Experiments and Modeling at the Microscale

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Outline

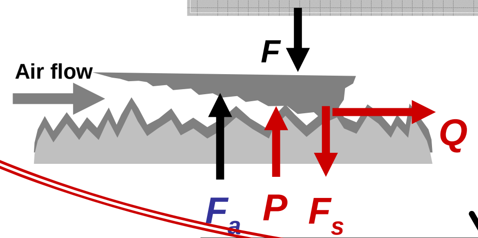
- **Continuum modeling approach for contacts with friction from "sub-micron" to the "cm" length scales**
- **The significance of roughness (measurement and statistical modeling)**
- **Successful predictions of normal contact stiffness and friction**
- **Unsuccessful predictions - Challenges**
- **Microslip/partial slip experimental studies**
- **Summary/Challenges**

Microtribodynamics

Develop physics-based interfacial models and then couple them with system dynamic models

I. Improved Rough Surface Interfacial Models

- Adhesion Energy, $\Delta\gamma$, Zo
- Geometrical Parameters (Roughness and A_n)
- Surface Texturing
- Material and "Lubricant" Properties



Adhesive, Contact, Friction Forces

II. Dynamic Model

- Dynamic Inputs
- Contact Model (e.g., Stiffness, Damping)
- Nominal *FH*, Impulse

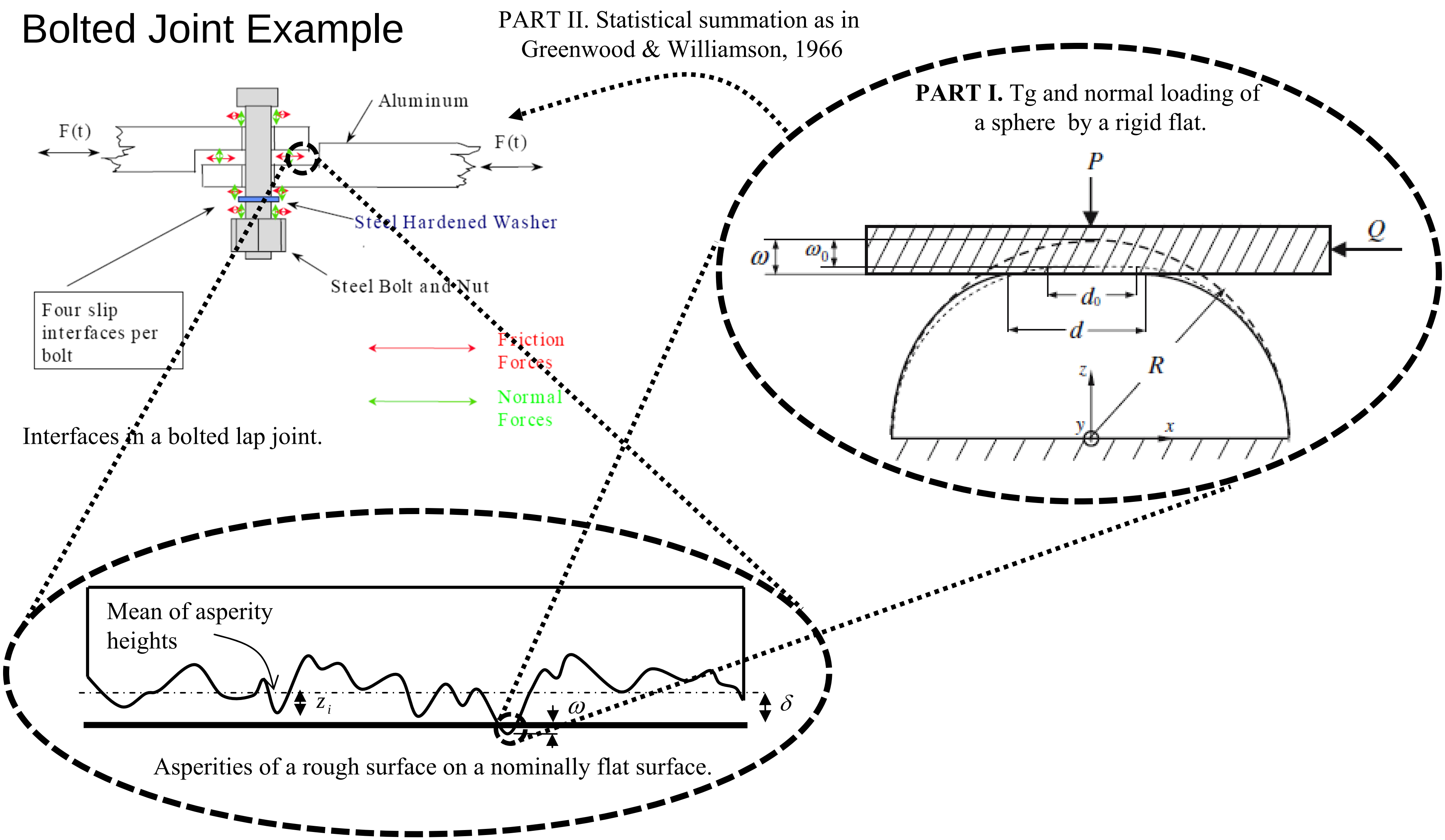
Time-Varying Slider Motion And Interfacial Forces

Mean *FH*, *FHM*, *BV*, and Time-averaged F_s, *P*, and *Q*

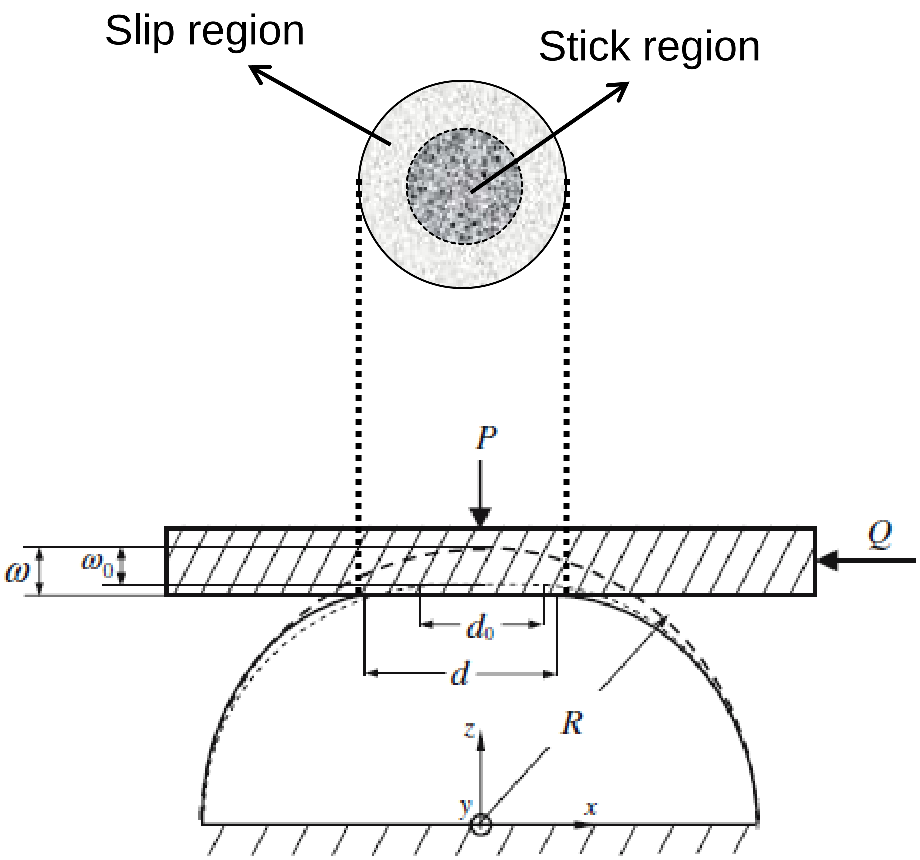
III. Design Optimization via DOE-Assisted Parametric Study

Modeling Approach

Bolted Joint Example



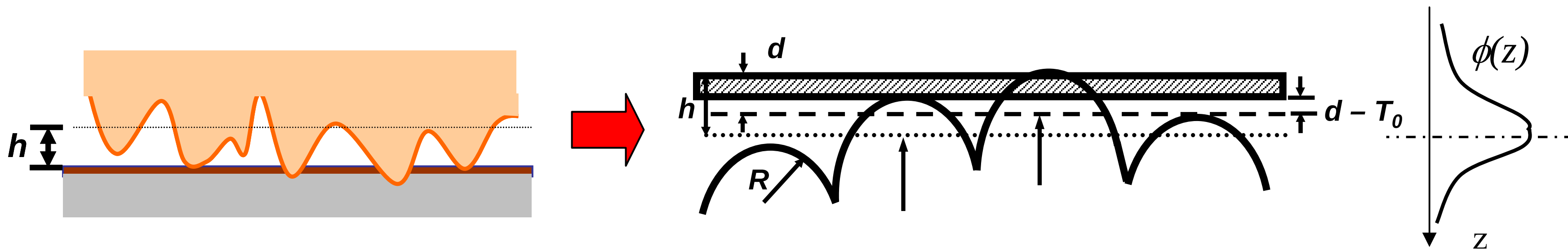
Single Asperity



- Deformable sphere of radius R in contact with a rigid flat
- Loading starts with normal preload (clamping force), P
- Tangential load, Q is applied while keeping P constant
- Interference due to preload, ω_0 < interference after tg. loading, ω
- Contact diameter due to preload, d_0 < contact diameter after tg. loading, d (junction growth)
- Contact region contains both stick and slip regions before gross sliding occurs (partial slip)

With assumptions one can do, full slip, full stick, elastic plastic

Rough Surface Statistical Model



$F_s = f\,(h,\ \sigma,\ R,\ \eta,\ \phi,\ A_n,\ T_0,\ E,\ H,\ \nu,\ \Delta\gamma)$

Micro contact Roughness/Geometrical: $h, \sigma, R, \eta, \phi, A_n, T_0$ — Material: $E, H, \nu, \Delta\gamma$

$P\ ,\ Q = f\,(h,\ \sigma,\ R,\ \eta,\ \phi,\ A_n,\ E,\ H,\ \nu)$

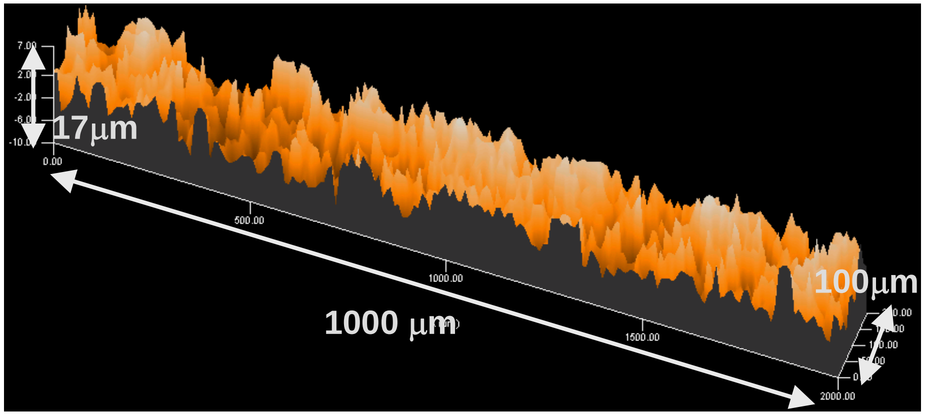
Micro contact Roughness/Geometrical: $h, \sigma, R, \eta, \phi, A_n$ — Material: E, H, ν

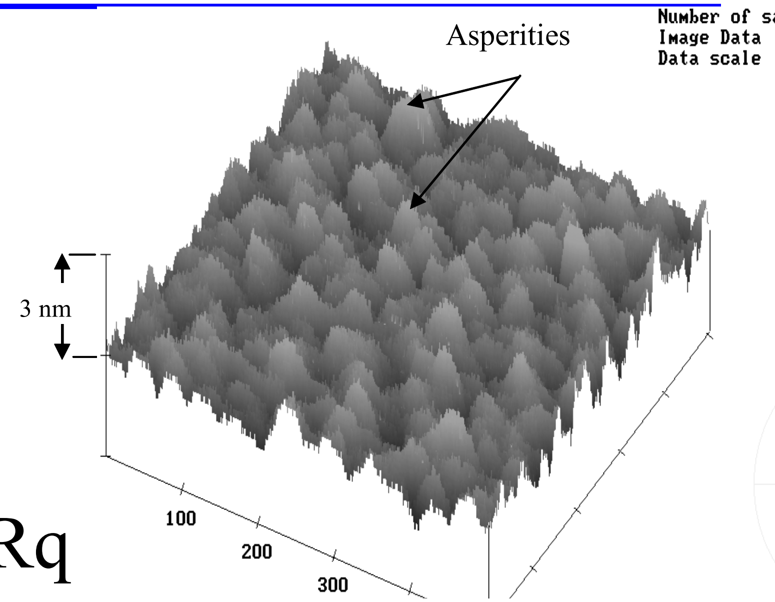
Despite the known limitations of the GW model (e.g., scale dependence of some of its parameters, asperities act independently, constant R etc, it gives good results in some engineering situations

Note that in this work, models include elastic/plastic contact, may have asymmetric asperity distribution and may contain a trace of thin lubricant on the surface

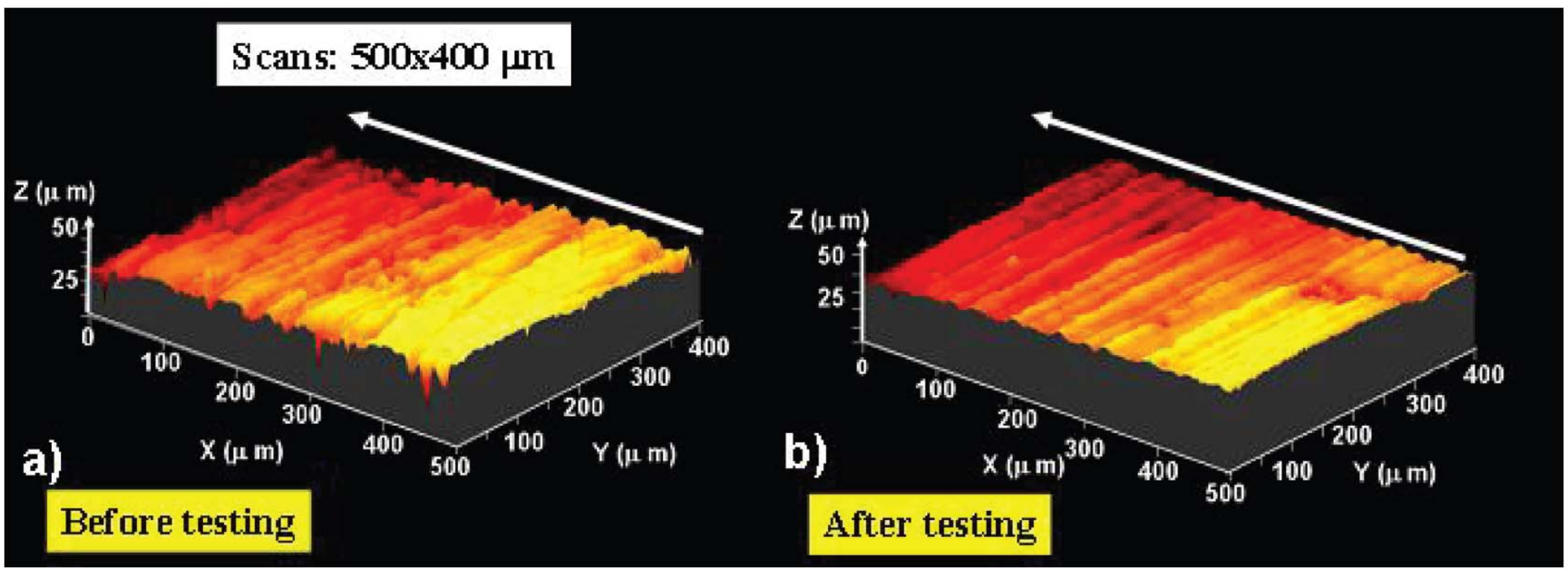
Do asperities exist?

Surface Roughness at Different Length Scales



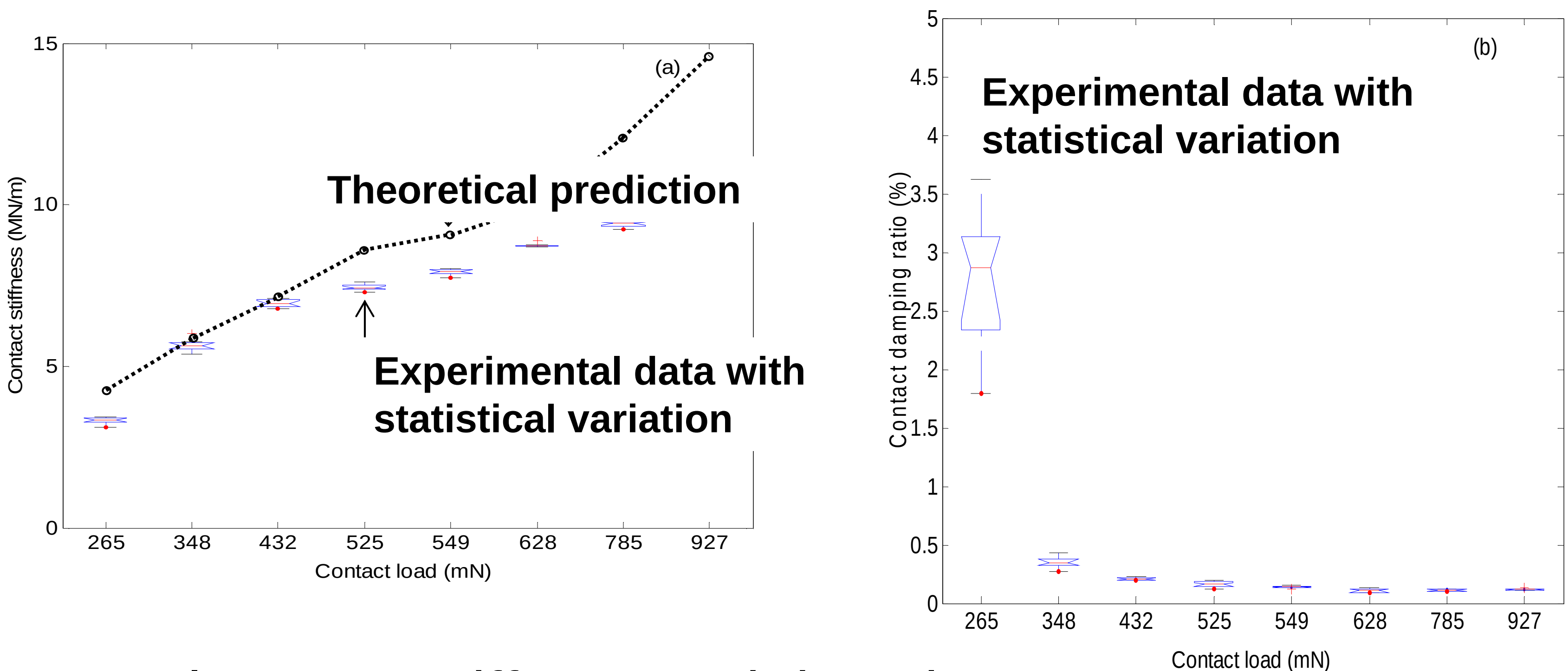


Joint-type surfaces of about 1 µm Rq



Comparisons with Experiments

	Individual surface parameters					Combined interface parameters			
	E (GPa)	H (GPa)	R_q (μm)	R_s (μm)	$\eta(/\mu m^2)$	E^* (GPa)	R_s (μm)	$\eta(/\mu m^2)$	R_q (μm)
Sample 1	192.92	2.96	0.167	3.555	0.122	105.3	2.402	0.1256	0.189
Sample 2	192.92	2.96	0.088	7.409	0.144				

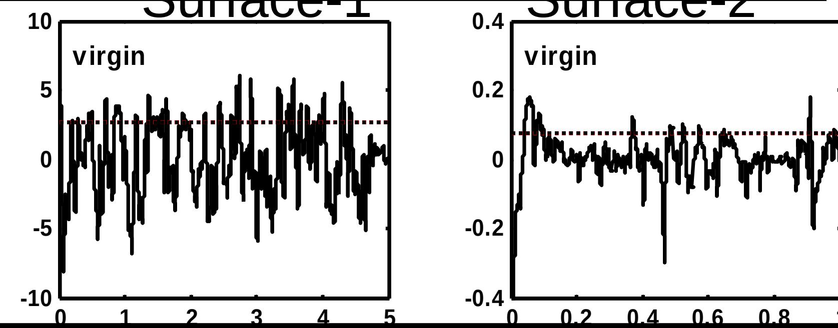


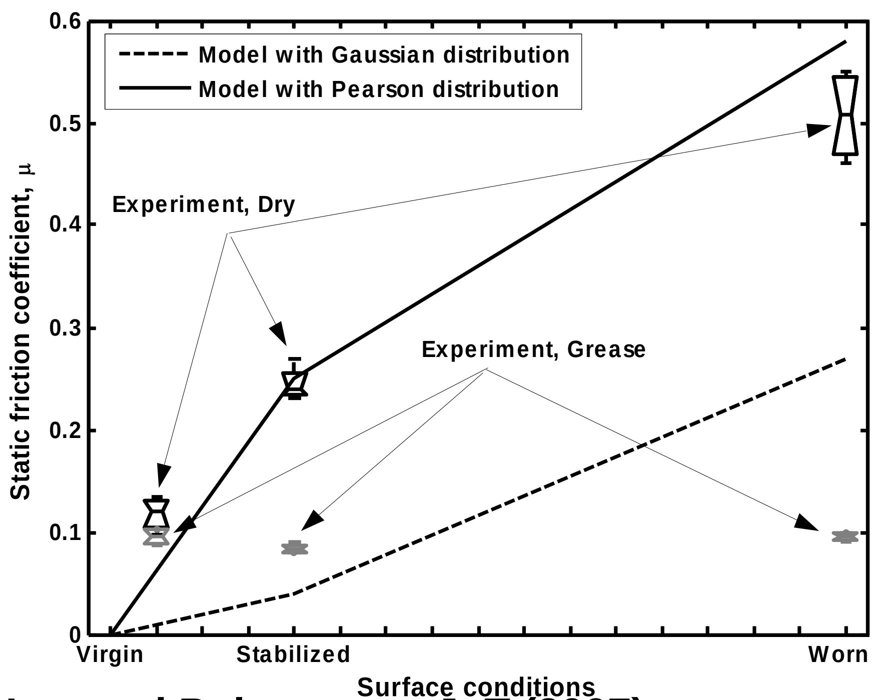
Normal contact stiffness and damping

Shi and Polycarpou, JVA, 2004

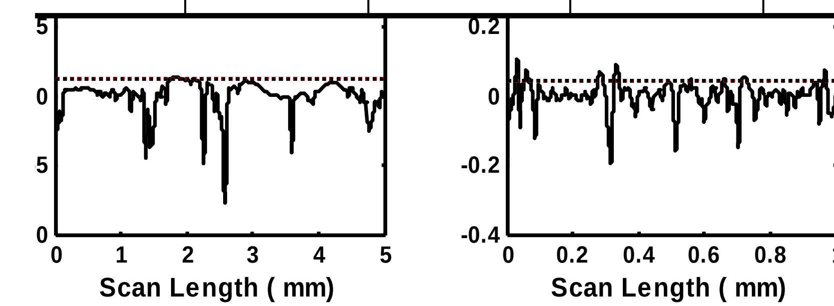
Material, Roughness Parameters (Physical Parameters) and Model Validation

Parts	Type	Young's modulus (GPa)
Surface-1	4121-H Steel	206.85
Surface-2	52100 Steel	206.85





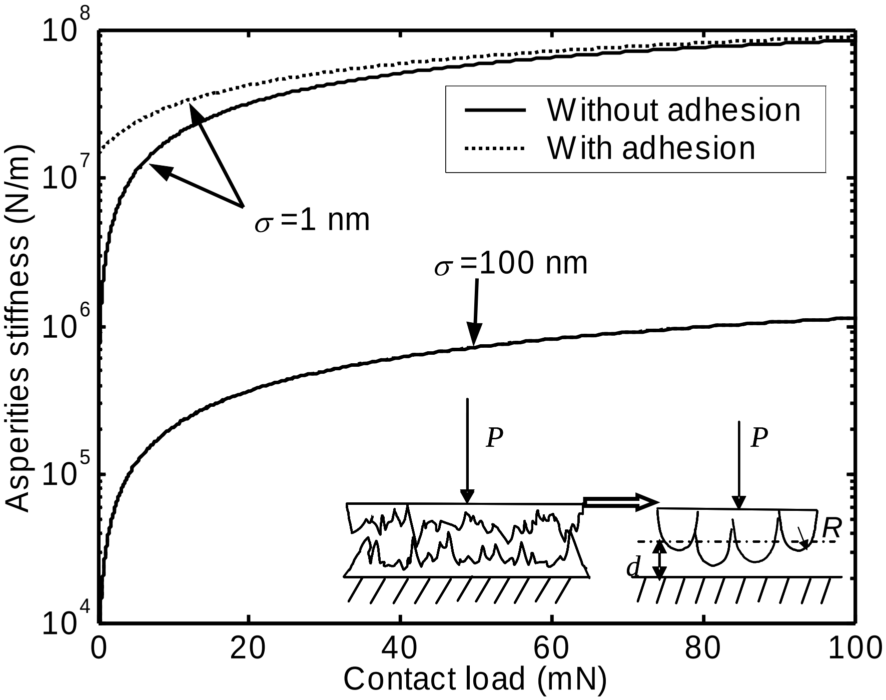
	Combined interface parameters			
(/ μ m^2)	R (μ m)	η (/ μm^2)	R_q (μm)	Ψ
0.373 12.213	37.49	0.500	2.661	4.55
0.143 4.794	97.54	0.290	1.771	2.30
0.151 4.645	156.11	0.335	1.241	1.52



Lee and Polycarpou, JoT (2007)

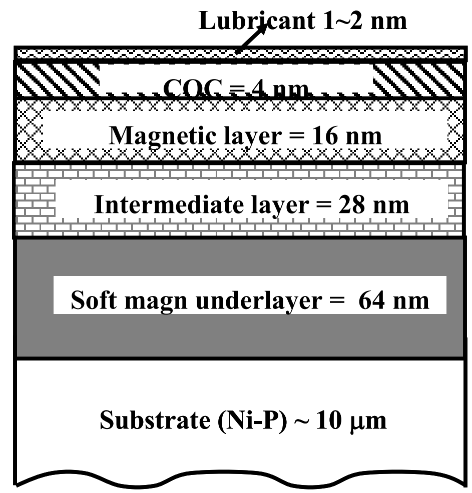
Model Validation (no surface layers, asperity interactions)

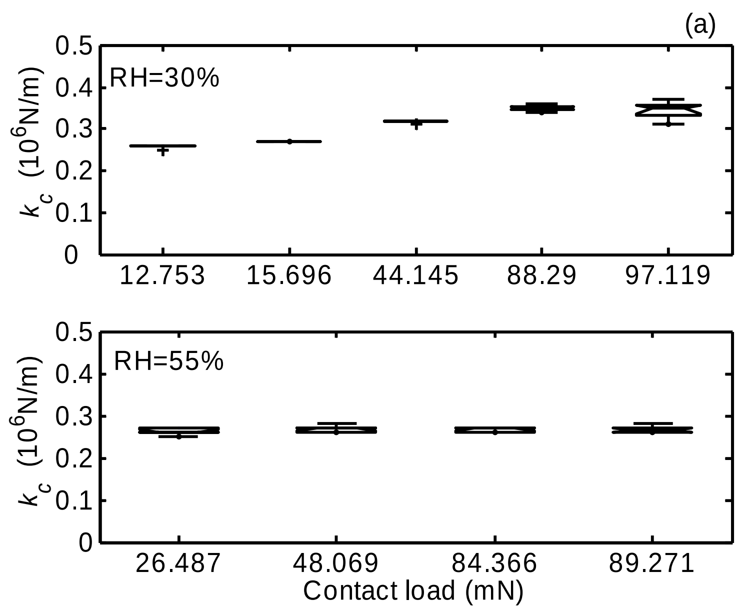
More Comparisons with Experiments



Existing models can not capture the much lower contact stiffness values, possibly due to (1) substrate deformation, (2) asperity interactions, (3) finite nominal area effects and uncertainty

An=1,000 μm²

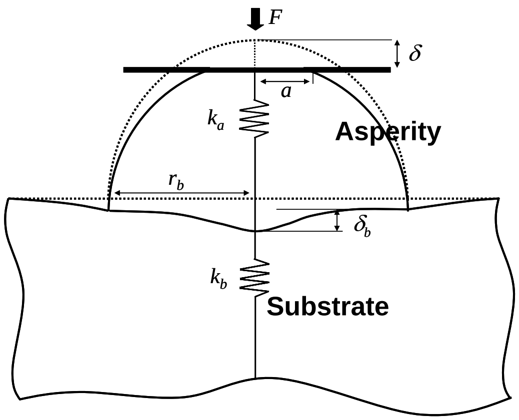




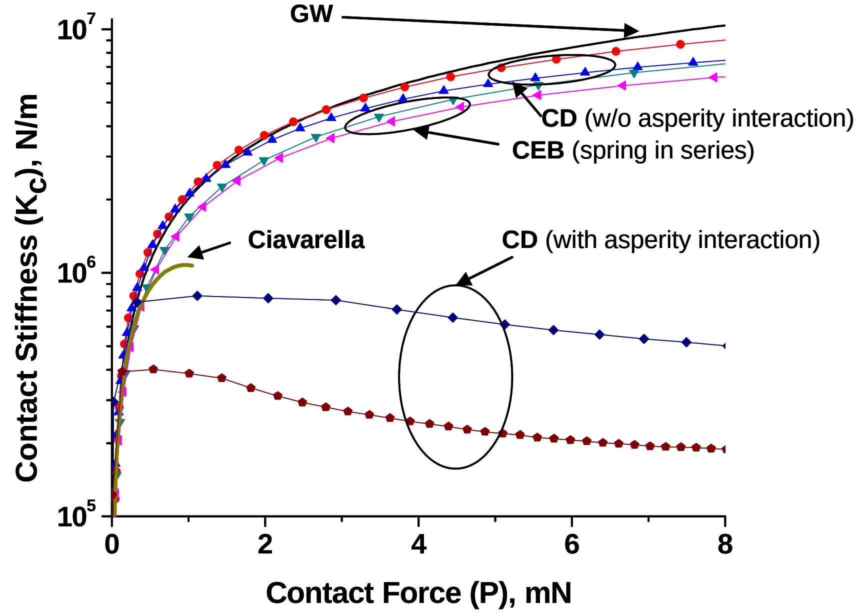
Shi and Polycarpou, JoT, 2008

Improved Contact Models-Needed

• Improved contact models to account for the **effects of bulk substrate** and **asperity interactions**



Hertz theory



- Asperity stiffness $k_a(\delta) = 2\sqrt{R}E_a\delta_a^{1/2}$
- Bulk stiffness $k_b = \frac{4}{3}r_b E_b$
- Combined effective stiffness

$$k(\delta) = \left[\frac{1}{k_a(\delta)} + \frac{1}{k_b}\right]^{-1}$$

- Contact force of asperities

$$F_{ci} = \frac{4}{3}E^* R^{1/2} h_i^{3/2} \qquad (h_i = z_{si} - d - u_{zi})$$

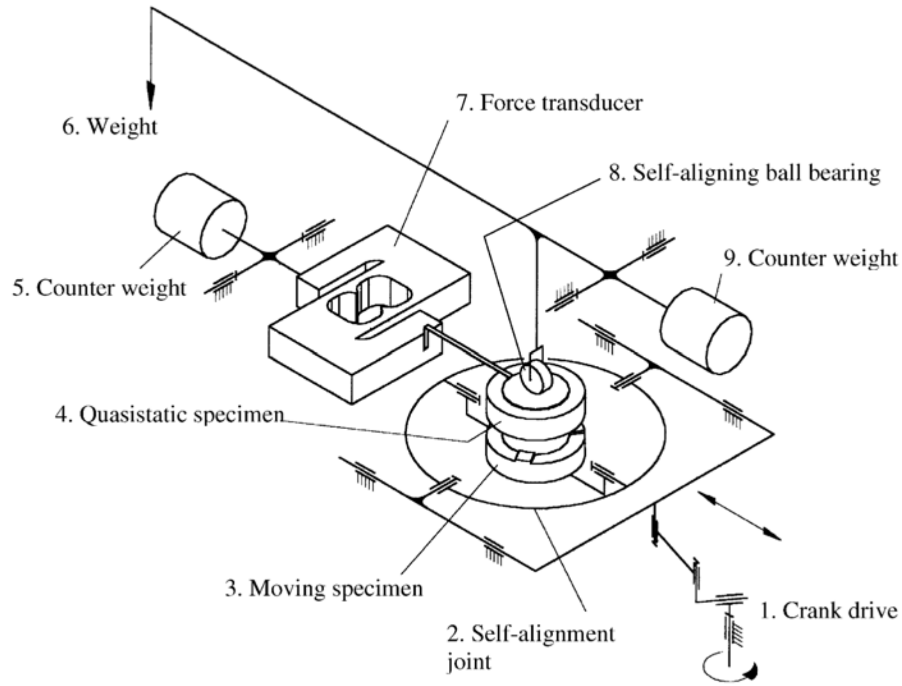
- Displacement of the neighboring asperities (Johnson, 1985)

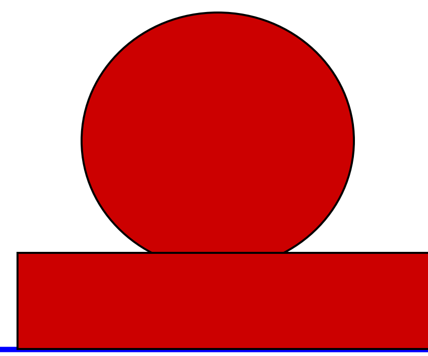
$$U_z = \frac{p_0}{2r_b E^*}\left[\left(2r_b^2 - r^2\right)\sin^{-1}\left(r_b/r\right) + r^2\left(r_b/r\right)\sqrt{\left(1 - r_b^2/r^2\right)}\right]$$

Having shown that the contact and static friction models (with simplifying assumptions) work well in several cases, can we apply them to the case of Joints?

Spherical Elastic Plastic Model with Slip

- Experiments: Varenberg et al.2004
- 5 mm diameter steel ball is fretted on a flat steel specimen
- Each surface has rms roughness of 40-50 nm (reasonable to assume Hertzian spherical contact)
- Oscillation frequency 16.5 Hz
- 2 sets of experiments with loads: 23, 35 N and imposed tangential displacements of 10 and 1.5 μm
- Only physical parameters input to the model: hardness or yield strength (of the softer material), Young's modulus, Poisson's ratio and radius of the sphere [i.e., no friction coefficient]

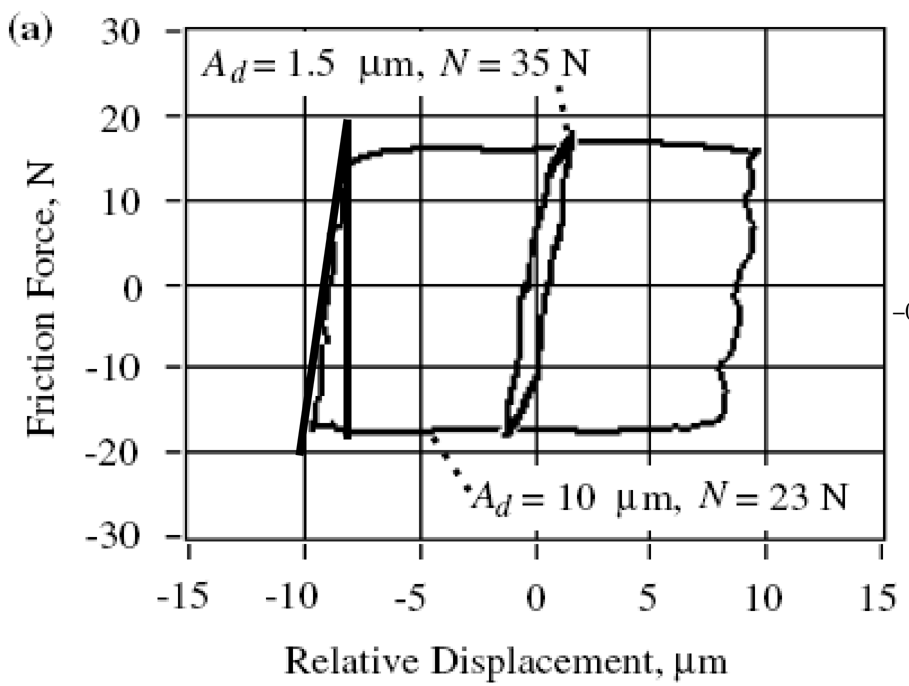


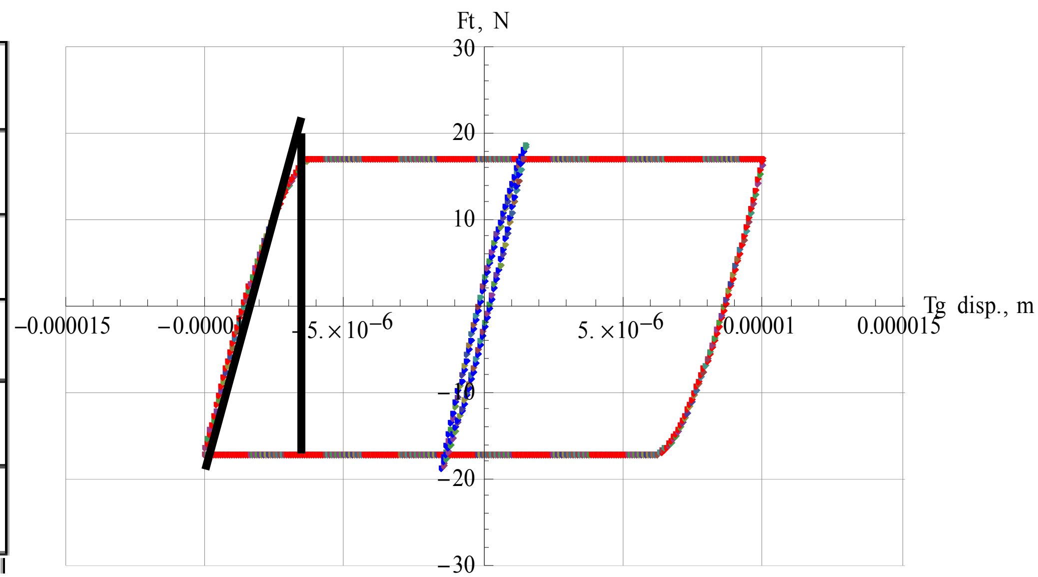


Spherical Elastic Plastic Model with Slip

- Kogut & Etsion contact model applied to partial slip
- Transition from elastic to elastic-plastic regime is designated by the critical normal load and interference values

$$P_c = \frac{(\pi(0.454+0.41\nu))^3}{6}\left(\frac{H}{E^*}\right)^2 HR^2, \omega_c = \left(\frac{\pi(0.454+0.41\nu)H}{2E^*}\right)^2 R$$





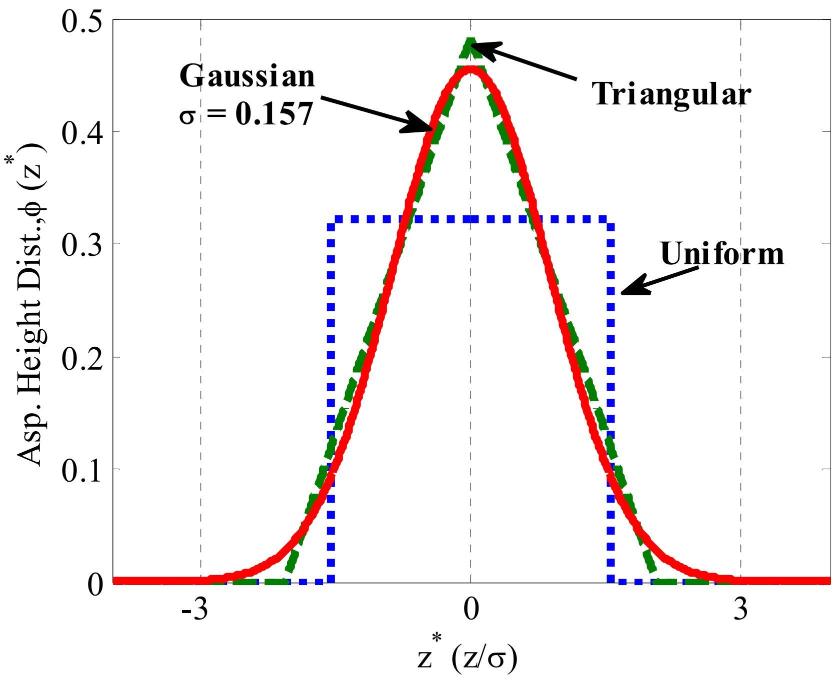
Stiffness 20 (test) Vs 12 MN/m (mod)

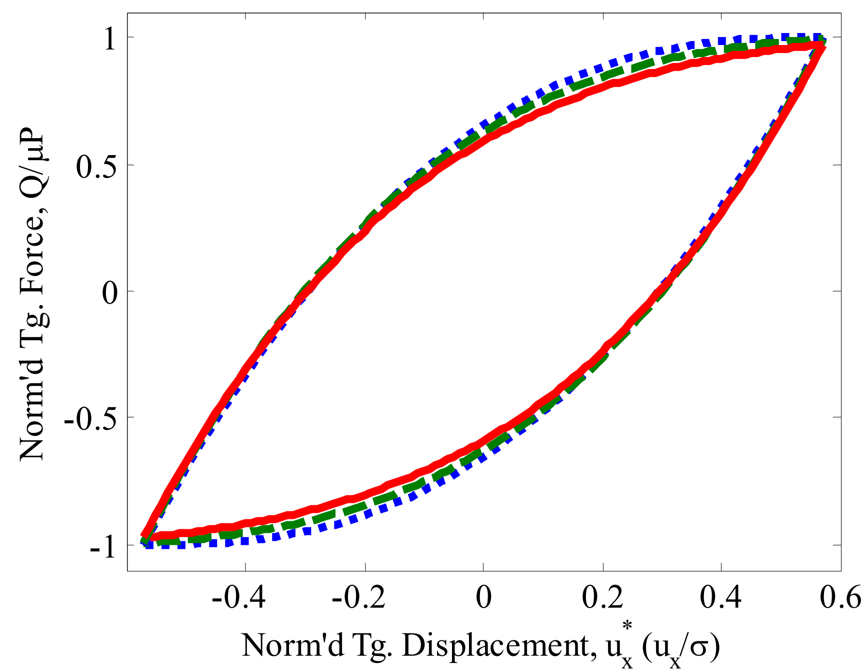
Magnitude of friction is captured well but not the stiffness

Roughness Model with Partial Slip

- Mindlin constant friction (μ=0.3) + Hertzian normal loading + Mindlin tg. Loading/unloading/reloading + GW statistical summation = Björklund (1997)
- Doesn't account for plasticity
- Type of asperity height dist. has almost no effect on microslip behavior (interesting and "opposite" to the gross sliding friction predictions)

No direct experimental comparison, ongoing

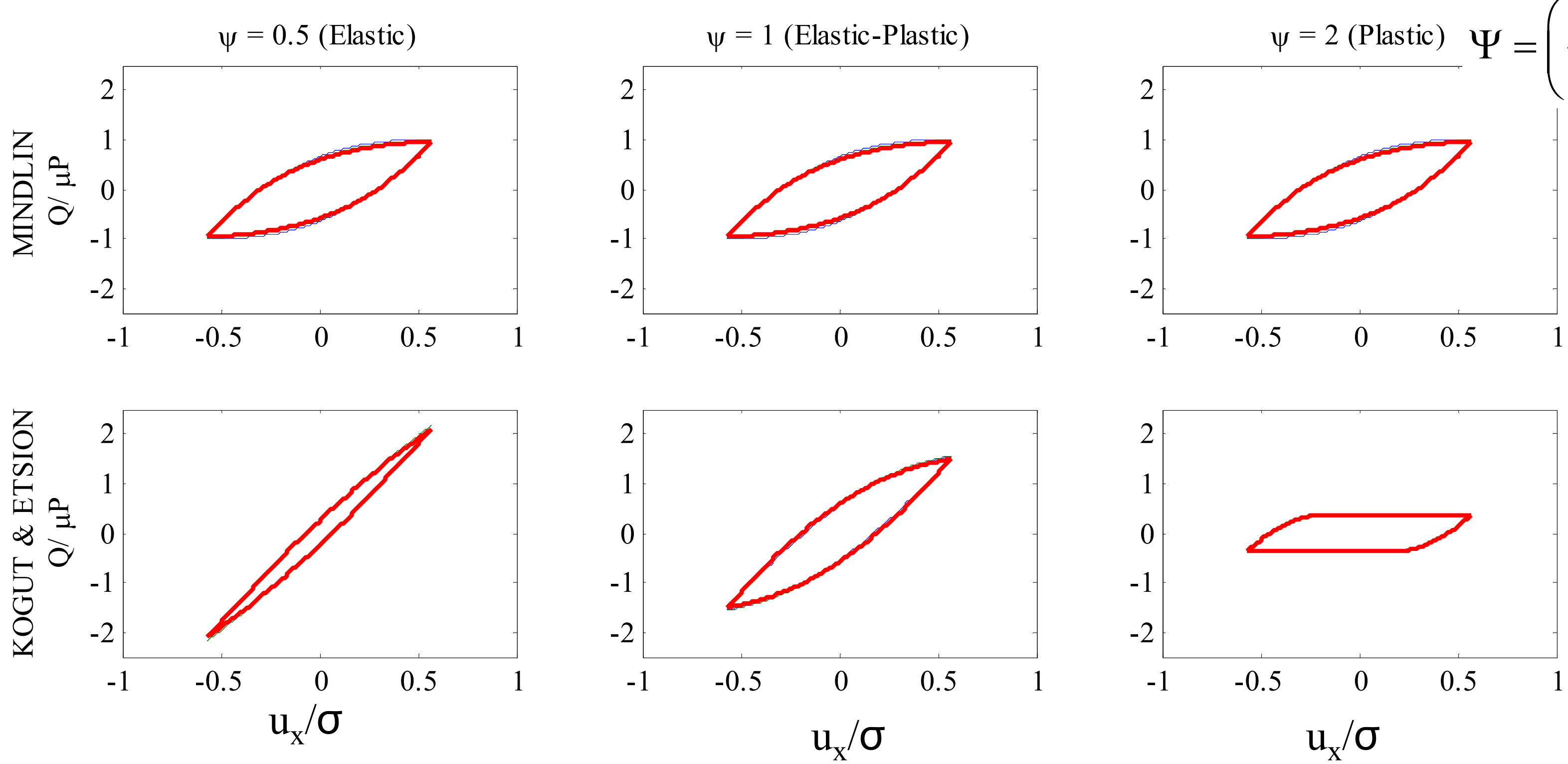




Based on physical parameters PLUS Friction Coefficient

Going Forward: Nominally Flat Contact

$$\Psi = \left(\frac{E^*}{H}\right)\sqrt{\frac{\sigma}{R}}$$



Friction loop predictions with only physical parameters of material properties, surface roughness parameters, and nominal contact area

Elastic/plastic model captures effect of plasticity index

Need to compare with experiments

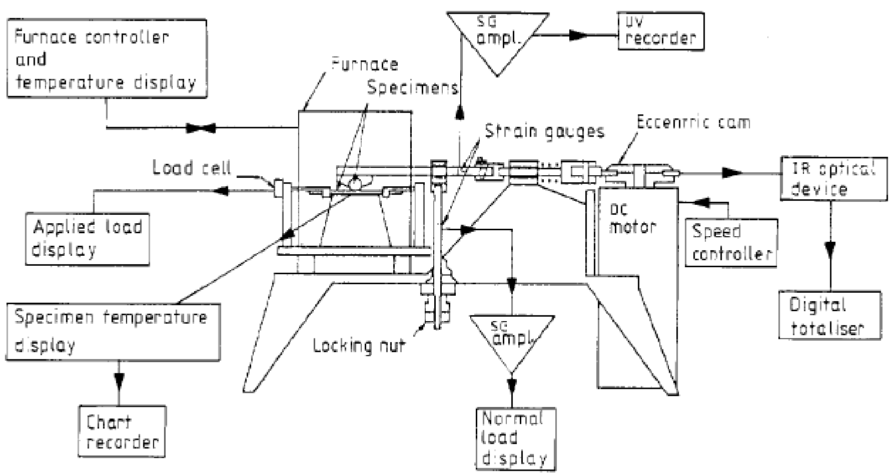
There are some model assumptions that could be challenged e.g., tangential loading doesn't affect the tractions obtained by frictionless normal loading

Asperity interactions, film effects, substrate effects, temperature effects etc

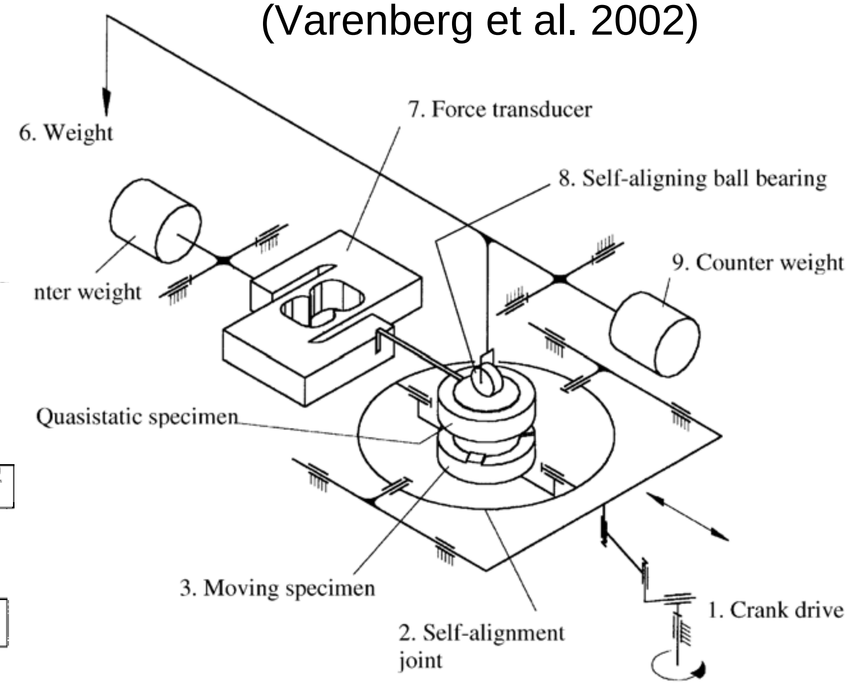
Experiments (Partial Slip)

Fretting parameters:
- •Normal loading
- •Slip magnitude
- •Fretting freq. & duration
- •Joint conditions + lubrication

(Kuno et al. 1988)

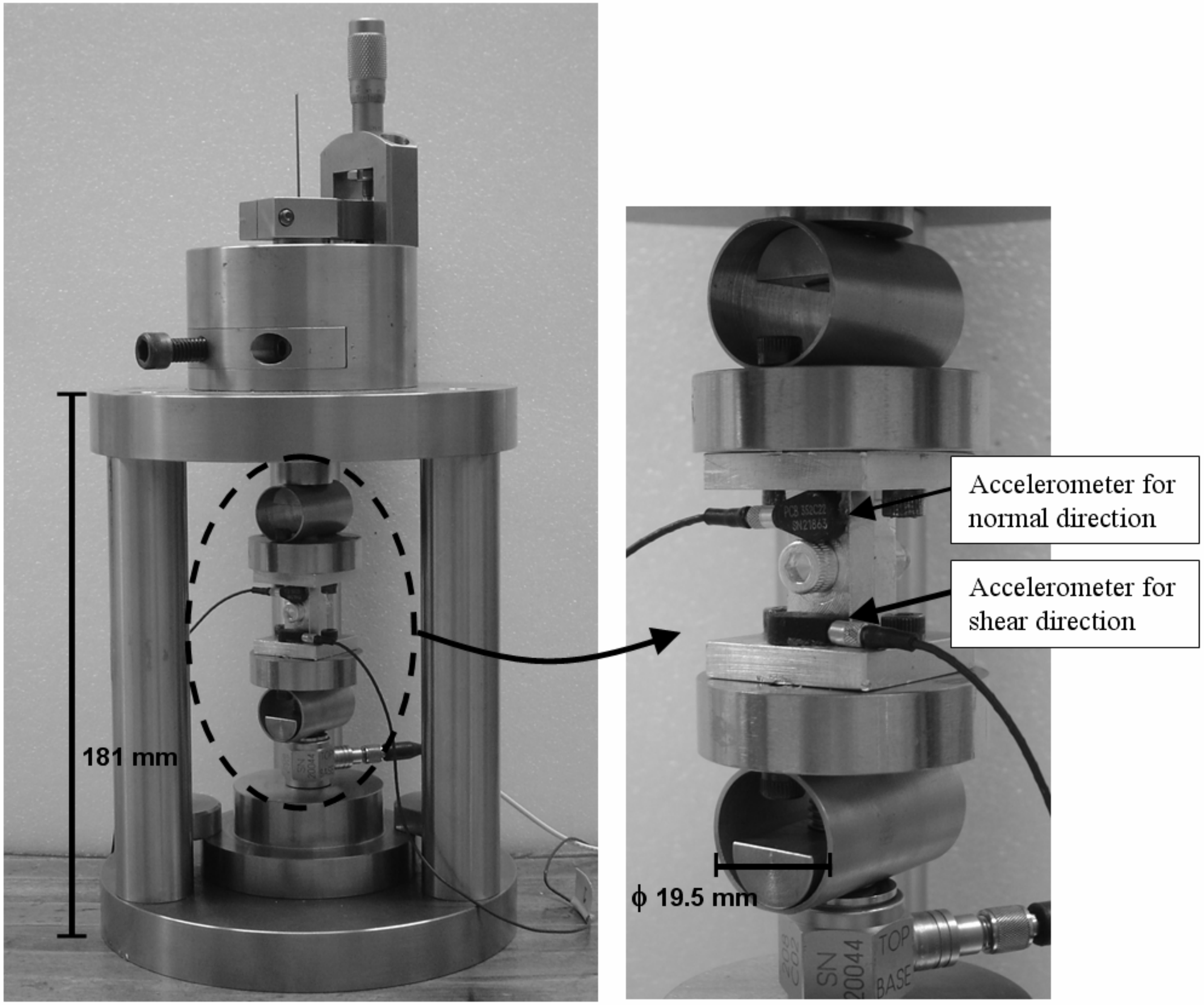


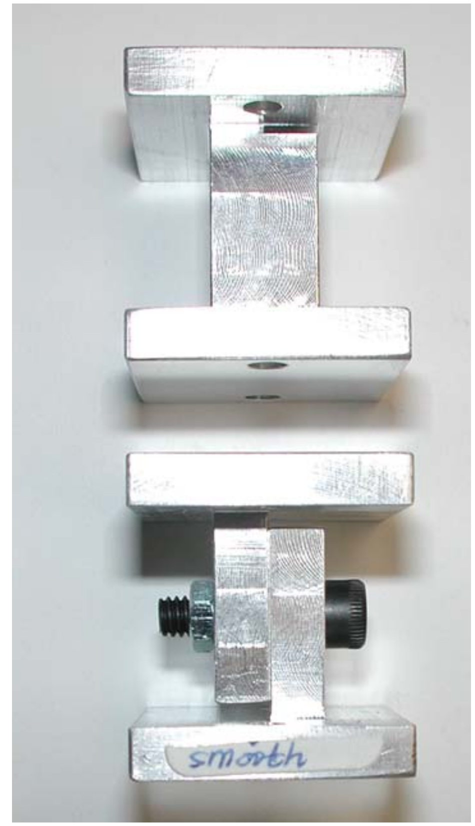
(Varenberg et al. 2002)



Testing machines use the following actuation mechanisms
- •Servo-hydraulic → High stress fretting studies
- •Electromagnetic → Flexibility in slip amplitude and frequency
- •Piezoelectric → Displacements of small amplitude and high frequency (better for micro-slip)
- •Rotational to linear motion mechanical devices (DC motor, eccentric cam, crank drive, etc.) → Easy to build and robust.

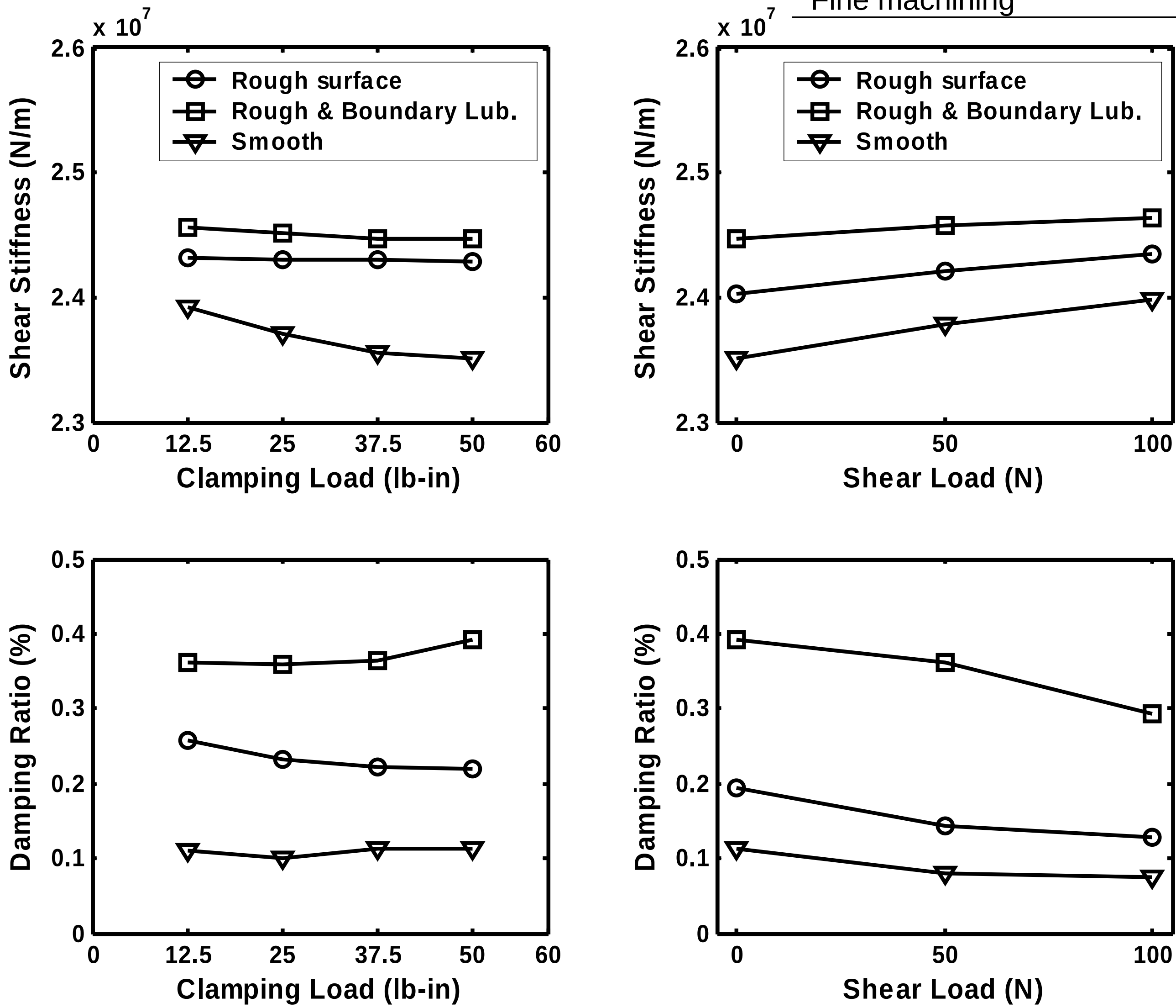
Stiffness and Damping of Shear Lap Joints





Experimental Results

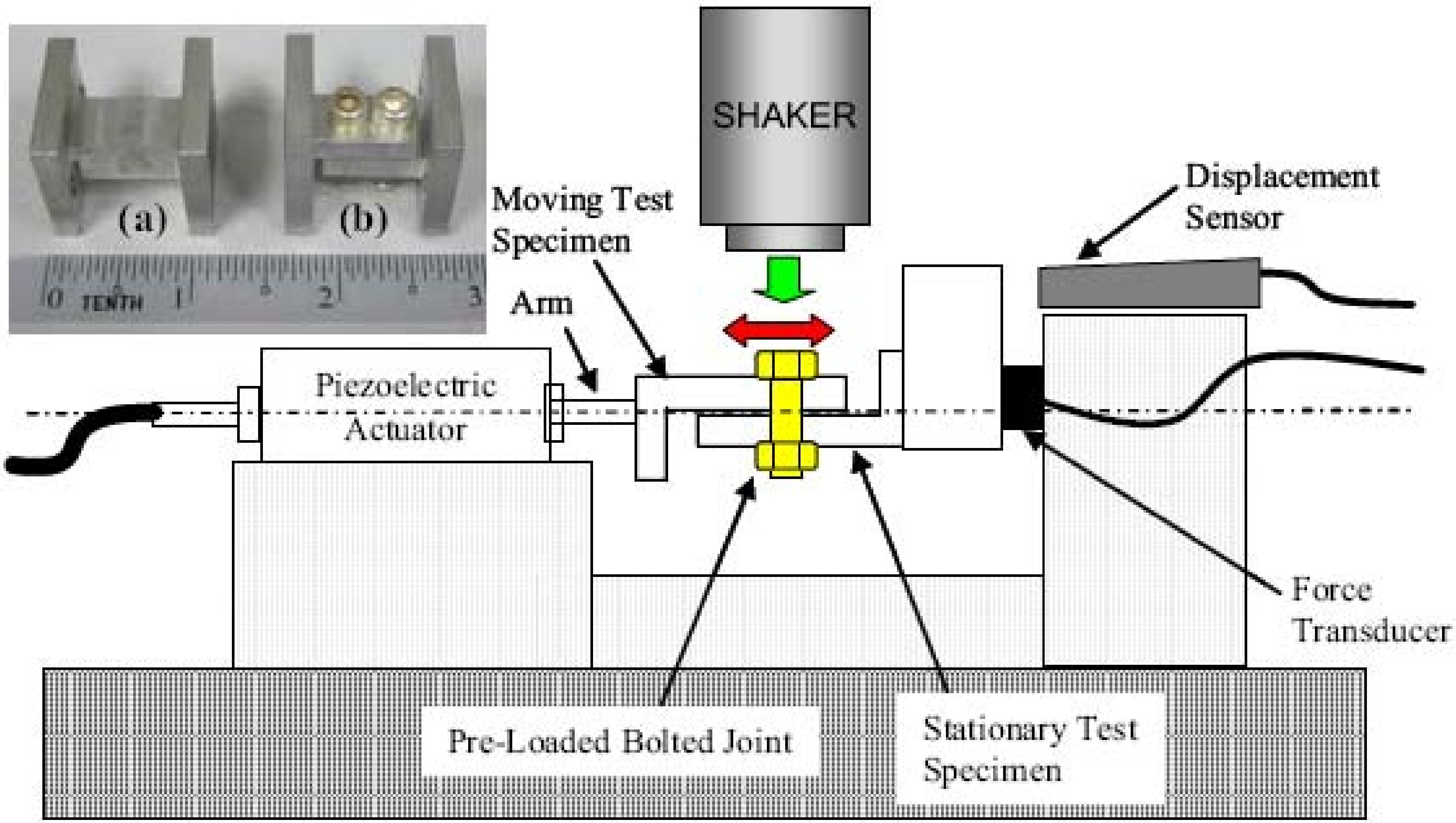
	E (GPa)	H (GPa)	R_a (μm)	R_q (μm)
Sample 1 (Smooth) Superfinishing	72	1.15	0.061	0.081
Sample 2 (Rough) Fine machining	72	1.15	1.154	1.628



No friction loop measurements possible with this set up

Need to investigate the coupling between normal and shear interfacial and dynamic interactions

“Rigid” Partial Slip Tester for Joints



Summary/Challenges

Micro scale parameters can be measured and used in continuum-based interfacial models to predict contact and friction, including friction loops encountered in joints

Some challenges: (1) Contact mechanics assumptions in the analysis; (2) identifying their range of applicability; (3) Improvements in the contact mechanics and roughness models; (4) correlation of testing methodologies and results