ON THE MODELLING OF ADHESIVE CONTACT AND STICTION FAILURE IN MICRO-SWITCHES

Ling Wu, Ludovic Noels, Jean-Claude Golinval

University of Liege, Belgium

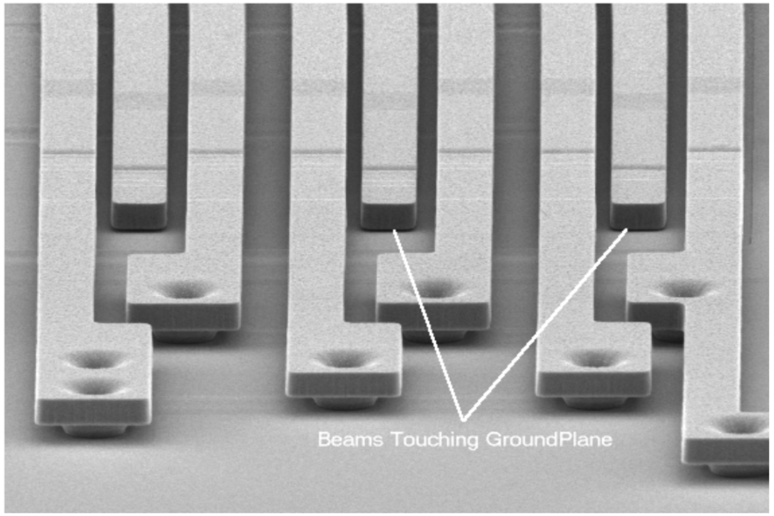
Department of Aerospace and Mechanical Engineering
Chemin des Chevreuils, 1 Bât. B 52
B-4000 Liège (Belgium)
E-mail : JC.Golinval@ulg.ac.be

Outline

1. Introduction
2. Micro-scale model
3. Multi-scale model
4. Elasto-plastic adhesive contact
5. Conclusions

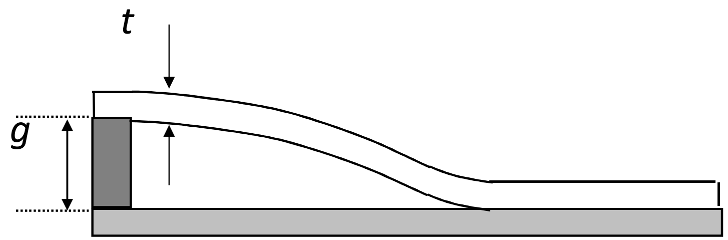
Introduction

Stiction failure in MEMS (major issue for micro-switches)



Stiction failure in a MEMS sensor

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



Reason

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, …

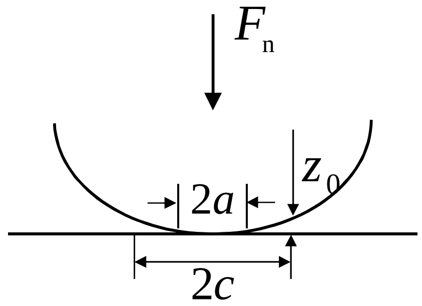
The risk of in-use stiction increases when plasticity is involved during contact.

Université de Liège

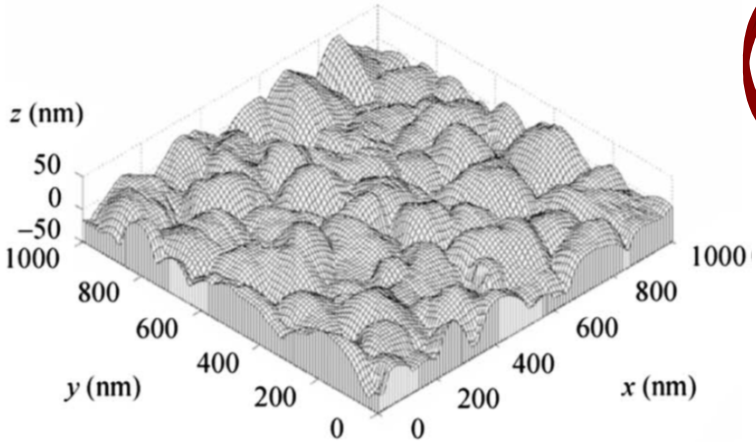
Introduction

Multi-scale approach

At the micro-scale



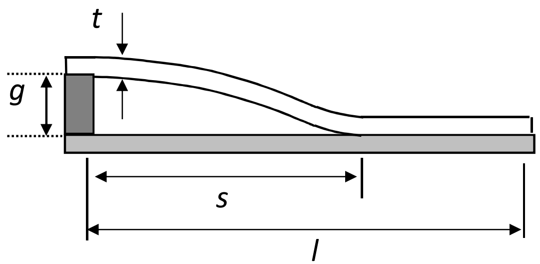
Single asperity subject to adhesive-micro contact forces



Contact model between rough surfaces
→ prediction of the adhesive force

Integration with FEM

At the macro-scale



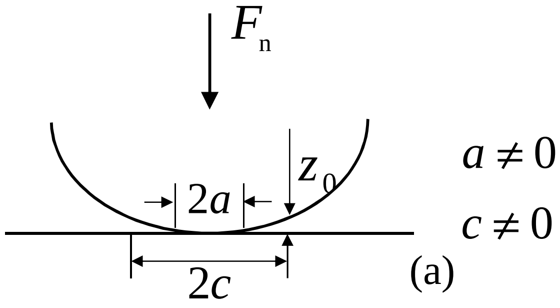
Outline

1. Introduction
2. Micro-scale model
   - Single asperity adhesive-elastic contact
   - Statistical model for rough surface
3. Multi-scale Model
4. Elasto-plastic adhesive contact
5. Conclusions

Micro-scale model

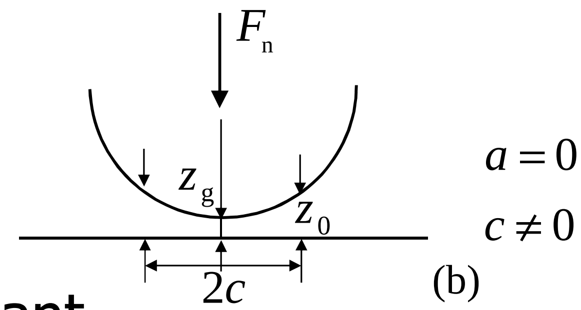
Single asperity adhesive-elastic contact (Hertz) theories

- **Johnson, Kendall, and Roberts (JKR)**
  - The surface forces are short ranged and act only inside the contact area



⇨ Ideal for compliant materials with high surface energy and large contact curvature surface

- **Derjaguin, Muller and Toporov (DMT)**
  - Accounts for the long-ranged adhesive forces acting outside the contact area



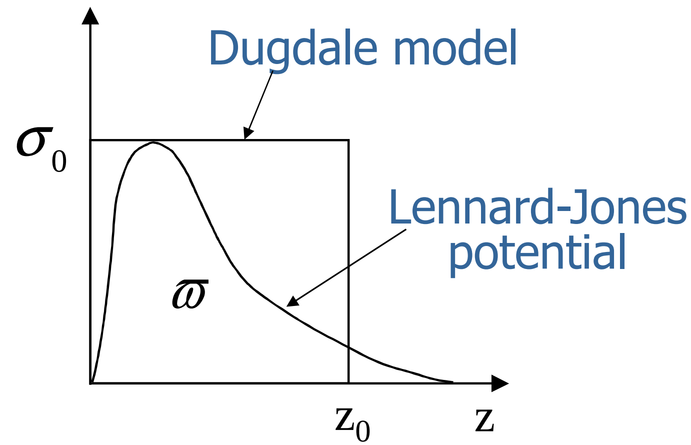
⇨ Well suited for harder, less compliant materials with low surface energy and small asperity tip radius

Université de Liège

Micro-scale model

- **Maugis model**
  - for all elastic materials
  - provides transition solutions for intermediate cases between the JKR and DMT regimes
  - is based on a Dugdale assumption for interaction potential

  - Constant traction σ_0 within a critical value of separation z_0
  - Zero traction for gap larger than z_0



Work of adhesion: $\varpi = \sigma_0 \cdot z_0$

Single asperity adhesive-micro contact

The Maugis transition parameter λ is defined in terms of the surface properties:

Work of adhesion: ϖ

asperity radius: R

$$\lambda = \frac{2\,\varpi^{2/3} R^{1/3}}{z_0\,(\pi\,K^2)^{1/3}}$$

equivalent elastic constant: K

$$\Rightarrow \quad \begin{array}{l} \varpi\uparrow, R\uparrow, K\downarrow \;\Rightarrow\; \lambda\uparrow \\ \varpi\downarrow, R\downarrow, K\uparrow \;\Rightarrow\; \lambda\downarrow \end{array}$$

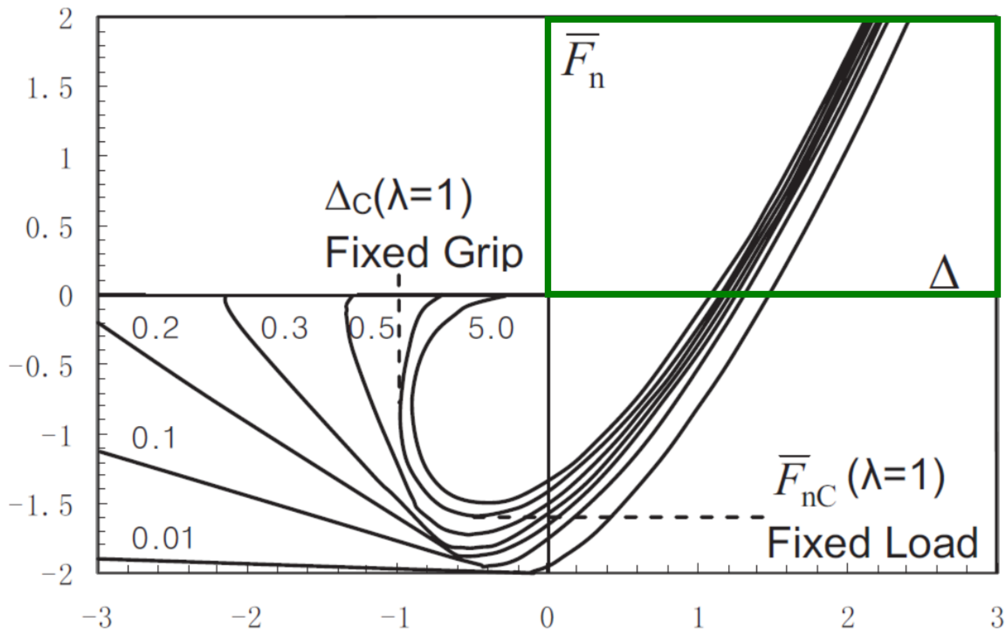
JKR model (short-ranged)

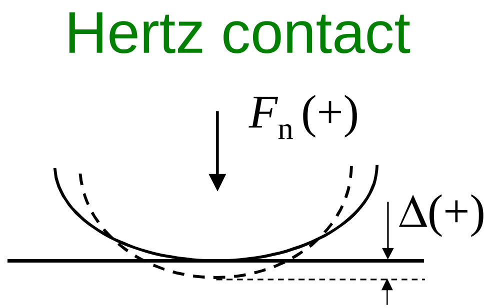
DMT model (long-ranged)

Single asperity adhesive-micro contact

- Maugis transition solution

Calculation of the load in terms of the deflection for different values of the transition parameter λ

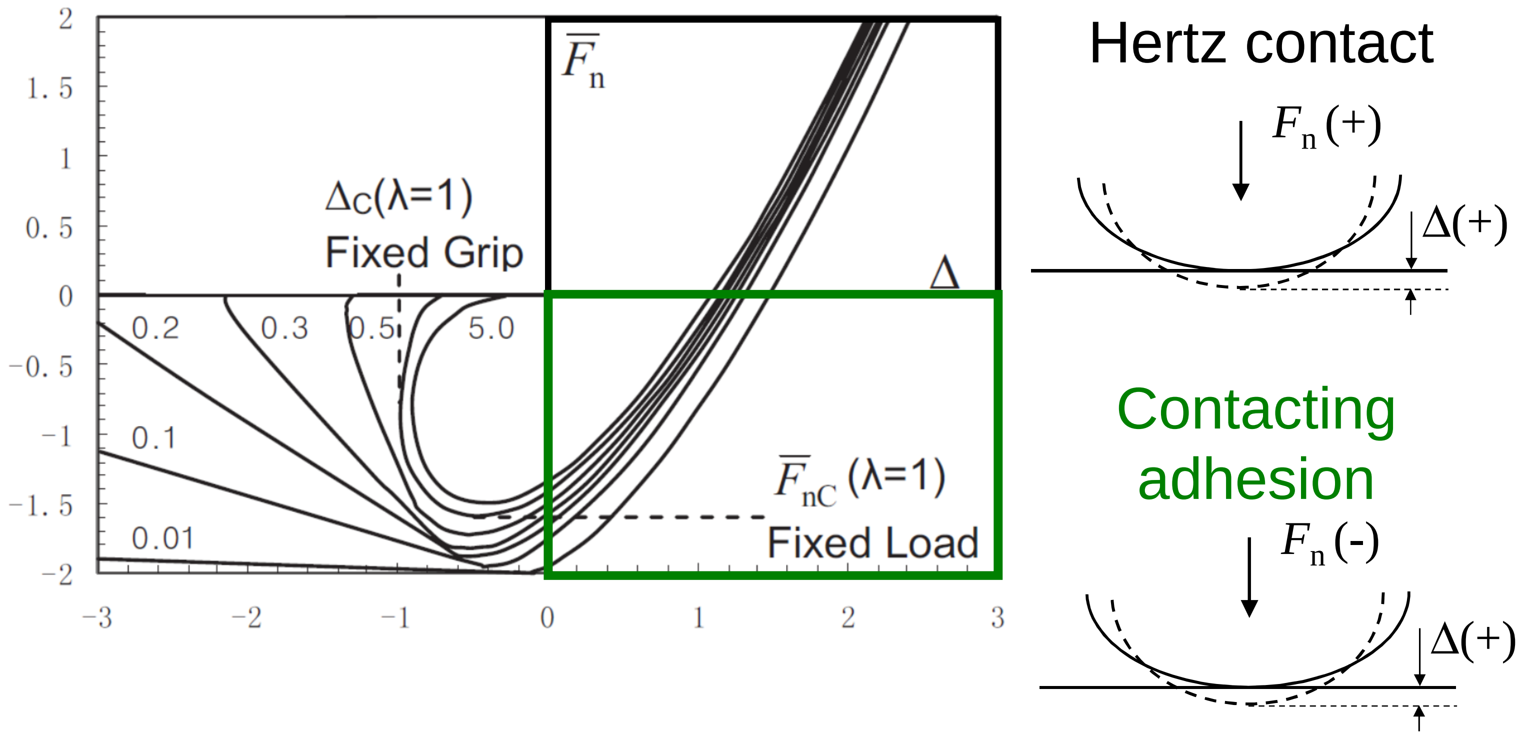




Single asperity adhesive-micro contact

- Maugis transition solution

Calculation of the load in terms of the deflection for different values of the transition parameter λ

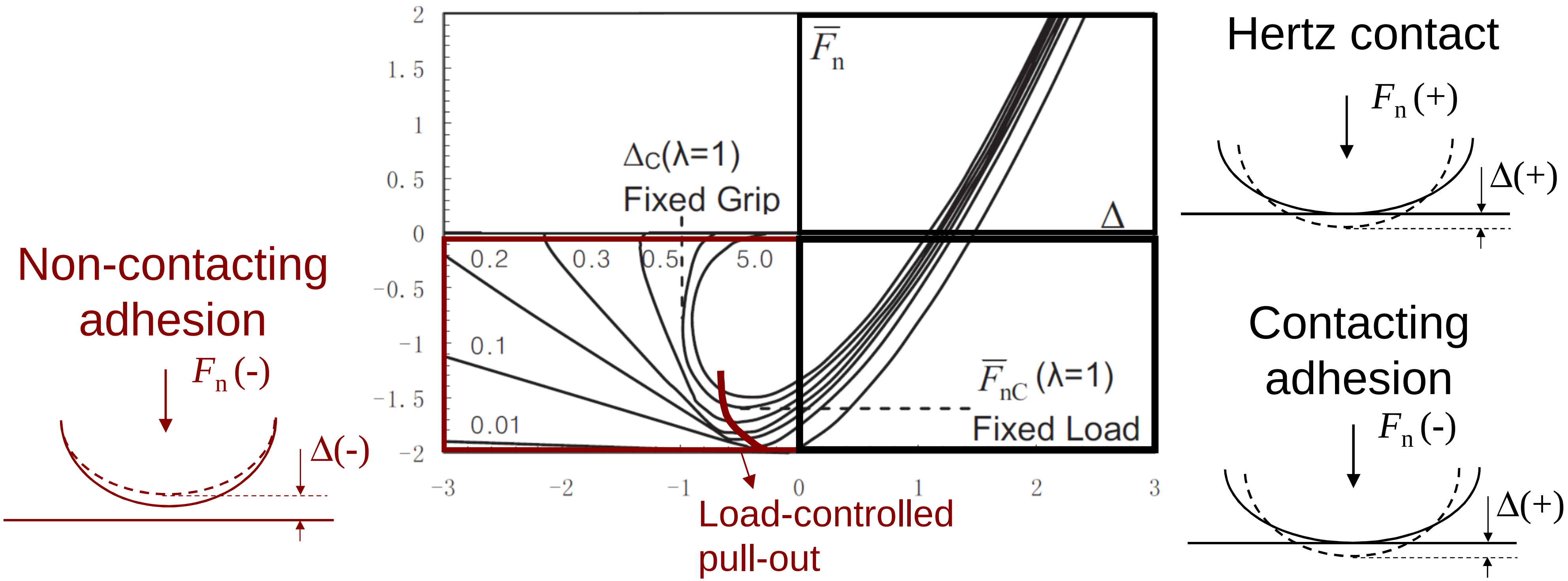


Université de Liège

Single asperity adhesive-micro contact

- Maugis transition solution

Calculation of the load in terms of the deflection for different values of the transition parameter λ



Université de Liège

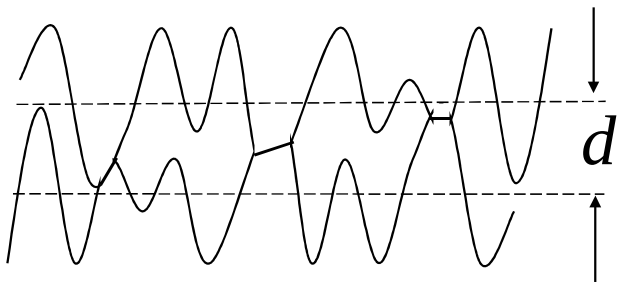
Micro-scale model

Statistical model for rough surfaces

- The rough surface is described by a collection of spherical asperities with constant tip radius.

  The heights h have a statistical distribution:

$$\varphi(h) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-h^2}{2\sigma^2}\right)$$



- Rough surfaces interaction
  - Reduced number of interacting asperities
  - The distance between the surfaces is defined in terms of distance d

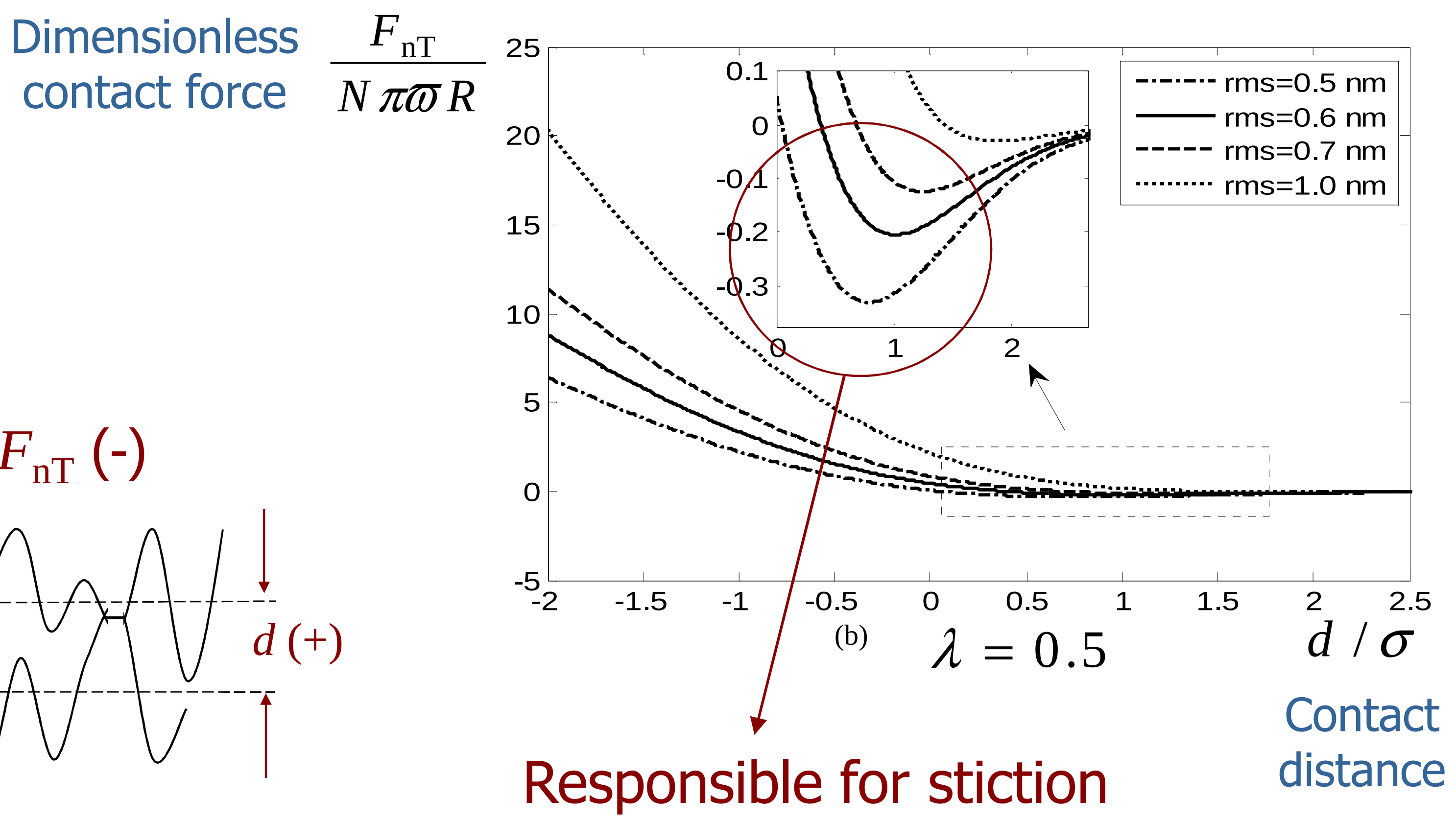
Université de Liège

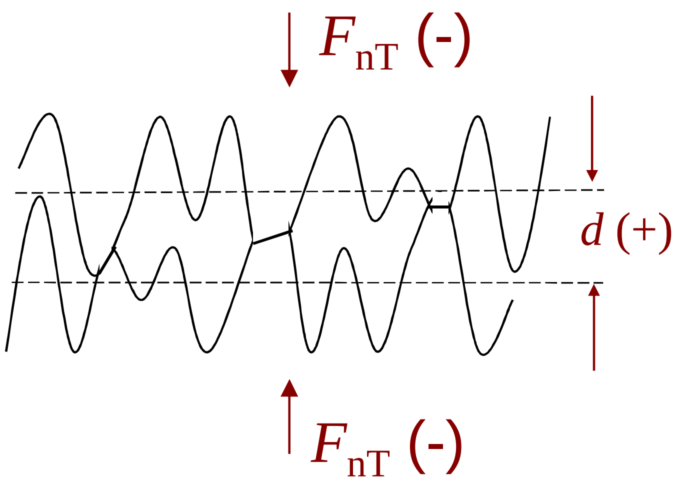
Micro-scale model

The micro adhesive contact forces between rough surfaces may be computed

by integration of the Maugis solution using

$$\varphi(h) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-h^2}{2\sigma^2}\right)$$





Université de Liège

Outline

1. Introduction
2. Micro-scale model
3. **Multi-scale Model**
    - **Design example: cantilever beam (FEM)**
    - **Polysilicon to polysilicon interaction**
    - **Validation with experiments**
4. Elasto-plastic adhesive contact
5. Conclusions

Université de Liège

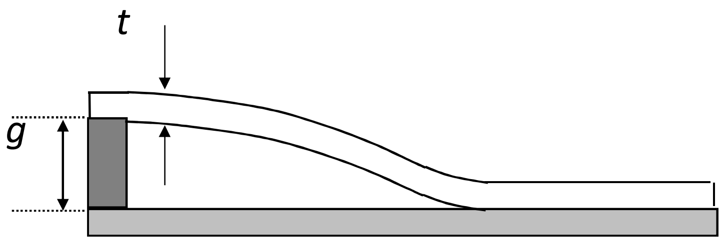
Multi-scale model

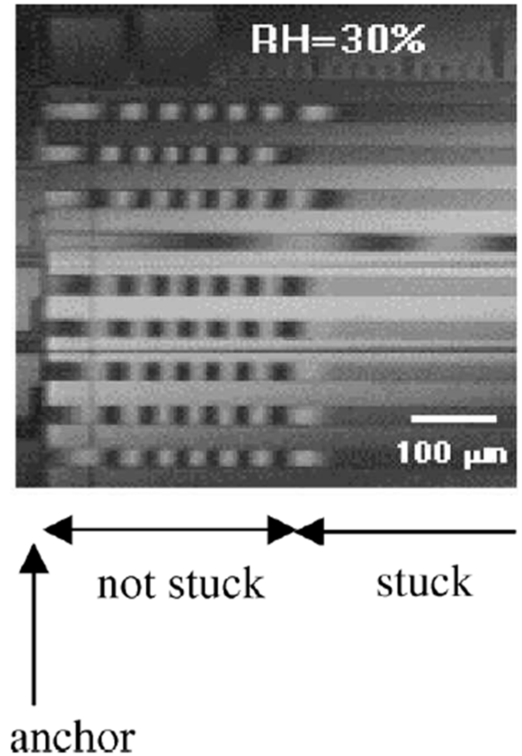
Design example: cantilever beam entering into contact with the substrate

- Finite element model
  - Timoshenko beams
- Use of adhesive contact law at interface
  - Polysilicon-Polysilicon interactions
  - Surfaces properties from
    - AFM
    - Surface energy measured

In vacuum	ϖ =2.54 J/m^2
In air	ϖ =0.167 J/m^2

  - Contact remains elastic
- Validation vs literature experiments*



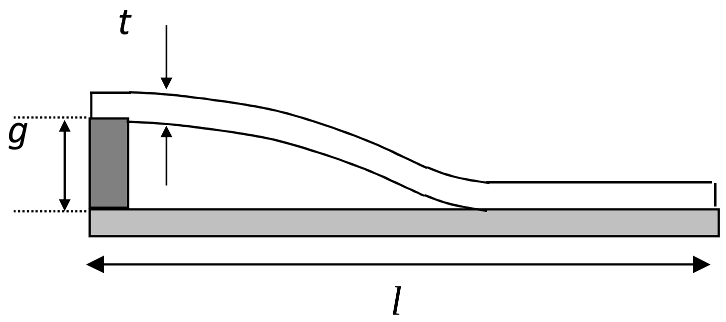


* W. M. van Spengen,, R. Puers and I. De Wolf, "On the physics of stiction and its impact on the reliability of microstructures," *J. Adhesion Sci. Technol.*, vol. 17, no. 4, pp. 563–582, 2003 (Analytical)
* M.P. de Boer, "Capillary adhesion between elastically hard rough surfaces," *Experim. Mech.*, vol. 47, pp. 171–183, 2007 (Experiment)

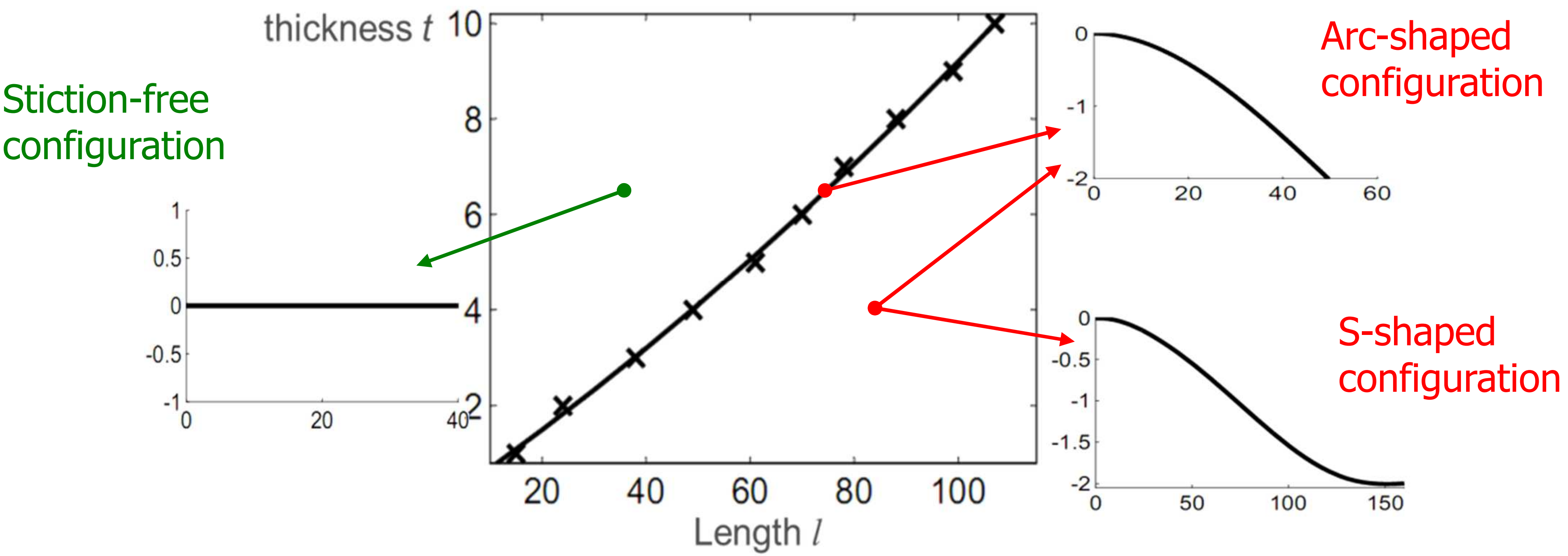
Multi-scale model

Design example: cantilever beam

Initial gap g = 2.0 µm



The design limitations avoiding in-use stiction are calculated in terms of the beam's geometrical properties (thickness and length) for ϖ =2.54 J/m²



Université de Liège

Outline

1. Introduction

2. Micro-scale model

3. Multi-scale Model

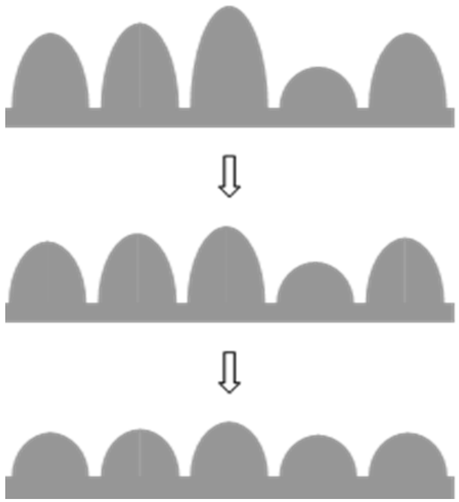
4. **Elasto-plastic adhesive contact**
    - Plastic deformation of a loaded single asperity
    - Adhesive unloading of a single deformed asperity
    - Adhesive unloading of rough surfaces
    - Lifetime of MEMS

5. Conclusions

Elasto-plastic adhesive contact

- Extension of the multiscale model → plastic deformations of asperities
- In case of repeated contacts (cycling loading)

The height distribution and the tip radii R
of asperities change until accomodation is reached



Surface roughness R_q ↓

⇩

Adhesive forces ↑

⇩

Stiction may appear after a few cycles

→ Elasto-plastic adhesive contact model is required !

Elasto-plastic adhesive contact

Basic idea

- Adhesive contact model of the elastic-plastically deformed asperity

  1. The elasto–plastic deformation resulting from the contact of a single loaded sphere is first solved without considering adhesive effect.

  2. The Maugis' adhesive contact theory is performed on the equivalent elastic deformed asperity.

- Asperity-based rough surface model based on the statistical distribution of asperities.

Université de Liège

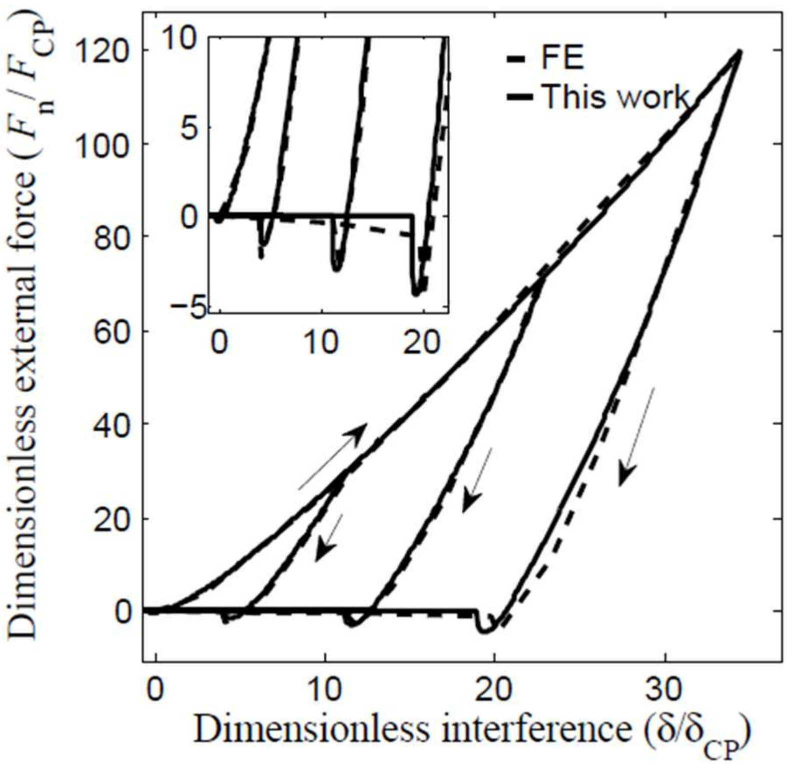
Elasto-plastic adhesive contact

Adhesive loading/unloading of a single asperity

- Material: Ru

R	E	ν	S_Y	z_0	ϖ
4 nm	410 GPa	0.3	3.42 GPa	0.169 nm	1 J/m^2

- Model vs FE*



* 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)

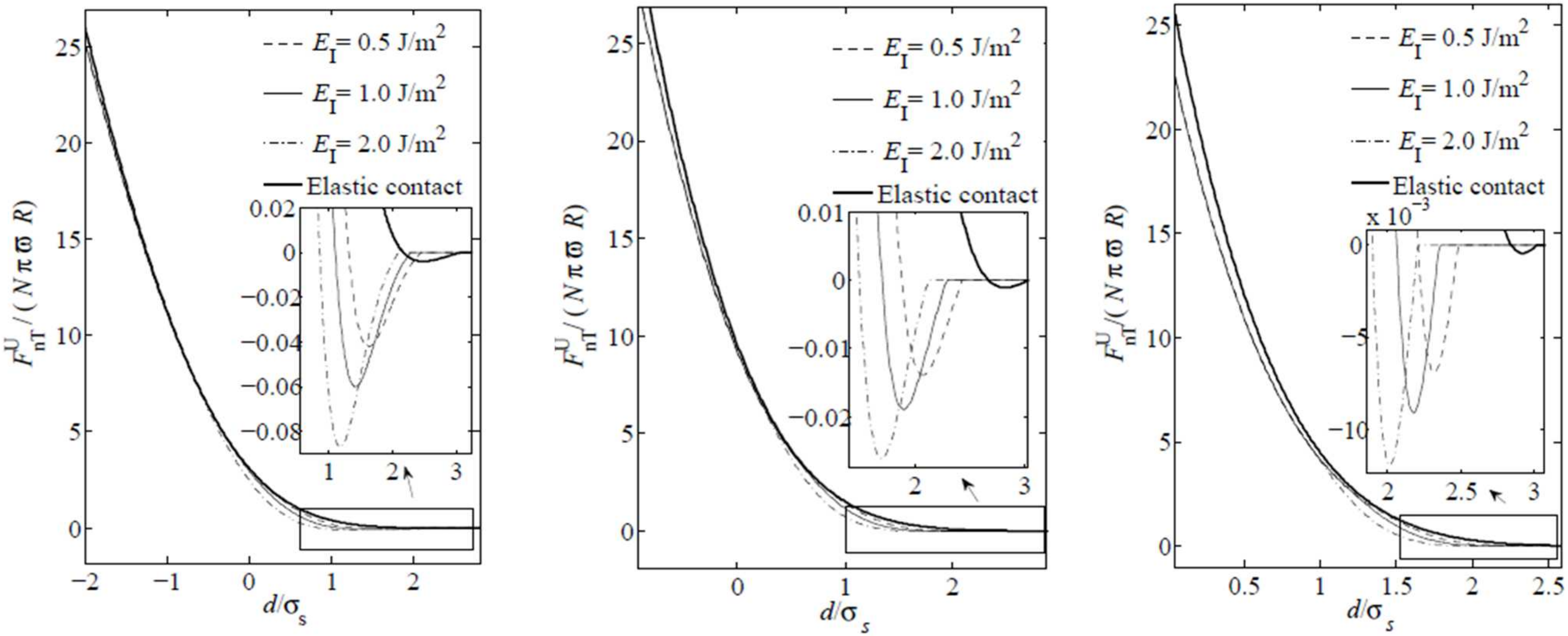
Elasto-plastic adhesive contact

Adhesive contact forces during unloading

- For different Ru surface samples

Sample	A	B	C
R_q (nm)	2.03	3.99	7.81

- Effect of impact energy at pull-in on plastic deformations



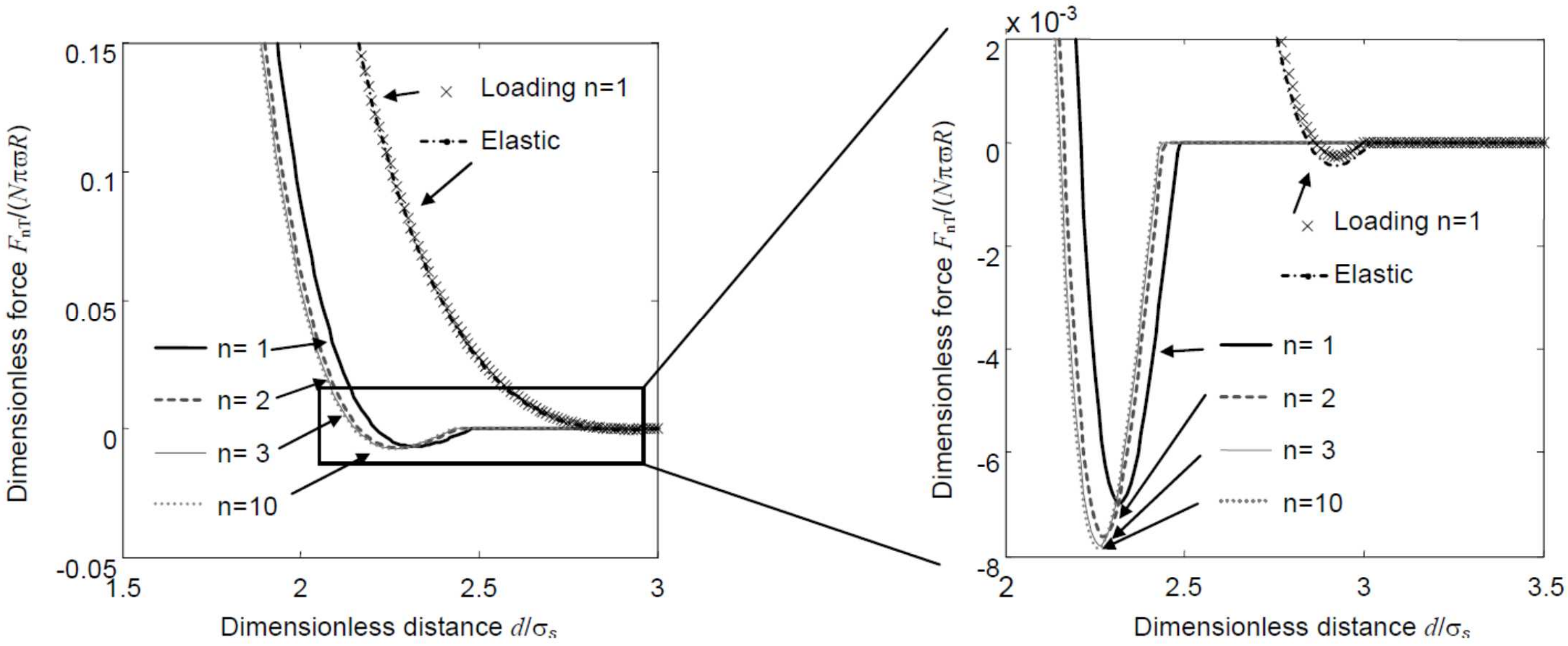
(a)Sample A (b)Sample B (c)Sample C

Elasto-plastic adhesive contact

Lifetime of MEMS

- Repeated loading/unloading ⇨ changes in surfaces profile
- Ru sample

Sample	Rq (nm)	E_I (J/m^2)
C	7.81	0.5



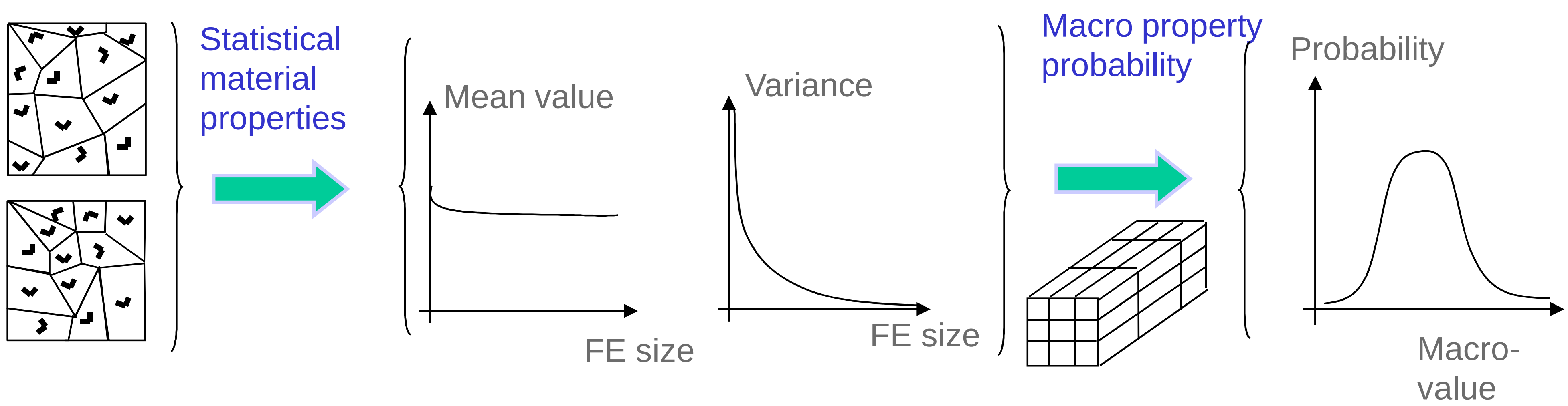
Conclusion

- The adhesion between the contact surfaces has a large influence on the design of micro-switches and needs to be considered carefully.
- The adhesive work and the surface roughness are the main factors to take into account.
- The analytical adhesive contact results can be combined with FEM to predict the stiction of more complicated structures.
- Effect of plasticity can be accounted for.
- The other kinds of adhesive forces, such as capillary force, electrostatic force from dielectric charging, are not considered.

Université de Liège

3-Scale Stochastic Modeling for MEMS

- 3-scale modeling
  - MEMS
  - Separation of length scale violated
  - Uncertainties should be considered



- Application to robust design (Stiction risk, Q-factor range)
- 3SMVIB MNT.ERA-NET project
  - Open-Engineering, V2i, ULg (Belgium)
  - Polit. Warszawska (Poland)
  - IMT, Univ. Cluj-Napoca (Romania)

Thank you for your attention.