A micro-meso model to predict van der Waals and capillary induced stiction in micro-structures

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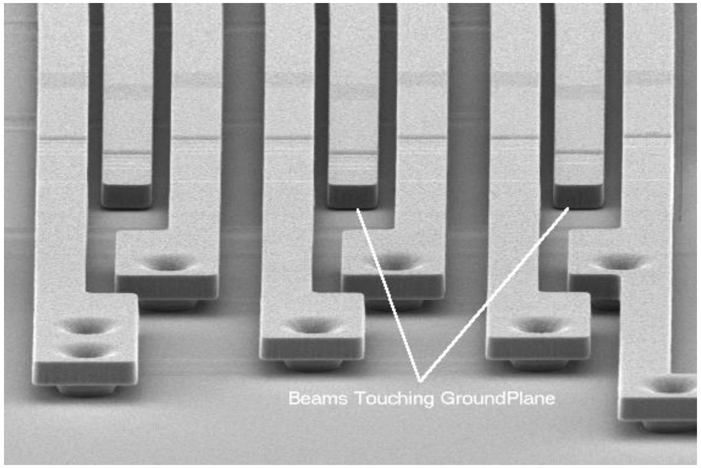
Introduction

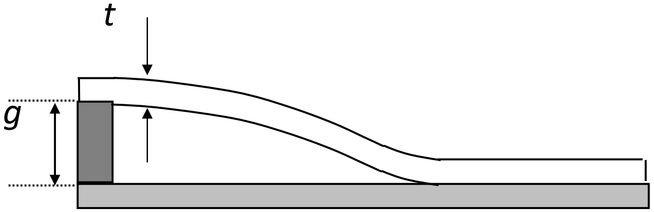
- Stiction in MEMS
  - Reasons
    - Relatively high surface area: volume ratio (1,000:1 to 10,000:1 m-1)
  - Adhesive forces
    - Electrostatic force,
    - Van der Waals force,
    - Capillary force
    - Hydrogen bridging…



Stiction failure in a MEMS sensor

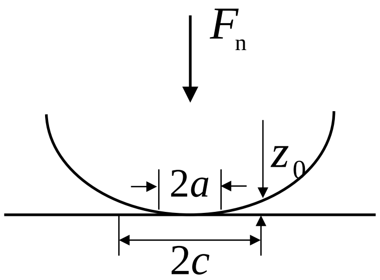
(Jeremy A.Walraven Sandia National Laboratories. Albuquerque, NM USA)

- How can it be predicted / simulated?

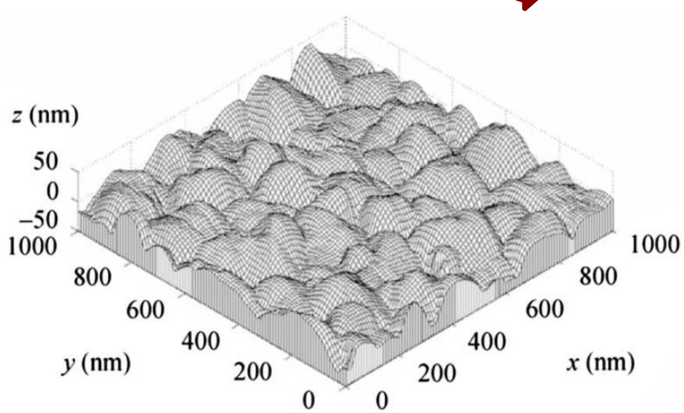


Introduction

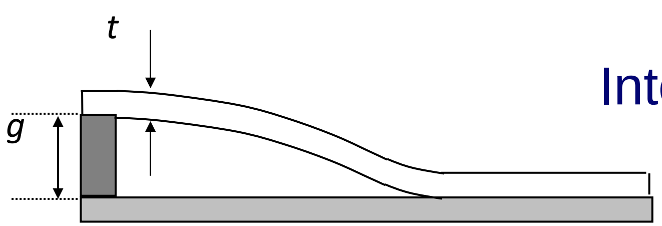
- Multiscale approach



Single asperity adhesive-micro contact



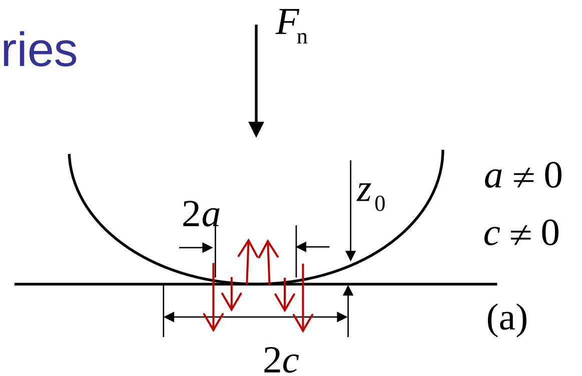
Adhesive elastic contact model between rough surfaces



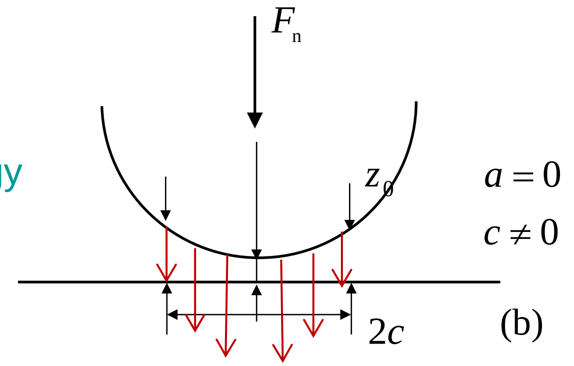
Integration with FEM

Van der Waals forces

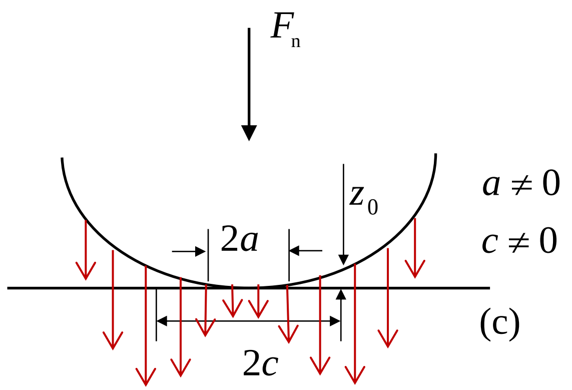
- Asperity level: Adhesive-elastic contact (Hertz) theories
  - Johnson, Kendall, and Roberts (JKR)
    - Short ranged surface forces
    - Act only inside the contact area
    - Soft, compliant materials with high adhesion energy



  - Derjaguin, Muller and Toporov (DMT)
    - Long-ranged adhesive forces
    - Outside of the contact area
    - Harder, less compliant materials with low adhesion energy and small asperity tip radius

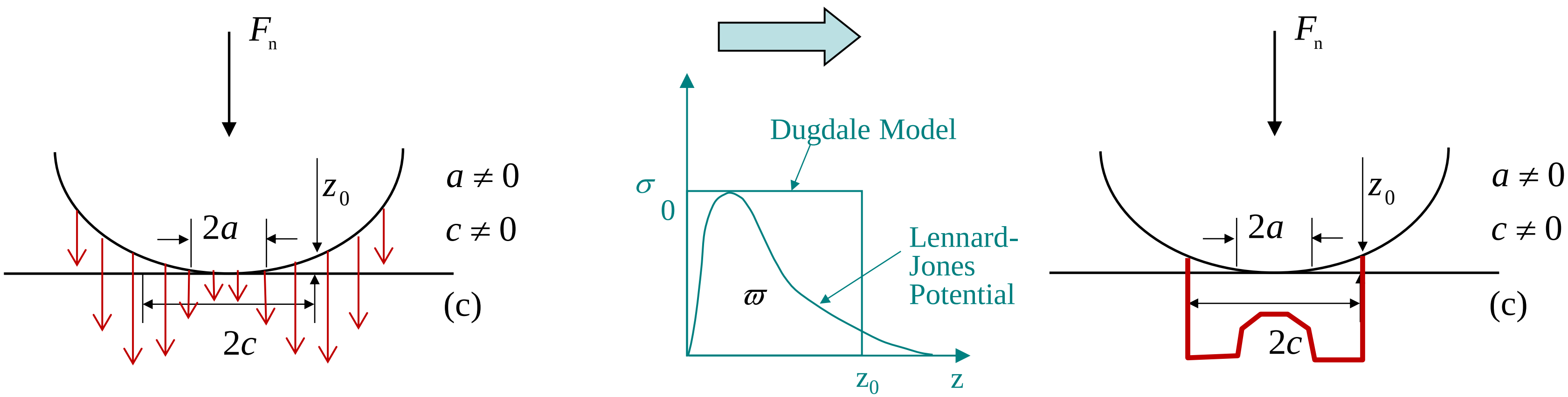


  - Maugis transition solution
    - Intermediate cases between JKR and DMT
    - For all elastic materials



Van der Waals forces

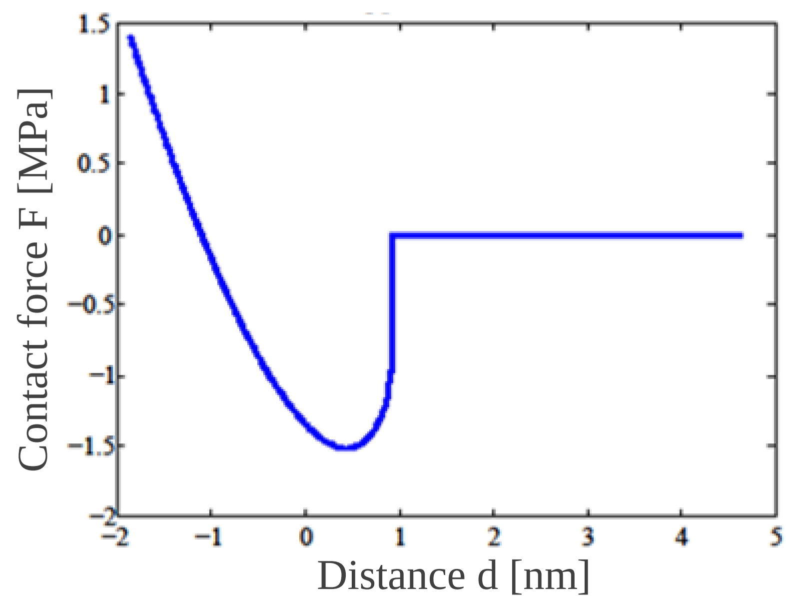
- Asperity level: Maugis – Dugdale semi-analytical solution
  - Approximate potential



$$\varpi = \sigma_0 \cdot z_0$$

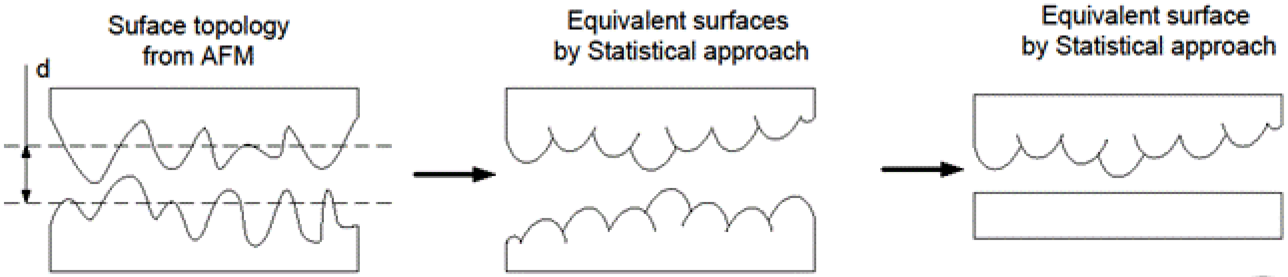
  - Force-distance curve
    - Can be solved for given
      - Sphere radius
      - Adhesion energy
      - Sphere Young modulus

Surface energy ϖ	Aperity Radii R
2.54 J/m^2	260.5 nm



Van der Waals forces

- Rough surfaces
  - Representations

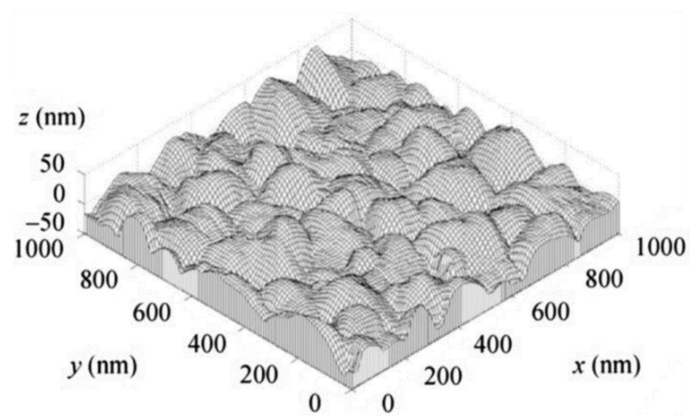


  - Parameters

    - Asperity height follows a Gaussian distribution

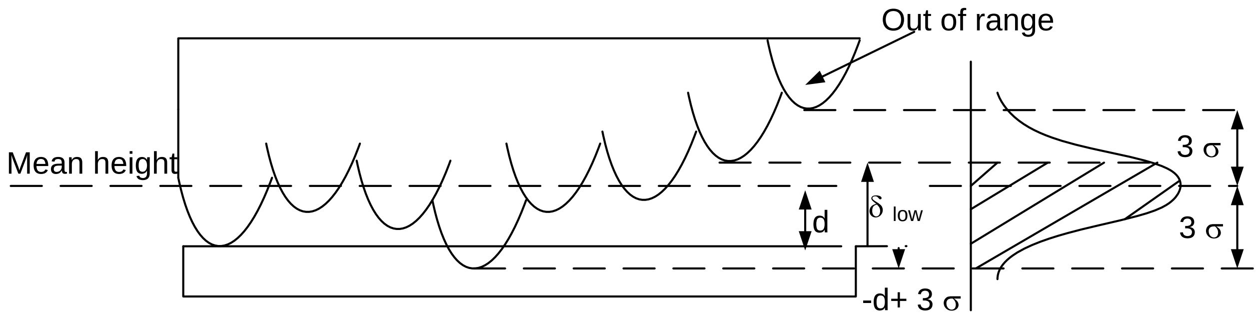
      with std σ: $\varphi(h) = \frac{1}{\sigma\sqrt{2\pi}} \exp(\frac{-h^2}{2\sigma^2})$
    - N asperities per square meters
    - Asperity radius R= cst

  - N, R, σ are calculated from real surface (AFM)
    - Variance of height m_0,
    - Variance of slope m_2,
    - Variance of curvature m_4,



Van der Waals forces

- Rough surfaces
  - Integrate the sphere responses



$$F_s(d) = N \int_{\delta_{low}} F(\delta) \exp\left[-\frac{(\delta+d)^2}{2\sigma^2}\right] d(\delta).$$

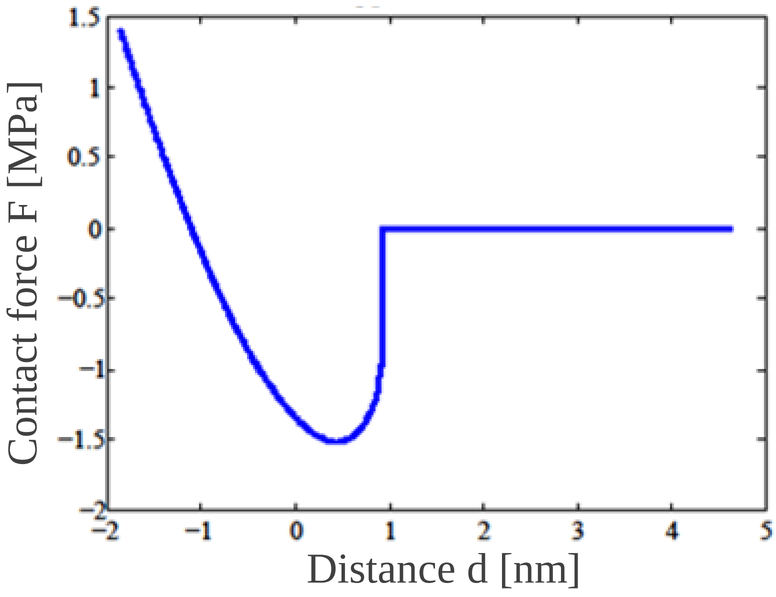
- Cut-off effect
  - Gaussian tail distribution decreases slower than Hertz contact force increases
  - Effect of (much) higher asperities overvalued

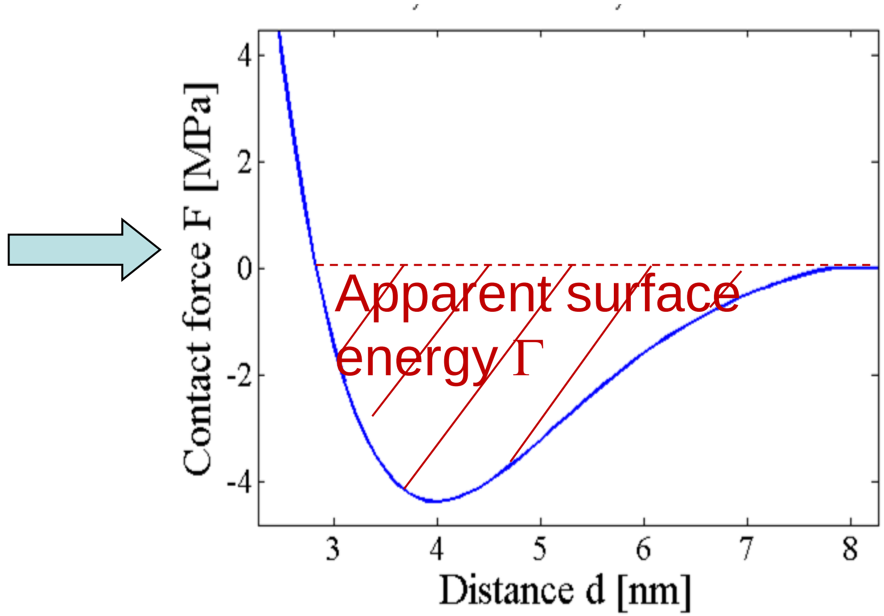
$$F_s(d) = N \int_{\delta_{low}}^{-d+2.5\sigma} F(\delta) \frac{\phi(d+\delta)}{\Phi(d+2.5\sigma)} d(\delta).$$

Van der Waals forces

- Rough surfaces
  - Integrate the sphere responses

$$F_s(d) = N \int_{\delta_{low}}^{-d+2.5\sigma} F(\delta) \frac{\phi(d+\delta)}{\Phi(d+2.5\sigma)} d(\delta).$$





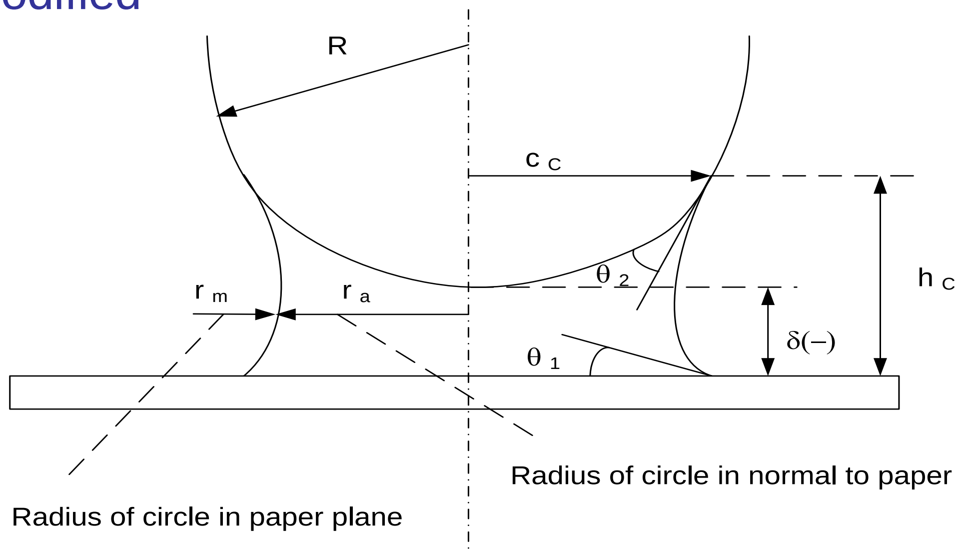
Surface energy ϖ	Asperity density N	Aperity Radii R	Standard derivation σ
2.54 J/m^2	80 x 10^{12} /m^2	260.5 nm	2.5 nm

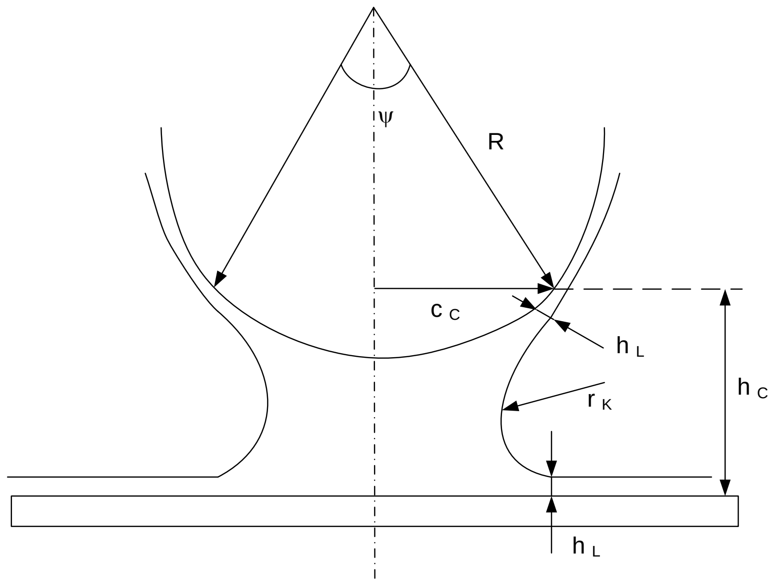
- Integration on the rough surface is modified
  - Meniscus
    - Size depends on Relative Humidity (RH)
    - Uniform Laplace pressure

New adhesion energy

$$\omega_C = \Delta P \times h_C = 2\gamma_{LV}\cos(\theta)$$

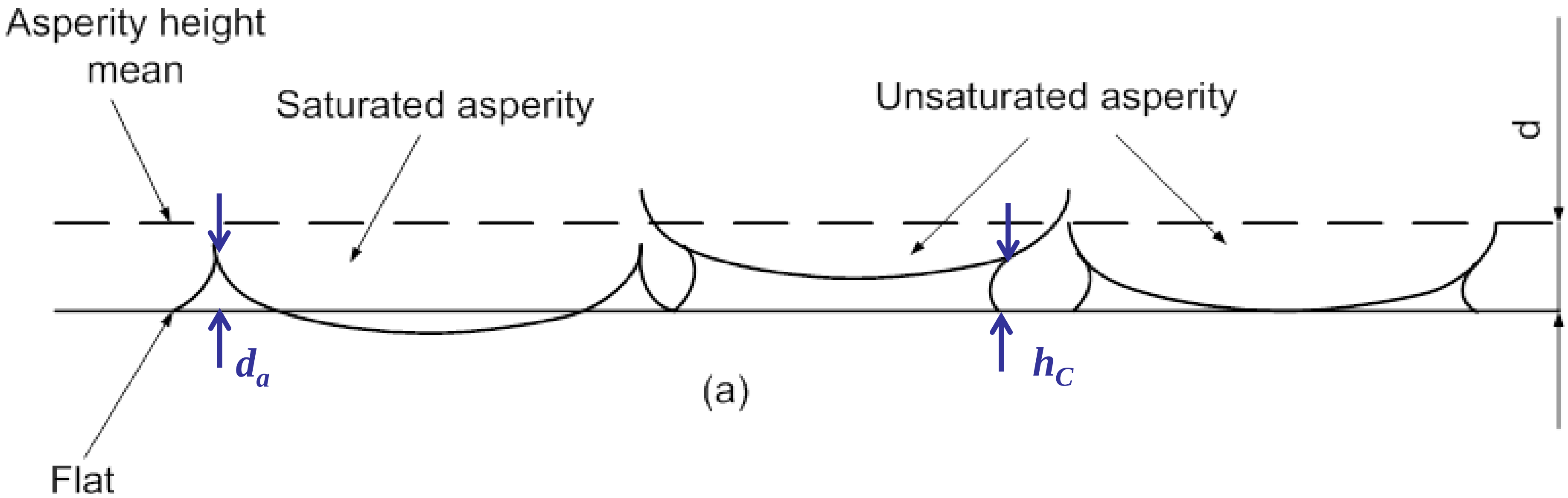
    - Interaction distance h_C
      - Depends on the relative humidity
      - Below 30% the height comparable to molecular height
  - Absorbed surface layer
    - Modifies the interaction height
    - Height from literature (measures)





Capillary effects

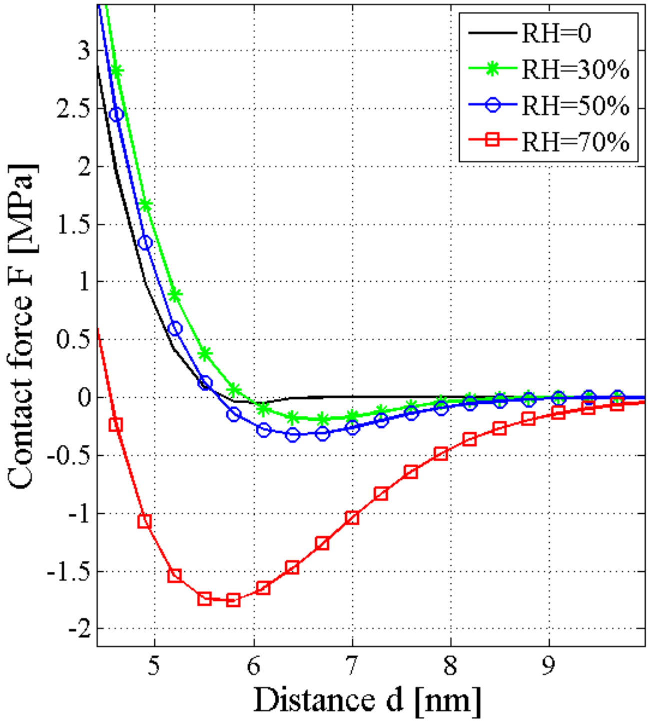
- Force on a single asperity is modified*
  - At high humidity, meniscus are merged to create the continuous layer

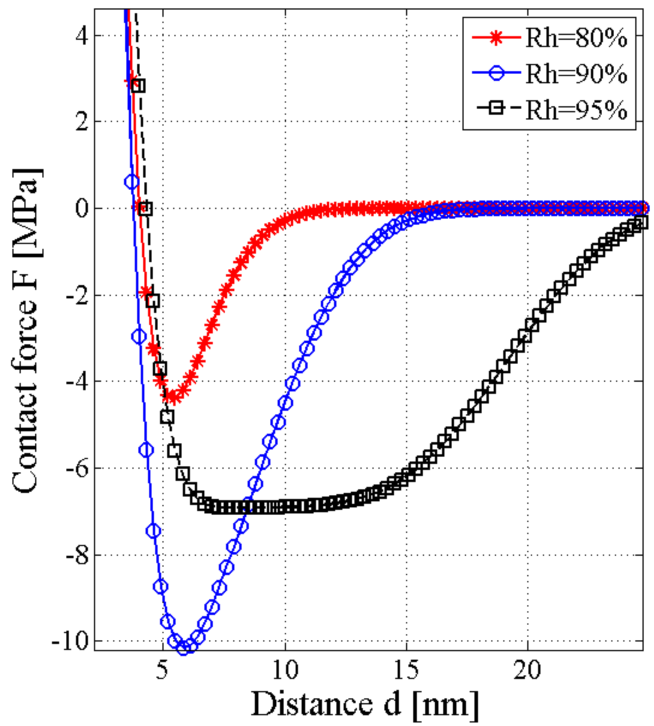


  - Saturation: to avoid duplication in the integration process h_C is reduced to d_a

* M.P. de Boer, “Capillary adhesion between elastically hard rough surfaces,” *Experim. Mech.*, vol. 47, pp. 171–183, 2007 (Experiment)

- Adhesive-contact curves
  - In air
  - For different humidity levels

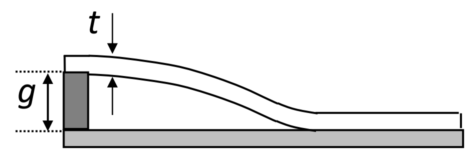


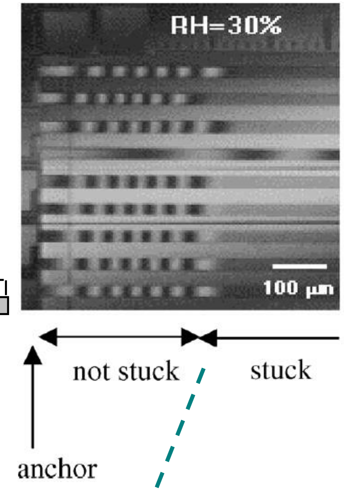


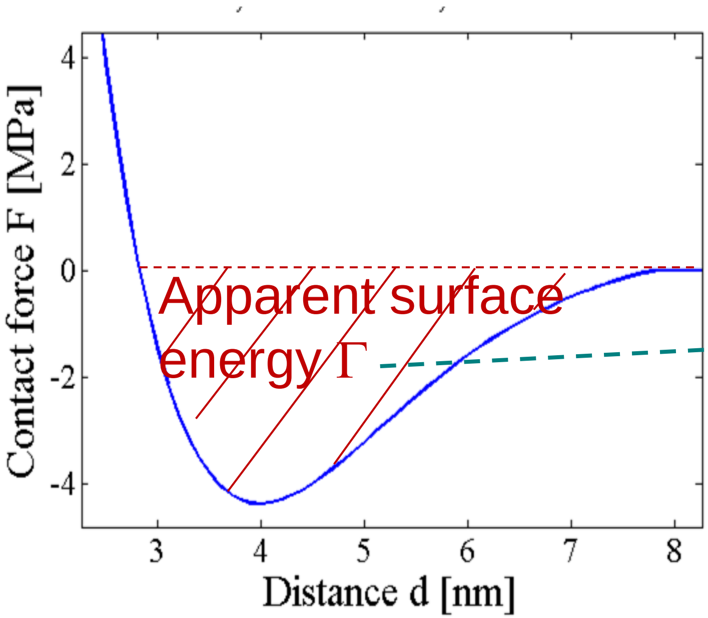
VDW surface energy ϖ	Asperity density N	Aperity Radii R	Standard derivation σ
0.167 J/m^2	80 x 10^{12} /m^2	260.5 nm	2.5 nm

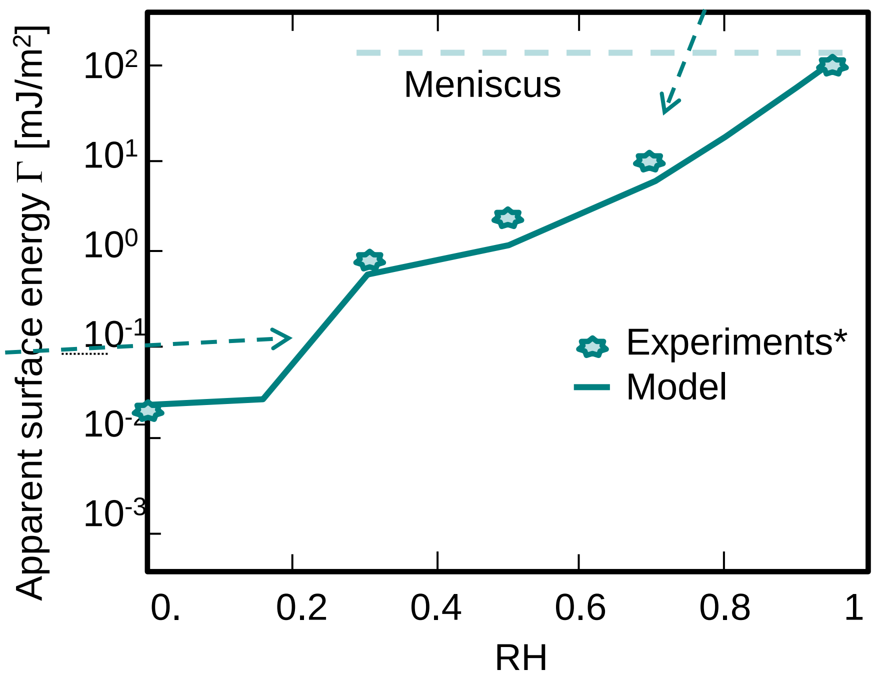
- Validation
  - De Boer's experiments(*)
    - Apparent adhesion energy from the shortest S-shaped stuck beam
  - Can be compared to the model
    - Adhesive area of the rough surfaces curves

$$\Gamma = \frac{3}{2} E \frac{g^2 t^3}{s^4}$$





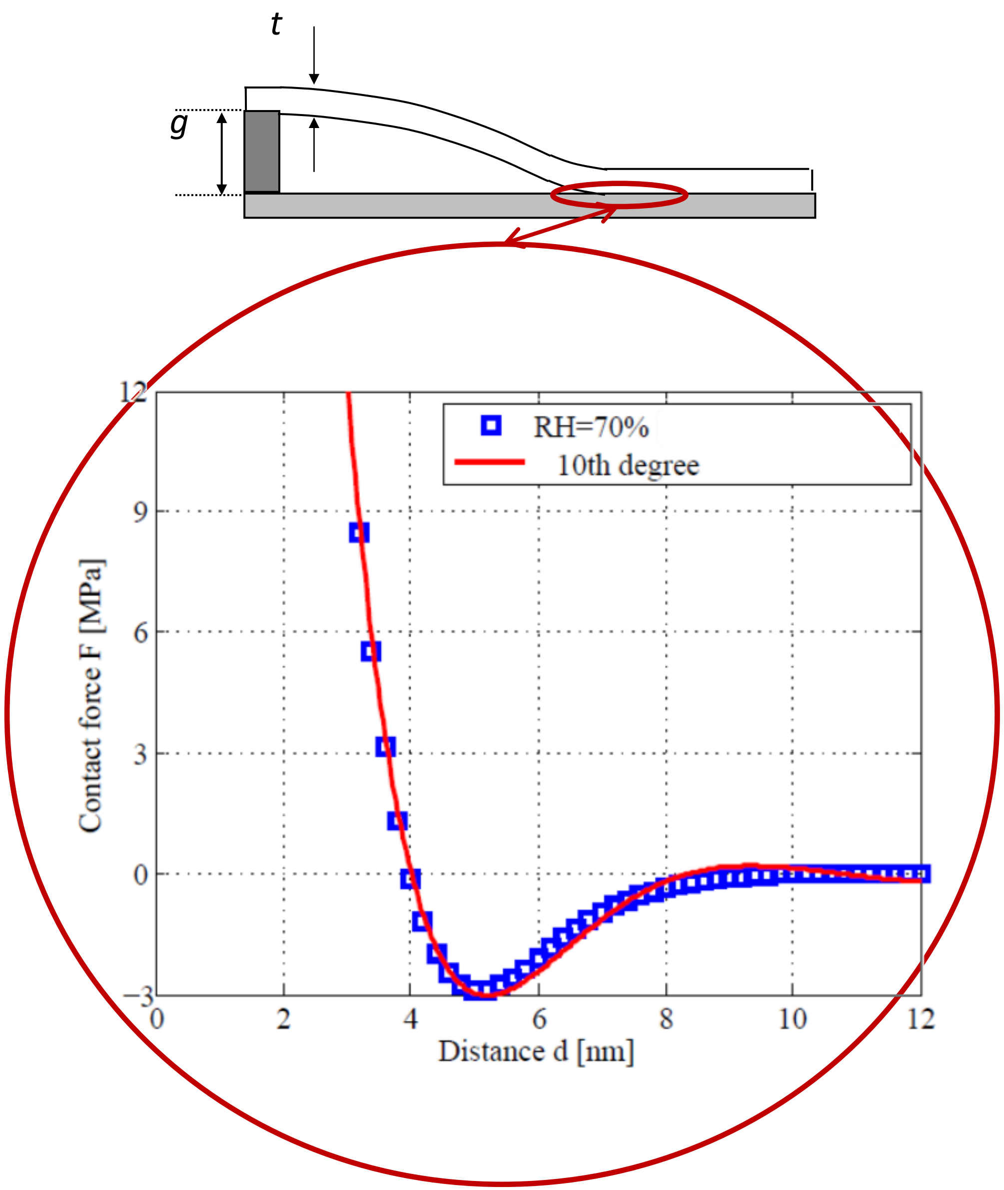




* M.P. de Boer, "Capillary adhesion between elastically hard rough surfaces," *Experim. Mech.*, vol. 47, pp. 171–183, 2007 (Experiment)

Beam multi-scale framework

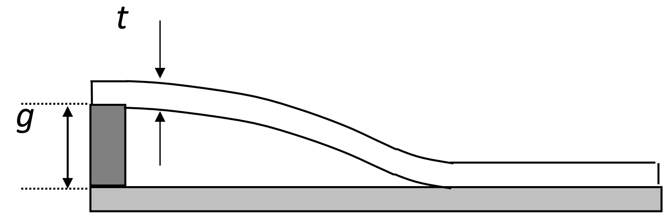
- Design example: cantilevers
  - Finite element model
  - Timoshenko Beams
  - Interacting with pad



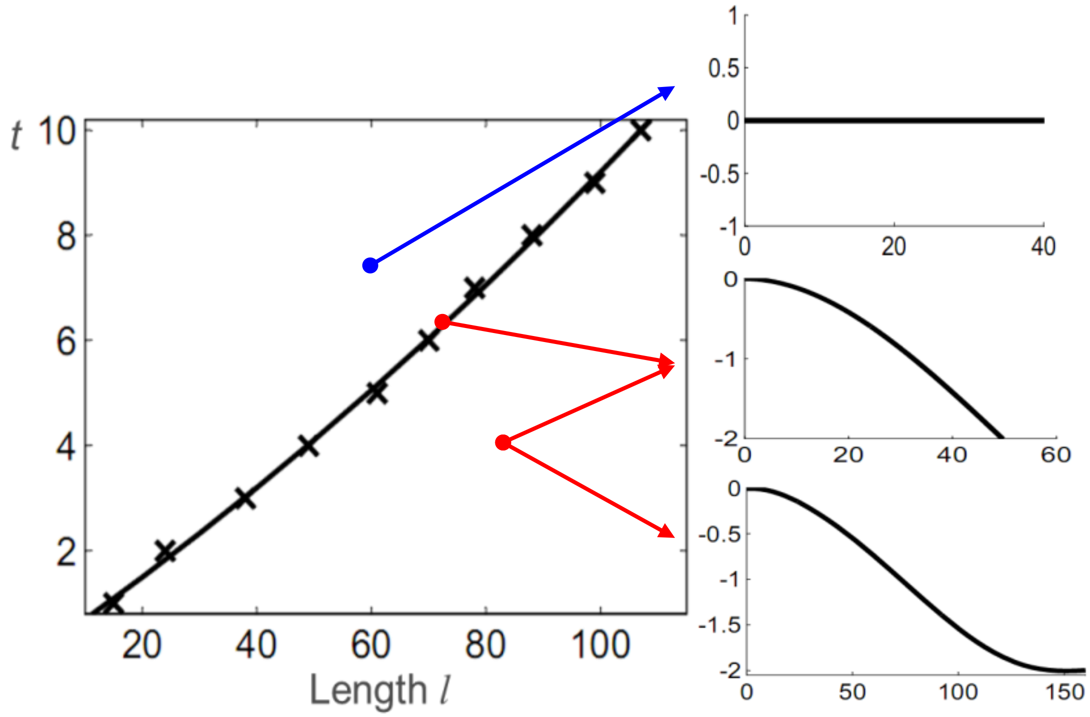
- Use adhesive micro-contact law at interface

Beam multi-scale framework

- Finite element model
  - Put into contact
  - Release the external forces

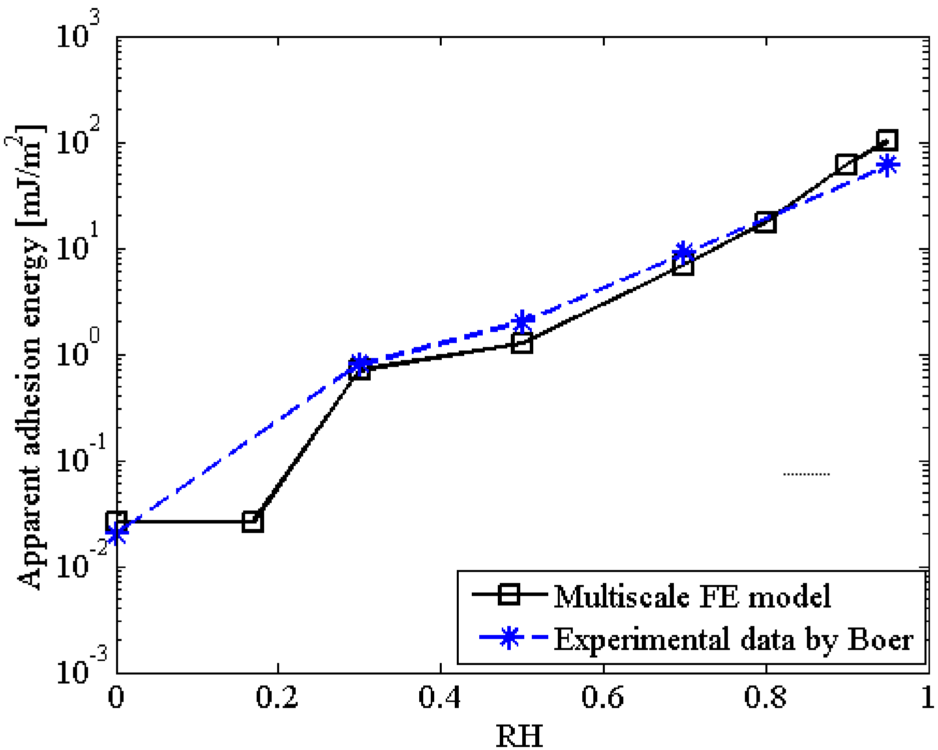


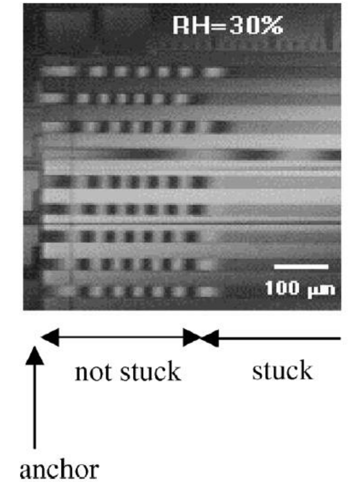
- After contacting, three final configurations are possible



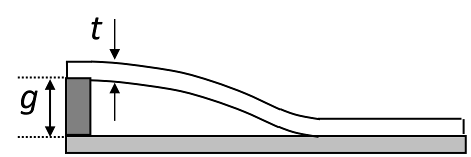
Beam multi-scale framework

- Validation
  - De Boer's experiments(*)
    - From shortest stuck beams
  - Can also be computed from FE solutions
    - Apparent adhesion energy from the shortest Arc-shaped stuck beam

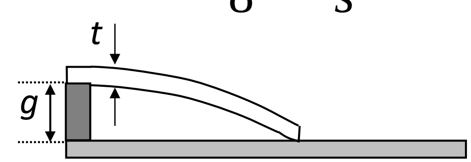




$$\Gamma = \frac{3}{2} E \frac{g^2 t^3}{s^4}$$



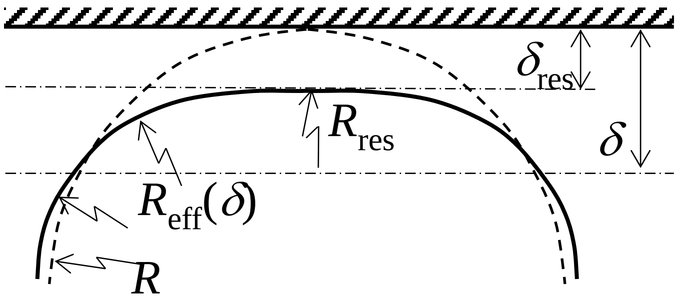
$$\Gamma = \frac{3}{8} E \frac{g^2 t^3}{s^4}$$



* M.P. de Boer, "Capillary adhesion between elastically hard rough surfaces," *Experim. Mech.*, vol. 47, pp. 171–183, 2007 (Experiment)

Perspective: Plasticity effect

- Surface impact: modification of asperity shapes
  - Effect of maximum interference δ_{max} reached during loading
  - Material parameters: yield σ_Y, yield interference δ_{CP}

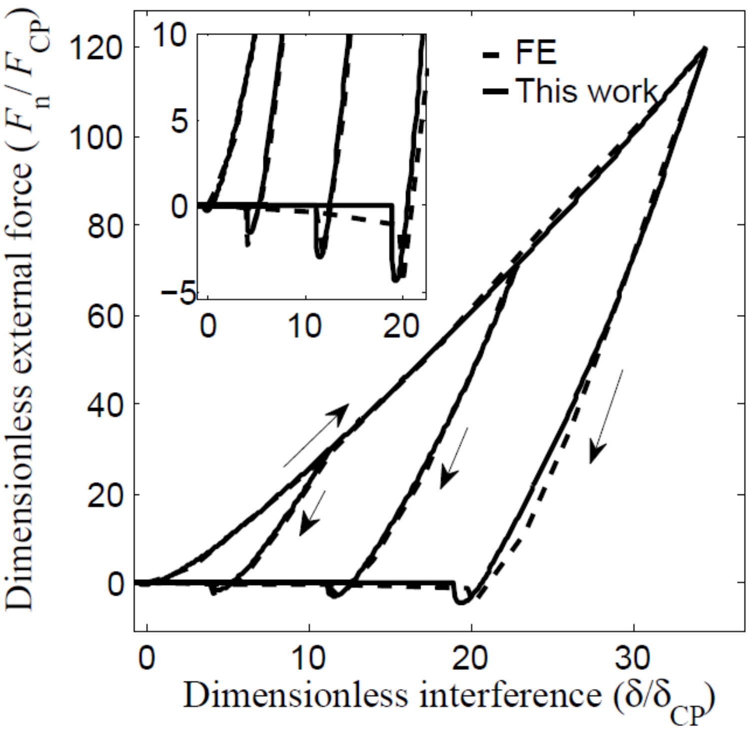


- Model: new asperity profile

$$\delta_{res} = \delta_{max}\left(1-\left(\frac{\delta_{CP}}{\delta_{max}}\right)^{0.28}\right)\left(1-\left(\frac{\delta_{CP}}{\delta_{max}}\right)^{0.69}\right)$$

$$R_{res} = R\left(1+1.275\left(\frac{S_y}{E}\right)^{0.216}\left(\frac{\delta_{max}}{\delta_{CP}}-1\right)\right)$$

- Loading/unloading curves differ
  - Ruthenium surfaces
  - Model vs FEM*



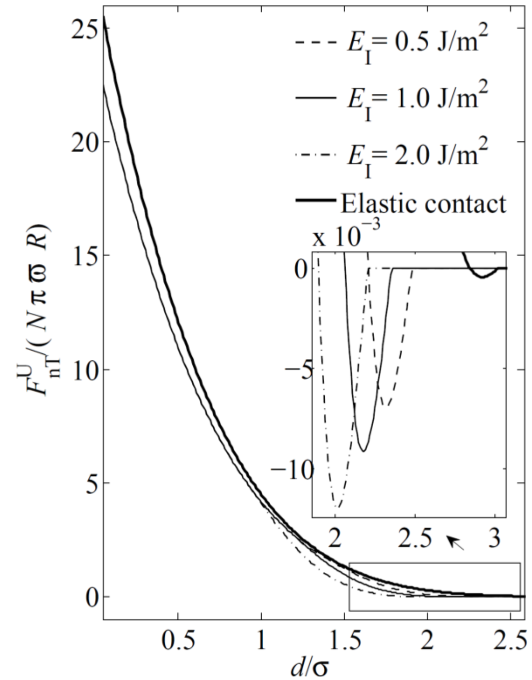
* 28Y. Du, L. Chen, N. McGruer, G. Adams, and I. Etsion, Finite element model of loading and unloading of an asperity contact with adhesion and plasticity," Journal of Colloid and Interface Science 312, 522 - 528 (August 2007)

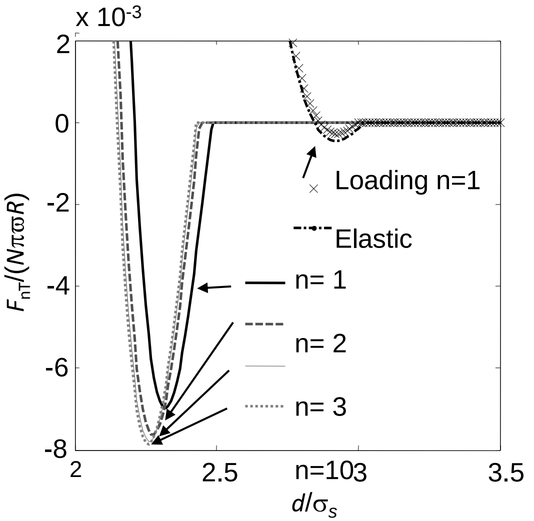
Perspective: Plasticity effect

- Rough surfaces adhesive curves
  - Unloading curves depend on the maximum loading (impact energy)
  - Ruthenium surfaces

VDW surface energy ϖ	Yield σ_Y	Aperity Radii R	Standard derivation σ
1 J/m^2	3.42 GPa	4 nm	7.81 nm

- Cyclic loading
  - Unloading curves modified at each cycle

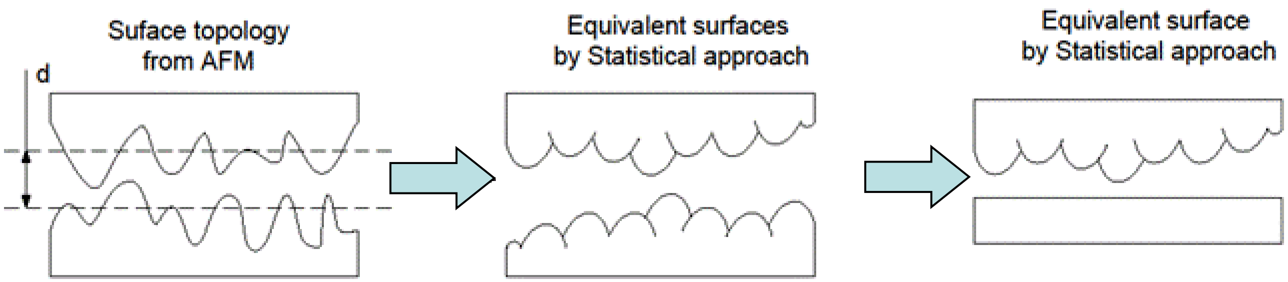




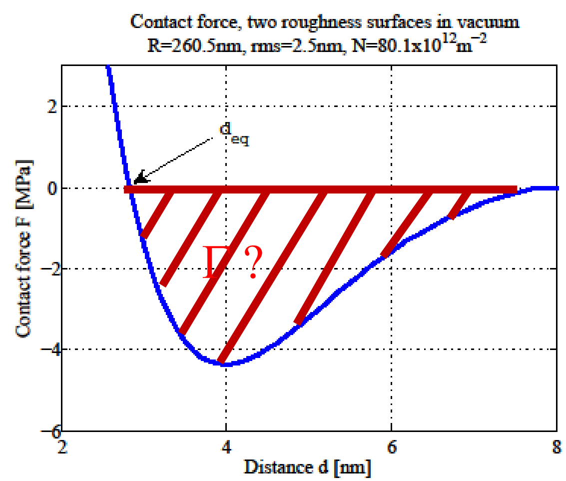
Perspective: Surfaces uncertainties

- Inside stiction model
  - Using descriptions of the surface to build the equivalent surface:
    - N asperities per square-meter,
    - Radius R, and
    - Standard derivation σ
  - These parameters are calculated from surface AFM measures

Surface 1: m_0, m_2, m_4 — Surface 1: N, R, σ — Eq. surface: N, R, σ



Surface 2: m_0, m_2, m_4 — Surface 2: N, R, σ



- Effect on the uncertainties
  - In: m_0, m_2, m_4
  - On the apparent energy Γ

Conclusions

- Stiction model
  - Capillary effects
    - Accounts for RH range
  - Cut-off distance?
    - New distribution
- Surface uncertainties
  - Ongoing work
- Multi-scale approach
  - To be coupled with BEM