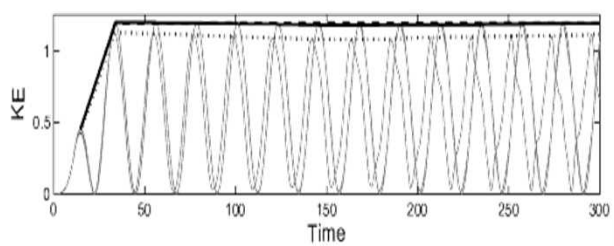




Spatial Integration

5 Eigen Modes

1 Eigen Mode + 1 Joint Mode

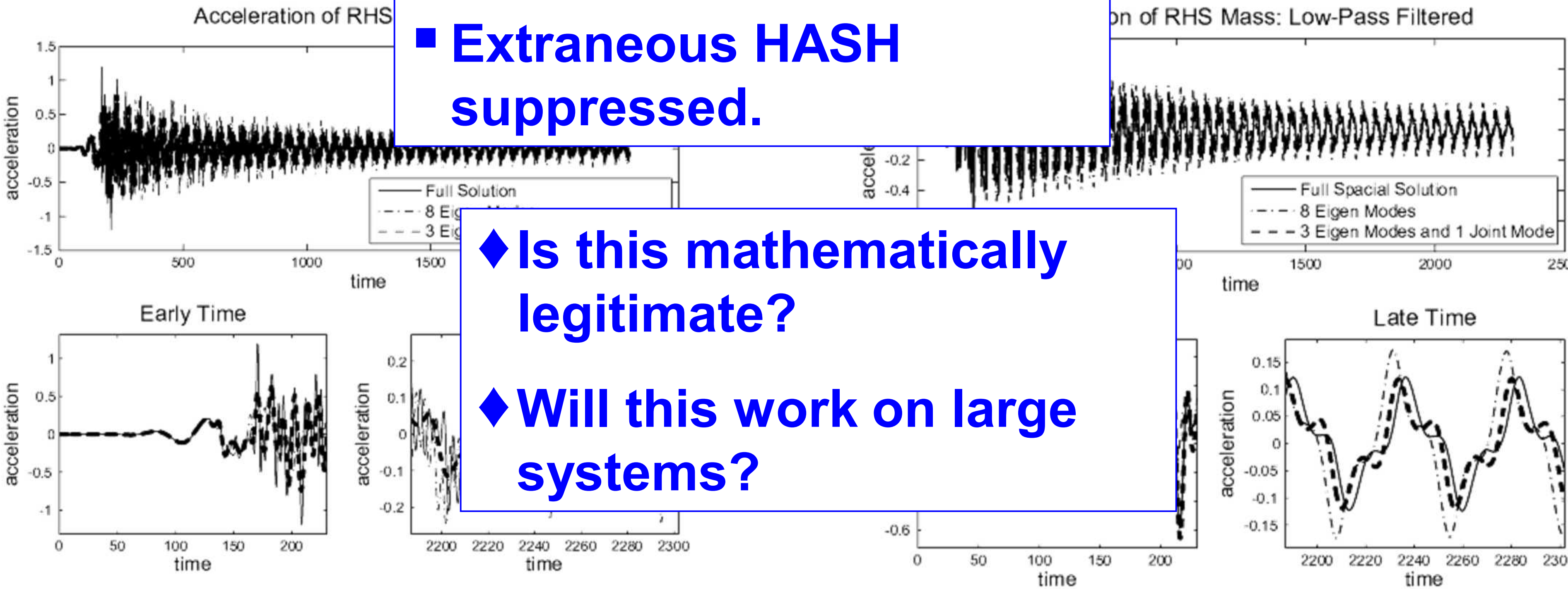


National Nuclear Security Administration

Sandia National Laboratories

Case of Joint Nonlinearity & High Impulse

- Number of DOF reduced.
- Time step increased.
- Extraneous HASH suppressed.



♦ Is this mathematically legitimate?

♦ Will this work on large systems?

The reduced order model appears to capture the low frequency response.

The full solution and the reduced solution are similar when filtered.

NNSA National Nuclear Security Administration

Sandia National Laboratories

Conclusions: I

- **Conventional structural dynamics is not predictive in the manner now required**
- **There are fundamental barriers to incorporating micro-meshes in structural dynamics calculations**
- **Employing joint models explicitly in structural dynamics can greatly improve the quality of predictions**

Conclusions: II

- The whole-joint approach, though a significant improvement is no where near adequate
  - Does not account for the multi-dimensional nature of loads.
  - Does not account for the true complexity of contact: moving contact patch, varying normal loads …
  - Induces fallacious stress fields near contact.
- Fundamental research must be done in understanding joint mechanics and realizing that understanding in terms of predictive and useful structural dynamics tools.

We need not new models, but better models

Structural Dynamics of Jointed Structures is Analogous to Hydrodynamics with Turbulence

Turbulence	Joints
• Multiple scales limit DNS	• Multiple scales limit DNS
• Closure models are postulated to connect micro-mechanics to continuum	• Closure models are postulated to connect micro-mechanics to continuum
• Fundamentally important in Fluid Mechanics	• Fundamentally important in Structural Dynamics
• Long-Standing Problem	• Long-Standing Problem
• Very significant in drag, less significant in lift	• Very significant in damping, less significant in stiffness
• Heuristic, qualitative understanding	• Heuristic, qualitative understanding

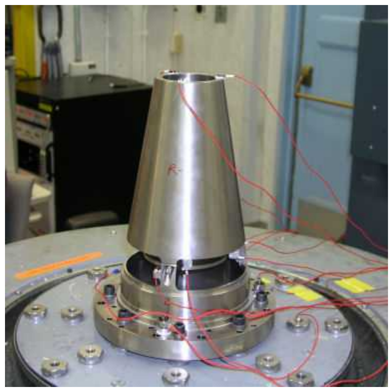
Backup

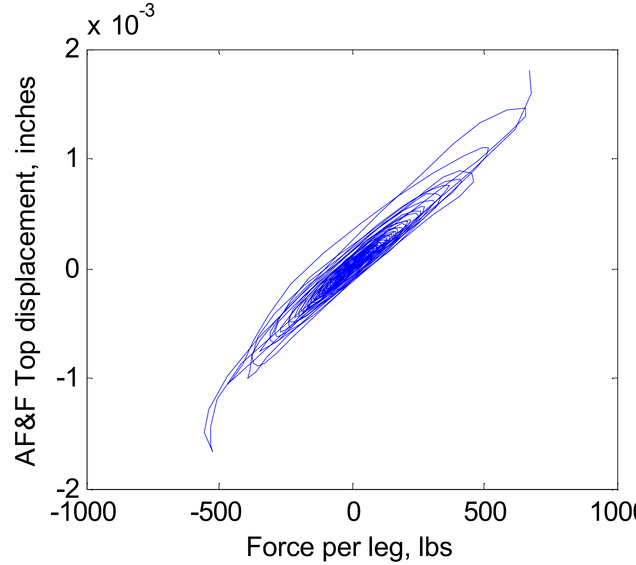
Deducing Joint Parameters

Shaker and Quasi-static Testing Determined Macro-slip Break-Free Force

Nominal macro-slip force (forward mount and internal)

Ti-SS mass mock 3-leg hardware

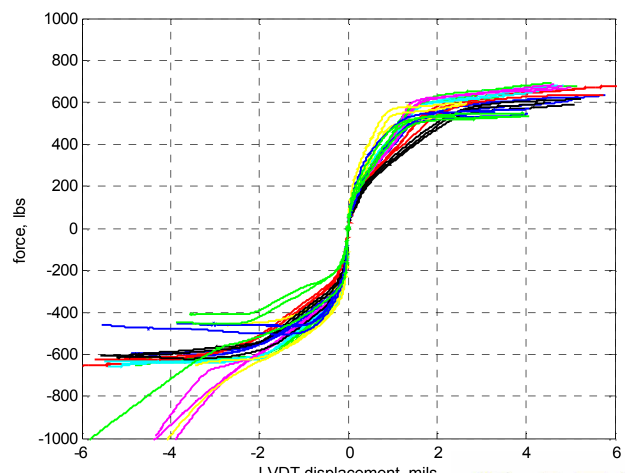




F_S = 615 lb

Joint bounding range

SS-SS single leg hardware

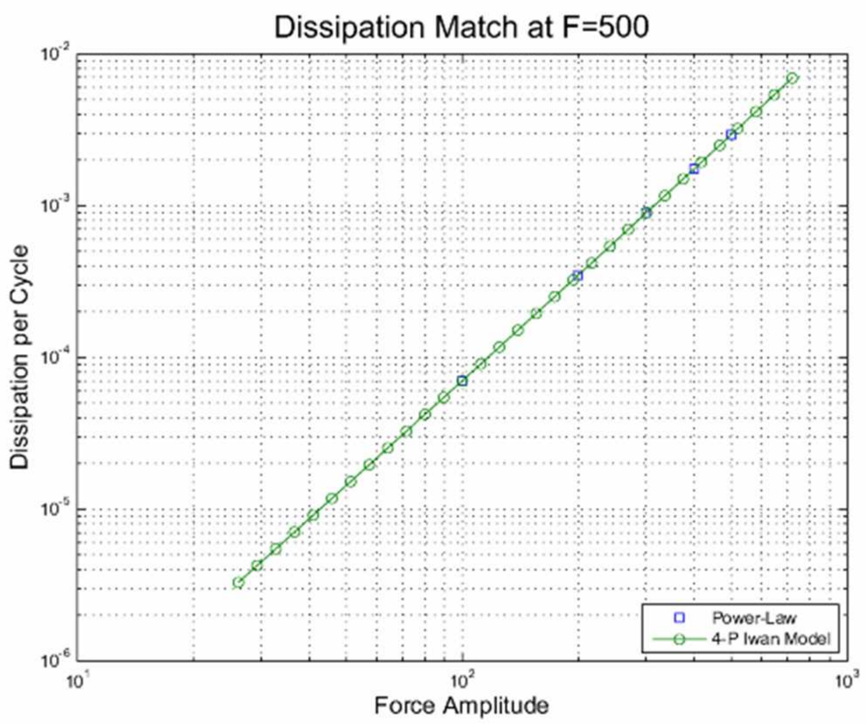


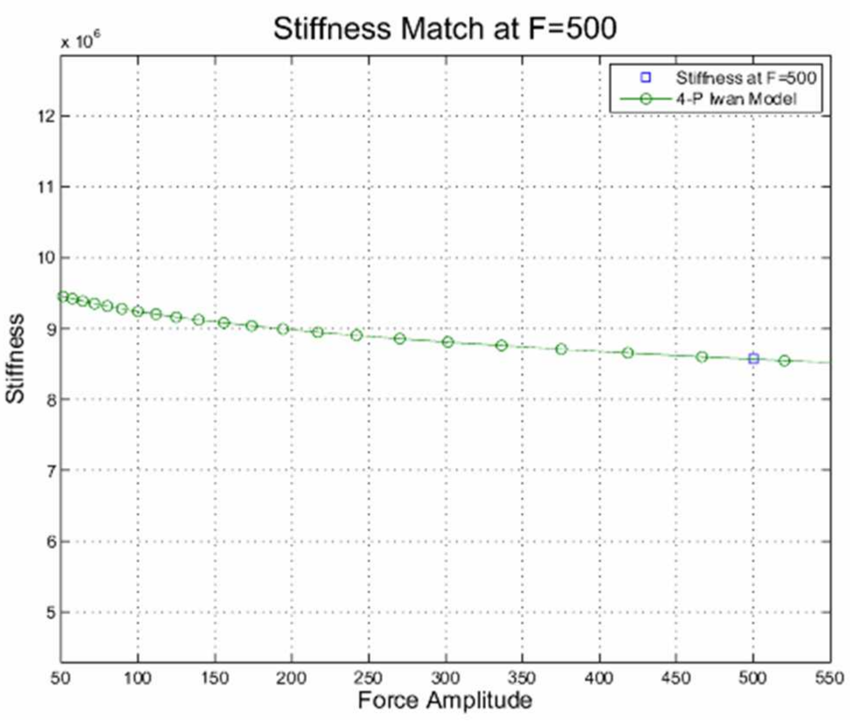
F_S = 450 lb to 634 lb

NNSA National Nuclear Security Administration

Sandia National Laboratories

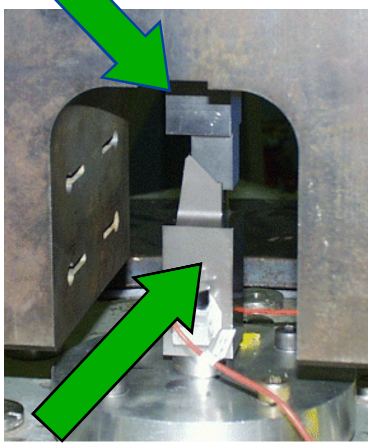
Quality of Fit for 4-Paramerter Iwan Model





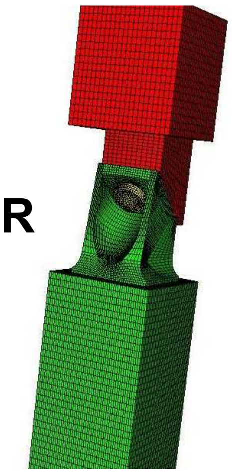
Characterize 1-Legged Experiment to Predict 3-Legged Response

Stainless Steel



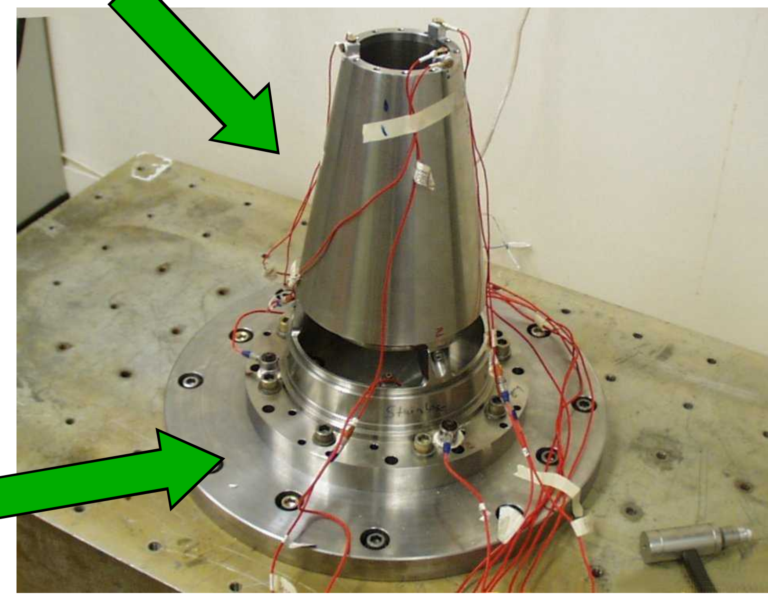
Titanium

OR



Prediction

Stainless Steel



Titanium

Steady-State
Resonance
Experiments

Deduce
Model
Parameters

National Nuclear Security Administration

Sandia National Laboratories

Review and Approval
Unclassified, Unlimited Release