Modeling Interfaces in Structural Dynamics Analysis

Enriching our joints models and capabilities

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We Wish to Develop New Tools and Capabilities That Retain a Connection to Our Physical Understanding of Interfaces

- Enhanced capabilities in structural dynamics analysis
- Reduced-order interface constitutive models
- Handbook to aid analysts in populating models
  - generalized classes of joints and configurations
  - enriched parameter sets through variability

Historically we have used experimental data to populate models. We would like to move toward numerical "experiments" to derive model parameters, *e.g.* postulate phenomena that manifest as variability observed in experiments and sample from that physical space to generate a statistical representation.

Extracting Reduced-Order Joint Parameters from Fine-Mesh Finite Element (FMFE) Models

Parameter Extraction in the Absence of Experimental Data

There are Fundamental Experimental Difficulties that Make Numerical Analysis Appear Attractive

- The physics to be measured all occurs exactly where it cannot be measured directly.
- Kinematics of joint displacements cannot be well-defined in an experimental context.
- Every specimen mounting adds its own features to measurements.
- Specimen compliances drown out joint response except at very high loads.

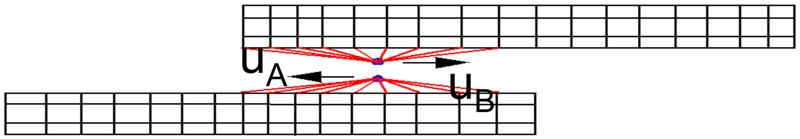
Potential benefit of running FMFE:

We, of course recognize the importance of verifying the accuracy of any prospective finite element code we intend to use in our analyses

The Development of a Reduced-Order Interface Model Was Driven By Necessity

- FMFE models are not suitable for direct implementation in structural dynamics because of imitations of Courant time step (explicit) conditioning (implicit). This is why we must seek continuum level constitutive models.

- Connect the kinematics of element nodes in the “process zone” to that of a representative node.



- This approach has weaknesses
  - it does not account for the multi-dimensional nature of loading.
  - it does not account for the true complexity of contact.
  - it relies on the postulated interface law.
  - it ignores micro-level effects that lead to wear-in.

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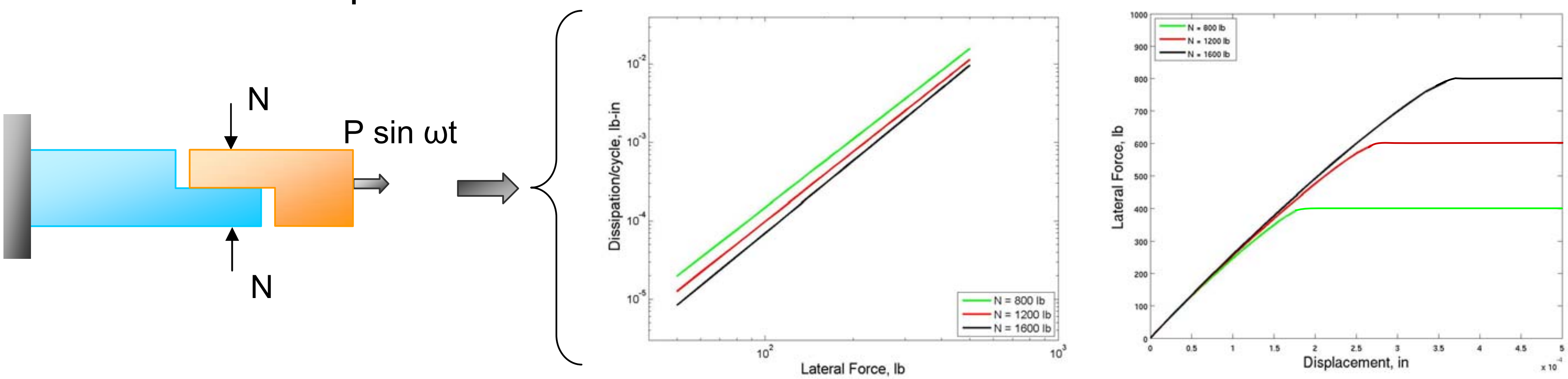
Iwan Parameters Can Be Deduced From a Small Set of Numerical Experiments

Calculated quantities required to fully populate the Iwan 4-Parameter constitutive model:

- Dissipation per cycle over a range of loads below macroslip
- Joint stiffness over a range of loads
  - Joint stiffness calculated for a monolithic specimen
  - Elastic compliance of the jointed specimen
- Macroslip force



These quantities could be calculated deterministically to satisfy known distributions, or stochastically using a scheme that reproduces the distributions of known measured quantities.

Predictions of Dissipative Response For Generalized Lap and Flange Joints

Employing a Coulomb friction interface constitutive model

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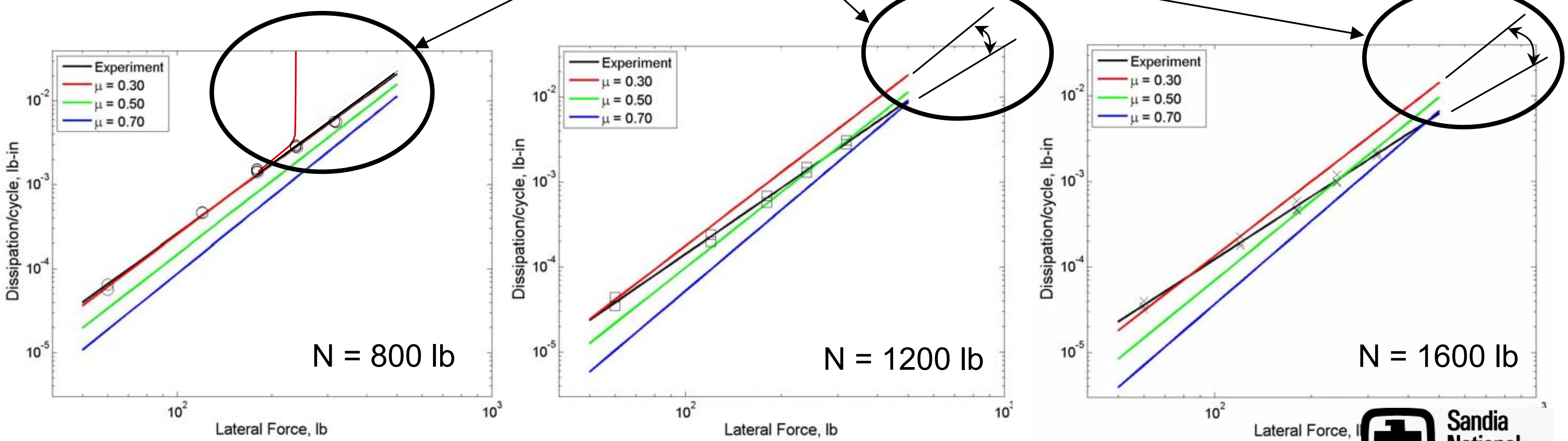
It is Not Efficient for Analysts to Run Full Suites of Simulations to Capture Variability and Uncertainty Using FMFE

- Provide a “Roark’s Handbook” of joint response for each important class of joint, providing estimates of the following for arbitrary values of geometry and material parameters
  - Joint dissipation and softening
  - Joint constitutive behavior
  - Variability in the above as a function surface characteristics

“missing” physics

- Handbook calculations per friction model in the microslip regime despite its limitations (micro-level effects, chemistry, etc.)



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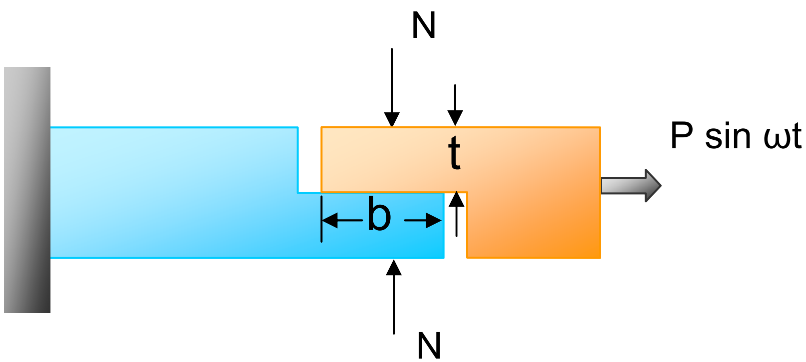
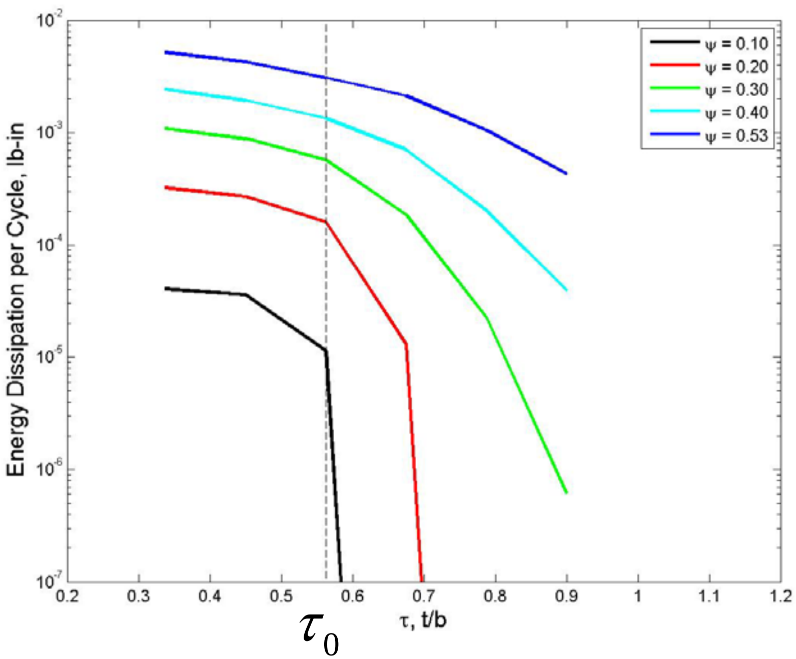
Non-Dimensional Parameter Studies of Generalized Jointed Interfaces were Performed to Better Understand the Contact Mechanics

- Focused on a convenient non-dimensional parameter, $\psi = P/\mu N$, which characterizes the fraction of the macroslip load acting across the interface.



$$\tau = t / b$$



- Tuning to a particular experimental measurement, these results can be used to interpolate or extrapolate to other geometries, stiffnesses, and loads.

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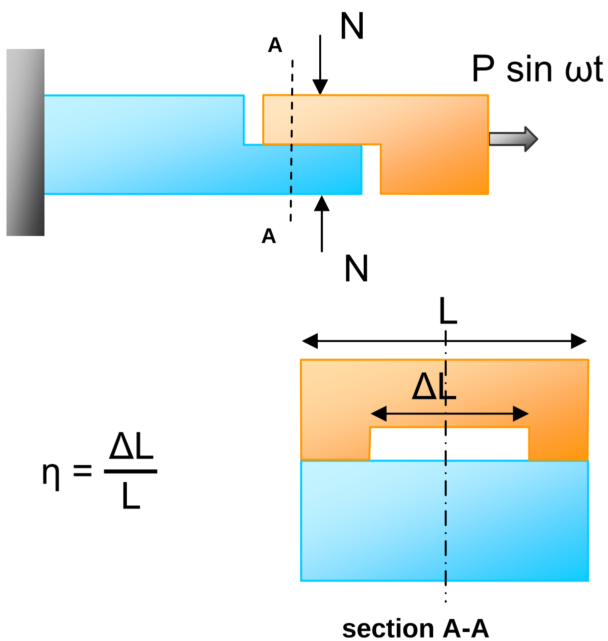
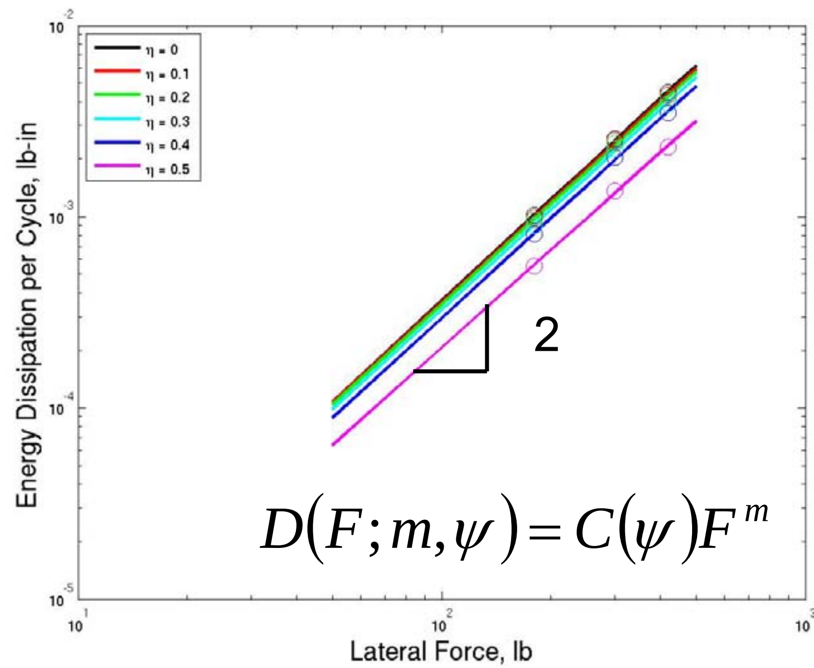
Though Coulomb Friction is not Quantitatively Correct, It May Be a Useful Tool For Leveraging Sparse Experimental Data

- FMFE simulations for several cases of loading conforming to ψ = P/μN = constant exhibited a power law response in dissipation, D, with slope $m \approx 2.0$





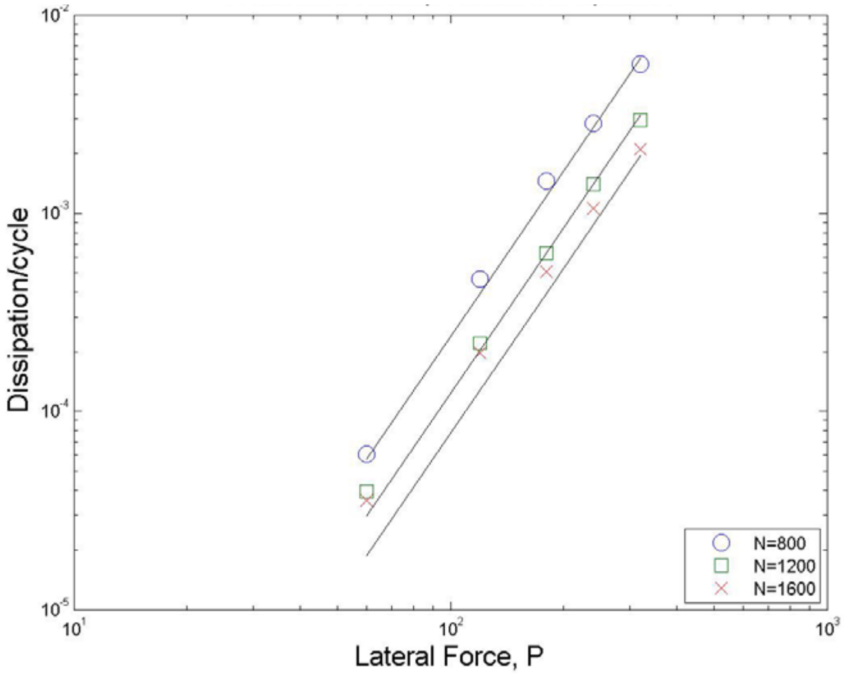
- The power law behavior is also independent of actual contact area for constant ψ.

FMFE Suggests Relationships to Look For in Experimental Data

- Given one small set of experimental data at ψ = constant and another small set at N_0 = constant, a relationship can be derived to predict energy dissipation at other force levels.

$$D(\mu N, P) = C_0 (\mu N_0 \psi)^{\alpha_0 - m} P^m$$

$$C_0, \alpha_0, m \left\{ \begin{array}{l} \text{determined from} \\ \text{experimental data} \end{array} \right.$$



- The Ψ-relationship asserts that the power law dissipation slope is the same for all clamping loads (good assumption for numerical work, bad assumption for experiments).

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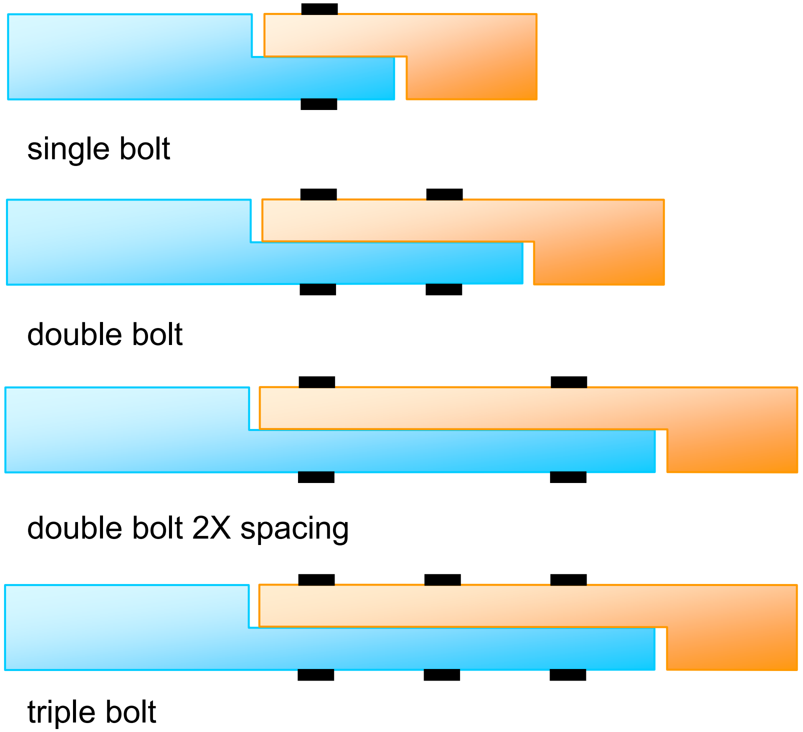
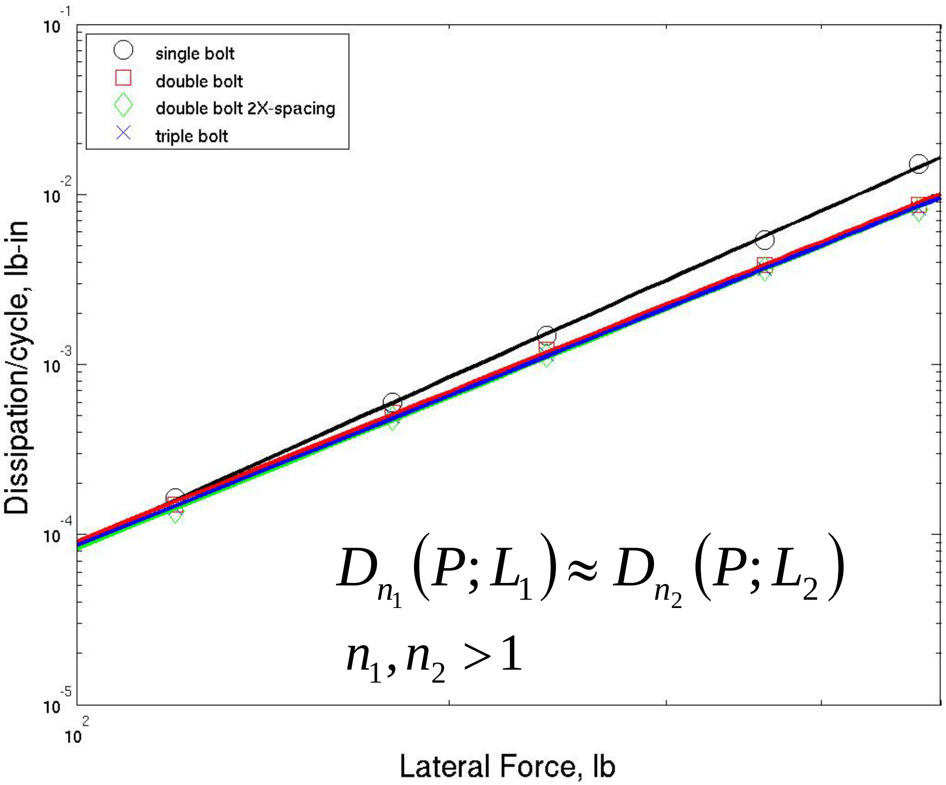
Coarse Relationships Have Been Developed for "Serially" Bolted Flange Connections

- There are two principal flange orientations that generalize a flange ring, the so-called parallel and serial (shown here) configurations.



several serial configurations



- The predictions of energy dissipation per cycle are similar between the double bolt and triple bolt cases despite the obvious differences in loading levels and normal stress distributions on the interfaces.

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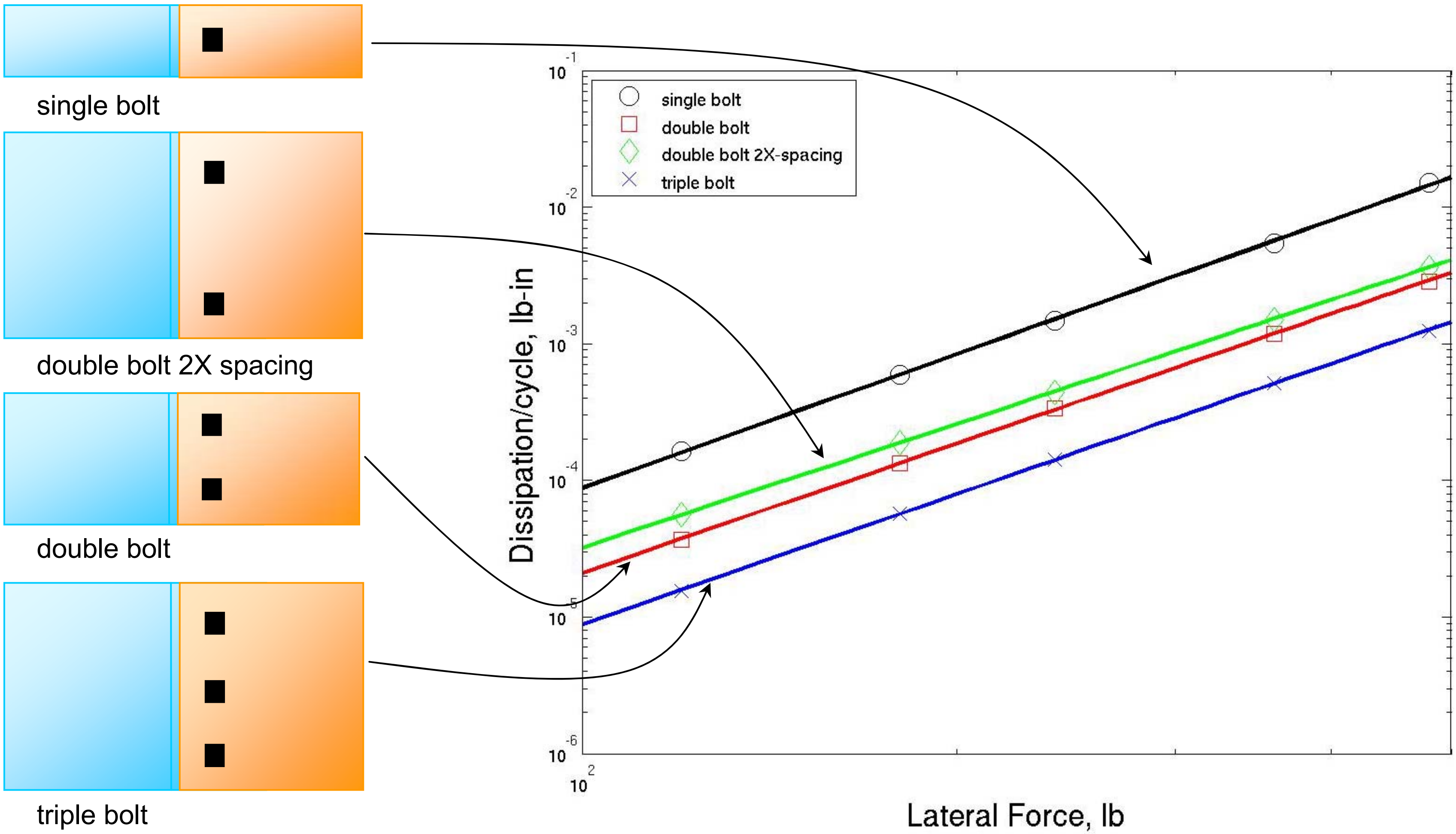
Coarse Relationships Have Also Been Developed for "Parallel" Bolted Flange Connections

- The parallel configuration behaves differently than the serial configuration.



several parallel configurations

- Let's plot the results somewhat differently.

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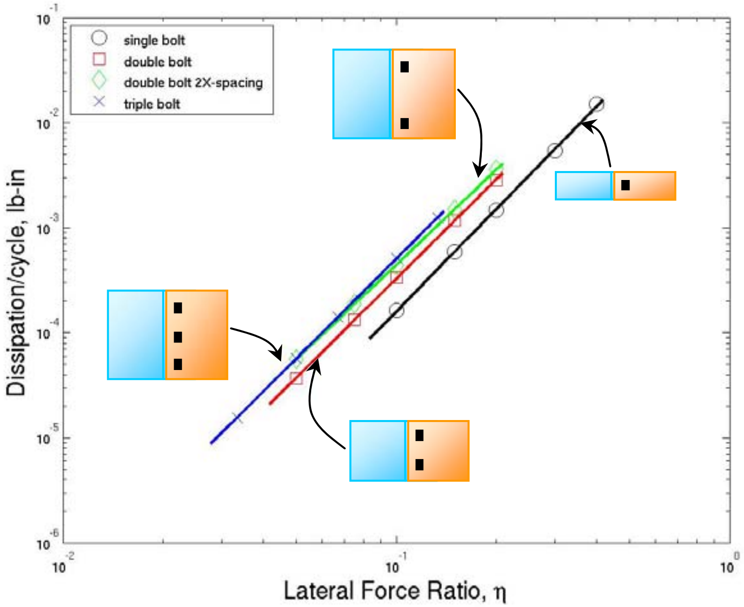
Normalizations Expose Relationships Between Numerical Predictions

- Define lateral force ratio as η = P/nN, where n is the number of bolts in the flange.

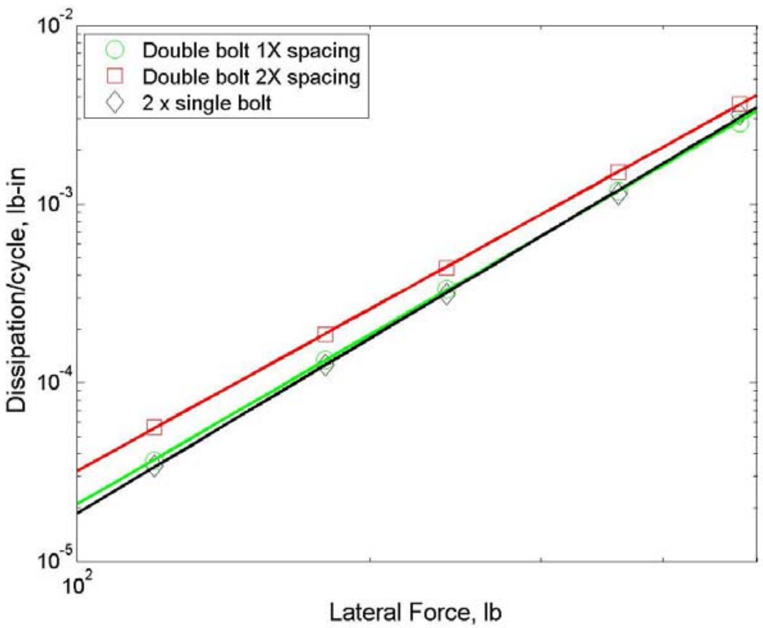


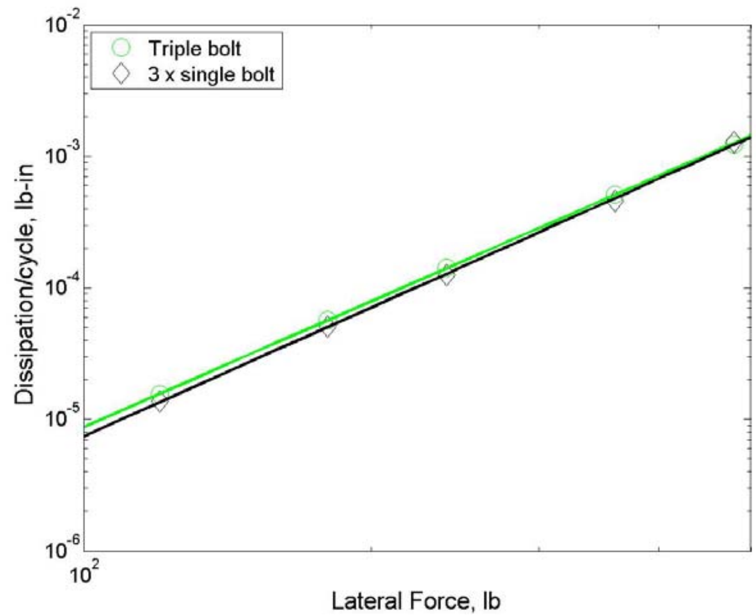
- The double bolt "looks like" the triple bolt at low η, but more interestingly there appears to be a functional relationship between the curves at constant, η.

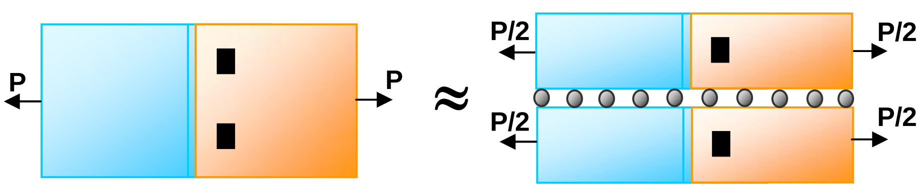
$$D_n(P;n) \approx nD_1\left(\frac{P}{n};1\right) = nC_0\left(\frac{P}{n}\right)^{\alpha} = n^{1-\alpha}D_1(P;1)$$

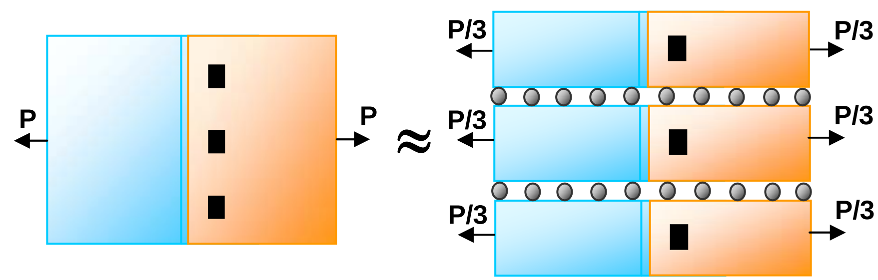
A Reasonable Approximation for the Parallel Flange Configuration

- The prediction is reasonable for the single-spaced geometries.









FMFE Predictions Without Incorrect Interface Constitutive Models are not Without Merit

- Phenomenologically motivated numerical simulations have been performed to understand the impact of boundary conditions, joint misfit, and surface features (machining and intrinsic roughness) on predictions of dissipation.
- Although the numerically deduced relationships struggle to extrapolate to experimental data outside of its calibration range, they extrapolate exceptionally well to numerical predictions.
- A very sparse set of numerically calculated data can be used in conjunction with small number of experimental sources to fully populate variability studies from which model parameters can be deduced (such as the four-parameter Iwan model).

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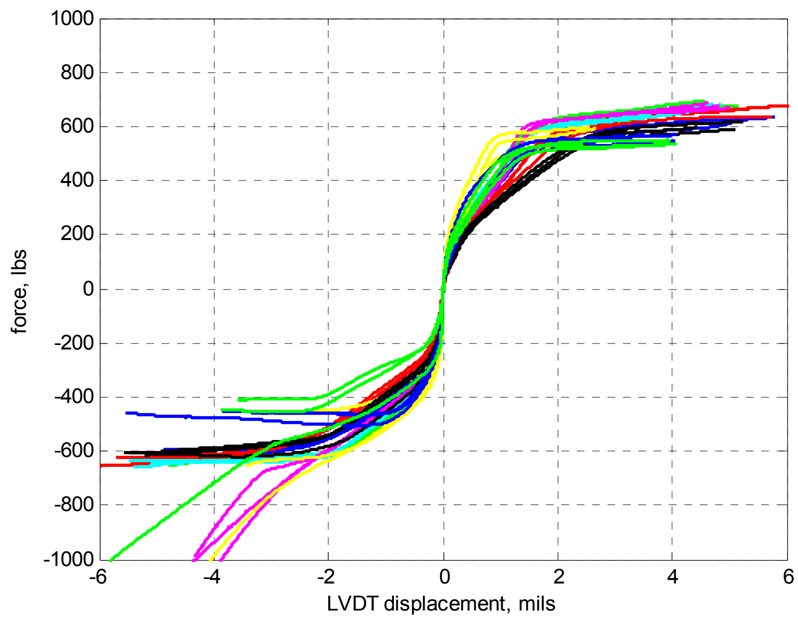
Physical Connections to Observed Variability in Jointed Structures

Continuum Modeling of Causal Variability Phenomena

The Major Source of Variability in Measured Physical Quantities is Part-to-Part Variability

- Even for a simple monotonic, quasistatic pull, with nominally identical clamping load, force saturates in a broad range, $F_S \in (450,634)$ lb

three “tops” and three “bottoms” yield nine unique conformal joint assemblies



- For a given clamping load (say 1200 lb), we could conclude that the Coulomb friction coefficient is distributed within the range, $\mu \in (0.375,0.528)$, but this doesn’t address the underlying phenomena that manifests this distribution.

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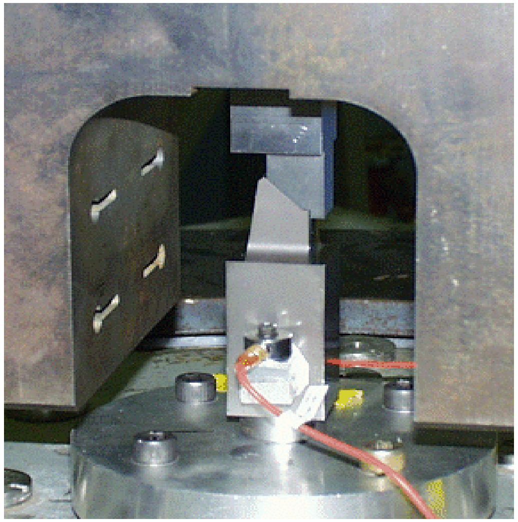
Observation of Trends in Data Give Clues to Causal Phenomena of Variability

- The most dissipative assembly of nominally identical joint pairs is three times as dissipative as the least dissipative assembly.



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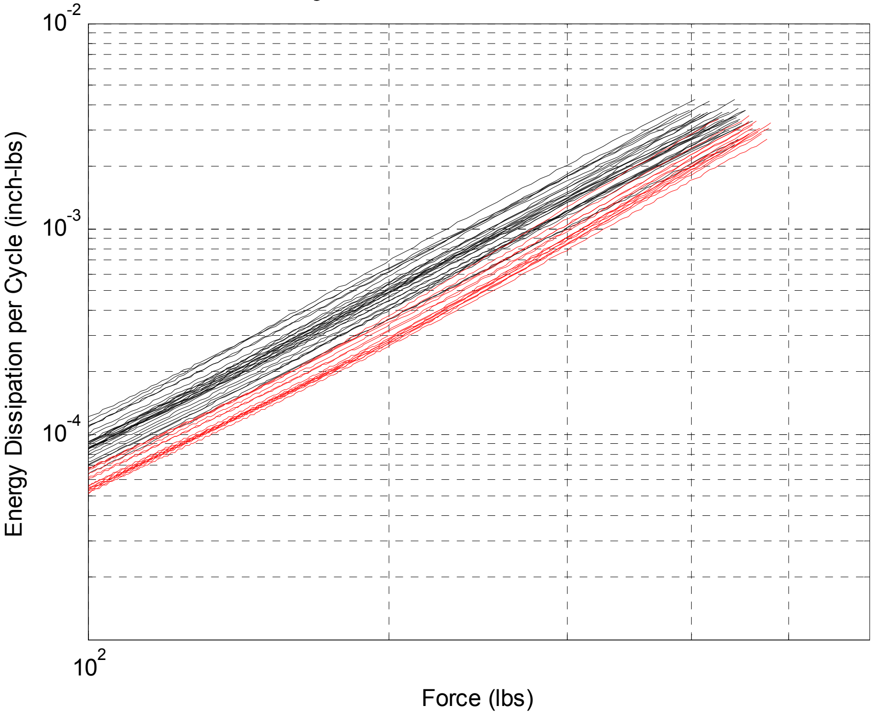
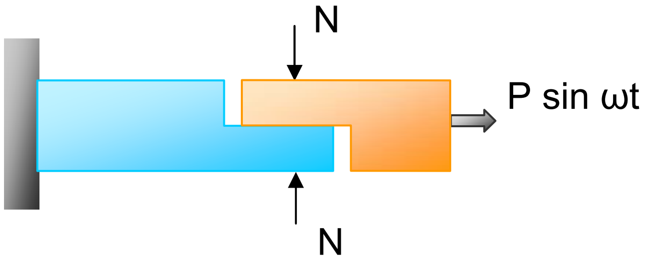
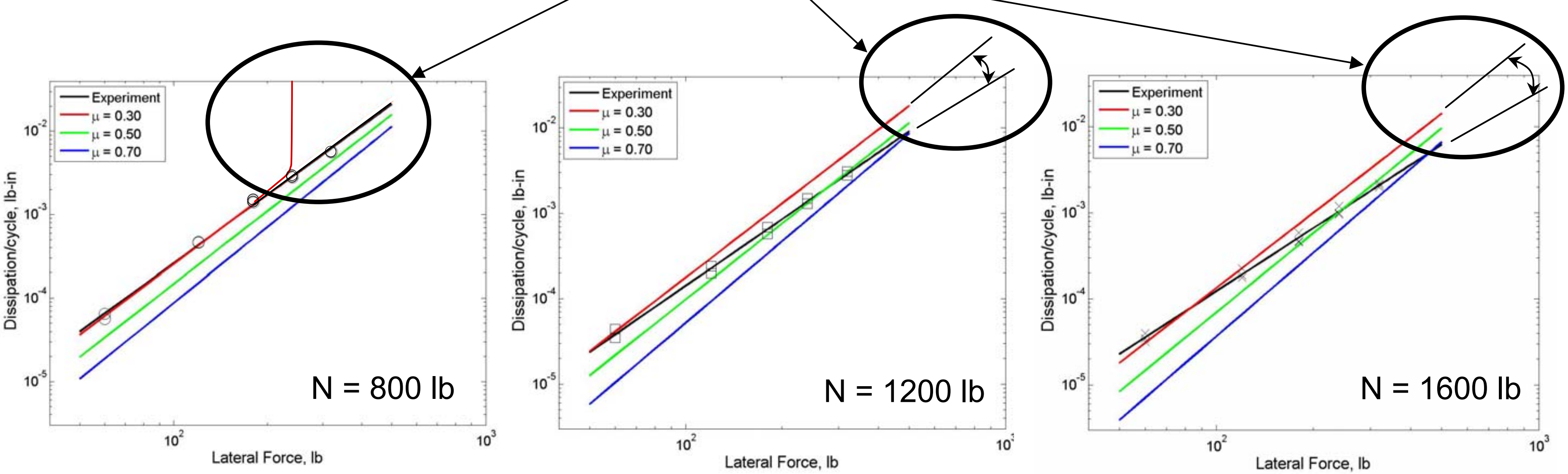


- Are there physical characteristics with length scales on the order of the microslip zone that could lead to the observed spread in energy dissipation?

Coulomb Friction-Based Constitutive Modeling Has Limitations in Microslip Regimes

- Apparently simple dissipation behavior can not be predicted by a simple dry friction model

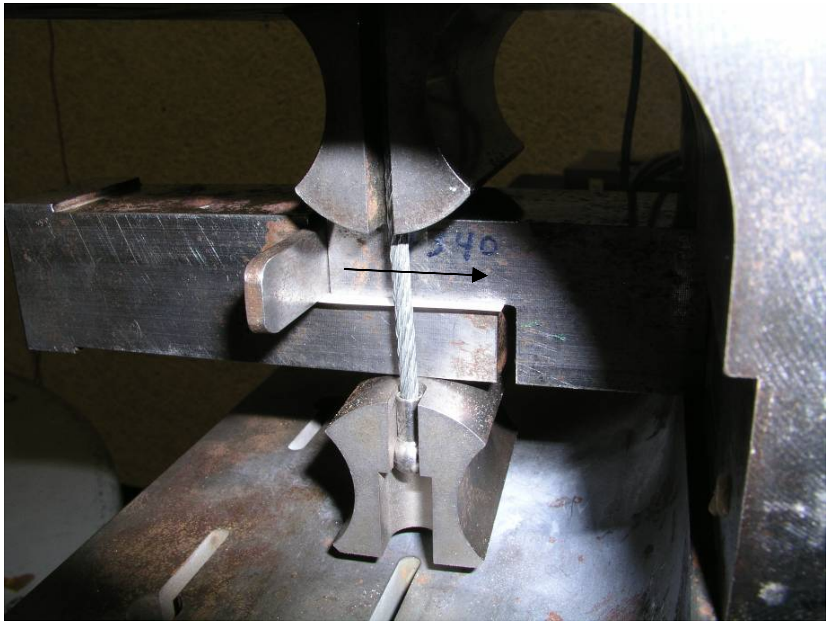


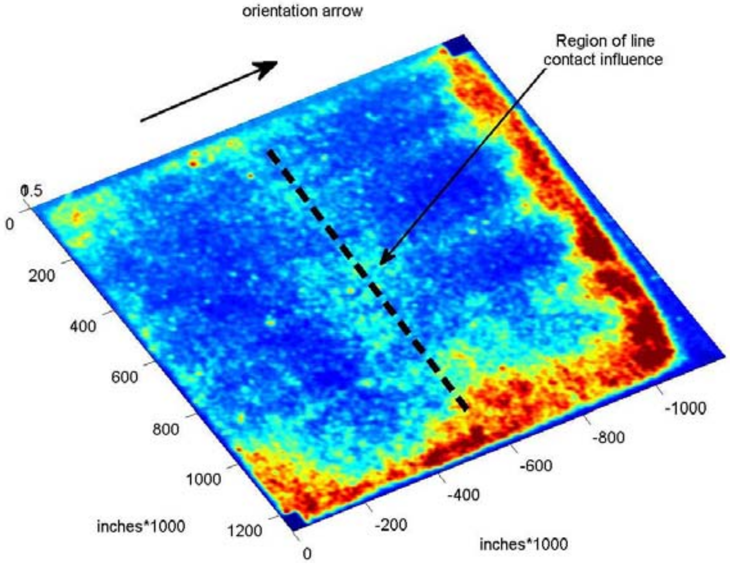


- This systematic deficiency in the Coulomb friction interface constitutive model can not be resolved through mesh refinement.

The Contact Patch Process Zone is Still 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.
- Let's postulate that these features, all of "continuum" length scale, are the causal phenomena which produce the observed variability in measured quantities.

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We Would Like to Advance Our Understanding of the Physical Phenomena While Providing Enhanced Tools for Analysts

- It is not realistic to expect analysts to model features such as surface roughness, machining characteristics, and misfit in their analyses of engineering structures.

- Use a reduced-order model to replace discrete and distributed interfaces.
  - Iwan model
  - Distributed modal damping

- In a Joints Handbook provide tables of parameters that could be used to populate those reduced-order models.
  - Perform suites of non-dimensional joint studies to allow the selection of nominal parameters consistent with individual geometries and loading conditions.
  - Perform stochastic simulations to create distributions of parameters consistent with those observed experimentally.

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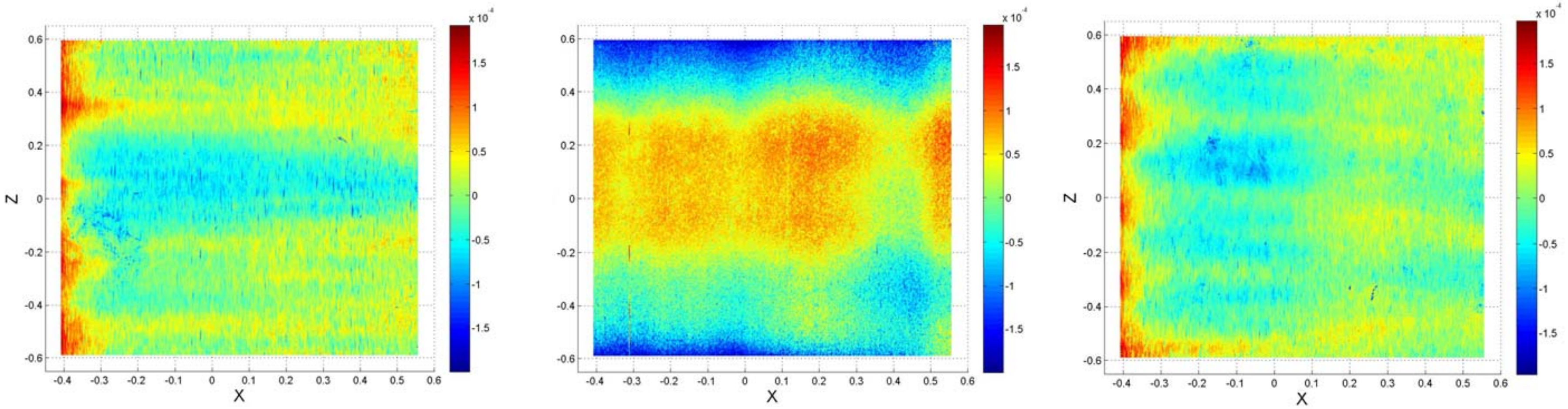
Two Analysis Paths Can Add to Our Qualitative Understanding of Interface Mechanics

The pressure film data is an exceptionally rich set of information. The contributions of feature to overall variability cannot realistically be deconvolved.

- Perform simulations on representative interfaces that account for surface features.



Confocal microscopy scans of flat lap joint surface heights

- Use the surface heights on the contacting surfaces as defined by microscopy and perform fine-mesh finite element simulations to predict mechanical properties of jointed structure.

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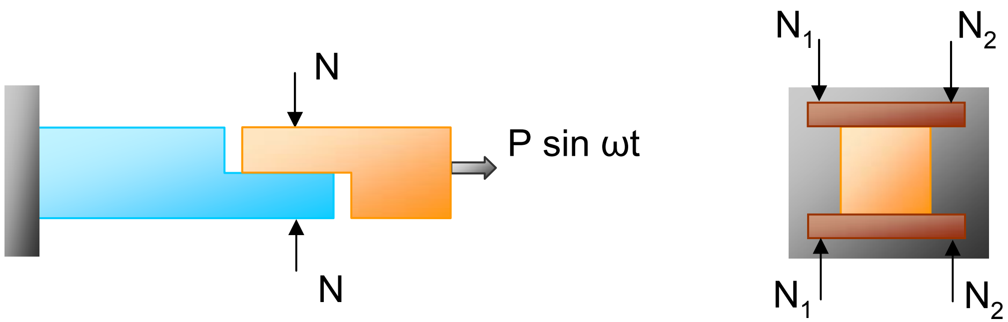
Numerical Modeling and Predictions can Guide the Design of Experimental Explorations

- Remove effects of surface features from simulations and predict impact of introducing misfit through preferential loading of lap interface.



$N_1 + N_2 = N, N_1 \neq N_2$

Schematic of preferential loading configuration as proxy for interfacial misfit.

- Compare to experiment and confirm/invalidate predicted trends in mechanical response of jointed interface.

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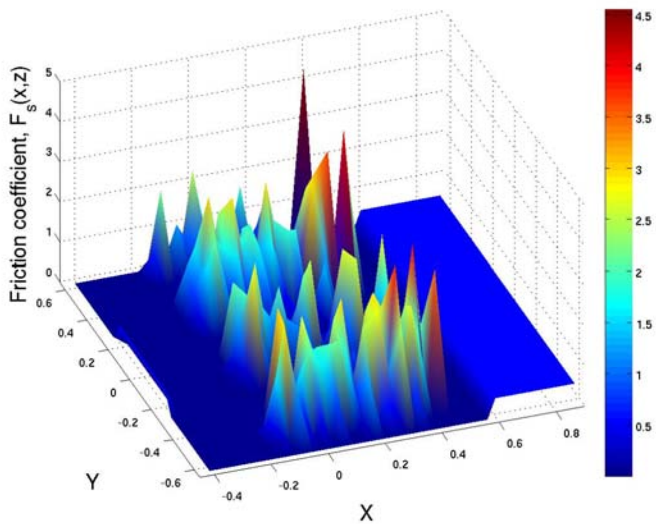
Indirect Modeling Technique for Recovering Quantitative Joint Properties and Variability

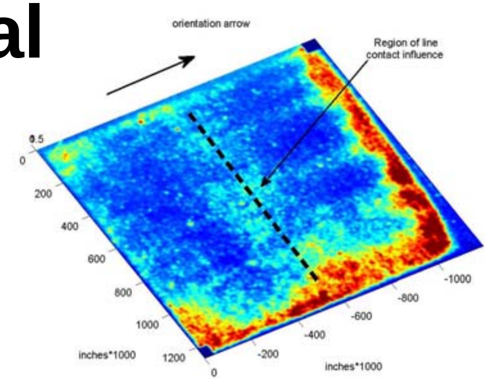
- Recognize the simplicity and elegance of Coulomb's friction relationship, but concede that it was never intended to be applied locally. However, the simple, point-wise equilibrium relationship is still valid (Micro-mechanical approach).



Spatial friction map deduced from assembly of rough contacting interfaces, designed to macroslip as a smooth interface with constant friction coefficient.

- Can the "missing" physics be explained through a spatial variation in friction coefficient?
- Is it essential to retain a connection to experimental observation?

Elements That Must Be Retained if the Spatial Surface Characteristics are the Causal Components of Variability



With regard to the flat lap pressure profile shown profile shown previously:

- The true contact area is some small fraction of apparent contact area.
- An admissible spatial field must achieve macroslip within a predefined range.
- A collection of admissible spatial fields must achieve macroslip in a distribution consistent with a given distribution.
- In order to best recover interface kinematics, there may be an additional requirement on the distribution of nodal friction values.