SAND2006-6541P

Challenges in Joint Modeling for Structural Dynamics

Why This Issue is Important and
Why These Problems are Hard

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Outline

- Predictive Modeling
  - Where it is Important
  - The Tall Pole in the Tent
- Empirical Properties of Joints: Softening and Dissipation
- Why Joint Modeling is Hard
  - More Elements is not a Solution
  - Local Properties are only Part of the Story
- Standard Practice
- The Beginning of an Approach to Accommodate Joint Nonlinearities
- How Life Should Be
  - Mapping from multiscale physics to FE environment
  - Roark's Handbook for properties and parameters

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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**

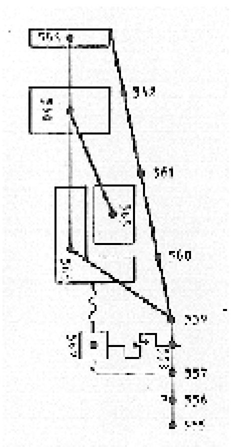
Predictive Modeling – Is that not what we already do?

- 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

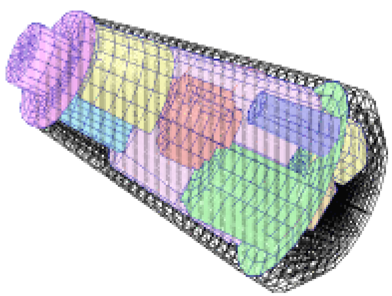
Traditional Barriers to Predictive Modeling

- 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

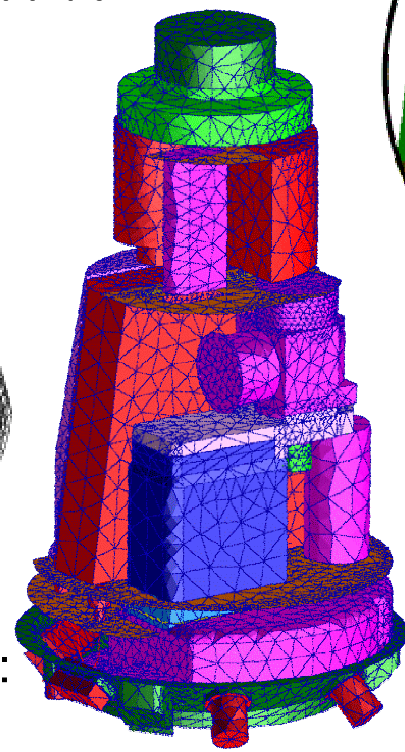


10 years ago:
Shellshock 2D
NASTRAN
200 dof

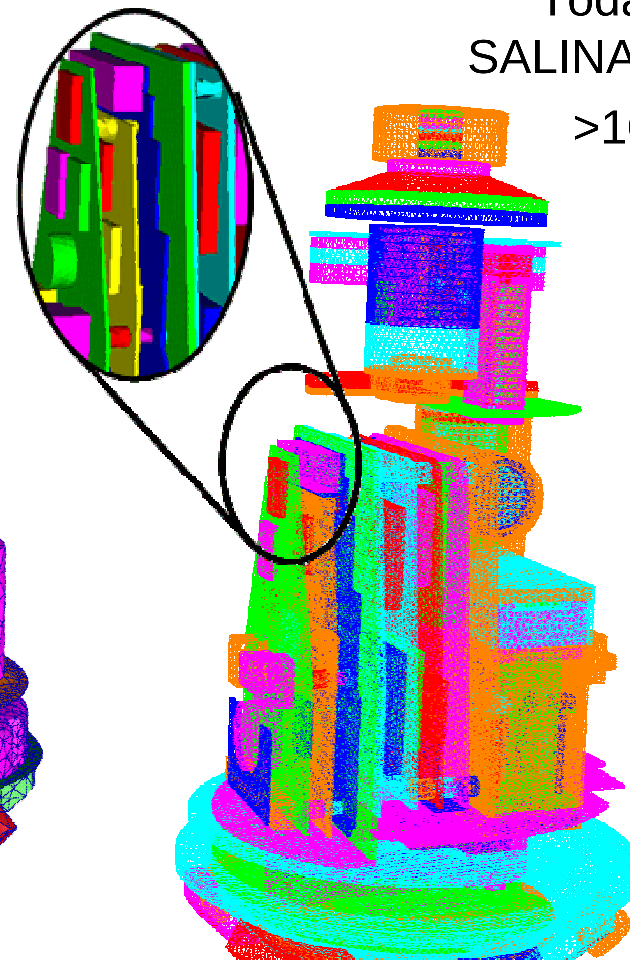


Recent Past:
NASTRAN
MC2912
30,000 dof

800,000 dof



Today:
SALINAS MP
>10M dof.



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 workshop

} Topics include misfit, interference, and variability

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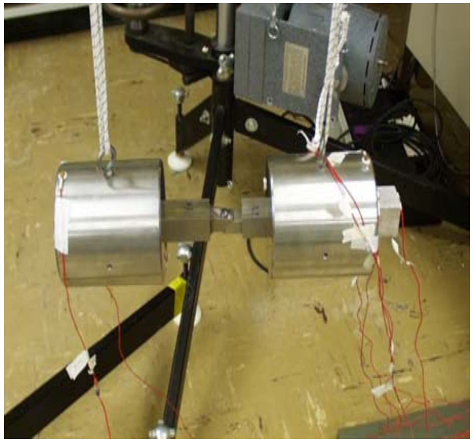
Significance of Joint Mechanics to Structural Dynamics

- **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

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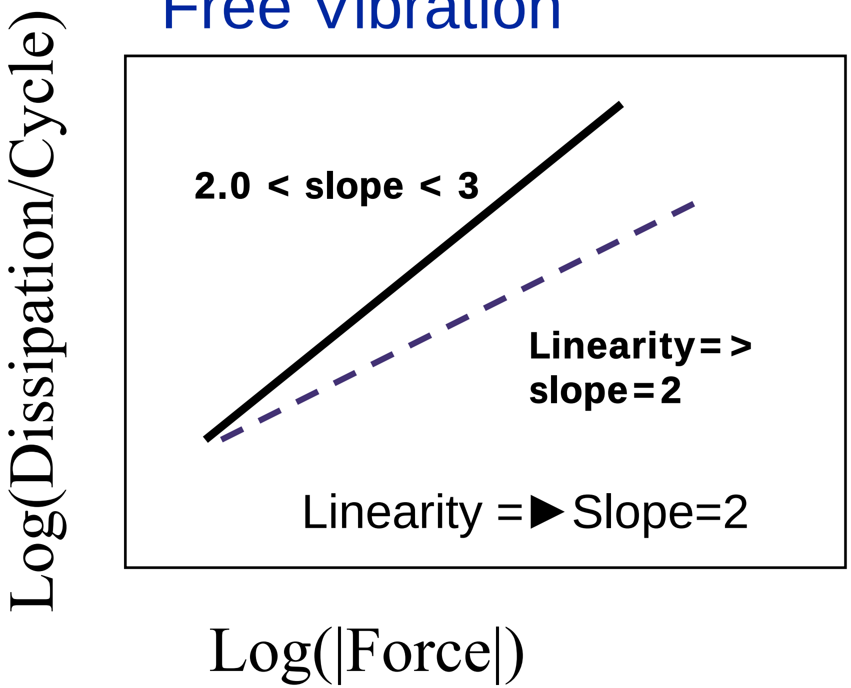
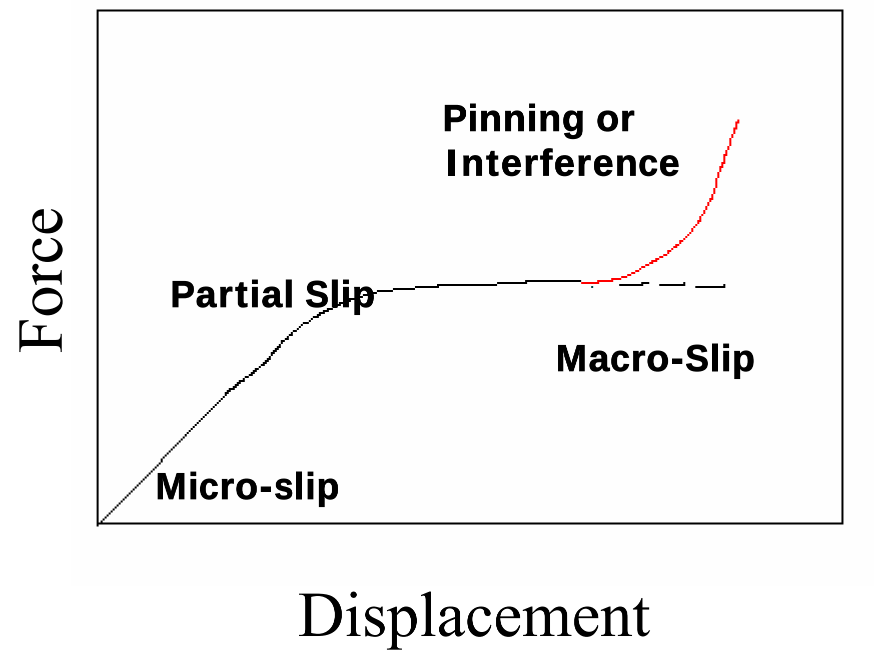
Empirical Nonlinearity of Joints

Base Excitation or Free Vibration

Monotonic Pull

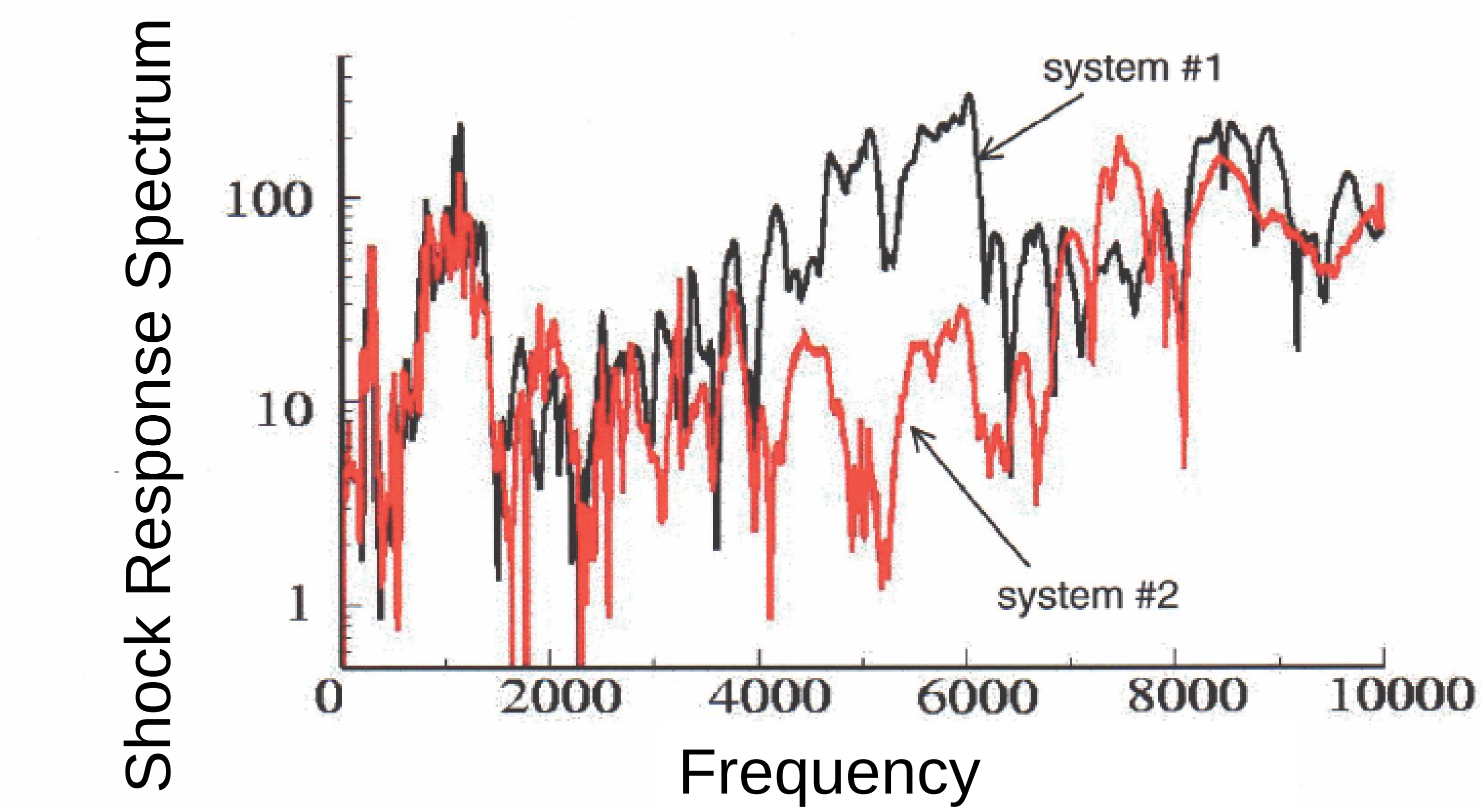




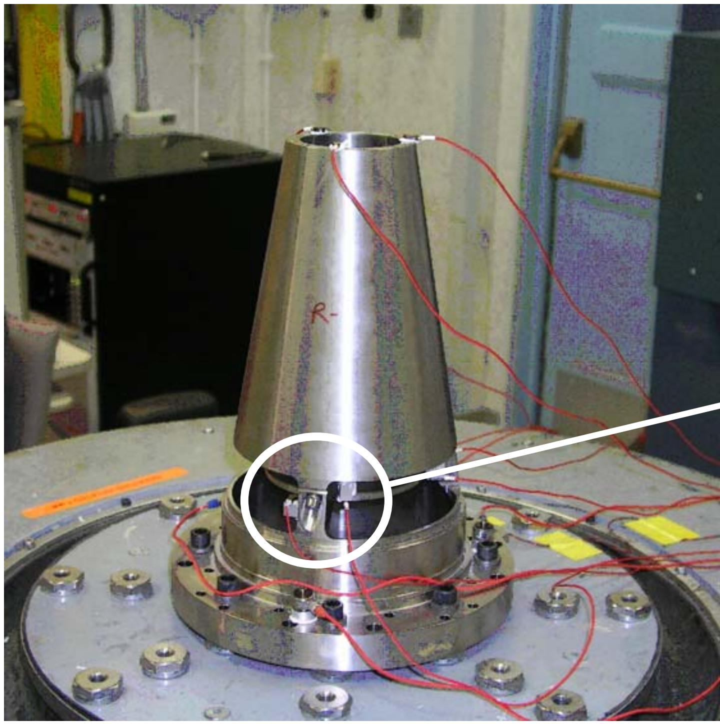
Nonlinearities even at Small Displacement

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.

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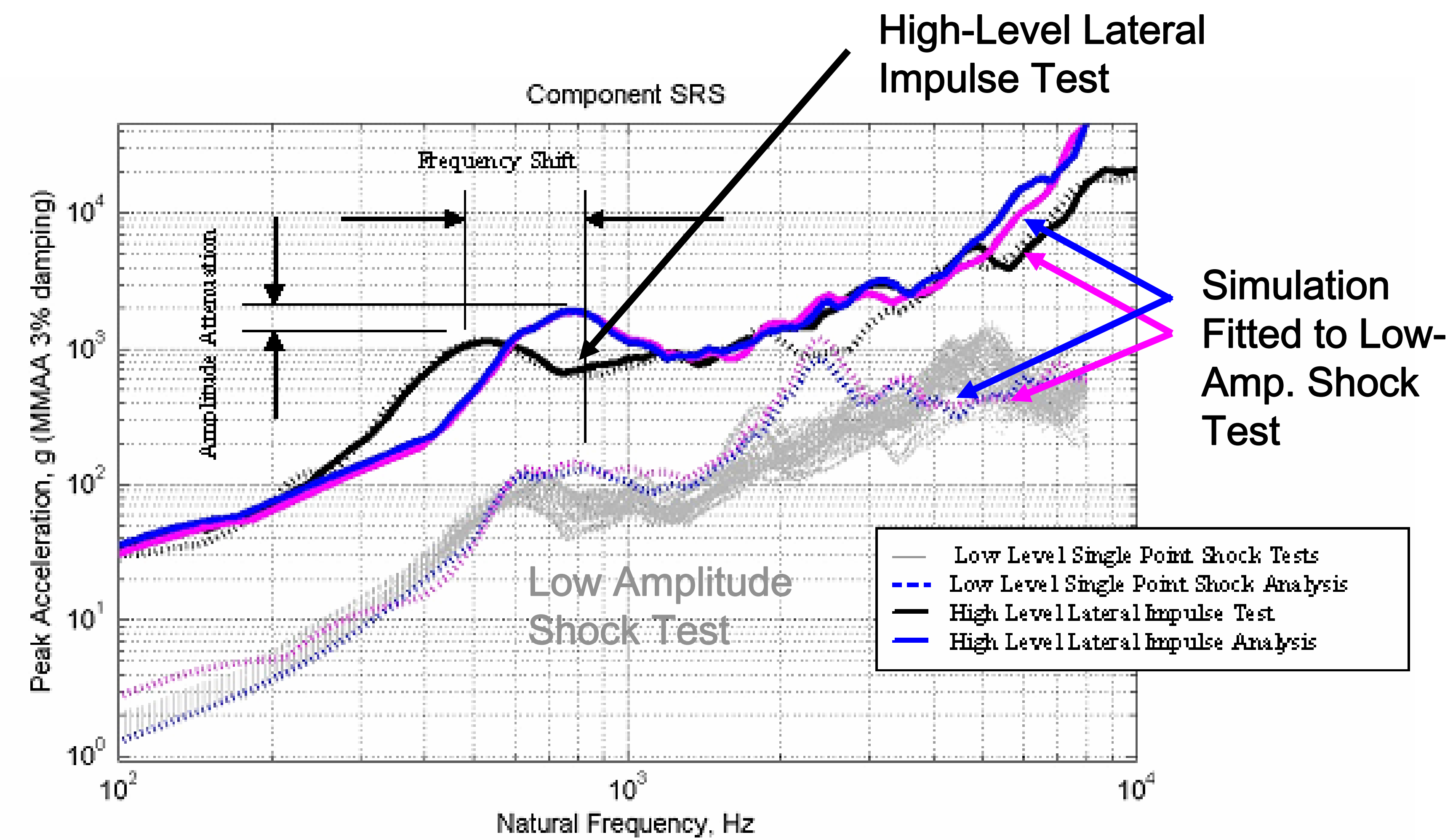
wah1

Nonlinearities Indicated by Shock Response Spectra: Particularly Stiffness Nonlinearity



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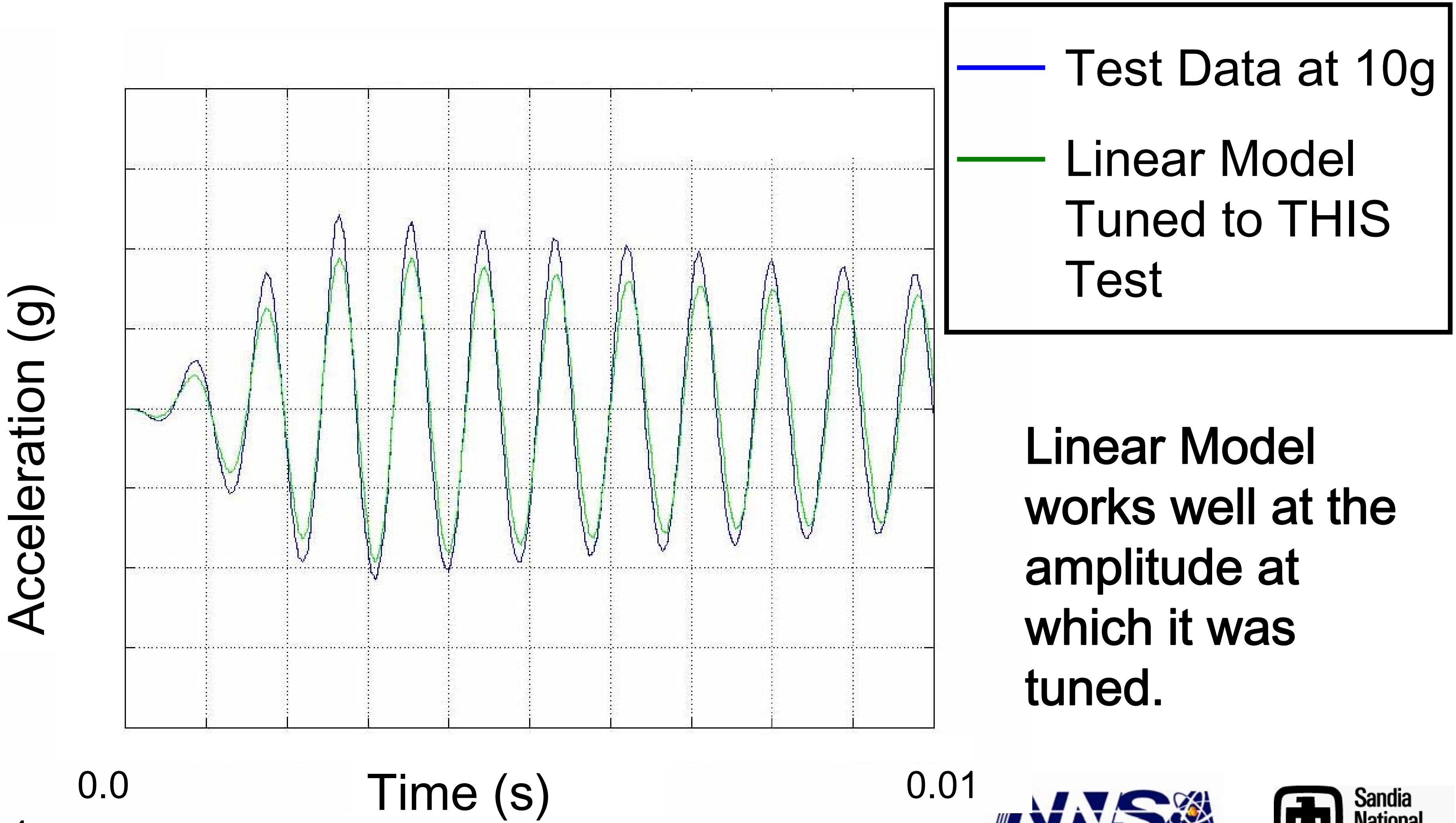
wah1 The upper blue and magenta curves correspond to simulation predictions (linear model) for high-level lateral impulse tests.
waholzm, 1/17/2005

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.

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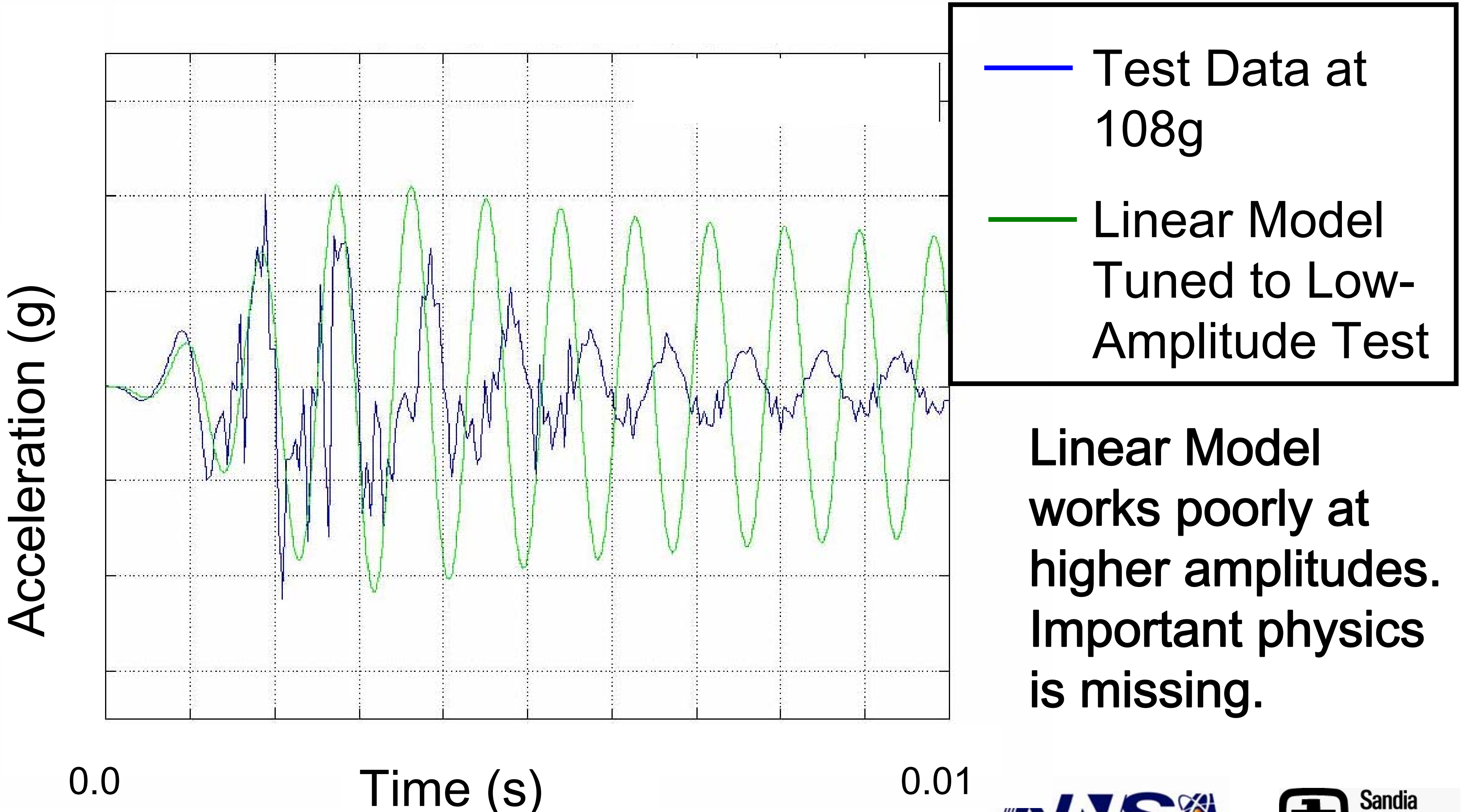
How Well Does that Linear Model Do when Tested on a Different Experiment?



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

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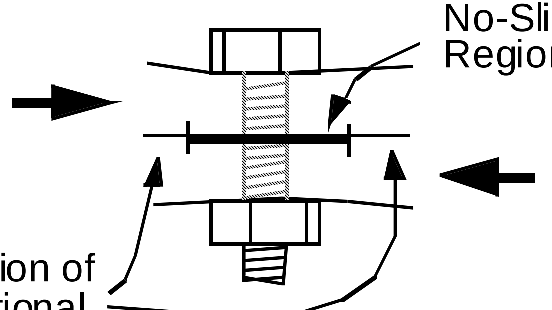
Why Joint Modeling is So Difficult

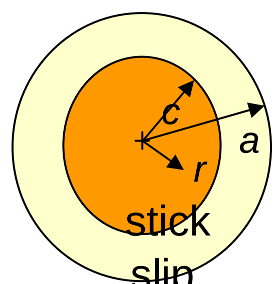
- **Moving boundaries**
- **Intrinsically multiscale**
- **Nonlocal**



“Slip”

Structure
~ meters

component ~
centimeters

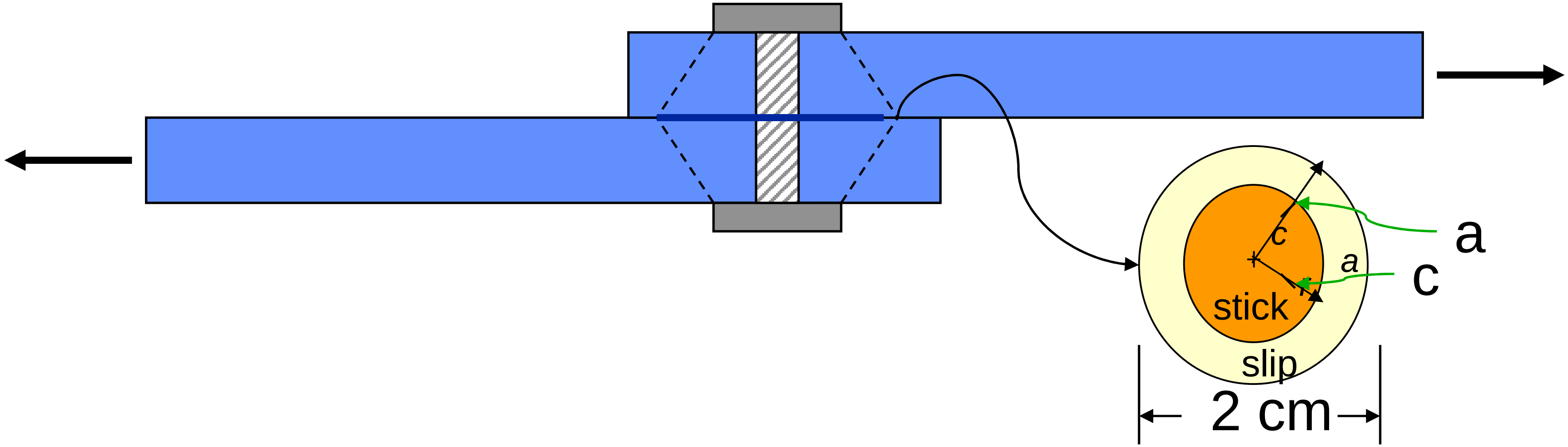


Contact
patch ~ cm

Slip zone
~100 µm

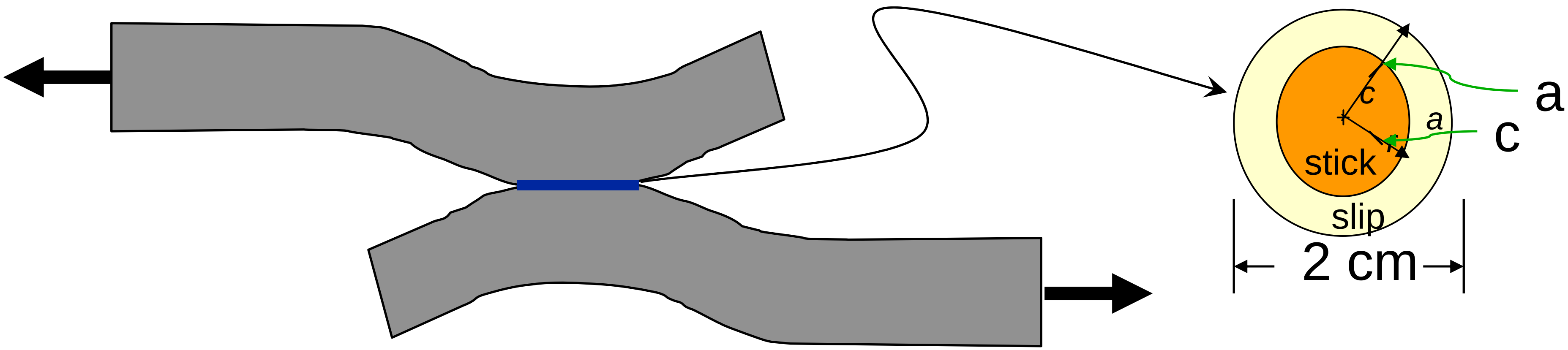
Illustration of Computational Difficulties

- **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

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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

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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… interfaces… 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 whole joint 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 ASME Journal of Applied Mechanics, V. 72, 752 (2005)

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

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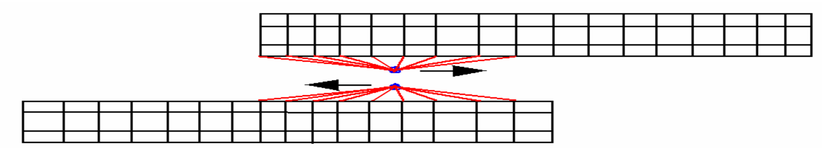
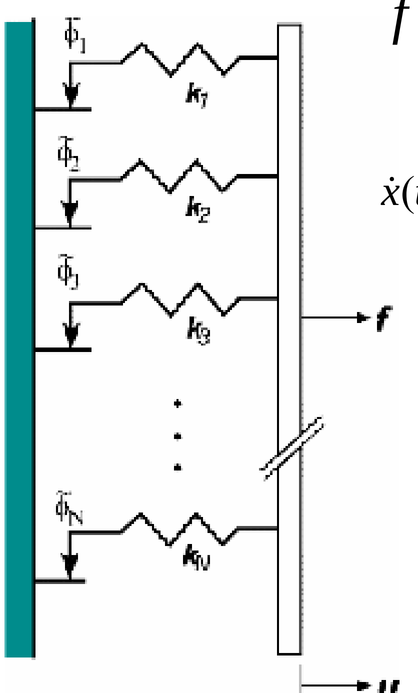
The Whole-Joint Approximation and Iwan Models for Shear Joints

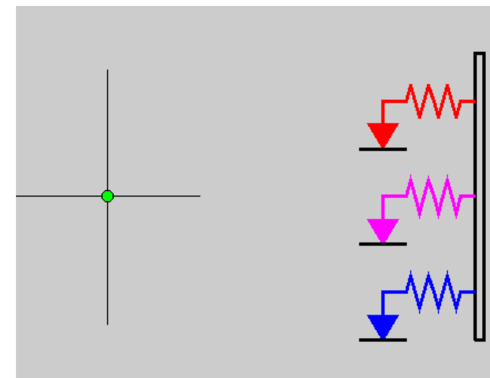


Whole-Joint approximation for interface



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

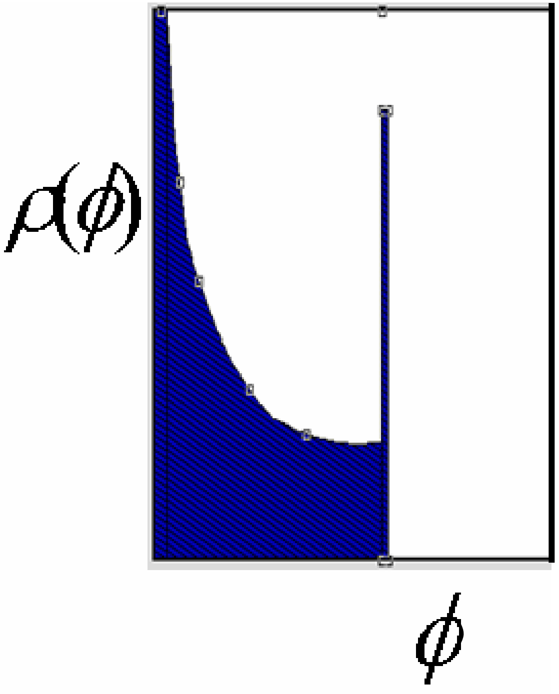
$$\dot{x}(t,\phi) = \begin{cases} \dot{u} & \text{if } |u - x(t,\phi)| = \phi \text{ and } \dot{u}\,(u - x(t,\phi)) > 0 \\ 0 & \text{otherwise} \end{cases}$$



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

A Four-Parameter Iwan Distribution

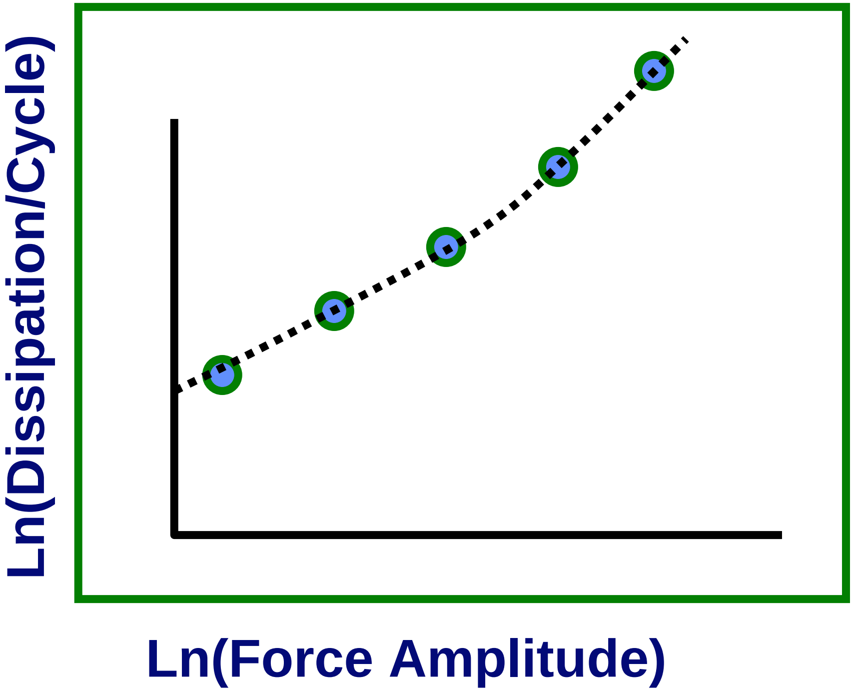
$$\rho(\phi) = R\phi^{\chi}\left(H(\phi) - H(\phi - \phi_{\max})\right) + S\delta(\phi - \phi_{\max})$$

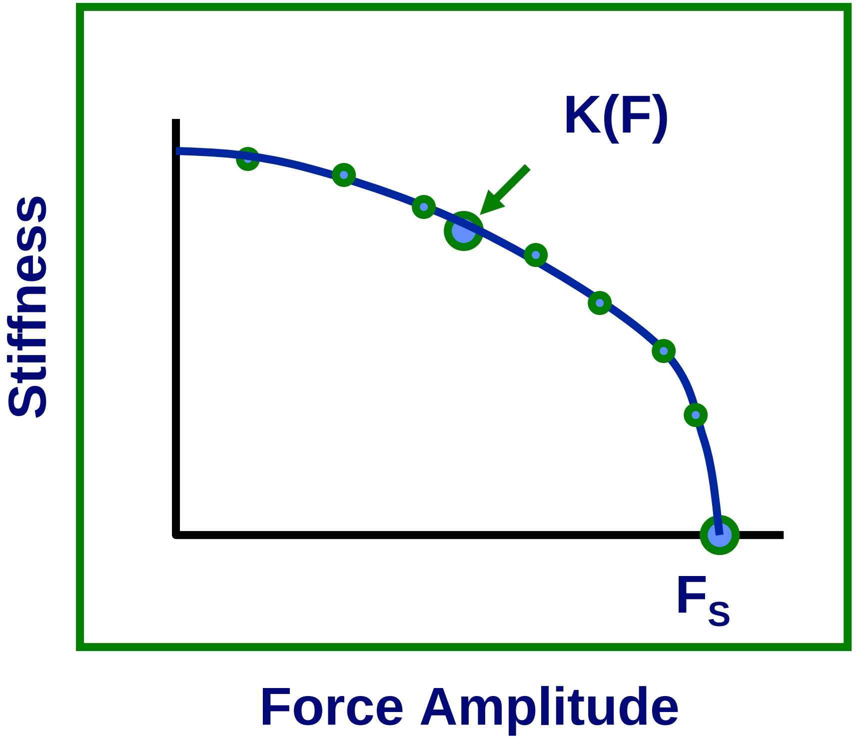


- **Nearly linear behavior at low amplitude.**
- **Power-law energy dissipation**
- **Manifests micro- & macro-slip**
- **Physically reasonable**
- **Tractable**

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.

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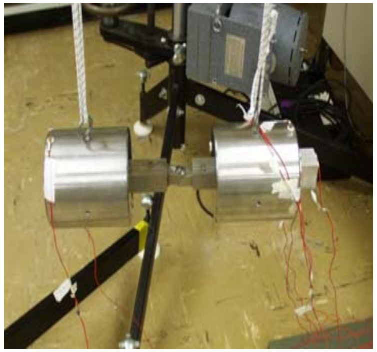
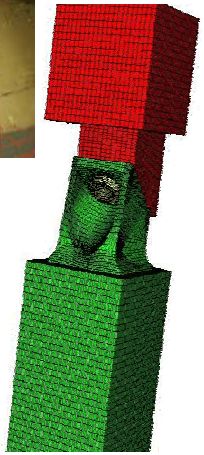
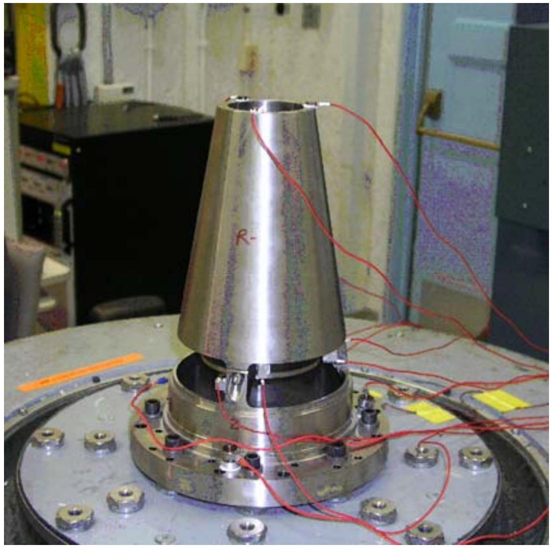
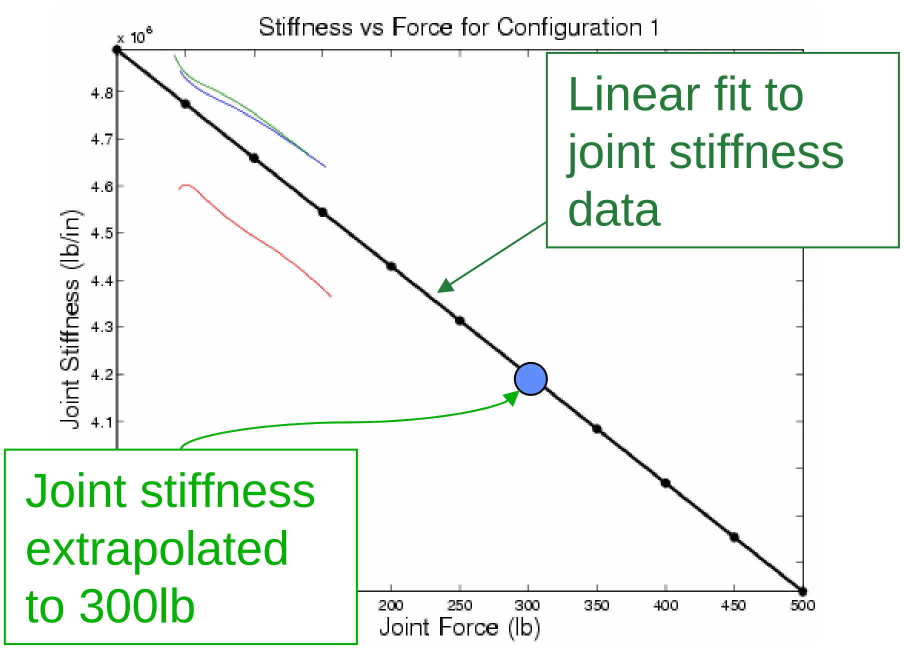
Calibration of Individual Joints to Predict Dynamics of 3-Legged Structure



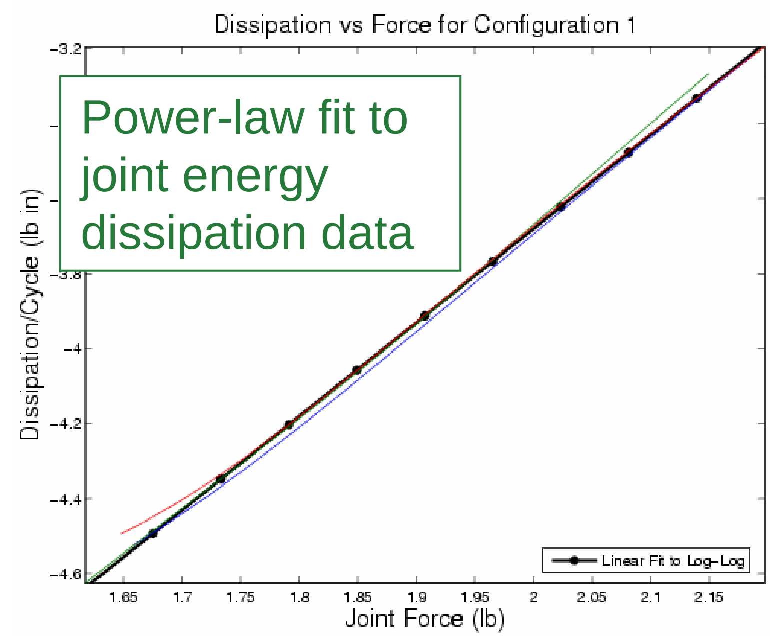




Plot Joint Stiffness and Dissipation as Functions of Joint Force



Joint Stiffness

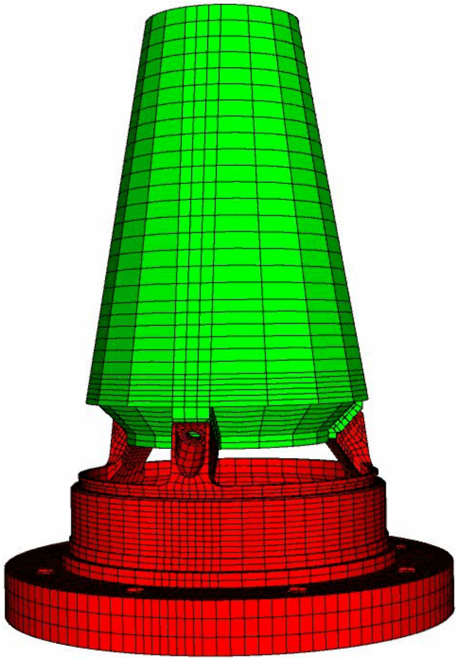


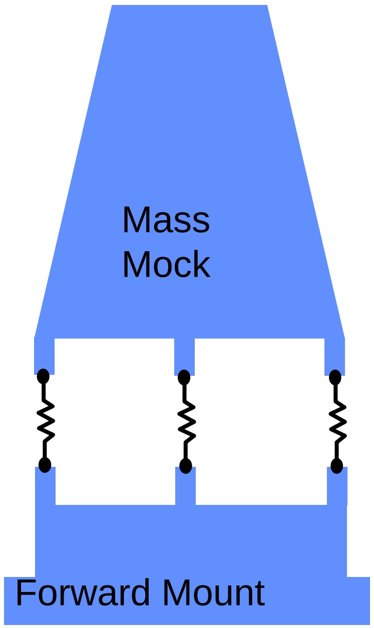
Joint Dissipation

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

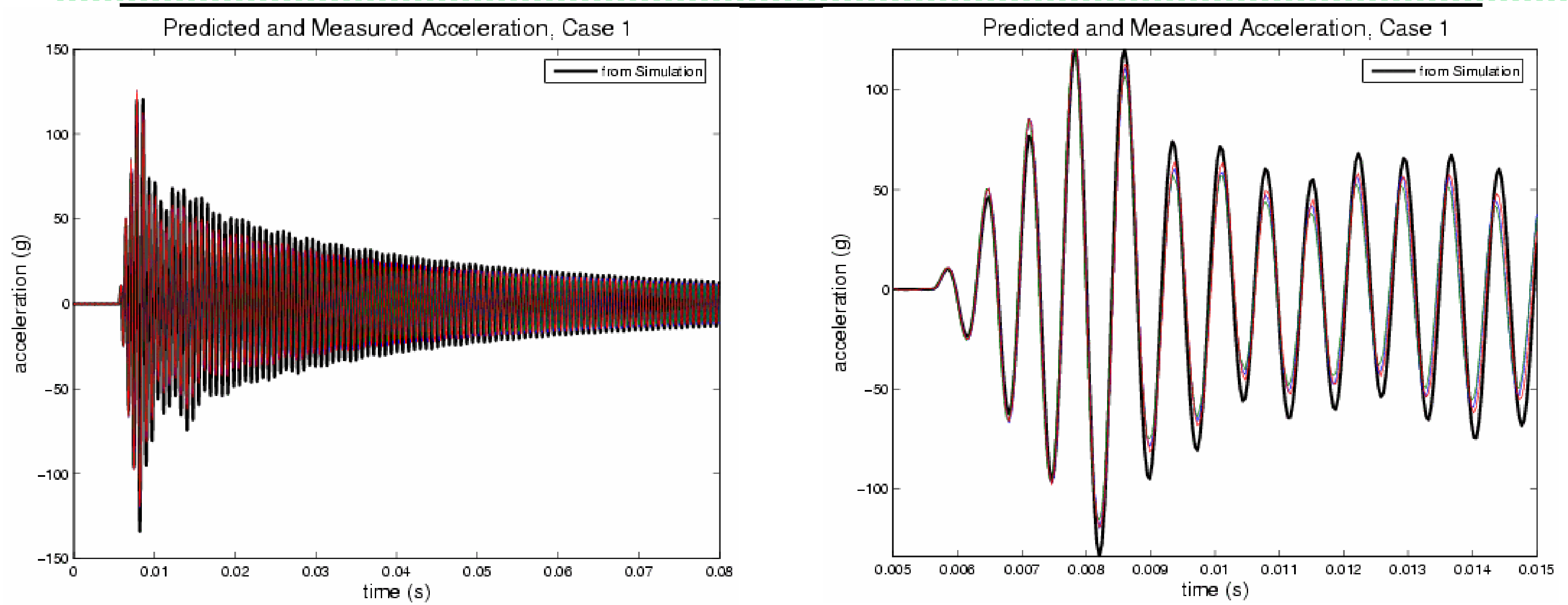
Predictions with Joint Model

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





Blast Simulation for Configuration 1



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

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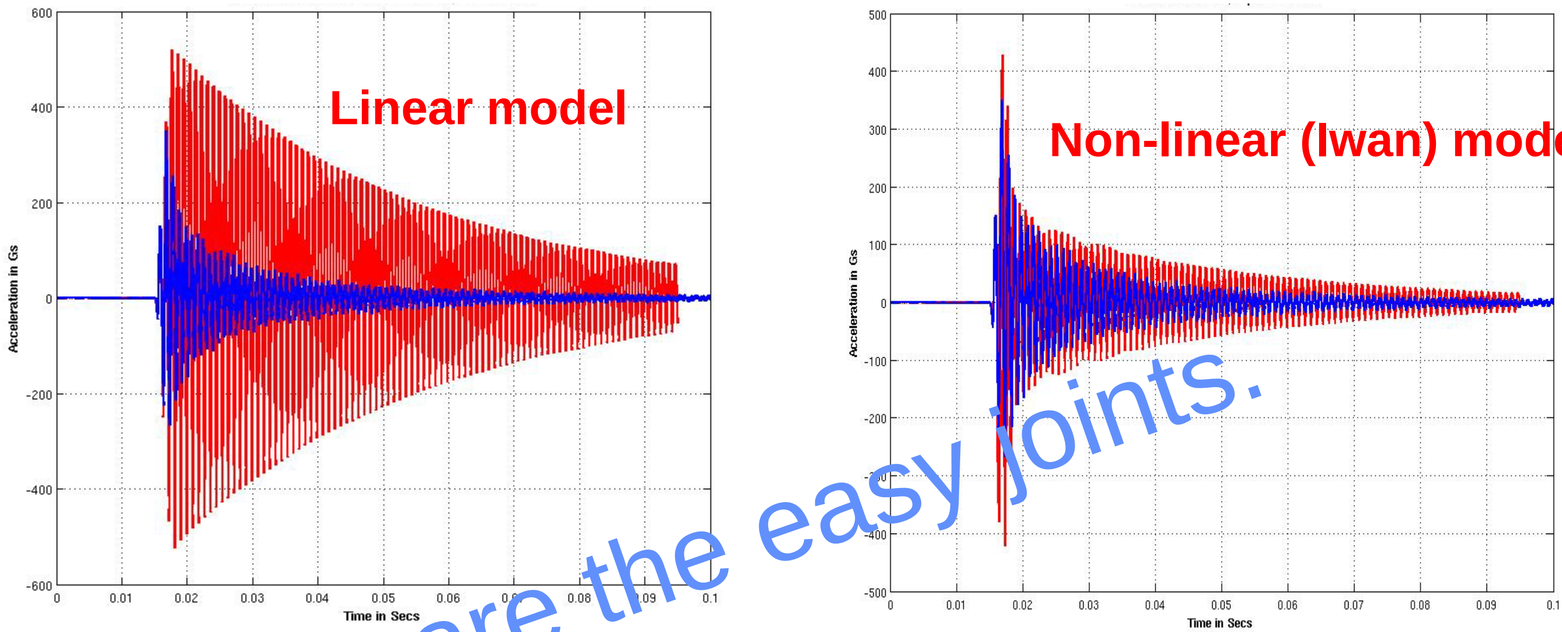
Predictions for Axial Base Excitation that Entails Macro-Slip



These are the easy joints.

Experiment

Model

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

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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

Expectation

- This is a class of problems whose core physics spans many length scales and will require
  - Research at several length scales
  - Development of conceptual tools to span those length scales
  - New methods of incorporating distributed constitutive response into structural dynamics

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

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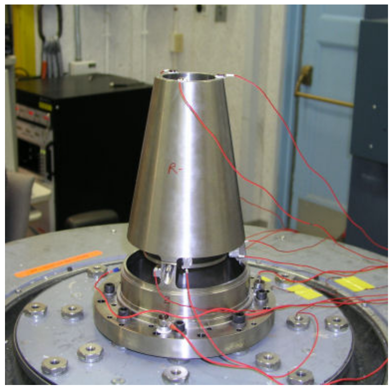
Backup

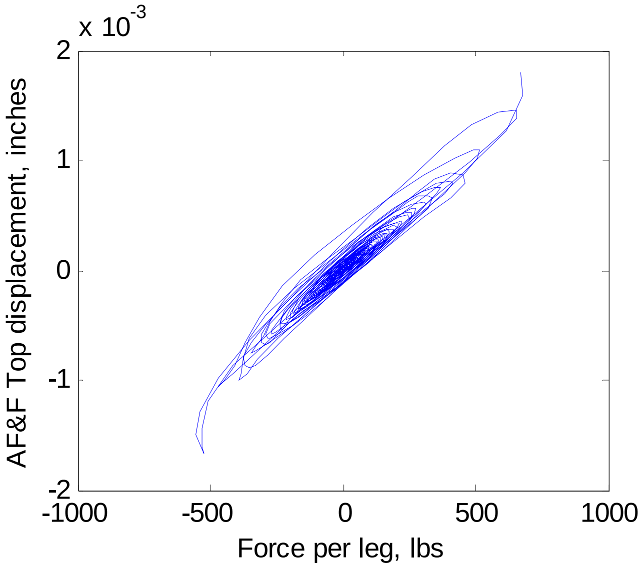
Deducing Joint Parameters

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

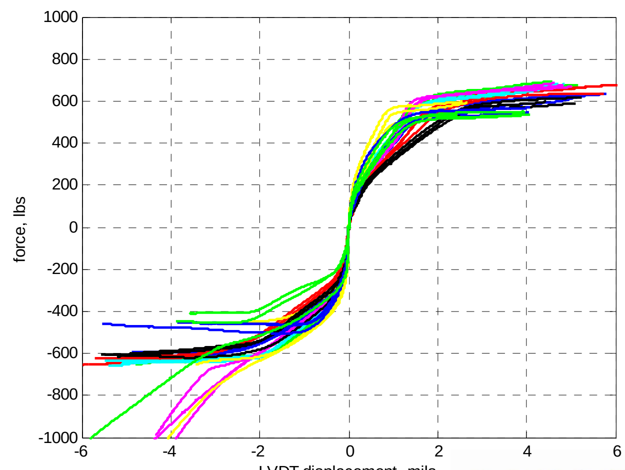




F_S = 615 lb

Joint bounding range

SS-SS single leg hardware



F_S = 450 lb to 634 lb

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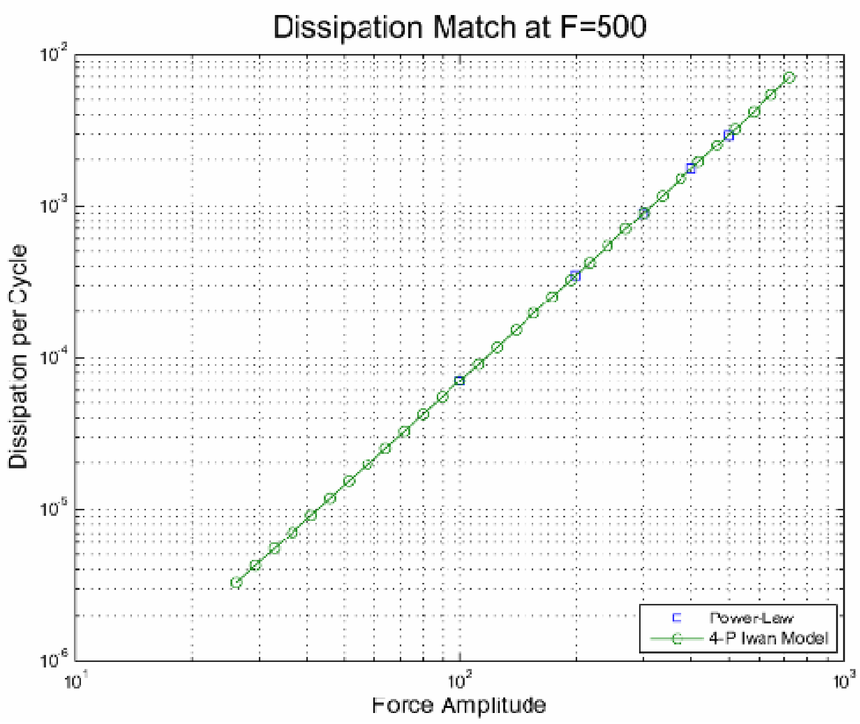
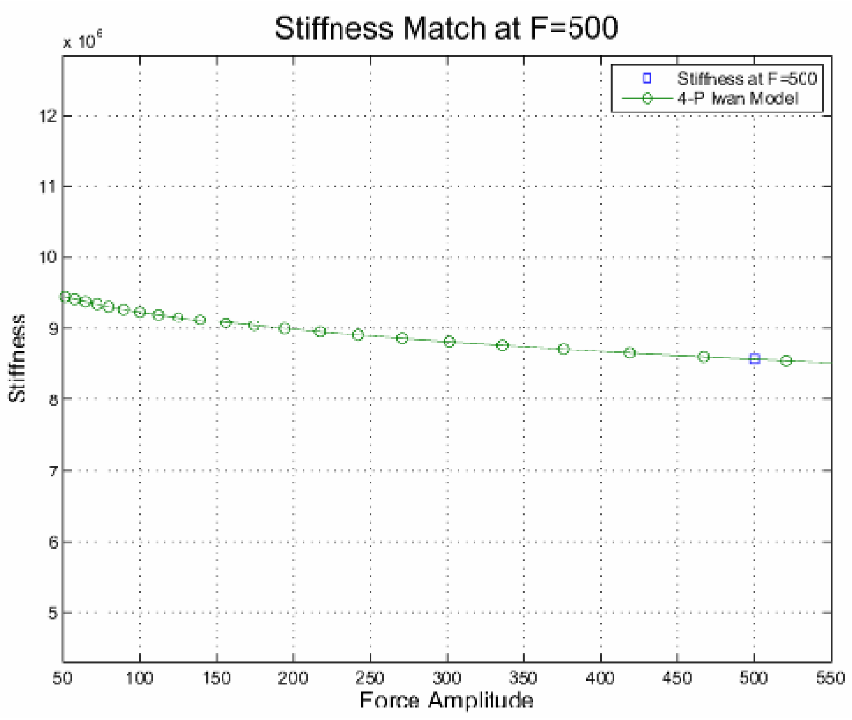
Quality of Fit for 4-Paramerter Iwan Model





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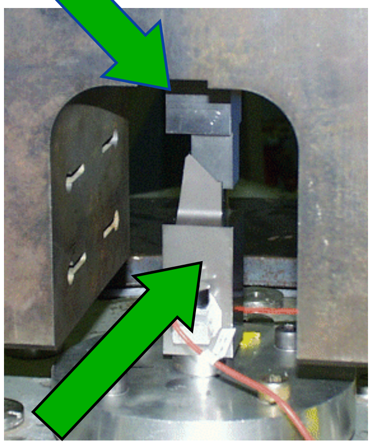
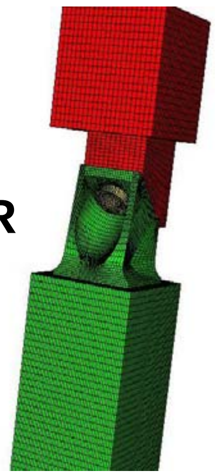
Characterize 1-Legged Experiment to Predict 3-Legged Response

Stainless Steel



Titanium

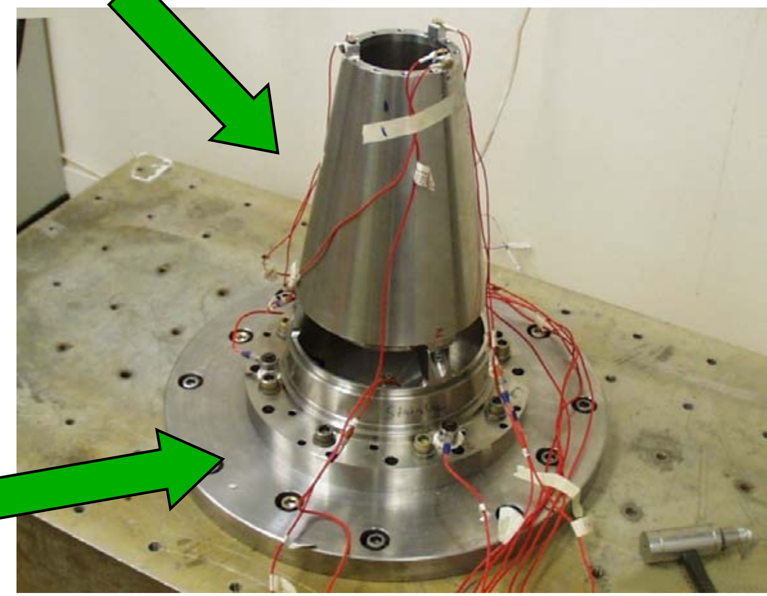
OR



Prediction

Stainless Steel

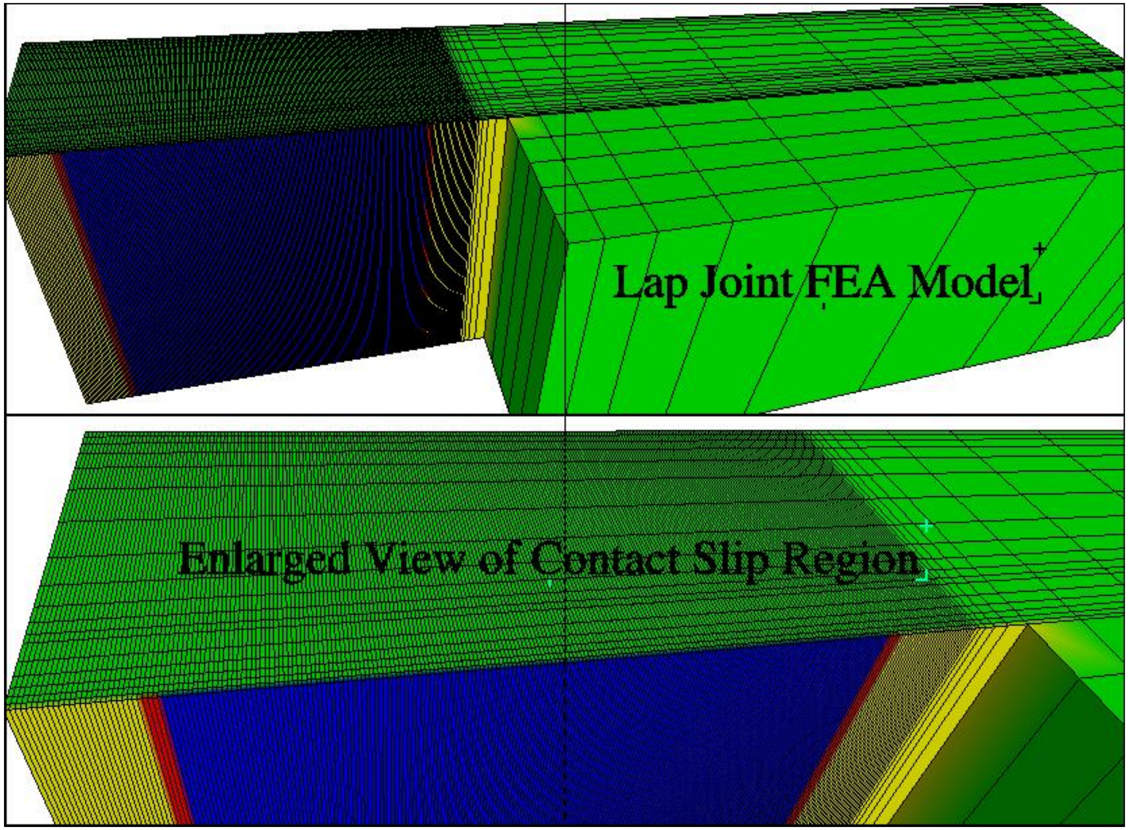
Titanium



Steady-State Resonance Experiments

Deduce Model Parameters

Understanding Joint Slip Mechanics via Finite Element Micro-Modeling



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