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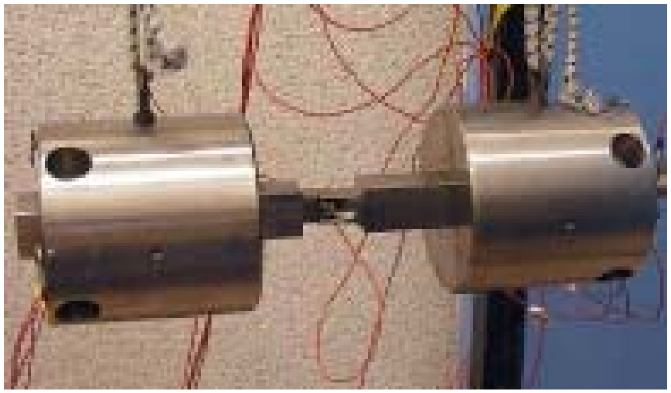
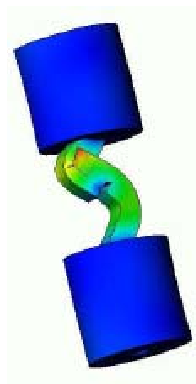

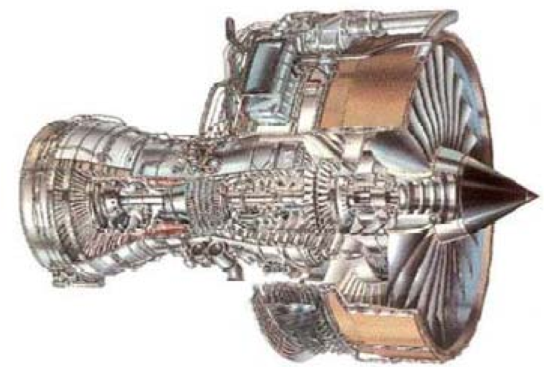

# Introduction to and Progress Towards the ASME Research Committee on the Mechanics of Jointed Structures' Joint Challenges


M.R. Brake, Sandia National Laboratories

Secretary, ASME Research Committee on the Mechanics of Jointed Structures


U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration


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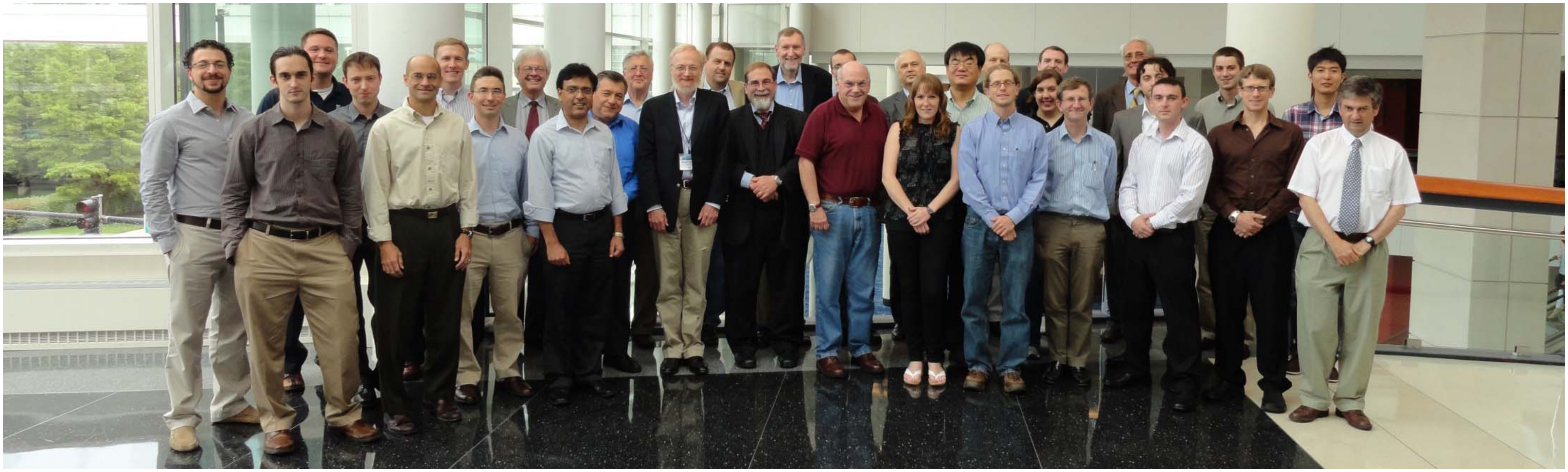
# Participants in the ASME Research Committee on Jointed Structures

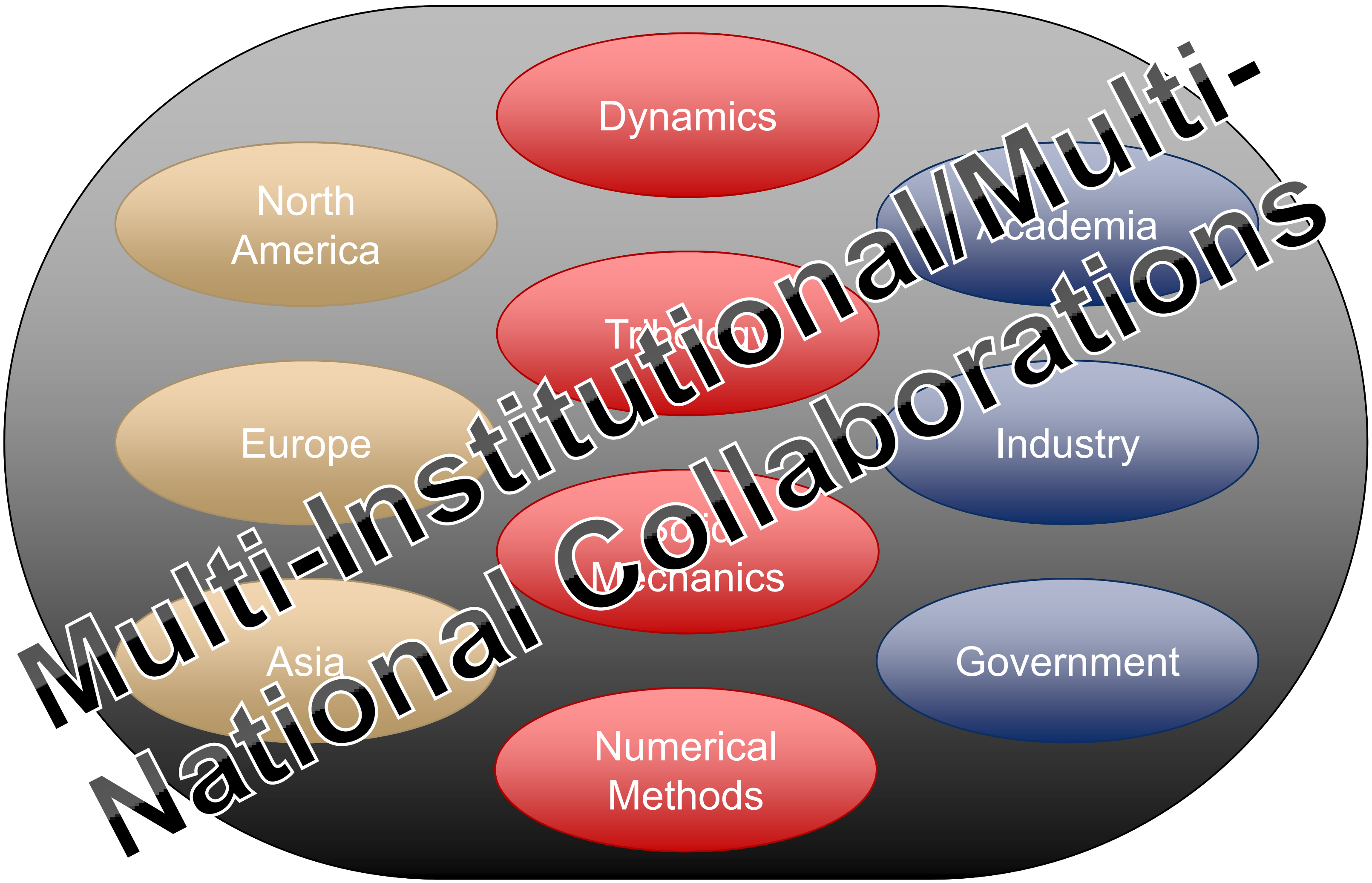


US: Air Force Research Laboratories, Akron, Arizona State, Georgia Tech, Illinois, Kansas City Plant, Maryland – Baltimore County, Michelin, Michigan, Nevada – Las Vegas, Sandia National Laboratories, Virginia, Virginia Tech, Wisconsin

UK: Atomic Weapons Establishment, Cranfield, Imperial, Oxford, Rolls-Royce, Sussex

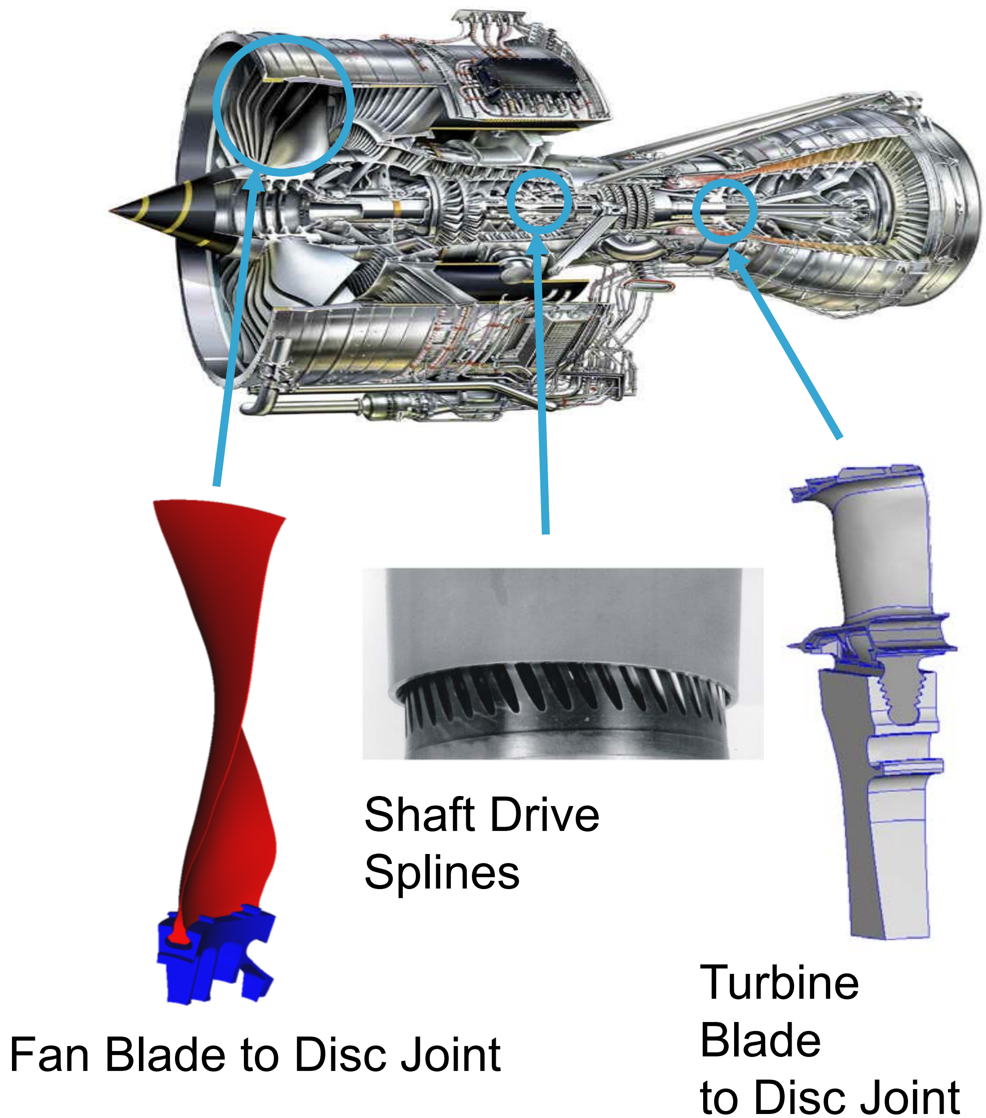
EU: Braunschweig, CSEM (Swiss Center for Electronics and Microtechnology), Hamburg, Hannover, Lyon, Nuremberg-Erlanger, Stuttgart, Supmeca, Torino

# Who Are We?


Dynamics
North America
Academia
Europe
Industry
Mechanics
Asia
Government
Numerical Methods
Multi-Institutional/Multi-National Collaborations

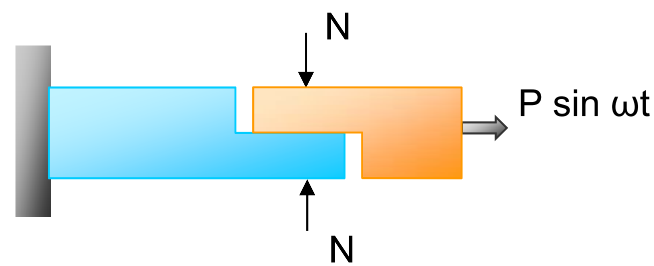
# Why Study Joints?

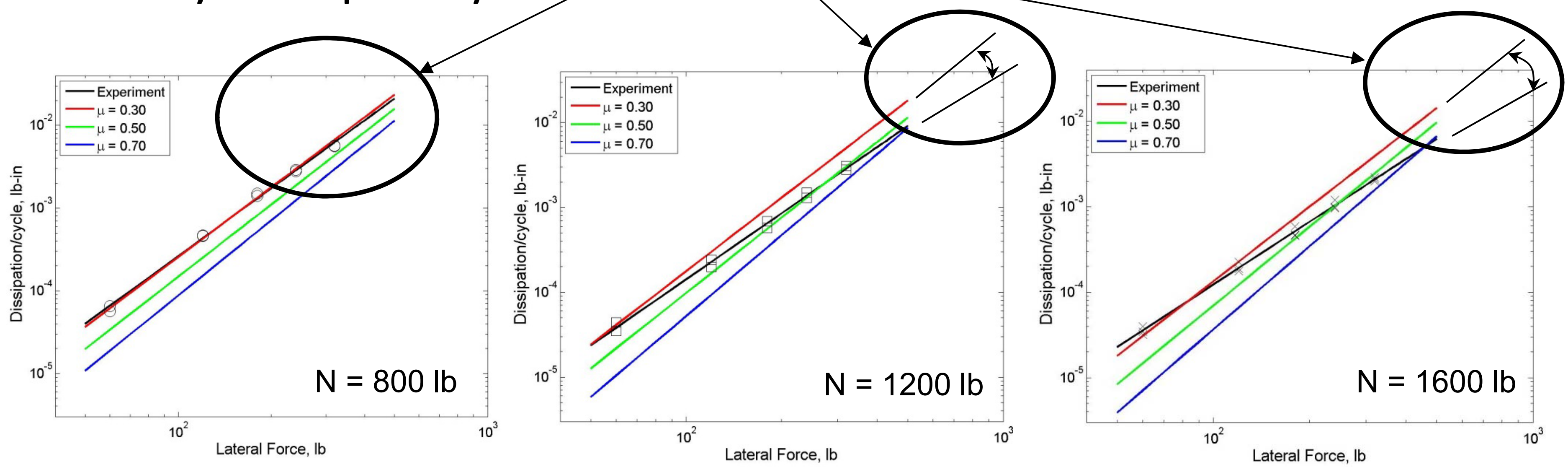
- Joints found in most engineering structures
- Early tribological research began with ancient Egypt
- Significant advances by Da Vinci, Amontons, and Coulomb
- Still do not understand local effects of friction
- Cannot develop predictive models
- Potential for saving billions of dollars though…



# Coulomb Friction-Based Constitutive Modeling Has Limitations in Microslip Regimes

- Apparently simple dissipation behavior can not be … by a simple dry frict… model.




- This systematic deficiency in the Coulomb friction interface constitutive model can not be resolved through mesh refinement.

# Brief History of the Joints Community

- Initially meetings at conferences…
- Evident that the problems were large and needed collaboration
- 1st workshop, 2006 (Arlington – SNL/NSF)
- 2nd workshop, 2009 (Dartington – SNL/AWE)
- Formation of the ASME Research Committee on the Mechanics of Jointed Structures
- 3rd workshop, 2012 (Chicago – SNL/AWE)

# Outcomes of the Third Workshop

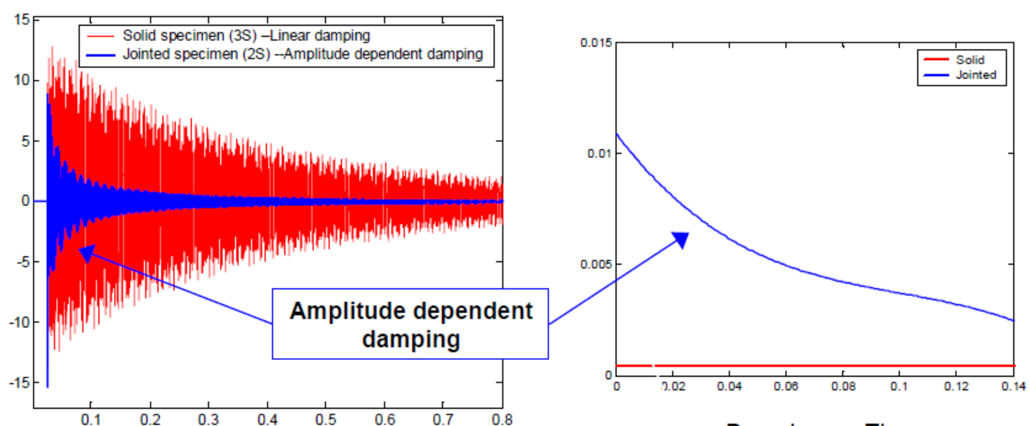
- Challenges defined:
  1. Round Robin/Benchmark Exercise for Hysteresis Measurements
  2. Round Robin/Benchmark Exercise for Measurement and Prediction of Dissipation in Standard Joints
  3. The Economics of Jointed Structures
  4. Defining the Mechanisms of Friction
  5. Epistemic and Aleatoric Uncertainty in Modeling and Measurements
  6. Derivation of Constitutive Equations Based on Physical Parameters
  7. Eventual Implementation of Prediction Methods in Commercial Numerical Codes
  8. Time Varying Model Parameters, Modeling and Experimental "Surface Chemistry"
- Actions:
  1. Write-up and Conclusions of the 3rd Workshop

# The Economics of Jointed Structures

Matthew Brake (lead, Sandia), David Ewins (lead, Imperial),
Hugh Goyder (Cranfield), Pascal Reuss (Stuttgart),
Christoph Schwingshackl (Imperial), and Matt Allen (Wisconsin)

# How to Frame the Question

- Detailed viewpoints:
  - What if we had a “next generation” joint design…?
  - What if we had data on joint usage and effects…?
  - How does a joint affect the dynamics of a structure…?
  - Could a joint actively monitor a structure’s health…?
- Abstract viewpoints:
  - Should we even have structures with joints…?
  - Is the uncertainty surrounding joints sufficient enough for us to switch to a monolithic approach…?



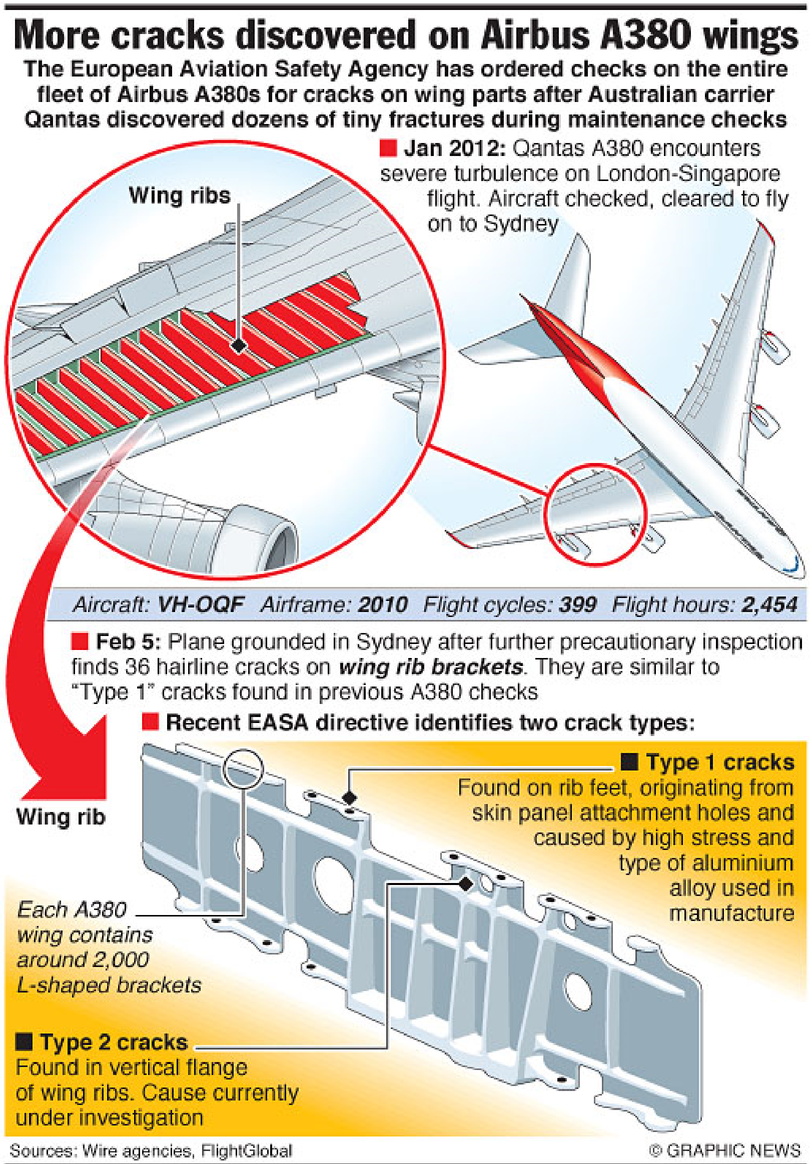

Damping vs. Time

# What are The Economics of Designing Structures With and Without Joints?

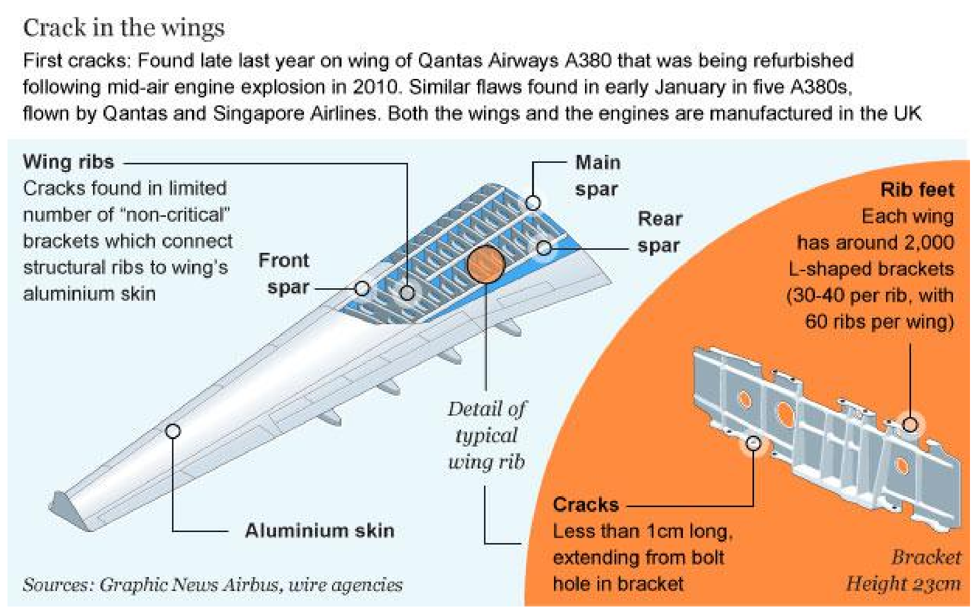
Before we can answer, there are several things we need:

- Predictive models
- Motivation for why we care about joints
- Quantification of what joints will do for us
  - In terms of response
  - In terms of savings
  - Cost/Benefit analysis
    - Cost of Failure
    - Cost/Benefit of Saving Weight
    - Cost/Benefit of Using Joints as Design Tools
    - Cost/Benefit of Using Joints to Monitor Structures

# Cost of Failure

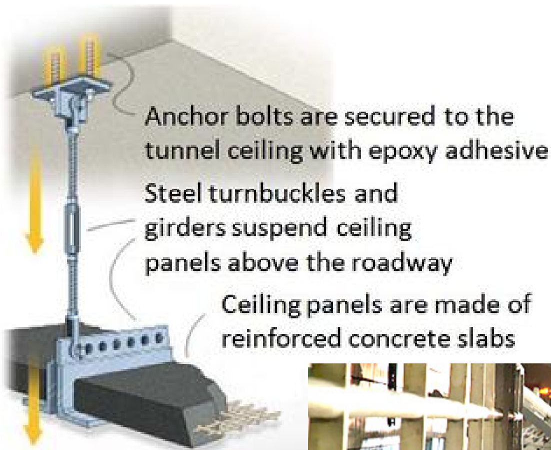


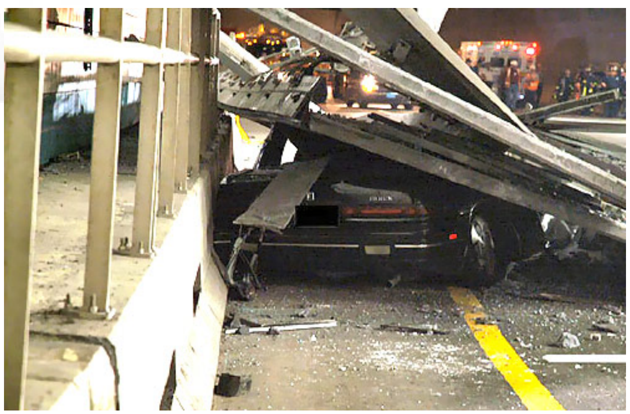

- An example: the Airbus 380
  - Cracks found adjacent to joints
  - Fleet grounded for several months
  - $330 million cost to repair
  - $30 million cost to airlines for not being able to use the planes
  - Additional costs for redesigning



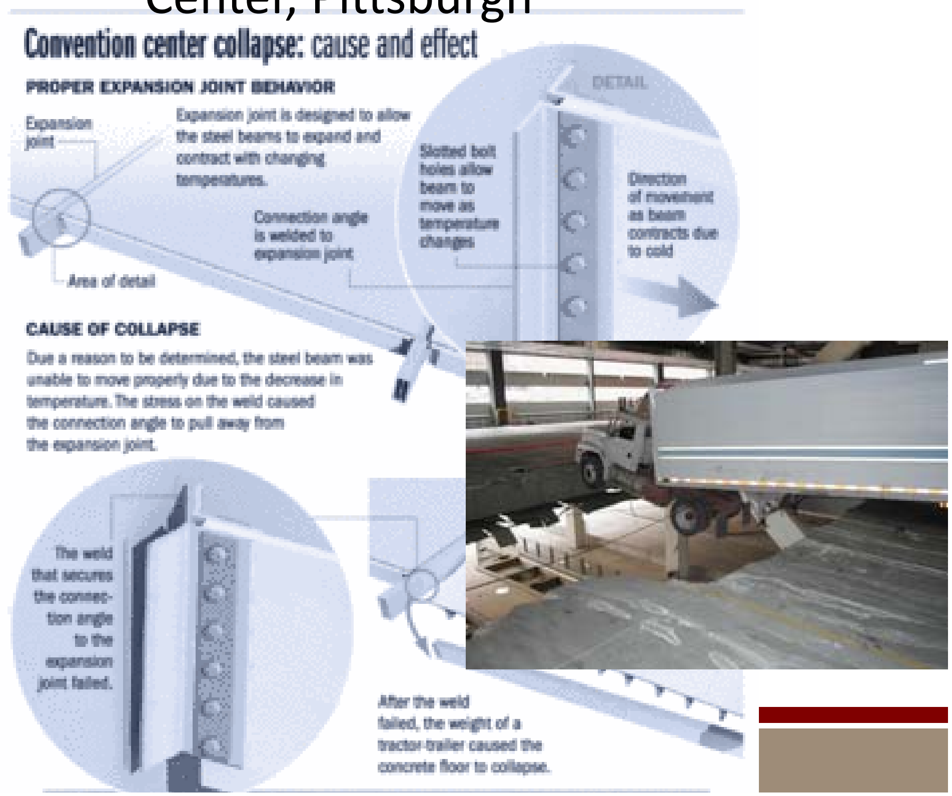
# Cost of Failure

- Big Dig ceiling failure
  - Bolted connections holding ceiling panels to tunnel failed
  - $54 million cost to repair
  - Additional costs due to liabilities



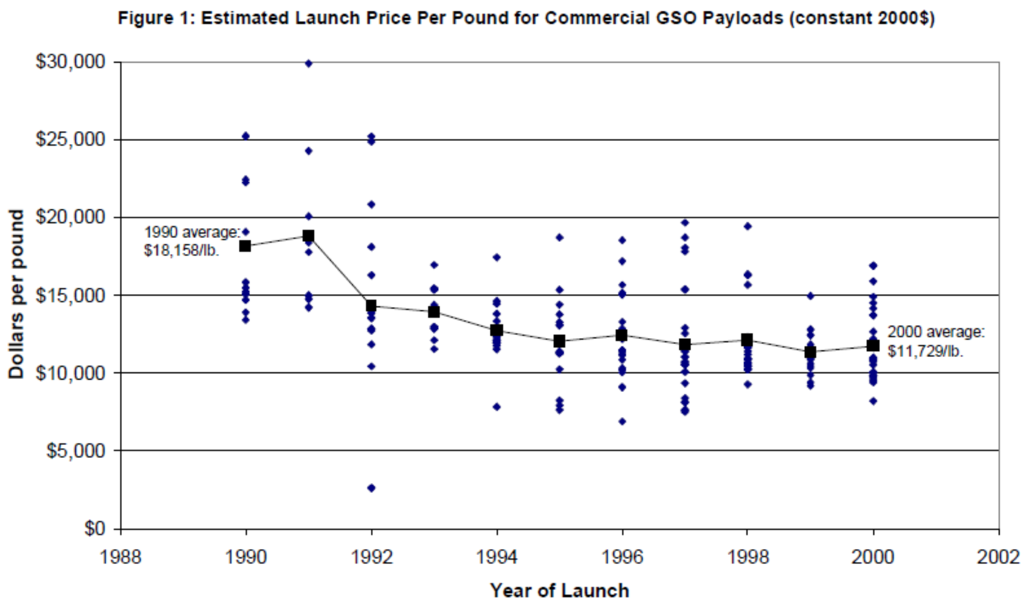



- Quick search of recent failures due to bolts:
  - I-35 Bridge, Minneapolis
  - Centergy Parking Deck, Atlanta
  - The San Antonio Parking Garage
  - Sayano-Shushnkaya Hydroelectric Power Station (cost in the billions)
  - David L. Lawrence Convention Center, Pittsburgh




Source: failures.wikispaces.com/

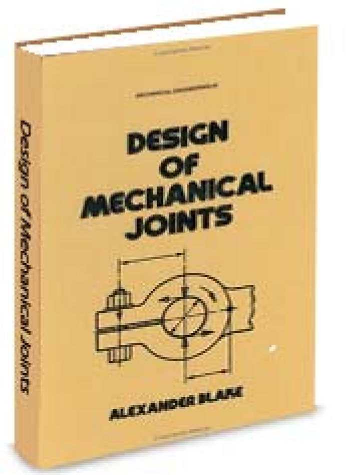
# Cost/Benefit of Saving Weight




- Most savings is in fuel efficiency (automotive, aerospace, turbines, etc.)
- Example 1: To launch a payload into low orbit: $4,000/pound; for a geosynchronous orbit: $16,000/pound. ($12,000/pound on average)
  - Reducing weight of joints by X pounds in a satellite directly saves $12,000*X per launch.
- Example 2: 1% reduction in weight of an aircraft reduces fuel consumption by approximately 0.5%.
  - Fuel costs are $10.5M/year, so reduction in joints leading to a weight savings of Y% saves $52,500*Y

**Sources:**
www.worldbank.org/
www.futron.com/upload/wysiwyg/Resources/Whitepapers/Space_Transportation_Costs_Trends_0902.pdf

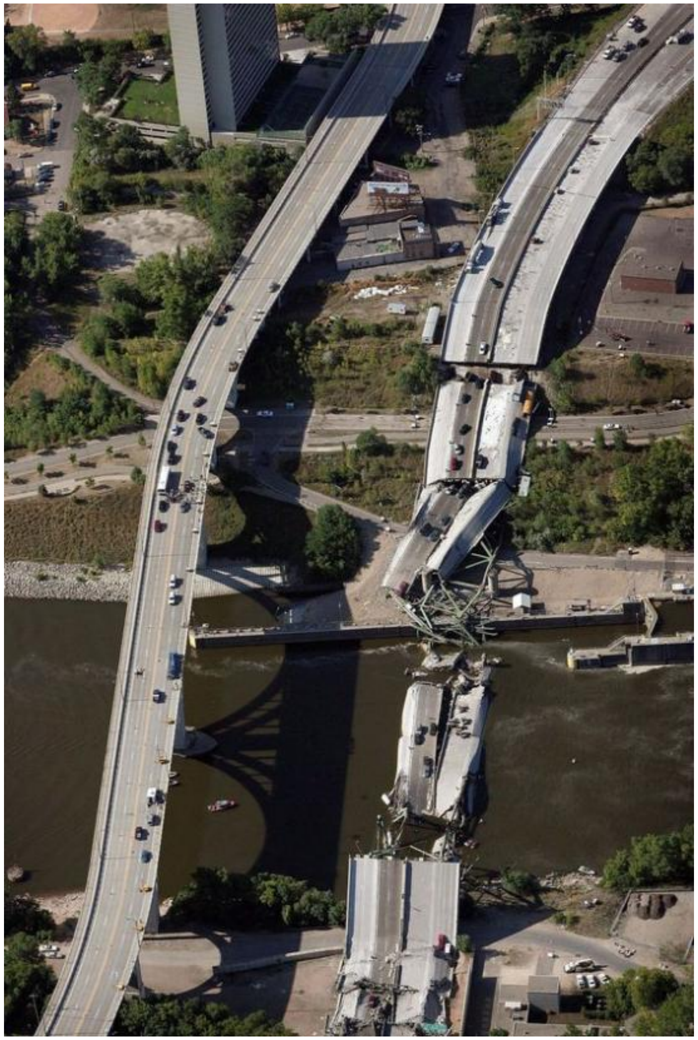
# Cost/Benefit of Joints as a Design Tool




- Ultimate goal: predictive model of joints
  - Pre-built model of joints with known performance
  - Handbook with easily understood metrics for how a specific joint performed
  - Ability to condition structural response by design of joints
- Impact on direct cost of design time, development cycle, product testing, and production
- If we had X capability from a better knowledge of joints, could we cut out a step in the design cycle?

# Cost/Benefit of Using Joints for Structural Health Monitoring

- Key idea: structural health monitoring built into joints
- Opportunity to optimally plan a repair cycle for a structure
- Early warning sign to avoid structural failures
- Many potential applications have catastrophic consequences associated with failures
- Cost benefit expected to be deduced from insurance company estimates



I-35 in Minnesota, August 1st, 2007

# Observations for the Economics Challenge

- High level question: What is the economics of designing a structure with and without joints?
- If joints are needed, what effect do they have on a system's performance?
- To answer some of these questions, a cost benefit is needed
- Several themes identified:
  - Cost of failure
  - Cost/benefit of saving weight
  - Cost/benefit of designing structures with joints
  - Cost/benefit of using joints to monitor structures
- All of this is predicate on developing a predictive model of joint behavior

# Defining the Mechanisms of Friction

**David Nowell (lead, Oxford), Matthew Brake and Somuri Prasad (Sandia), Melih Eriten (Wisconsin), and George Ostermeyer (Braunschweig)**

# Defining the Mechanisms of Friction

## Centuries-long Quest

Ancient Egypt (~2700 BC)

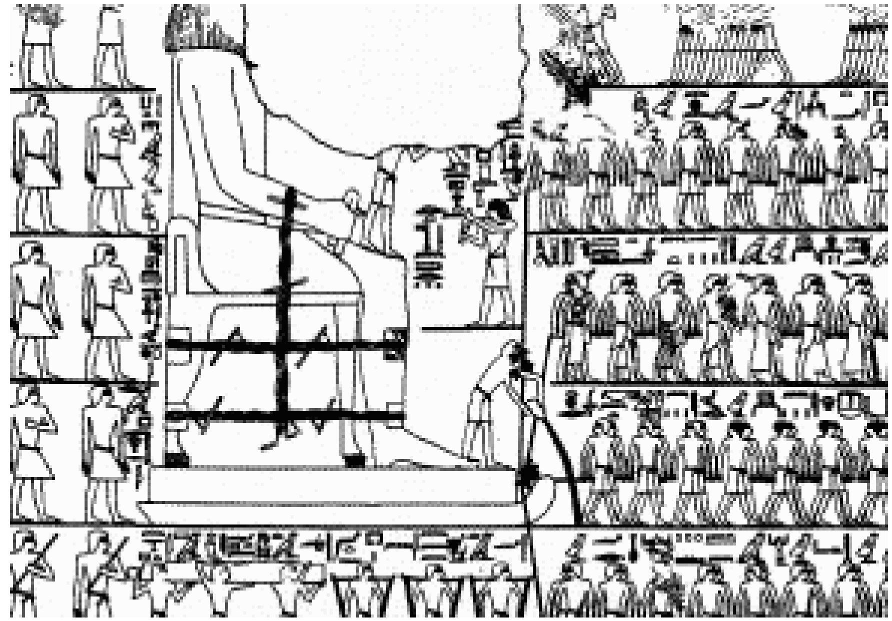
Da Vinci’s drawings (15th century)

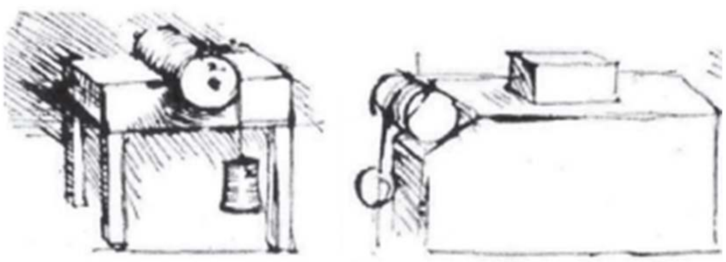
Amontons (17th century)

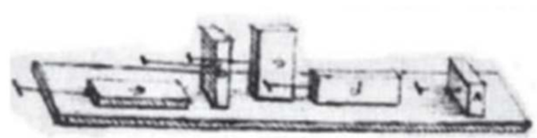
Euler (18th century)

Coulomb (18-19th century)

Bowden & Tabor (20th century)







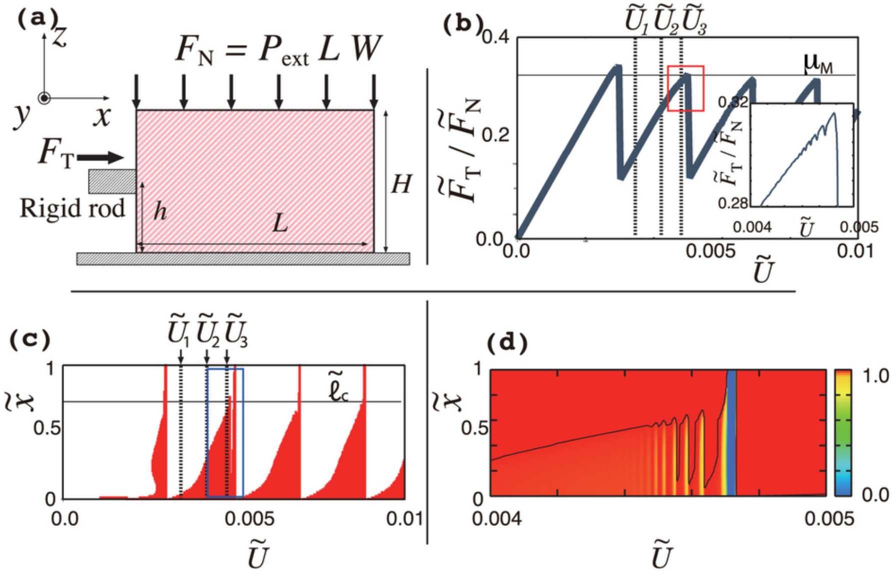
## Classical Laws of Friction

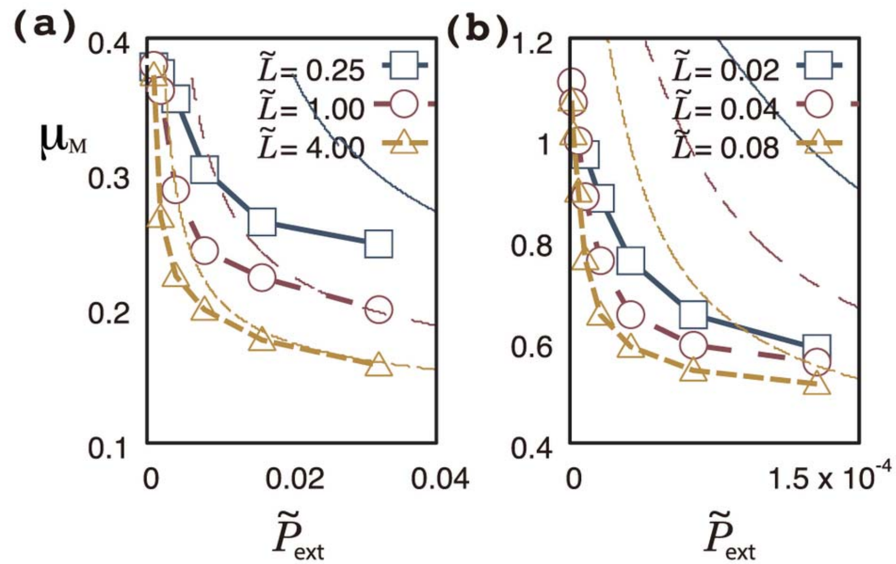
1.The area in contact has no effect on friction (apparently not, but in reality?)

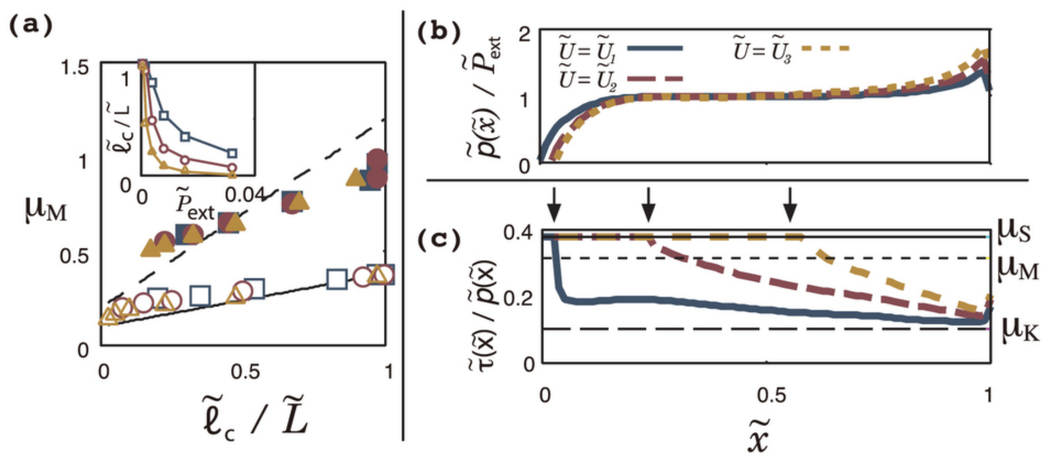
2.If the load of an object is doubled, friction will also be doubled. (constant friction coefficient)

3.Friction is independent of sliding velocity (velocity weakening?)

# Friction Coefficient: Not So Constant




Otsuki & Matsukawa, Scientific Reports, 3, 2013.

| | Kinetic | Static |
|---|---|---|
| Rubber on concrete (dry) | 0.68 | 0.90 |
| Rubber on concrete (wet) | 0.58 | |
| Rubber on asphalt (dry) | 0.67 | 0.85 |
| Rubber on asphalt (wet) | 0.53 | |
| Rubber on ice | 0.15 | |
| Waxed ski on snow | 0.05 | 0.14 |
| Wood on wood | 0.30 | 0.42 |
| Steel on steel | 0.57 | 0.74 |
| Copper on steel | 0.36 | 0.53 |
| Teflon on Teflon | 0.04 | |

# Where Does Energy go in Frictional Interfaces?

## An Interplay of Elasticity, Plasticity, Fracture, Interfacial Slip, Adhesion, Impacts, Acoustic Emission, etc.

Elasticity --> bond properties, atomistic properties

Plasticity --> crystal orientation, microstructure, dislocations

Fracture --> surface energy, microstructure, bond strength

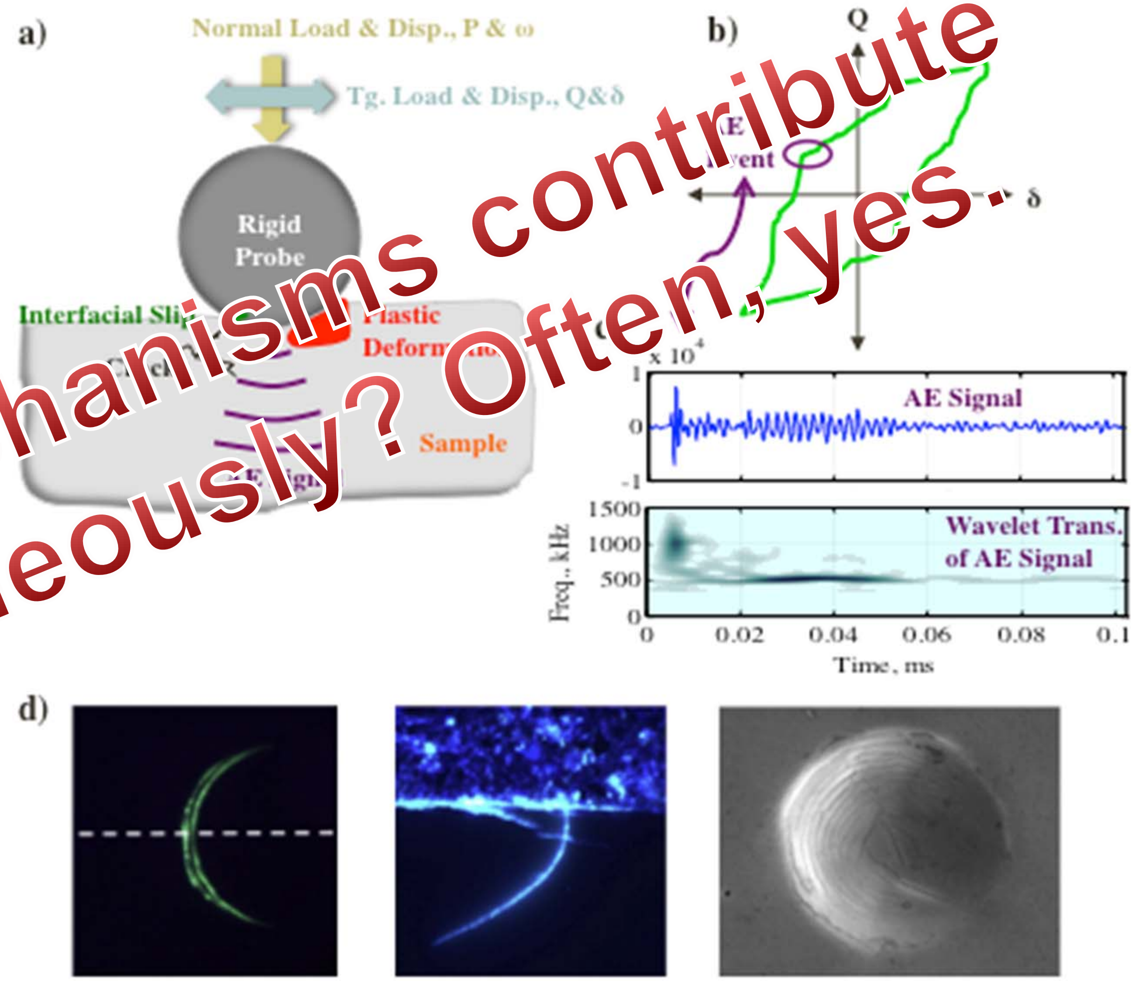
Interfacial slip --> elastic mismatch, interfacial bonds

Adhesion --> hysteretic separation/pull-off behavior

Impacts --> geometry, roughness

AE --> coupling with acoustic modes

**Do all mechanisms contribute simultaneously? Often, yes.**

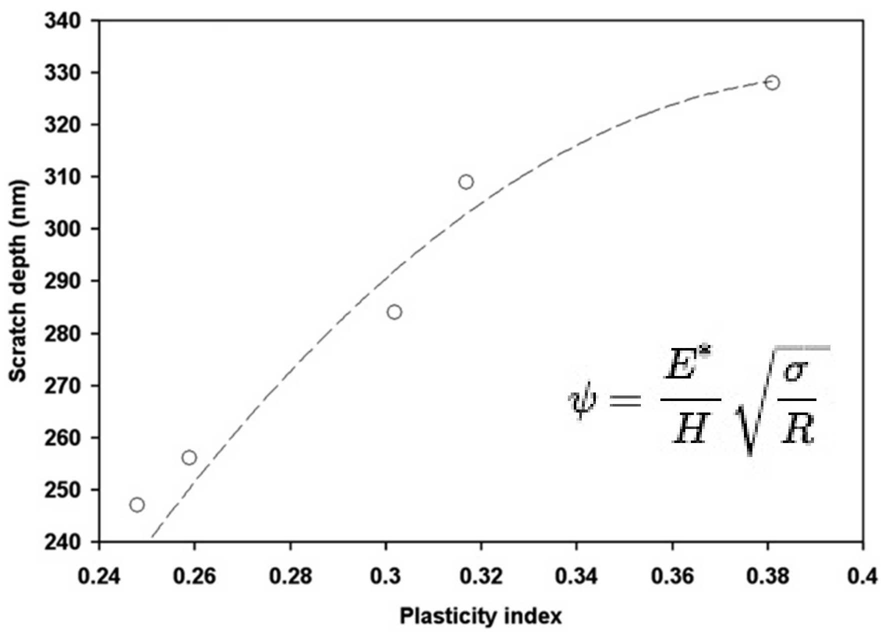


# What Can We Do?

In-situ contact measurements

Time-resolution is a big problem

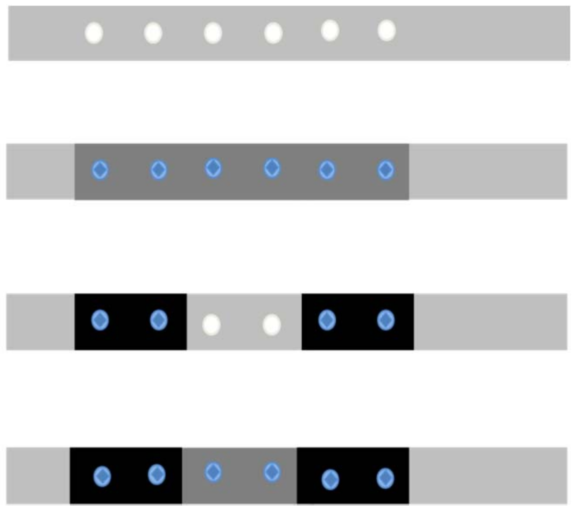
Sample preparation is intensive and intrusive

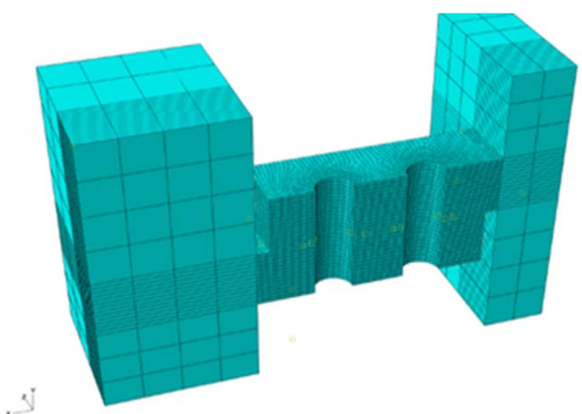

We have means to control the relative contribution of each mechanism

The plasticity index describes the relative importance of plastic deformations in a rough surface contact

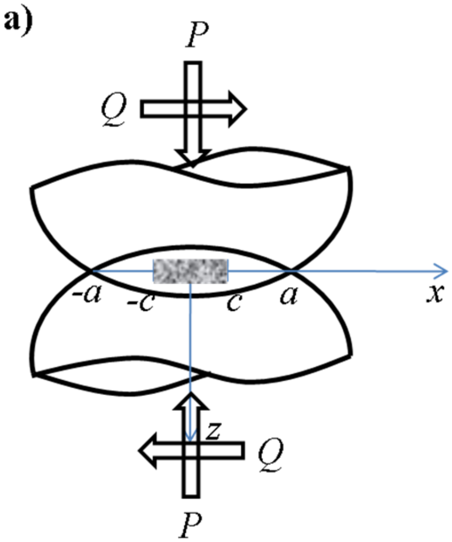
# Mechanisms Span Numerous Length Scales

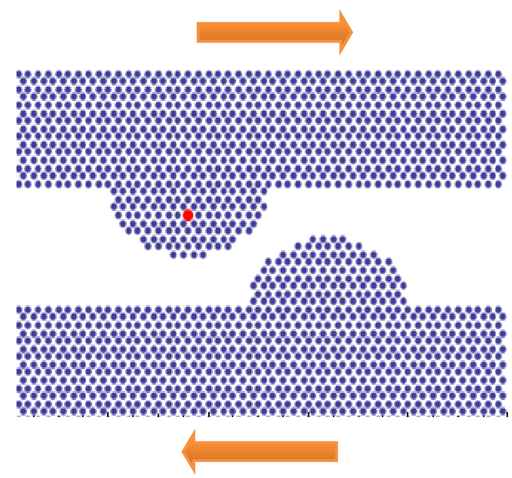


***Length/Time Scales ~ 1-10$^{-9}$***



a)



# Observations for the Friction Mechanisms Challenge

- Local friction effects diverge greatly from the Amonton/Coulomb friction model
- A deterministic model of friction represents a “grand challenge” for experimental and theoretical research in the 21st century
- Experimentation at a range of length scales is necessary
- Experiments must decouple the different energy dissipation mechanisms

# Epistemic and Aleatoric Uncertainty in Modeling and Measurements

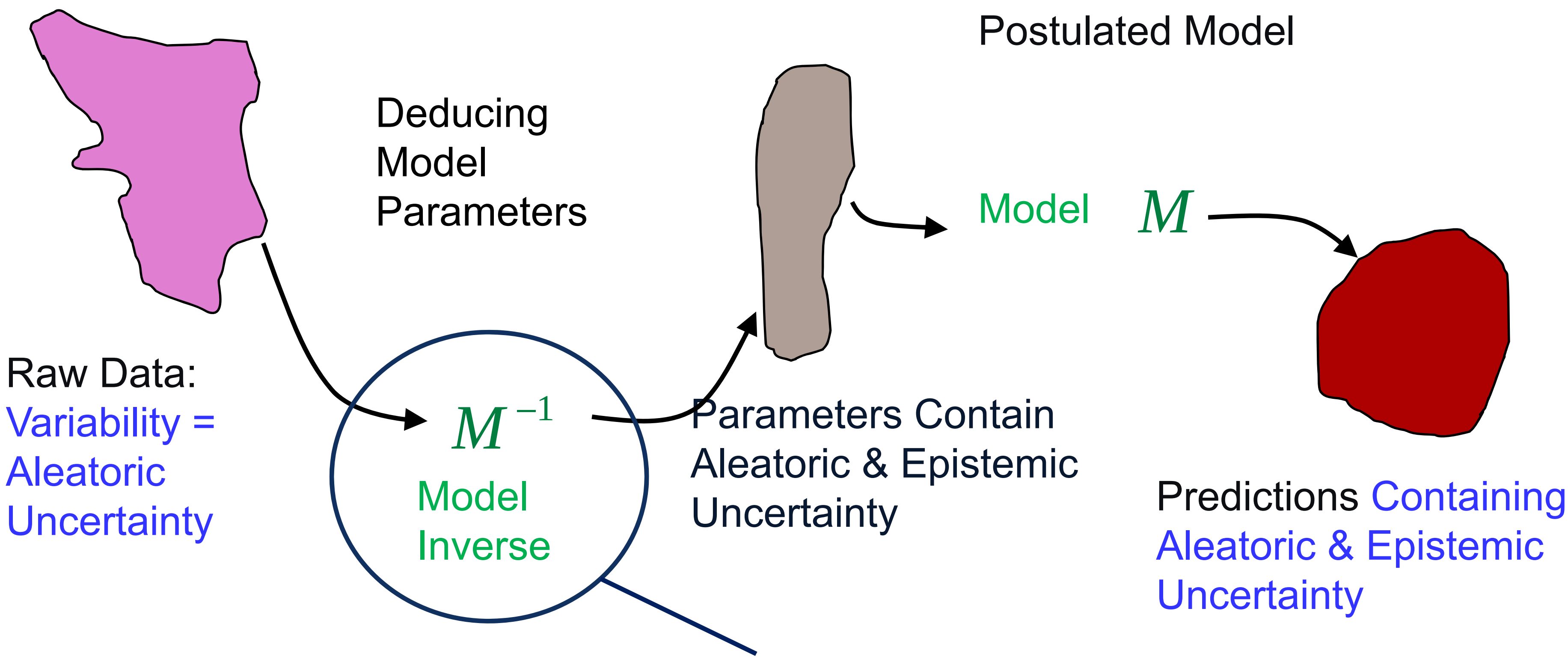
**Marc Mignolet (lead, ASU), Dan Segalman (lead, Sandia), Kai Willner (Erlanger/Imperial), Matthew Brake and Mike Starr (Sandia), Alex Vakakis (Illinois), Lothar Gaul (Stuttgart), and Larry Bergman (Illinois)**

# Usually Uncertainty is Categorized into Two Sorts

- Aleatoric Uncertainty: uncertainty due to intrinsic variability. This includes parametric uncertainty.
- There is a lot of this in mechanical joints!

- Epistemic Uncertainty: uncertainty which is due to things we could in principle know but don't in practice. This includes model form error.
- This includes things that we are unlikely ever to know in practice know.

# As It ACTUALLY Happens



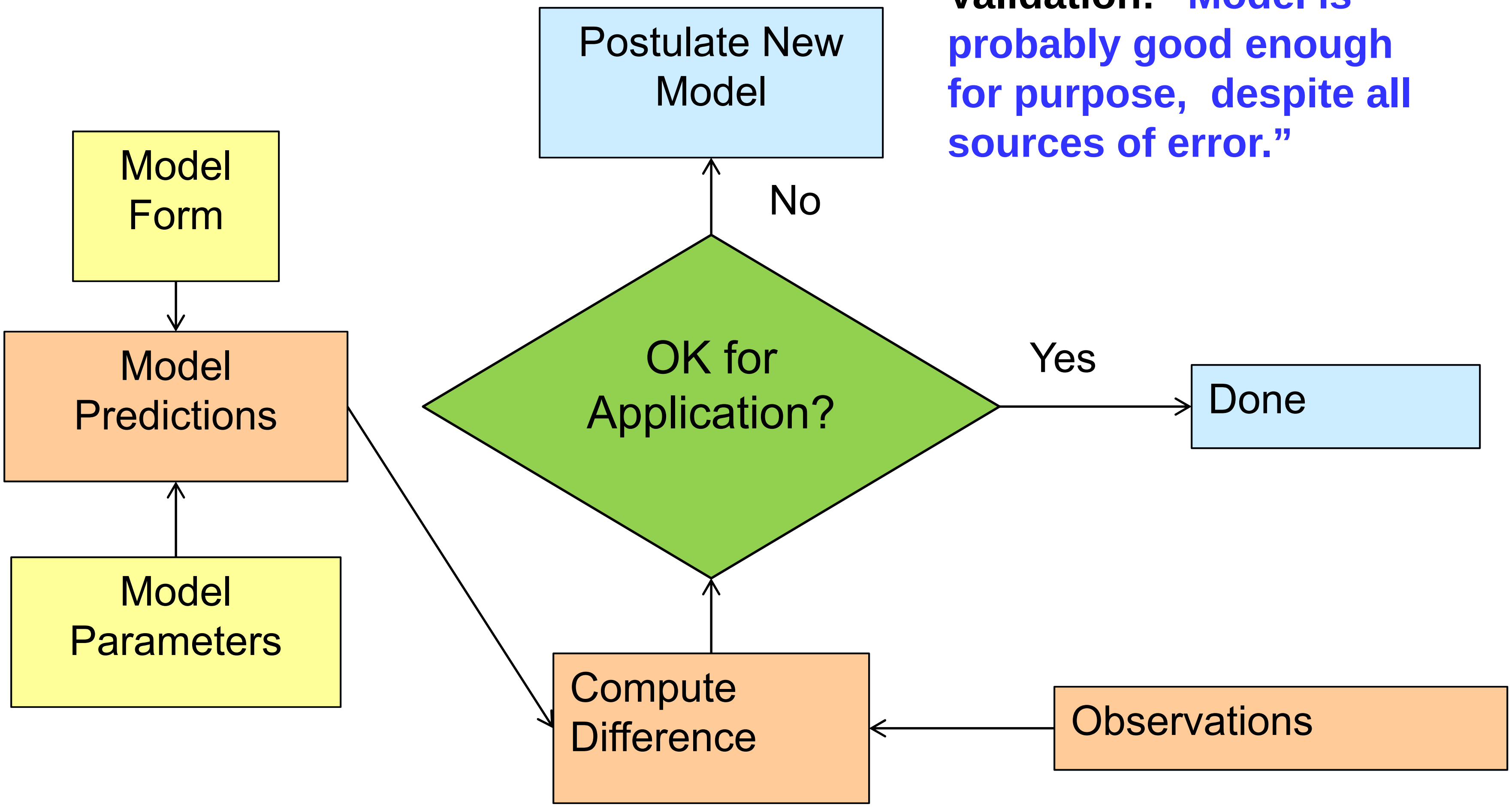

We cannot systematically decouple aleatoric and epistemic uncertainty in any but the most simple problems.

Assumption of a model introduces model form error, which is usually unknown/unidentified/unrealized…

# From Where Does the Confusion Arise?

- There is a common misunderstanding of what is a validated model.
- Definition - Validation: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.
- Misconception: A validated model is accurate and correct, modulo aleatoric – generally parametric – uncertainties.
- In reality, a validated model is sufficiently close to reality that using it for our intended purpose would not be imprudent.

# The Validation Process



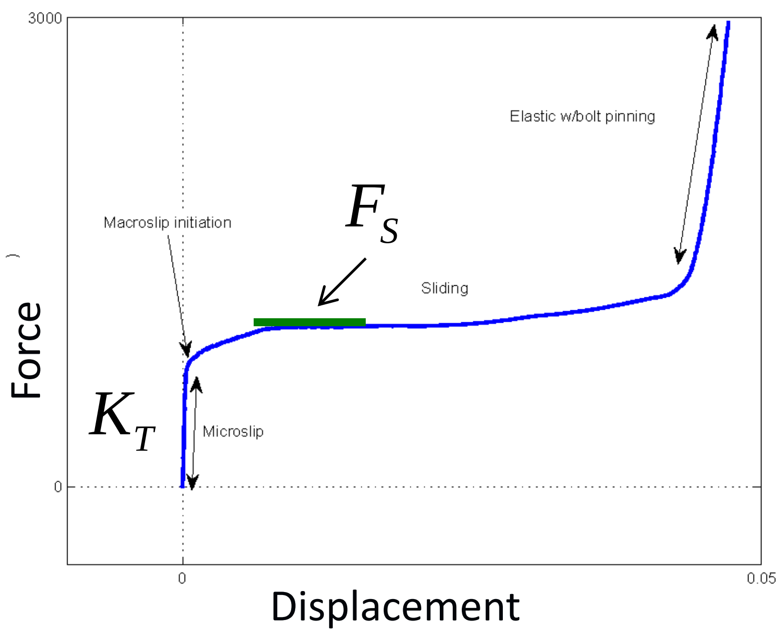

**Validation:** **"Model is probably good enough for purpose, despite all sources of error."**

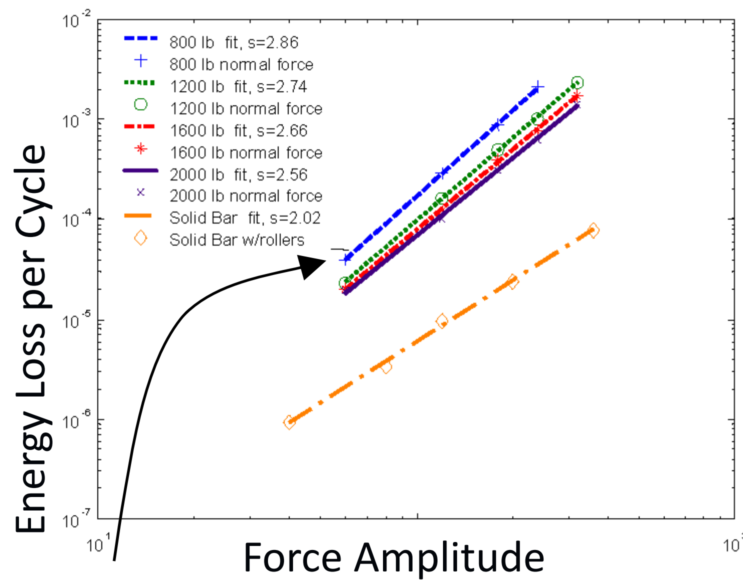
# Why Do We Care?

- In this process, we have not quantified our model form error – we do not even know how.
- We cannot in general distinguish error in our predictions due to model form (epistemic uncertainty) from parametric (aleatoric) uncertainty.
- Our ability to do overall uncertainty quantification (UQ) of our predictions is compromised.

# What About Jointed Structures?

For a bolted joint, there are several possibly measureable features:



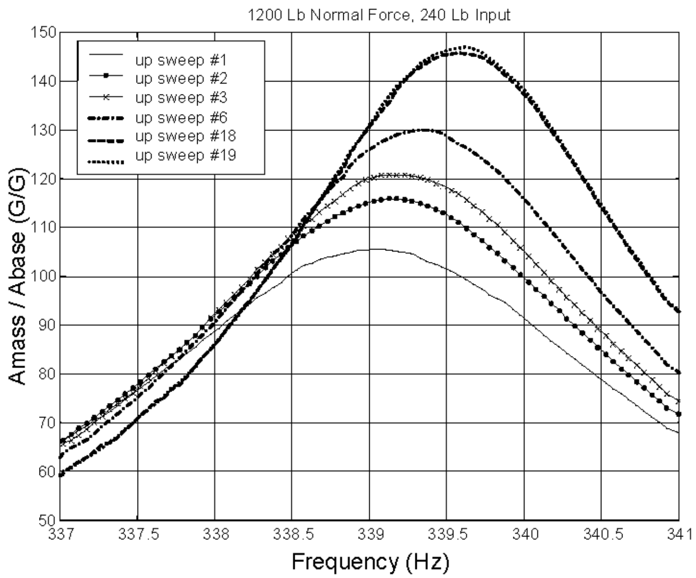

$$\mathrm{D} = CF^{3+\chi}$$

For only microslip

If considering macro-slip, we need at least four parameters

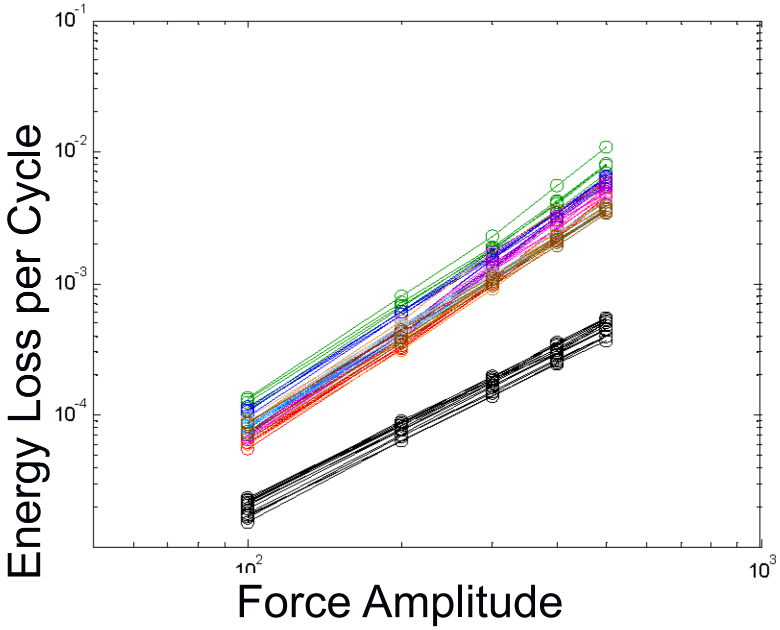
possibly $K_T, C, \chi, \cancel{F_S}$

# Meaningful Experimentation is Very Difficult




- Wearing in phenomena in steel and titanium
- Galling in aluminum
- Alignment issues

# Intrinsic Part-to-Part Variability with respect to Stiffness & Dissipation




It is common for **stiffness measurements** of nominally identical bolted joint hardware to vary by as much as 25%.

It is common for **energy dissipation measurements** on nominally identical bolted joint hardware to vary by as much as 300%.

# Observations for the Uncertainty Challenge

- There is a lot of intrinsic variability (aleatoric uncertainty) associated with nominally identical joints.

- Even how we define the parameters we use to characterize the experiments is imprecise – epistemic uncertainty.

- Further complicating things – we do not even know how to characterize epistemic uncertainty.

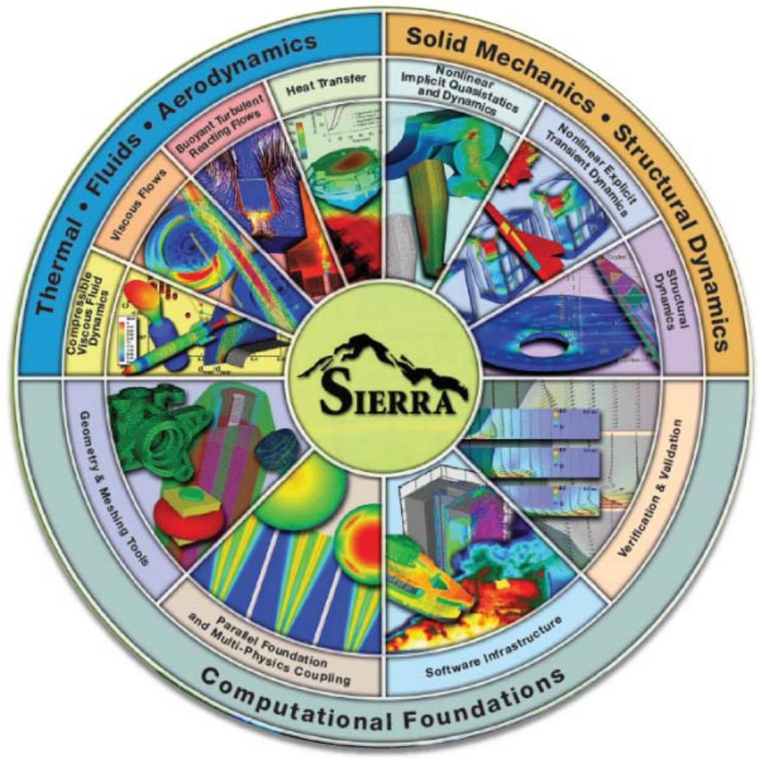
- This compromises our ability to do overall uncertainty quantification (UQ) of our predictions.

# Eventual Implementation of Prediction Methods in Commercial Numerical Codes

**Matthew Brake (lead, Sandia), Melih Eriten (lead, Wisconsin), Dan Brown (AWE), Hugh Goyder (Cranfield), and George Ostermeyer (Braunschweig)**

# Case Study: Sierra

- In house code developed at Sandia
- Designed to be massively parallel
- Several dedicated development teams
- Iwan models incorporated into it
- Issue: the joint models aren't used by analysts
    - Too computationally expensive
    - Mystery as to how to specify parameters



# Primary Issues

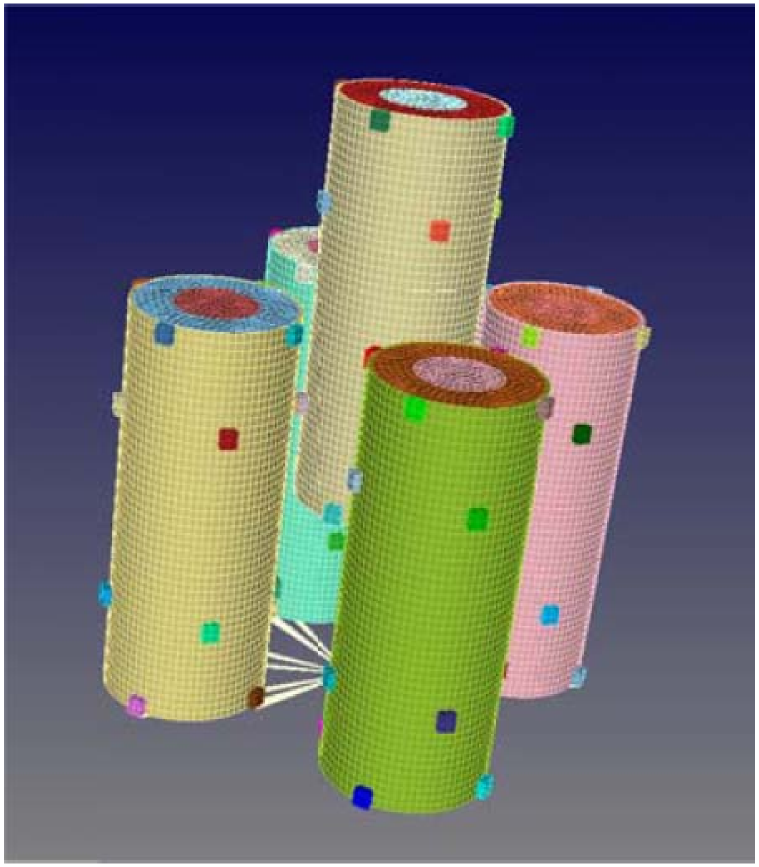
- Efficiency
  - Without an efficient implementation, joint models are unlikely to be adopted by analysts
- Accuracy
  - The Iwan model, or its future successors, is an improvement over existing techniques (linear springs)
- Usability
  - In order to be widely adopted, the model must require parameters that are easily found (contrast a Prony series with a Kelvin-Voigt model)

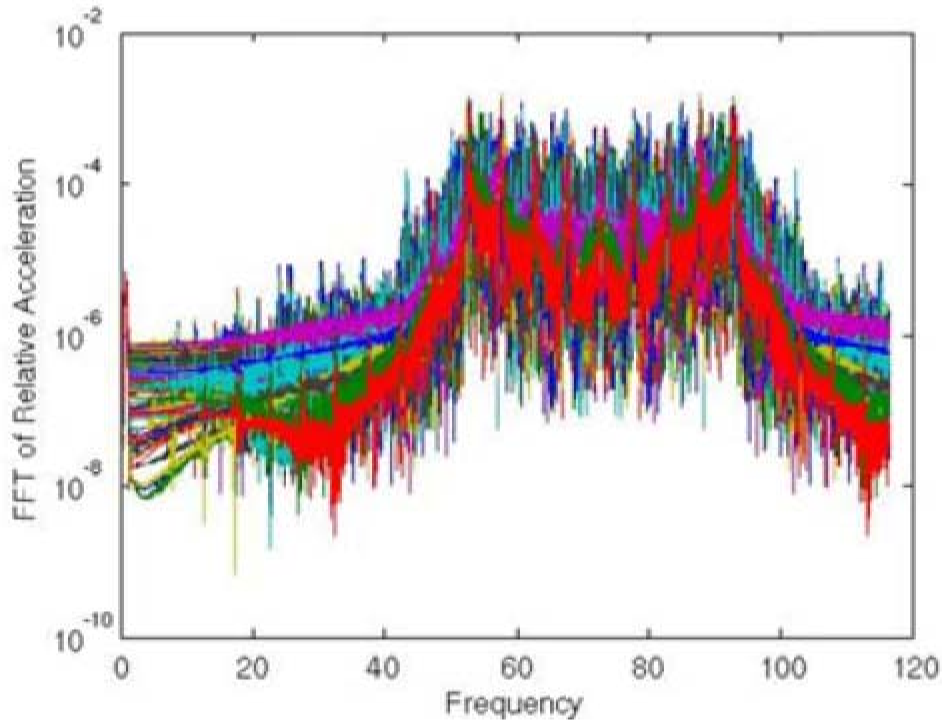
# Existing Research on Efficiency

- Model reduction techniques incorporating nonlinearities (a non-exhaustive list)
  - Frequency based substructuring (Reuss et al., 2012; de Klerk et al., 2008)
  - FRF based model reduction (Petrov, 2010; Popp and Maagnus, 2002)
  - Other harmonic balance methods (Firrone et al., 2011; Tangpong et al., 2008)
  - Non-smooth basis functions (Brake and Segalman, in press; Milman and Chu, 1994)
- Many approaches, but little consensus
- Collaborations directly comparing methodologies are necessary
  - **Outcome of last workshop** – collaboration between Sandia and Stuttgart to assess frequency based substructuring and non-smooth basis function methods

# Model Reduction of Nonlinear Systems

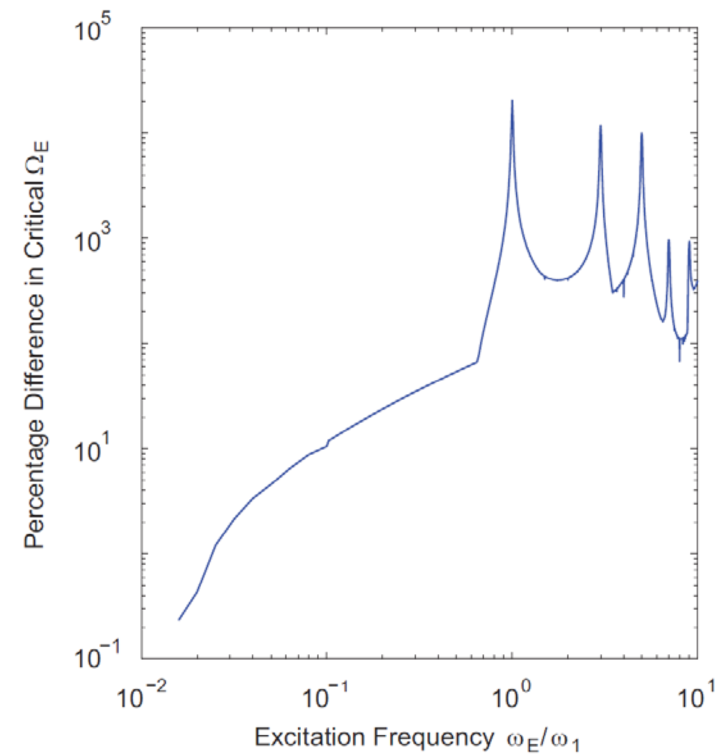
- Collaboration between Sandia and Stuttgart (Reuss et al., IDETC2013, Brake et al., WTC2013)

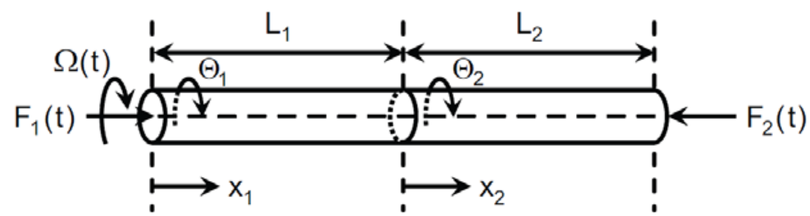




# Assessment of Accuracy

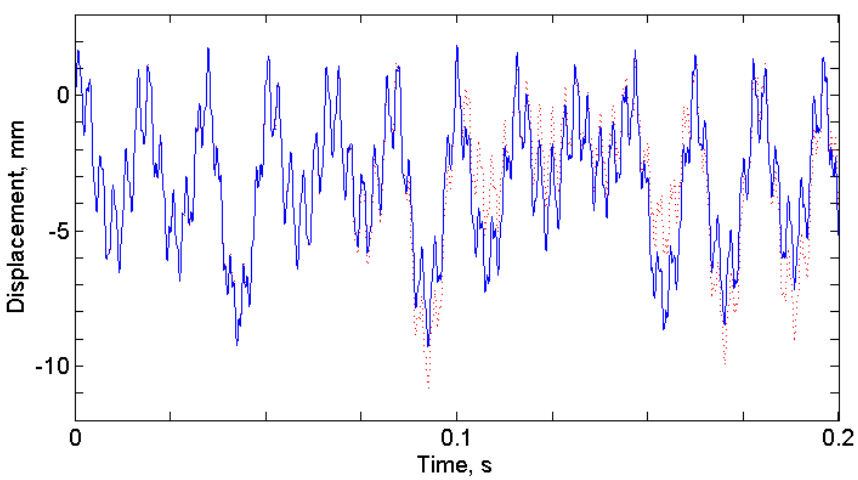
- Validity of model techniques
  - **Outcome of last workshop** – collaboration between Sandia and Oxford (Brake and Hills, 2013, Tribology International)
  - Quasi-static v. Dynamic modeling techniques
- Determining convergence for nonlinear systems
  - **Outcome of last workshop** – collaboration between Sandia and Wisconsin (Kuether, Brake, and Allen, IMAC2014)
- Accuracy of joint models…

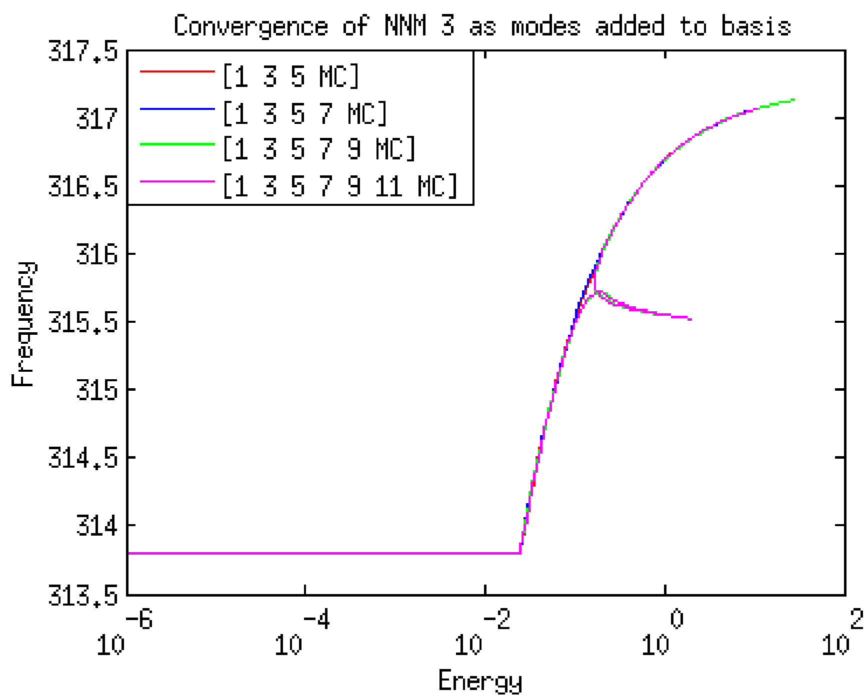


# Comparison of Nonlinear Systems

- How do you compare two different models of the same nonlinear system?
  - Time histories, dissipation, strain energy, $L_2$ norm, etc.
  - Use of nonlinear normal modes to measure convergence



# Usability

- Example of the Iwan model
- Long history of development: Baushinger, 1886; Masing, 1926; Prandtl, 1928; Ishlinskii, 1944; and Iwan, 1966 and 1967
- Four parameter Iwan model: Segalman, 2005
  - **Usability issue**: determining those four parameters ($\beta$, $\chi$, $K_T$, $F_S$)
  - Still not predictive…

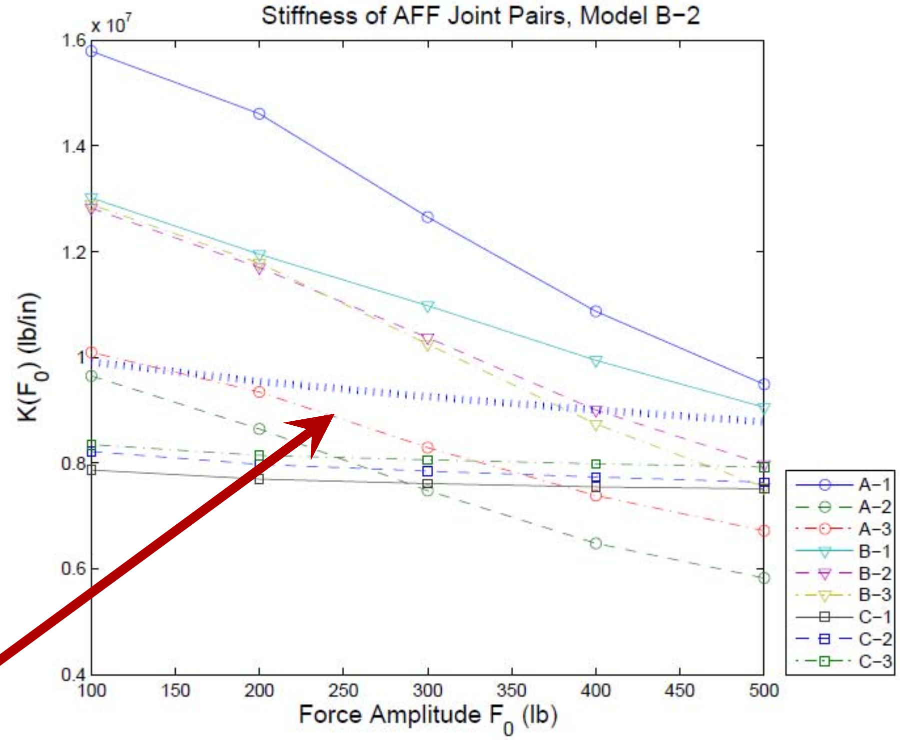



**Figure 12.15.** Stiffness of AOS Joint Pairs.

The thick dotted line is the stiffness of the four-parameter Iwan model, calibrated to reproduce the dissipation curve with fidelity and to match the stiffness of a load of 400 lb.

From the joint handbook (SAND2009-4164)

# Observations for the Numerical Implementation Challenge

- Not yet ready to involve commercial code developers
  - We could potentially involve research code developers once we address several questions…
- Three major issues to be addressed first: efficiency, accuracy, and usability
- Clear that we must simultaneously develop higher accuracy models with modeling techniques
- Several collaborations have been developed since the last workshop between Sandia and Oxford, Stuttgart, and Wisconsin
  - This research focuses on developing efficient ROMs for nonlinear problems, assessing the validity of ROMs, and assessing the validity of modeling techniques

# Concluding Remarks for the Challenges

- Set of 8 active research areas
- Ultimate goal is to have a predictive model of joints
  - Use of joints as a design tool
  - Improved performance, reduced weight, etc.
- These problems ***cannot*** be solved in isolation
- Large collaborations are needed

- For more information:

https://community.asme.org/research_committee_mechanics_jointed_structures/w/wiki/3787.about.aspx

# Joint Summer Research Institute

- Workshop planned for summer 2014
- Open to graduate students and early career researchers
- Both US and non-US citizens*
- Tentatively planned for July, 2014
- Research will be presented at IDETC2014 (August 17th-20th, Buffalo, NY)
- Teams working on problems germane to the joint challenges
- Example problems:
  - Numerical round robin of methodologies to model jointed structures
  - Experimental assessment of the sources of variability in joints
  - Developing a methodology for incorporating epistemic and aleatoric uncertainty in models
  - Currently soliciting proposals…
- Email: mrbrake@sandia.gov

# Outcomes of the First Workshop

- Challenges defined:

  1. Experimental Measurement of Joint Properties
     - Round-robin exercise for measuring hysteresis in joints

  2. Interface Physics
     - Development of physics-based contact and friction models
     - Understanding of surface roughness effects
     - Study of partial slip for realistic contact conditions

  3. Multi-Scale Modeling
     - Coupling of bottom-up and top-down modeling approaches

# Outcomes of the Second Workshop

- Challenges defined:
  1. Round Robin/Benchmark Exercise for Hysteresis Measurements
  2. Round Robin/Benchmark Exercise for Measurement and Prediction of Dissipation in Standard Joints
  3. Repeatability (measurement-to-measurement) and Variability (unit-to-unit)
  4. Framework for Multi-Scale Modeling
- Actions:
  1. Terminology and Vocabulary
  2. Development of the Hills Chart
  3. Classification of Standard Joint Types
  4. Classification/Catalog of Nonlinear ID Methods, Modeling Approaches, and Measurement Methods
  5. Benchmark Analytical Solutions Against Multi-Scale Methods
  6. Create a Formal Joints Modeling Network

# Derivation of Constitutive Equations Based on Physical Parameters

**Lothar Gaul (lead, Stuttgart), Randy Mayes (lead, Sandia), Norbert Hoffmann (Hamburg), and Mike Starr (Sandia)**

# Two Sets of Problems

1. How can we make in-situ measurements of quantities at/near the contact interface?

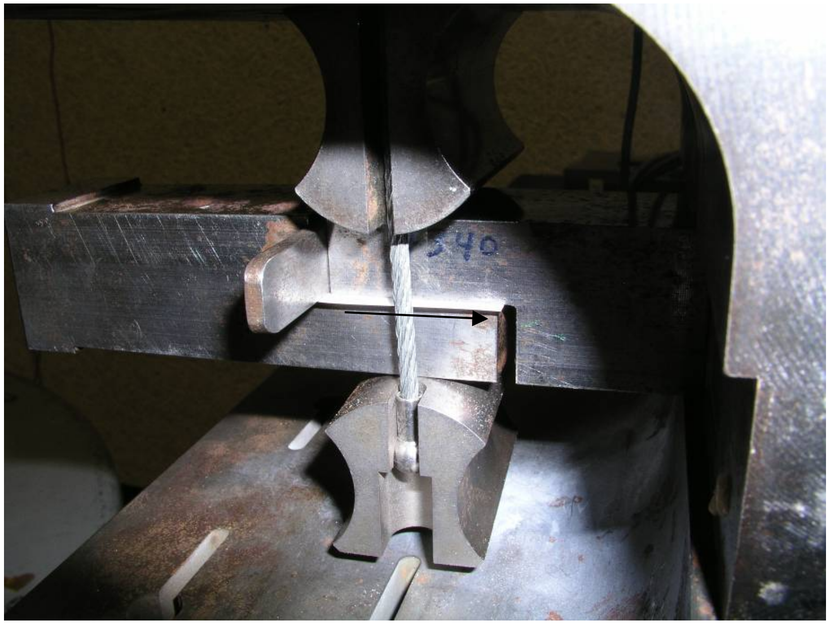
2. How can we use experimental knowledge to postulate an improved friction model?

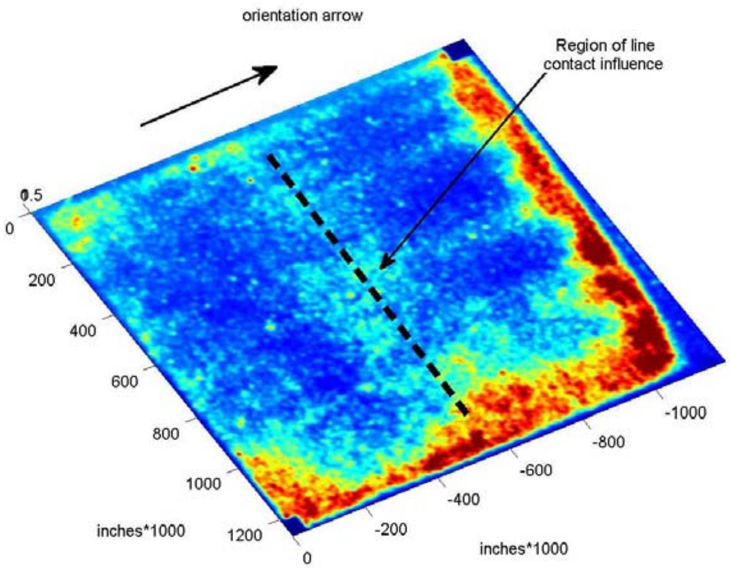
# Measuring Joint Properties

- Constitutive models cannot be validated without experimental data
- The state of the art is limited to measurements of the global joint stiffness and the loss of energy per cycle derived from force and response measurements across the joint
- A measurement of the forces and displacements at the interface is needed
- Installing sensors in the joint disrupts the physics we wish to measure
- Some commonly used non-contact methods investigated: digital image correlation, laser doppler vibrometry

# The Contact Patch Process Zone is Poorly Understood

- Assembling a pressure sensitive film into a simple lap joint interface provides a qualitative snapshot of normal pressure on a conformal, self-aligning interface.



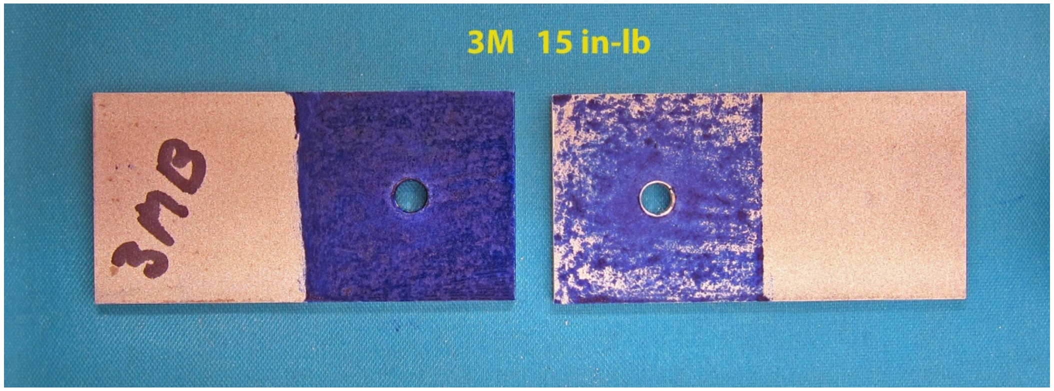



- The digitized film shows an apparent assembly misfit, periodic machining marks, and local surface roughness characteristics.

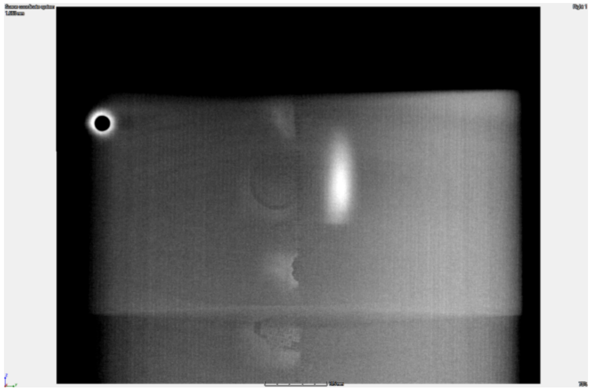
# Methods to Determine Contact Area of Two Plates with Bolt Through Center

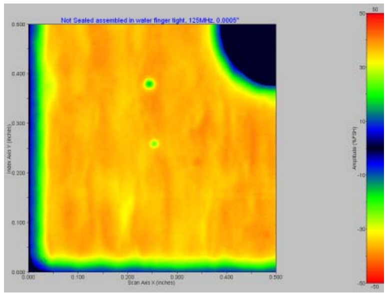
- Prussian blue ink
- Ultrasonic measurement
- Implanted Ions and Xray/Computed Tomography

**Prussian Blue**




**CT Slice**





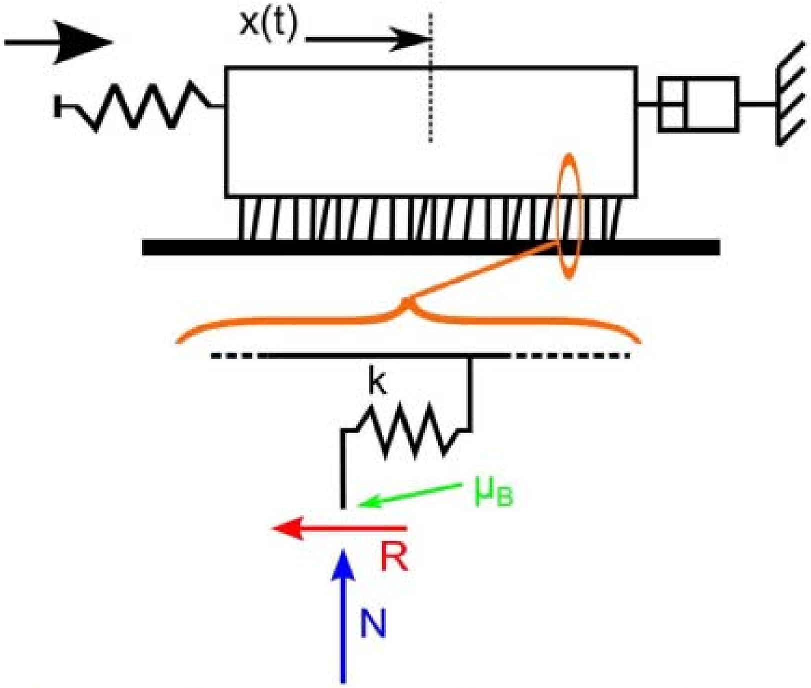
**Ultrasonic**

# Some Modeling Progress

**Roughness based**

- repeated shearing, failure and reattachment of asperities

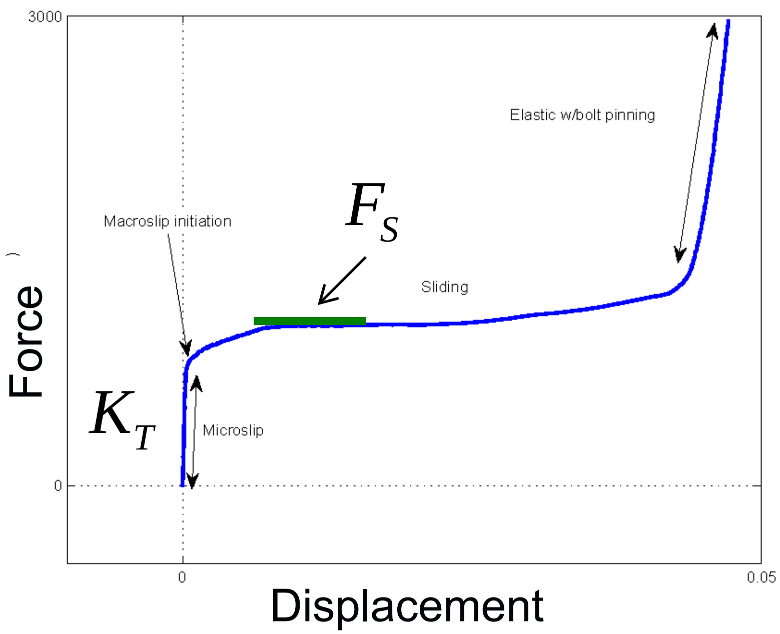
**Bristle Model**

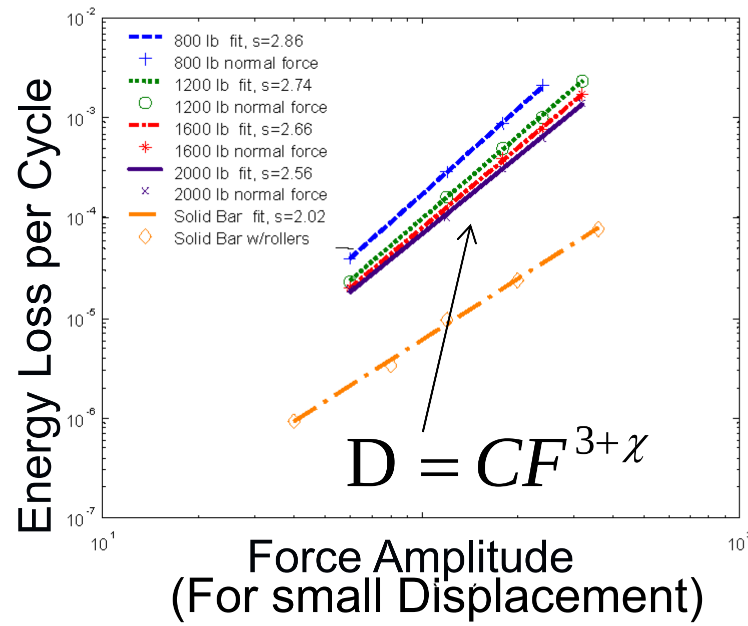



- rough interface: elastic bristles

# The Four Parameter Iwan Model

This is a single element constitutive model used to join together two faces in an interface




If considering macro-slip, we need at least four parameters, and these are given in the Four parameter Iwan model as

$$K_T, C, \chi, F_S$$

# Observations for the Constitutive Modeling Challenge

- In situ measurement of quantities at the joint interface a significant challenge
- Behavior of contact zone found to be significantly different than originally hypothesized
- More measurements are necessary to be able to postulate improved joint models

- Some progress is being made on heuristic friction models, but the development of a predictive friction model is stiff far off (see challenge 4)

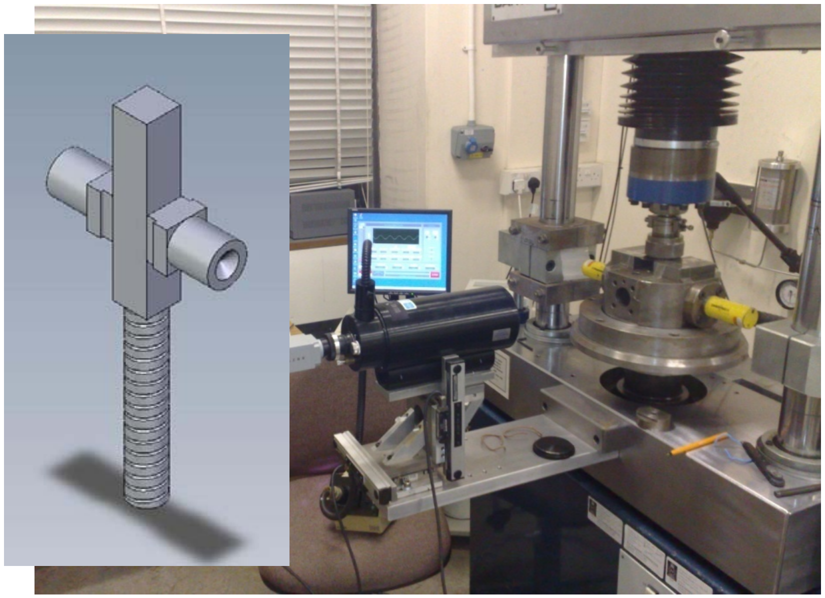
# Round Robin/Benchmark for Hysteresis Measurements

**David Ewins (lead, Imperial), David Nowell (Oxford), Muzio Gola (Torino), Christoph Schwingshackl (Imperial)**

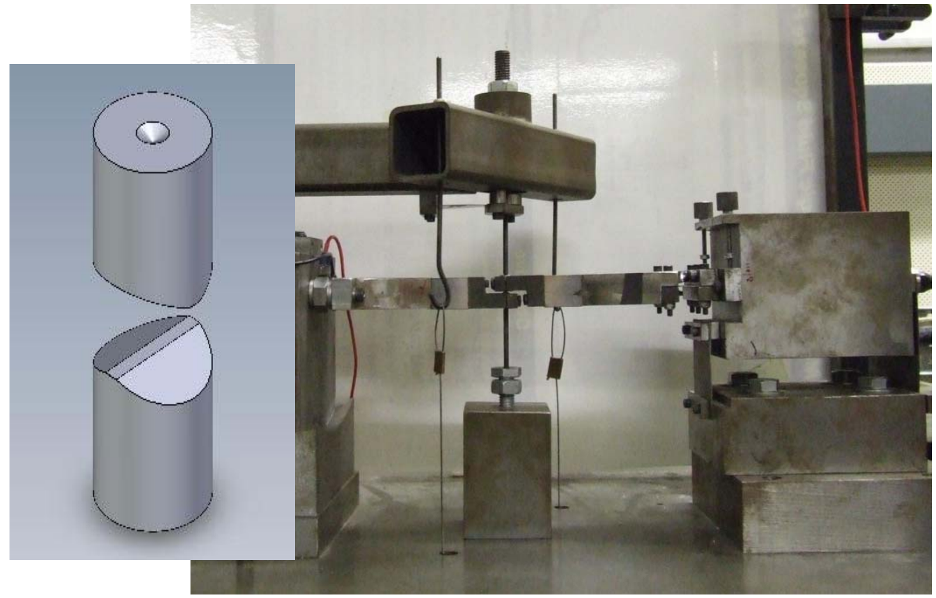
# Difficulties in Modelling Contacts

- In general, the normal and tangential stiffnesses of a joint need to be experimentally measured, along with the friction coefficient
- These properties may change with time (e.g. as the contact wears, with position, and with load)
- Progress is needed towards a model of interface behaviour, which is based on more fundamental properties (material properties, surface geometry etc).
  - We also need to understand how to incorporate the interface behaviour into global (FE) models of the system

# Measurement of Contact behaviour – Oxford and Imperial rigs

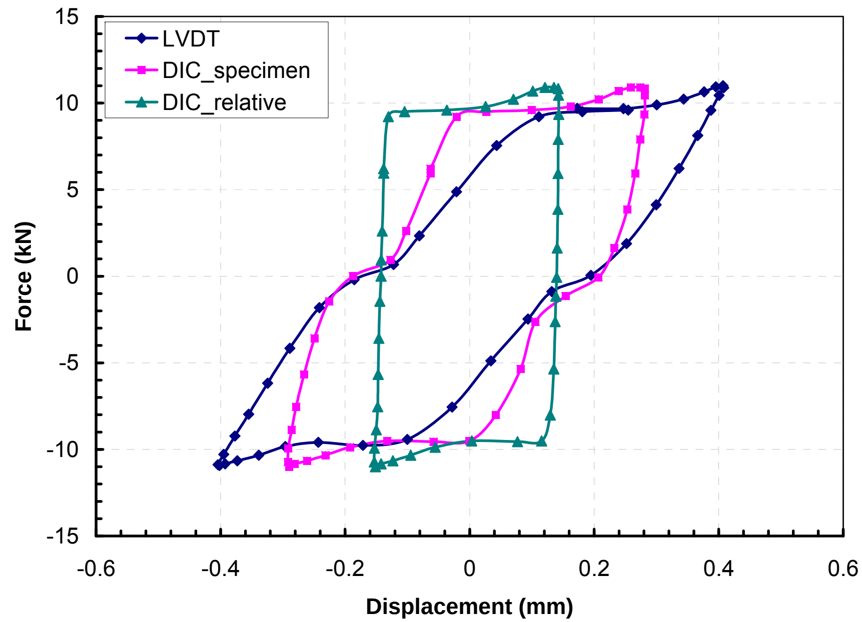


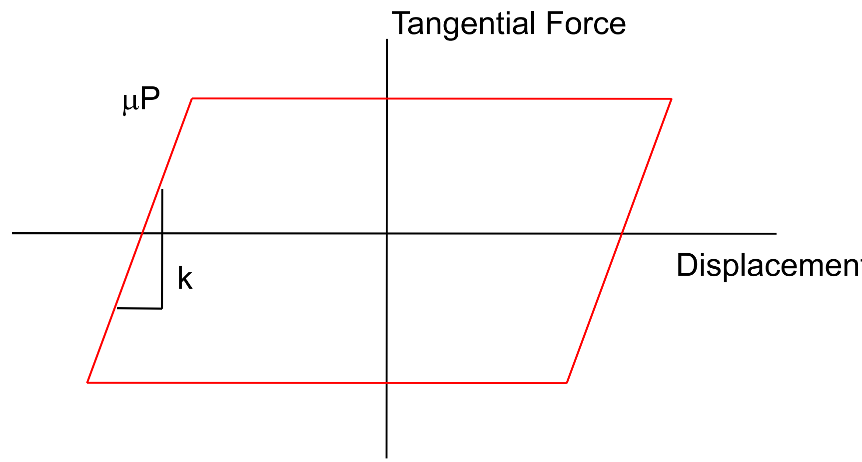
- 80 mm$^2$ flat and rounded contact
- 1Hz Frequency
- 0.6mm sliding distance
- Displacement measurement by remote LVDT or digital image correlation



- 1 mm$^2$ flat on flat contact
- ~100Hz Frequency
- 30$\mu$m sliding distance
- Displacement measurement integration of LDV measurements

# Measured and Idealised Hysteresis Loops


- Idealised loop is characterised by contact stiffness, k and friction coefficient, $\mu$
- These can be reasonably representative of real loops

# Observations for the Hysteresis Challenge

- Hysteresis loops measured in order to characterize energy dissipation characteristics of joints.
- Individual tests are useful for specific funding agents (Rolls-Royce, GE, etc), but the collection of data and systematic analysis and comparison between labs leads to greater understanding
- Need to quantify intrinsic and lab-to-lab variations in these measurements
- Currently efforts are limited to Imperial, Oxford, and Torino, but new collaborators are being sought

# Round Robin/Benchmark for Measurements and Predictions of Dissipation in Standard Joints

**Hugh Goyder (lead, Cranfield), Matt Allen (lead, Wisconsin), Lothar Gaul (Stuttgart), Laura Jacobs and Randy Mayes (Sandia), Gael Chevallier (Supmeca), Norbert Hoffmann (Hamburg), Kai Willner (Erlanger/Imperial), Christoph Schwingshackl (Imperial)**

# Observations for Challenge 2

- Wealth of issues regarding dissipation in joints that have been addressed
  - Currently being collected, summarized, and described on our webpage
- The round robin involves a set geometry analyzed at multiple locations, both experimentally and numerically
- Current collaborations are making data and hardware schematics freely available for new researchers to join in