Welcome and Charge

Joints Workshop
Dartington, UK
AWE/SNL/NSF

27 April 2009

Dan Segalman (SNL) and Phil Ind (AWE)

Sandia is a multi-gram 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.
Why SNL and AWE are Funding This

• These issues are very important to us and to others.
• This is a very difficult problem class. We shall not solve it on our own.
• It makes sense to excite interest in these problems in the general research community.
Accounting for Joint Mechanics is Prerequisite to Prediction. 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
Traditional Barriers to Predictive Modeling

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

We are not predictive?
Discretization Error: Less of an Issue Now Than in the Past

20 years ago:
Shellshock 2D
NASTRAN
30,000 dof

15 years ago:
NASTRAN
MC2912
800,000 dof

10 years ago:
- Fine Meshes of Subsystems
- Or Coarse Meshes of Systems

Today:
SALINAS MP
>10M dof

(Original Picture might be OUO if shown)
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
Empirical Nonlinearity of Joints

Nonlinearities even at Small Displacement

Log\(|\text{Force}|\) vs. Log\(\text{Dissipation/Cycle}\)

2.0 < slope < 3
Linearity => slope=2

Log\(|\text{Force}|\) vs. Displacement

Micro-slip
Partial Slip
Macro-Slip

Monotonic Pull

Dissipation from Base Excitation or Free Vibration

Pinning or Interference

Large Displacement
Example of Variability Due to Joints

![Shock Response Spectrum Graph]

- System #1
- System #2
Further Complications of Joint Mechanics to Structural Dynamics

- Part-to-Part and System-to-System Variability
- Aging Effects – a little oxidation or rubbing goes a long way.

- How are we expected to predict dynamic properties of systems put into the stock pile years ago?
How we traditionally do structural dynamics analysis

Analyst creates coarse mesh of model putting tunable springs at interfaces and postulating proportional/modal damping
Standard Practice for Ignoring the Nonlinearity of Joints in Structural Dynamics

How we traditionally do structural dynamics analysis

Build full structure or subsystem and test in modal lab at relevant amplitudes

Analyst creates coarse mesh of model putting tunable springs at interfaces and postulating proportional/modal damping
Standard Practice for Ignoring the Nonlinearity of Joints in Structural Dynamics

How we traditionally do structural dynamics analysis

- Analyst creates coarse mesh of model putting tunable springs at interfaces and postulating proportional/modal damping
- Build full structure or subsystem and test in modal lab at relevant amplitudes
How we traditionally do structural dynamics analysis

Build full structure or subsystem and test in modal lab at relevant amplitudes

Analyst creates coarse mesh of model putting tunable springs at interfaces and postulating proportional/modal damping

Analyst tunes joint stiffness and modal damping to match test. He then makes prediction
Standard Practice for Ignoring the Nonlinearity of Joints in Structural Dynamics

How we traditionally do structural dynamics analysis

Analyst creates coarse mesh of model putting tunable springs at interfaces and postulating proportional/modal damping

Build full structure or subsystem and test in modal lab at relevant amplitudes

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

Systems test is performed on updated model
Standard Practice for Ignoring the Nonlinearity of Joints in Structural Dynamics

How we traditionally do structural dynamics analysis

Analyst creates coarse mesh of model putting tunable springs at interfaces and postulating proportional/modal damping

Build full structure or subsystem and test in modal lab at relevant amplitudes

Systems test is performed on updated model

Analyst tunes joint stiffness and modal damping to match test. He then makes prediction
How we traditionally do structural dynamics analysis

**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 creates coarse mesh of model putting tunable spring at interfaces and postulating proportional/modal damping to match test. He then makes prediction.
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.
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.)
Why Big Computers Alone are Not Enough

- Multi Length Scales
- Long Duration Events (launch, steady state, …)
- Short Duration Events (blast)
- Very Low to Very High Amplitude Loads
Why Joint Modeling is So Difficult

• Moving boundaries
• Intrinsically multiscale
• Nonlocal

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** \( L \in (0.05\,\mu\text{N}, 0.8\,\mu\text{N}) \)
- **Elasticity that of Steel**
- **Slip Zone:**

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

Say our interest in structural response is in 100Hz-3500Hz.
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, each representing hundreds of iterations.

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
What We Need

• Better Models
  – Capture at least the qualitative properties of jointed structures.
  – Lend themselves to tractable – even routine – calculation.
  – Cover the full range of environments.

• Better Methods (experimental and computational) to populate the models.

• Better Methods to validate models for joints and jointed structures.
Conclusions

• This problem appears to be intrinsically difficult. We are not expecting magic bullets.
• There is room for significant improvement on all fronts.
Backup
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
Bottom-Up and Top-Down Vision for Research in Physics of Joint Mechanics

Much of the underlying physics is not understood.

The intrinsic multi-scale nature of the problem makes it resistant to a blind attack by computer simulation.

- Atomistic Simulation
- Statistical Mechanics
- Surface Chemistry
- Interface Physics at Grain Level
- Statistical Mechanics
- Elasticity
- Interface Models (Local or Non-local)
- Statistical Mechanics
- Multi-axial joint constitutive models
- Many fine-mesh finite element simulations
- Applications in Structural Dynamics

Properties of individual asperities

Test with AFM

Test methodology must be invented

Elasticity

MEMS level tests

Sophisticated multi-axial laboratory tests

0.5-5 nm

20-100 nm

200-500 nm

1-1000 μm

2mm-2cm

0.05-2mm

~m
### Submittal Details

#### Document Info
- **Title**: Welcome and Charge to the Participants of the International Joints Workshop
- **Document Number**: 5271230
- **SAND Number**: 2009-2295 C
- **Review Type**: Electronic
- **Status**: Approved
- **Sandia Contact**: SEGALMAN, DANIEL J.
- **Submit Date**: 04/09/2009
- **Requestor**: SEGALMAN, DANIEL J.
- **Submit Type**: Conference Paper
- **Comments**: Sandia and AWE are co-sponsoring this workshop and this presentation is to convey some of what we want to have accomplished there.
- **Peer Reviewed?**: N

#### Author(s)
- Ind, Philip
- SEGALMAN, DANIEL J.

#### Event (Conference/Journal/Book) Info
- **Name**: International Joints Workshop
- **City**: Dartington Hall
- **State**: Country: UK
- **Start Date**: 04/27/2009
- **End Date**: 04/29/2009

#### Partnership Info
- **Partnership Involved**: No
- **Partner Approval**: Agreement Number:

#### Patent Info
- **Scientific or Technical in Content**: No
- **Technical Advance**: No
- **TA Form Filed**: No

#### Classification and Sensitivity Info
- **Title**: Unclassified-Unlimited
- **Abstract**: Document: Unclassified-Unlimited
- **Additional Limited Release Info**: None.
- **DUSA**: None.