Computational & Multiscale
Mechanics of Materials
University of Liège, Belgium

A stochastic multi-scale analysis for MEMS stiction failure

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Maarten Arnst, Ludovic Noels

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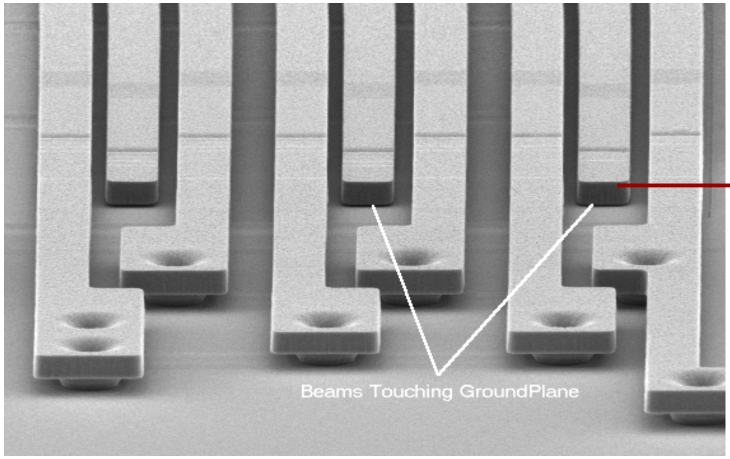
- (*) PhD candidate at the Belgian National Fund for Education at the Research in Industry and Farming (FNRS-FRIA).

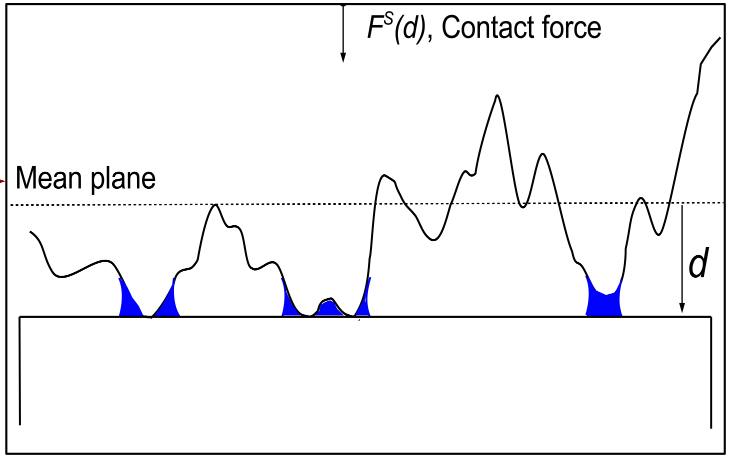
Introduction

- MEMS devices, e.g. accelerometers, digital mirrors, pressure sensors, resonators
  - Successfully applied in the industry. E.g. accelerometers for air bag systems
- **Stiction**: a common failure of MEMS
  - Due to dominance of surface adhesive forces at the micrometer scale
    - E. g., van der Waals forces and capillary forces
    - In humid conditions, the capillary forces are dominant
  - Depends on the surface topologies
    - The physical contact happens at the high asperities



Stiction failure in a MEMS sensor

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



Water condensing between two surfaces

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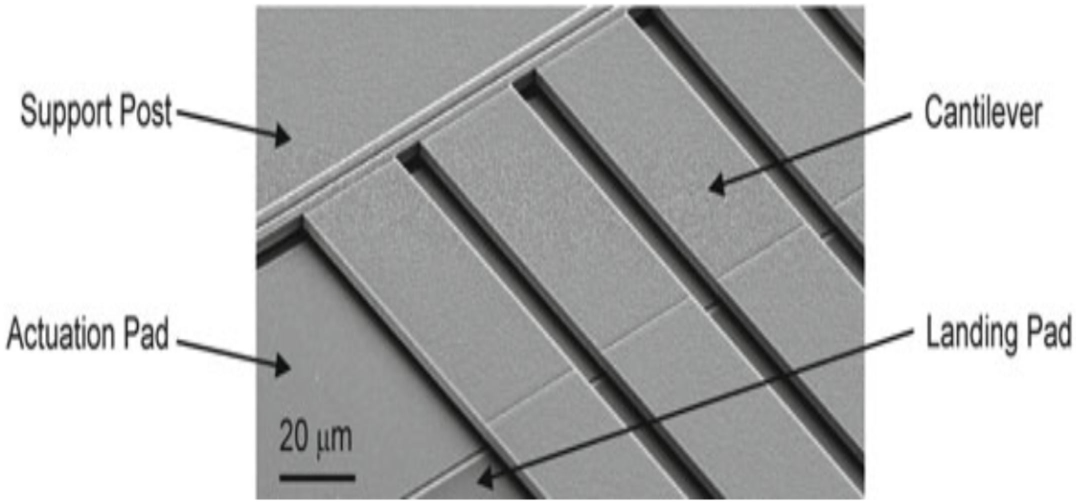
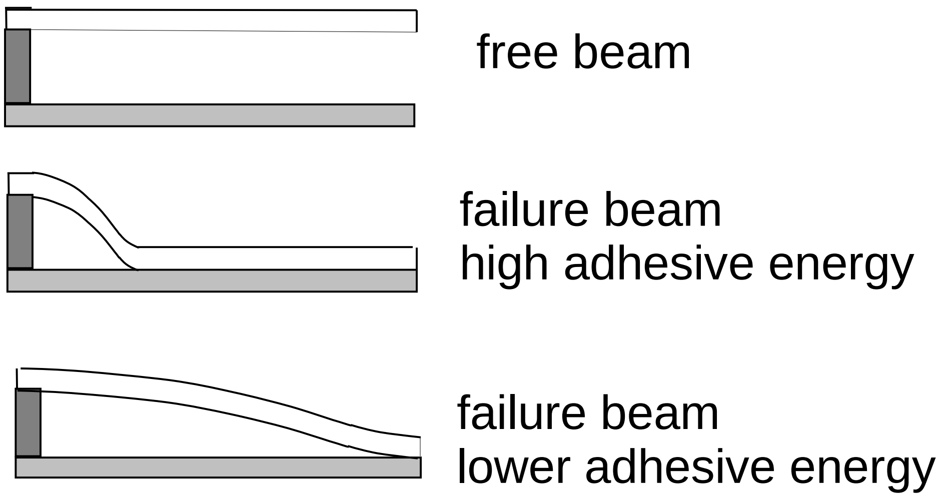
    - E. g., van der Waals forces and capillary forces
    - In humid conditions, the capillary forces are dominant
  - Depends on the surface topologies
    - The physical contact happens at the high asperities
  - An uncertain phenomenon: [Boer et *al.* 2007, 2013], [W. M. van Spengen 2003, 2015]
    - e.g. Stiction test: Some beams are stuck with different configurations, other beams are released

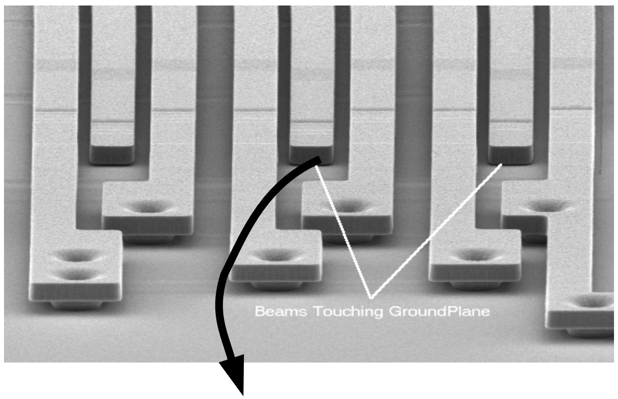


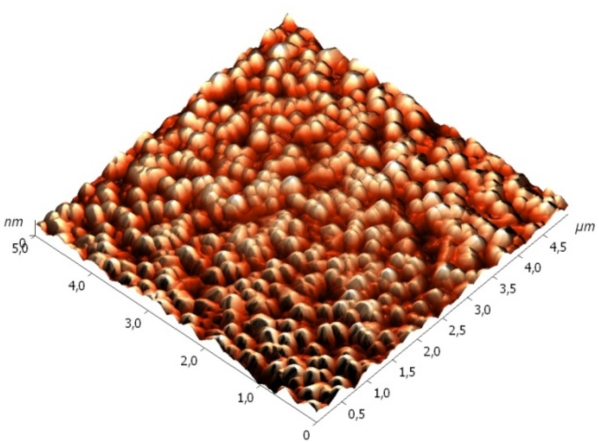
Cantilever beams array
[Boer et *al.* 2013]



Motivation

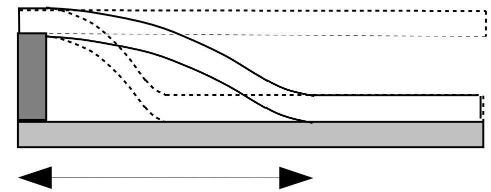
- Construct a **numerical model** for micro cantilever beam structures
  - To predict the crack length l_s and its uncertainties from the surface topology
  - At an acceptable computational cost



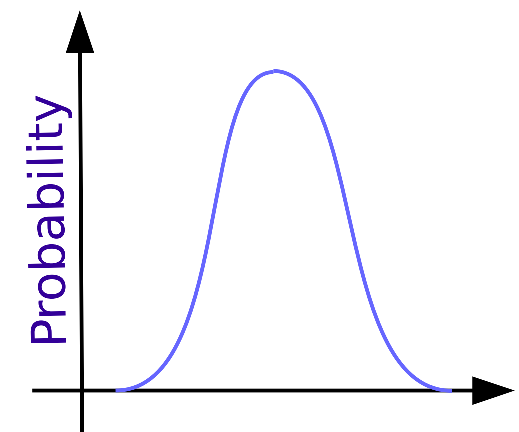


Atomic Force Measurements (**AFM**)
of **contact surfaces**

Reality



Numerical model



Crack length distribution

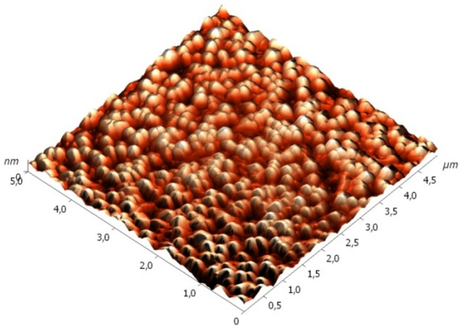
* The crack length l_s characterizes the required energy to release the cantilever beam out of the failure configuration

Methodology

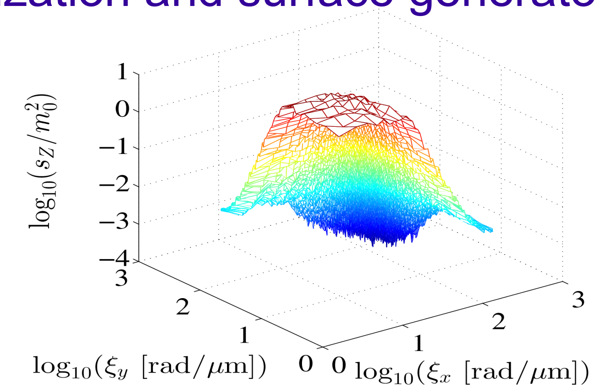
- Multiscale model
- Probabilistic multiscale model
  - Direct Monte-Carlo multiscale method (high computational cost)
  - Stochastic model-based multiscale method (acceptable computational cost)
- Numerical results: comparison, evaluation
- Conclusions and perspectives

Multiscale model

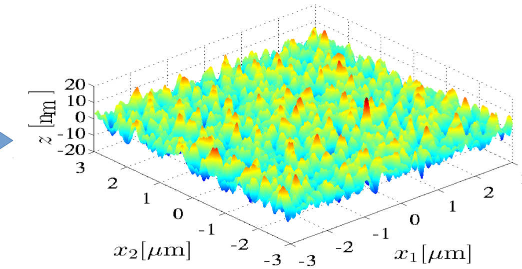
- **Lower scale**: surface characterization and surface generator



AFM measurements



Topology spectral density



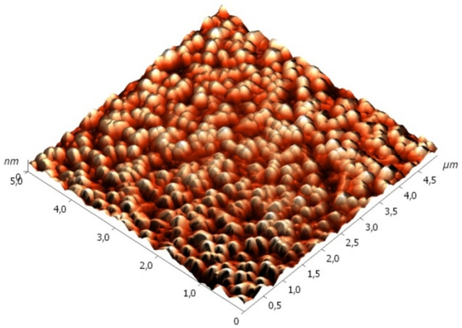
Generated surface

- **Meso-scale**: evaluate the contact forces by a semi-analytical contact model

- **Upper-sale**: Integrate the contact forces as contact law into FE model

Multiscale analysis

- **Lower scale**: surface characterization and surface generator



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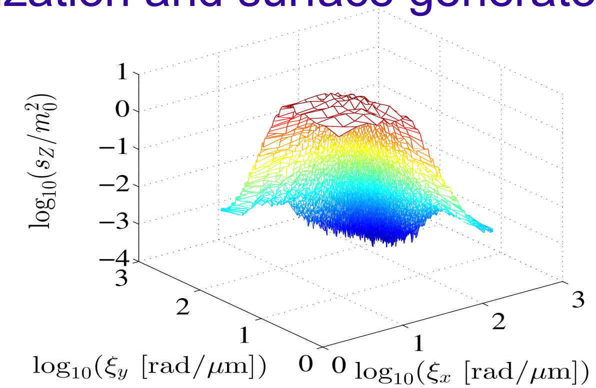
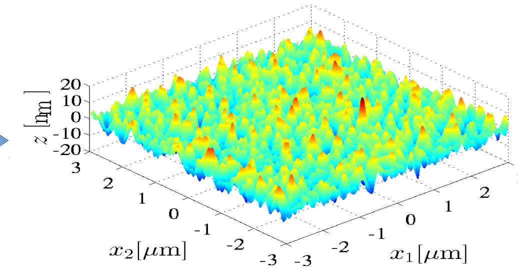


Topology spectral density



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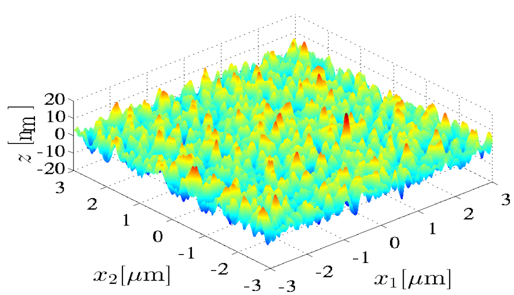
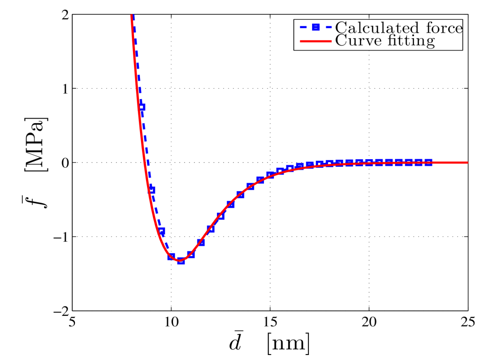
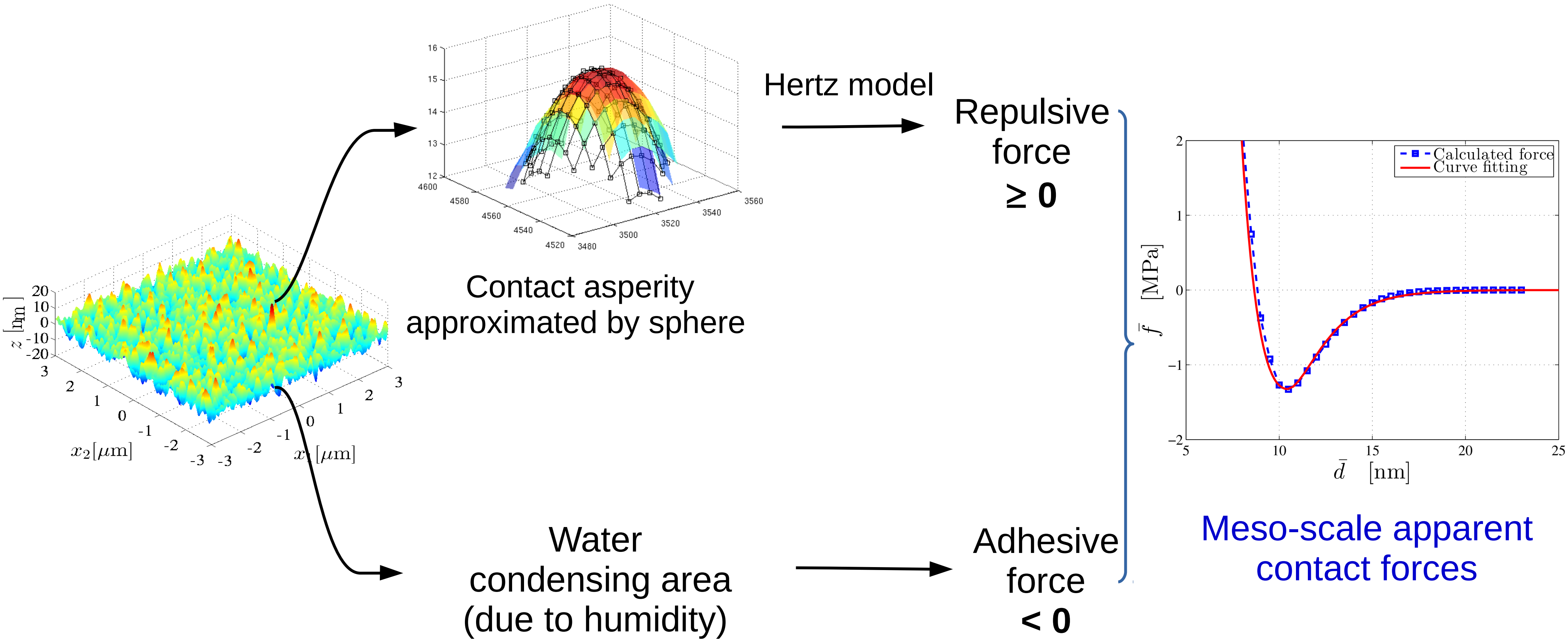




Apparent adhesive Contact forces

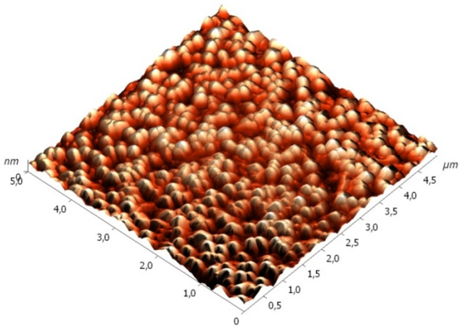
- **Upper-sale**: Integrate the contact forces as contact law into FE model

- **Semi-analytical contact model for adhesive contact problem**
  - Based on DMT spherical asperity contact model
  - Rough surface contact model



Multiscale analysis

- **Lower scale**: surface characterization and surface generator



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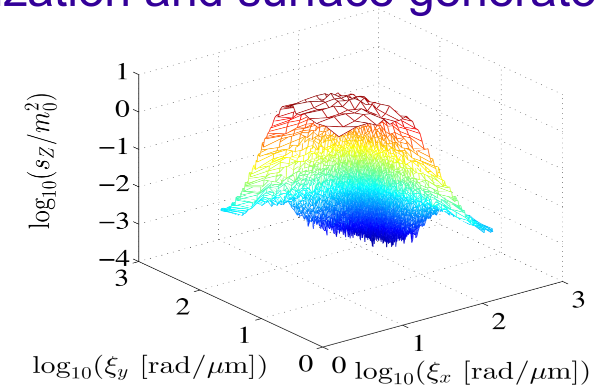
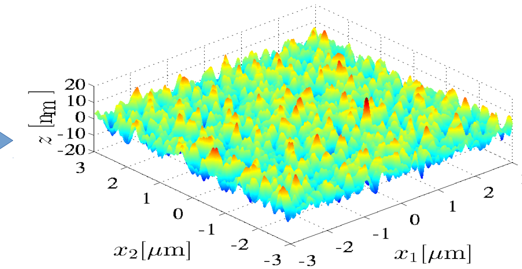


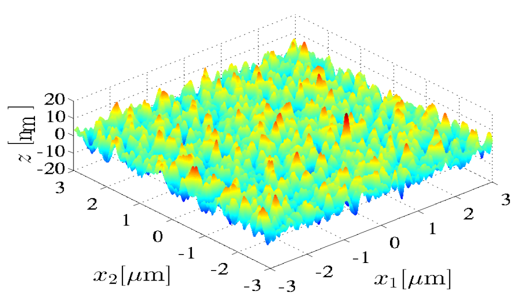
Topology spectral density

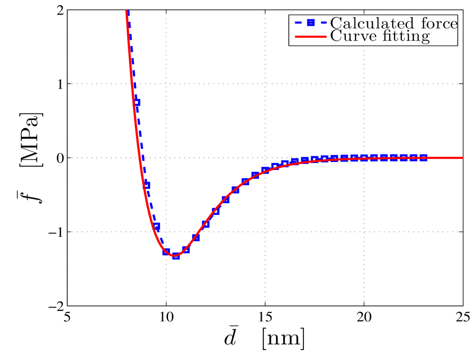


Generated surface

- **Meso-scale**: evaluate the contact forces by a semi-analytical contact model

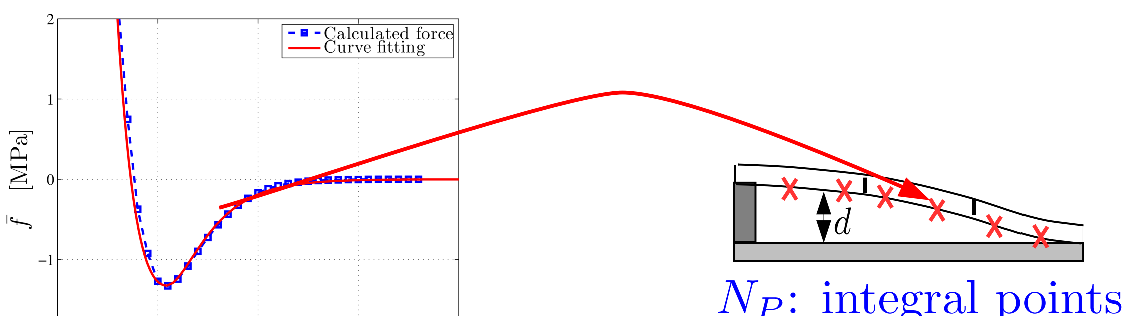
Generated surface



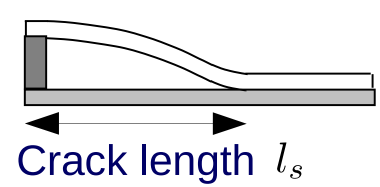


Apparent adhesive Contact forces

- **Upper-sale**: Integrate the contact forces as contact laws into a FE model



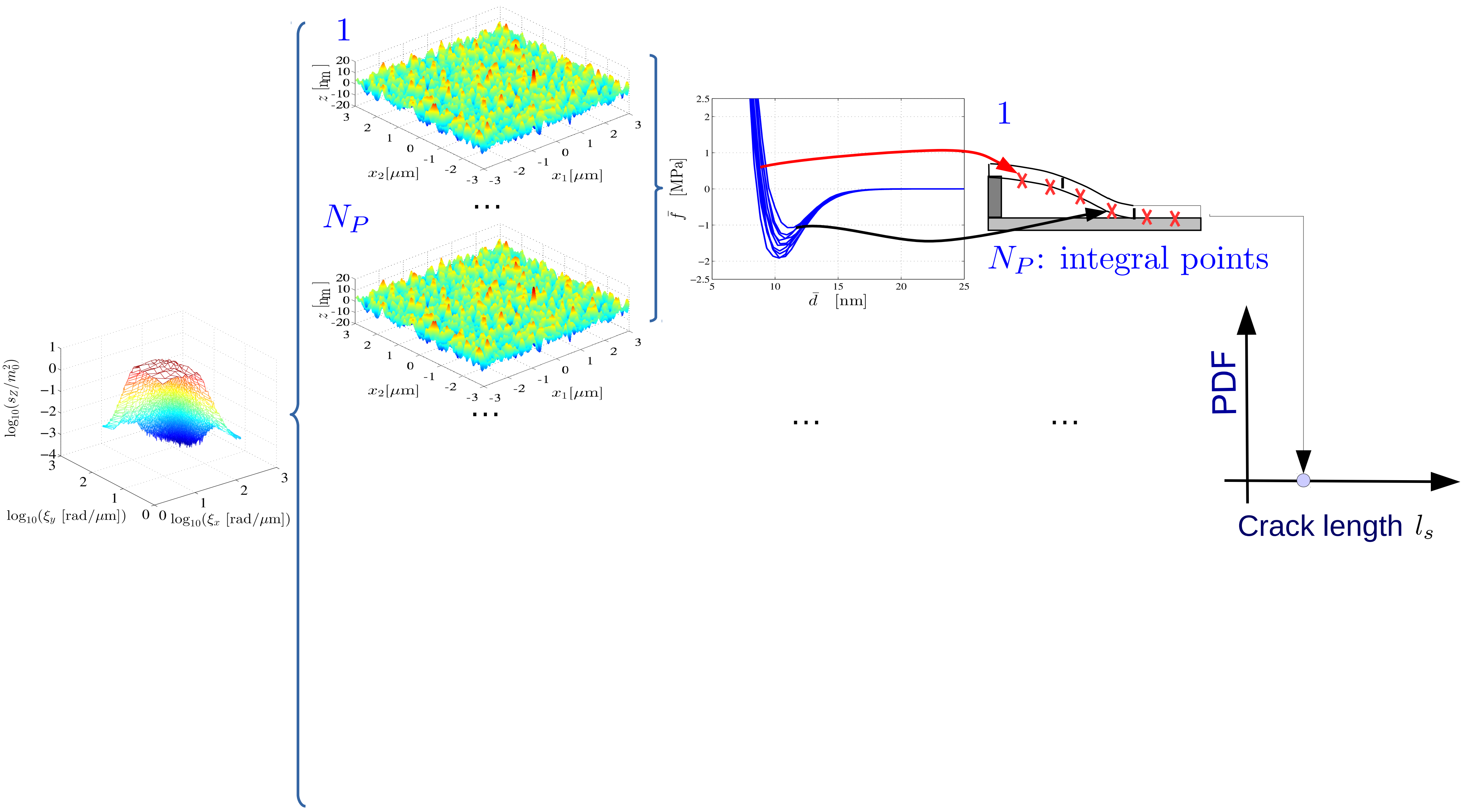
FE model



Stiction failure

Direct Monte-Carlo multiscale method

Spectral density → Generate surfaces → **Evaluate contact forces** → Solve FE model → Estimate Probability



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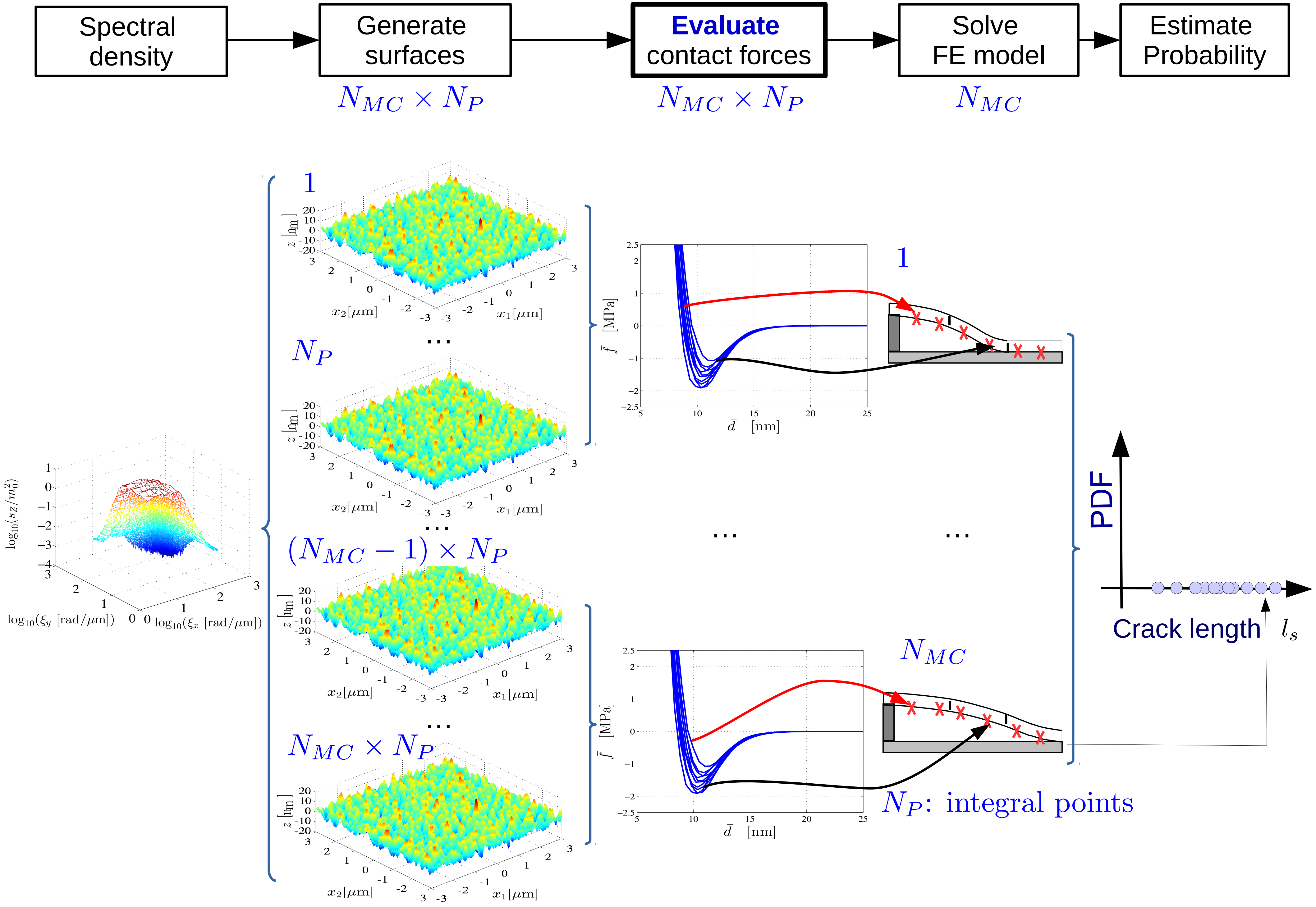
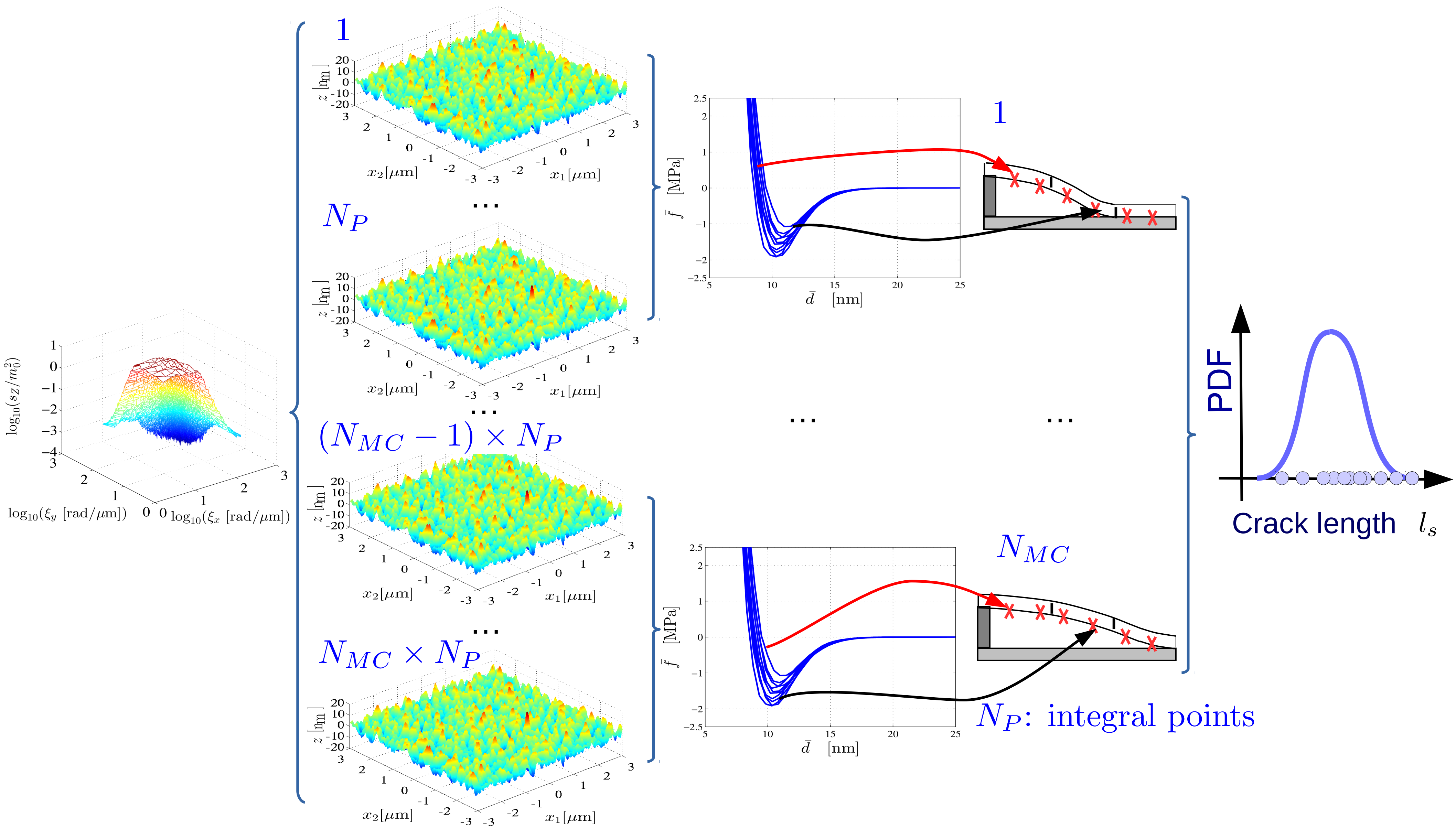
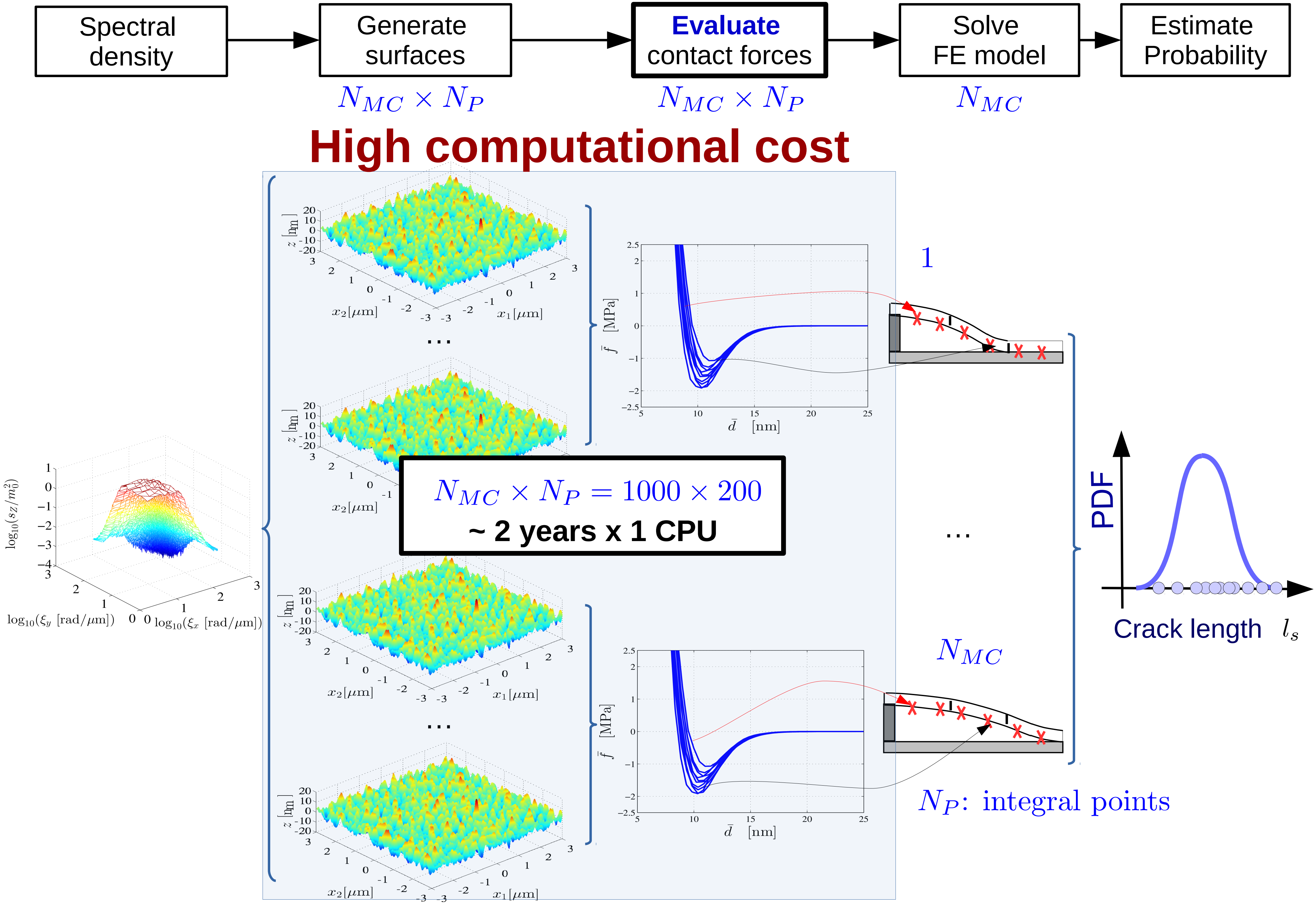


Direct Monte-Carlo multiscale method

Spectral density → Generate surfaces ($N_{MC} \times N_P$) → **Evaluate** contact forces ($N_{MC} \times N_P$) → Solve FE model (N_{MC}) → Estimate Probability

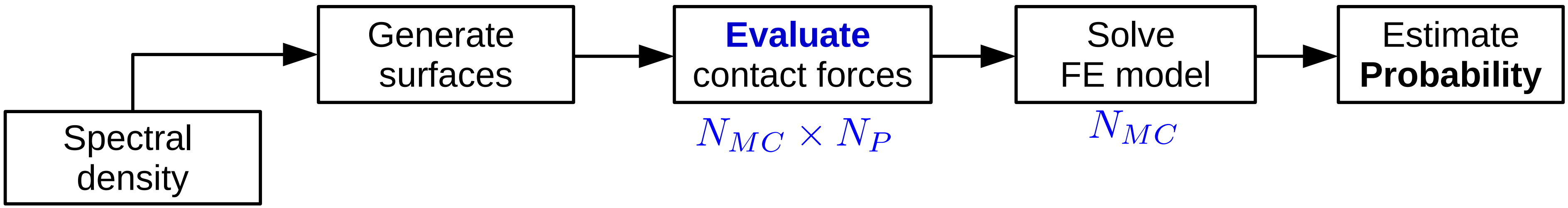


Direct Monte-Carlo multiscale method



Stochastic model-based multiscale method

- Direct Monte-Carlo multiscale method (high computational cost)



- Stochastic model-based multiscale method (**acceptable computational cost**)

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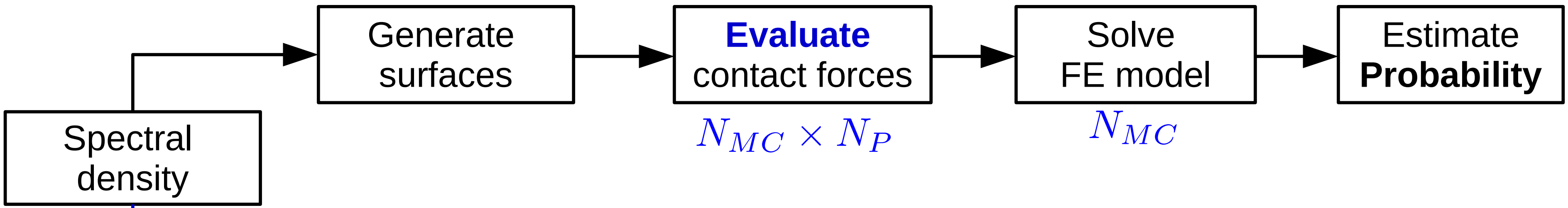

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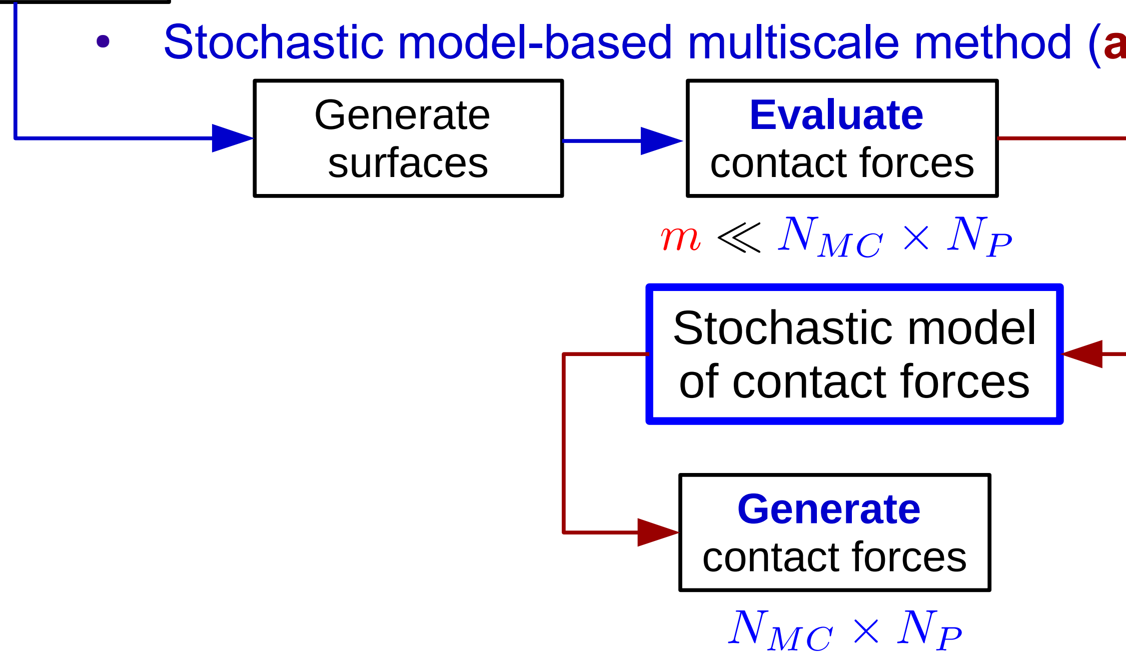

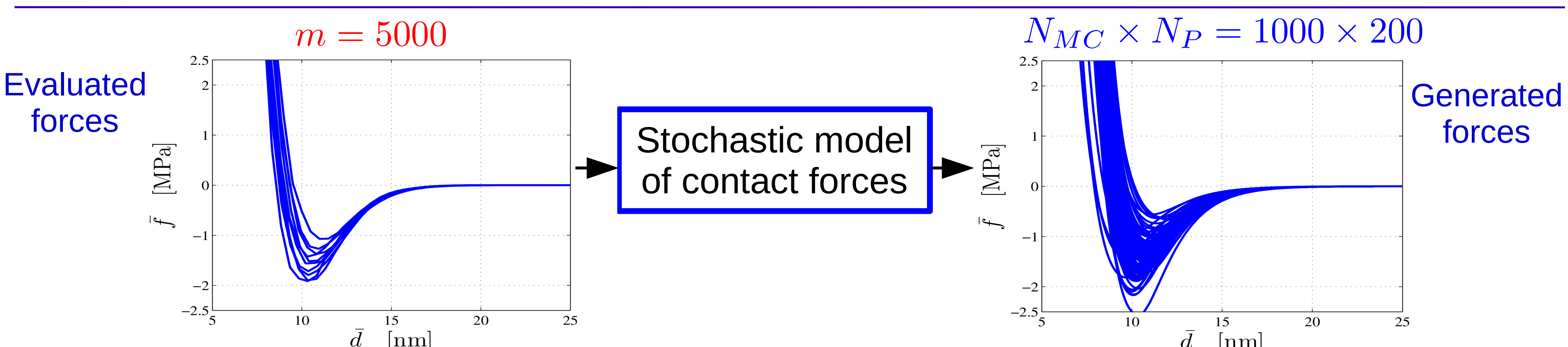

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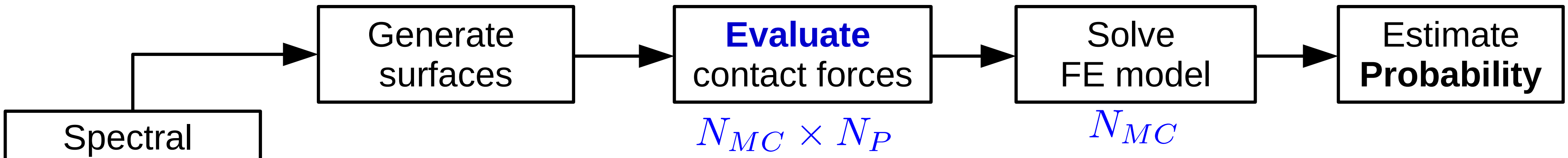

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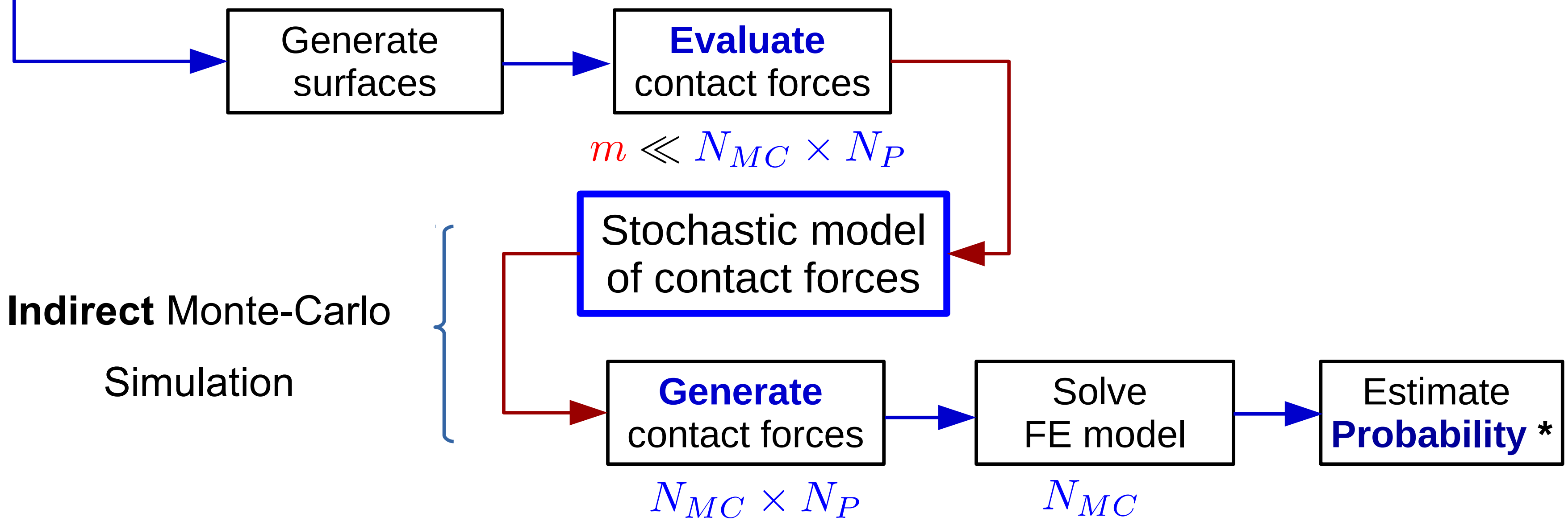
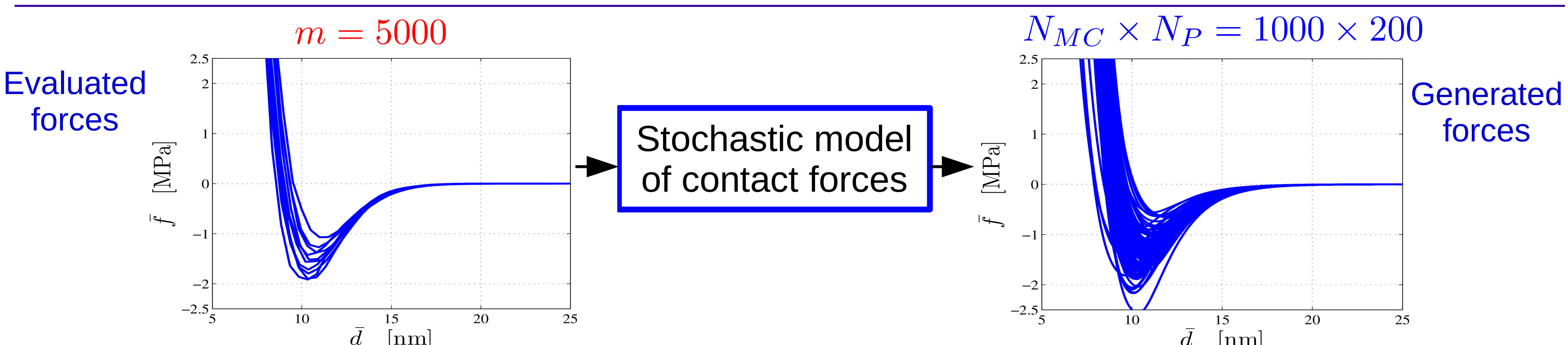




- Stochastic model for apparent contact forces: *generalized polynomial chaos expansion (**gPCE**)*
  - **Parameterization** of the apparent contact force using a modified Morse potential

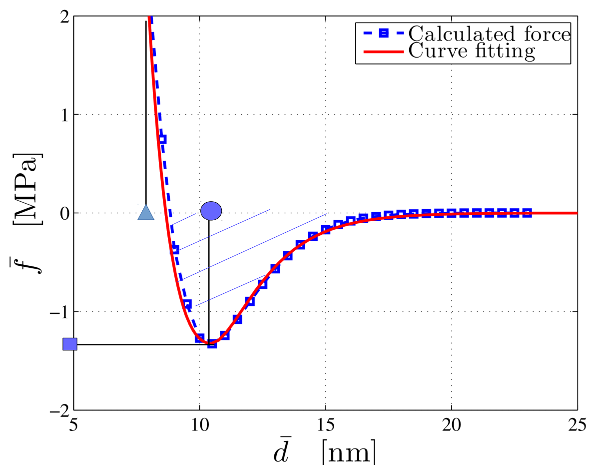
$$\bar{f}(\bar{d}) = \Phi(\bar{d}; \mathbf{v})$$

Force-distance curves

Curve fitting function

Parameters vectors

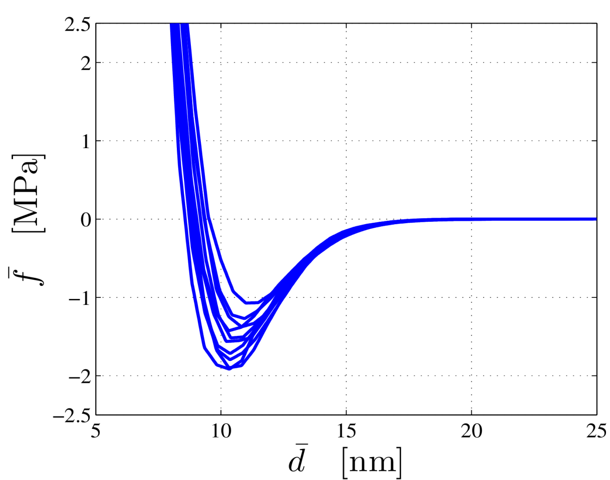
1 sample



Parameterization

$$\mathbf{v} = \begin{pmatrix} \bar{f}_{\max} \\ \bar{e} \\ \bar{d}_{\max} \\ \bar{d}_{\text{limit}} \end{pmatrix}$$

m samples $\ll N_{MC} \times N_P$



Parameterization

$$\{\mathbf{v}^{\{1\}}, \ldots, \mathbf{v}^{\{m\}}\}$$

- Stochastic model for apparent contact forces: *generalized polynomial chaos expansion (**gPCE**)*
  - Parameterization

$$\bar{f}(\bar{d}) = \Phi(\bar{d}; \mathbf{v}) \qquad \text{Input data:} \quad \{\mathbf{v}^{\{1\}}, ..., \mathbf{v}^{\{m\}}\}$$

  - Representing the parameters vectors by a **truncated gPCE model: order N_d**

$$\mathbf{v} \quad \overset{\text{d.}}{\simeq} \quad \mathbf{v}^{gPCE}(\xi | N_d) \quad = \sum_{\alpha=1}^{N} \mathbf{c}_\alpha \Psi_\alpha(\xi).$$

Legendre polynomials **order ≤ N_d**

Uniformly distributed random vector

Coefficients to be identified

$\overset{\text{d.}}{\simeq}$: approximately distribution

- The higher the order N_d, the better the approximation
- The coefficients are identified by the projection of the iso-probabilistic transformation on the polynomial chaos system

$$\mathbf{c}_\alpha : \quad \text{Distribution}(\{\mathbf{v}^{\{1\}}, ..., \mathbf{v}^{\{m\}}\}) \simeq \text{Distribution}(\mathbf{v}^{gPCE})$$

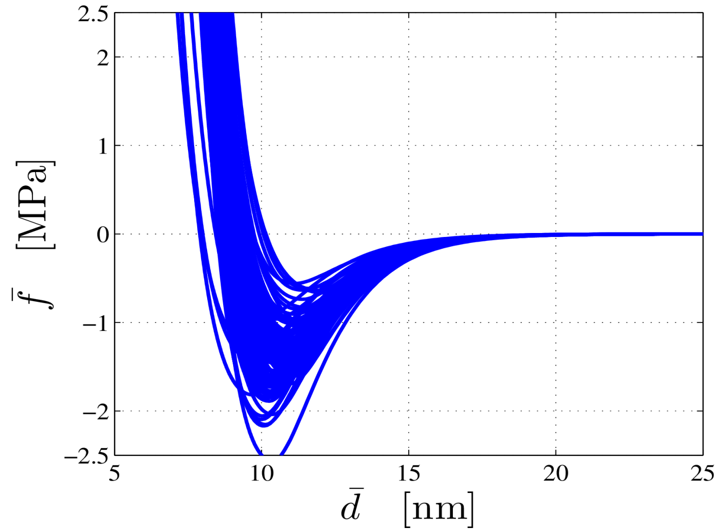
- Stochastic model for apparent contact forces: *generalized polynomial chaos expansion (**gPCE**)*
  - **Generate apparent contact forces**

$$\bar{f}(\bar{d}) = \Phi(\bar{d}; \mathbf{v})$$

$$\mathbf{v} \overset{\text{d.}}{\simeq} \mathbf{v}^{gPCE}(\xi | N_d) = \sum_{\alpha=1}^{N} \mathbf{c}_\alpha \Psi_\alpha(\xi).$$

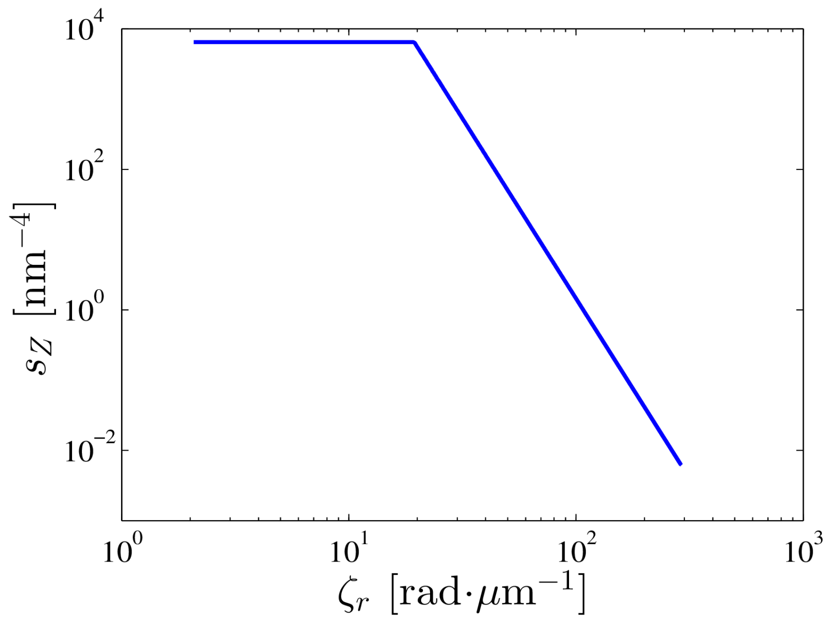
Sampling
Uniformly distributed random vector

Generated apparent contact forces

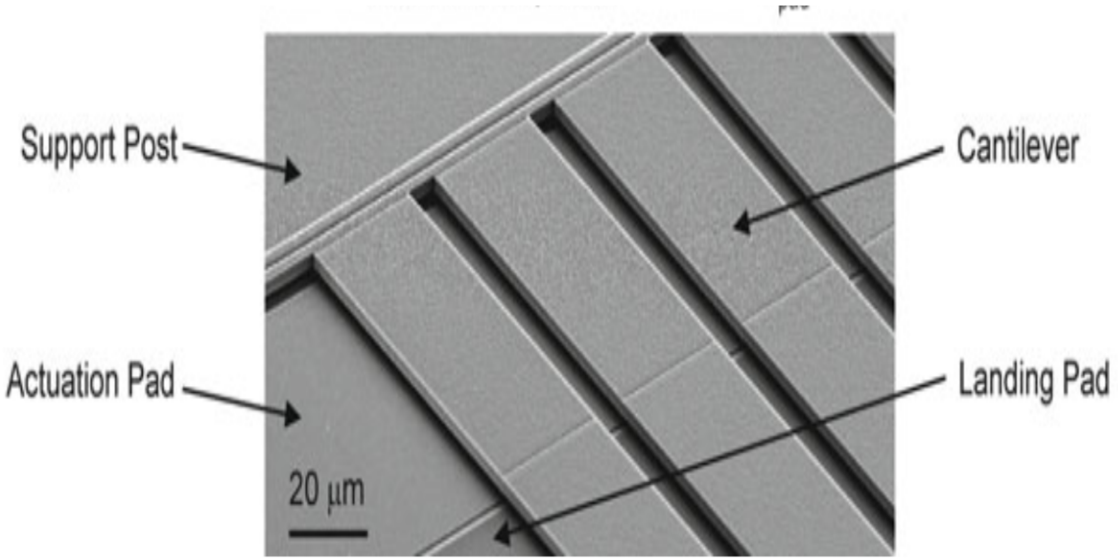


Numerical results

- Using the two methods: direct Monte-Carlo multiscale vs Stochastic-model based multiscale method to evaluate
  - Distribution of apparent contact forces parameters
  - Distribution of crack lengths
- Input: a constructed *isotropic* ***self-affine spectrum density*** function of the contacting surfaces based on ***experiments*** report in [Boer et *al.* 2013]



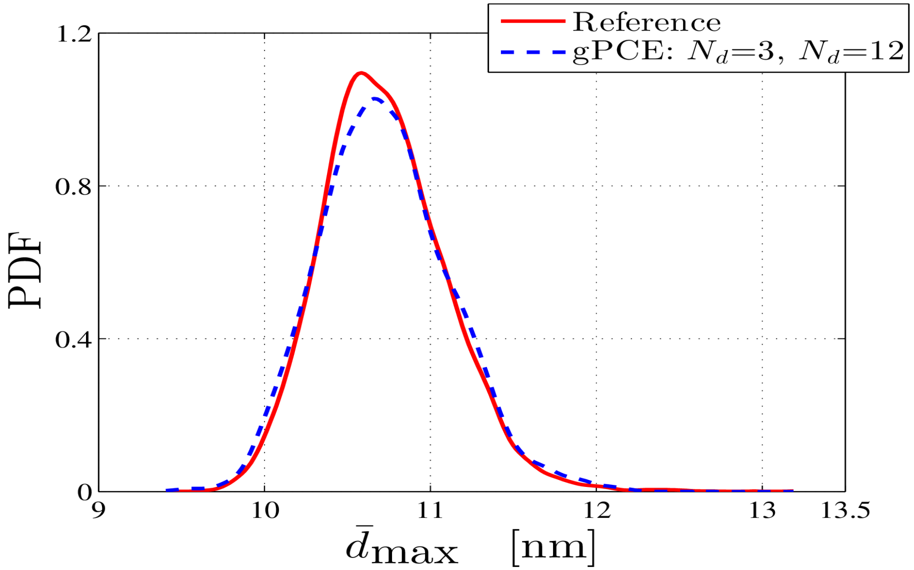
Isotropic self-affine spectrum density

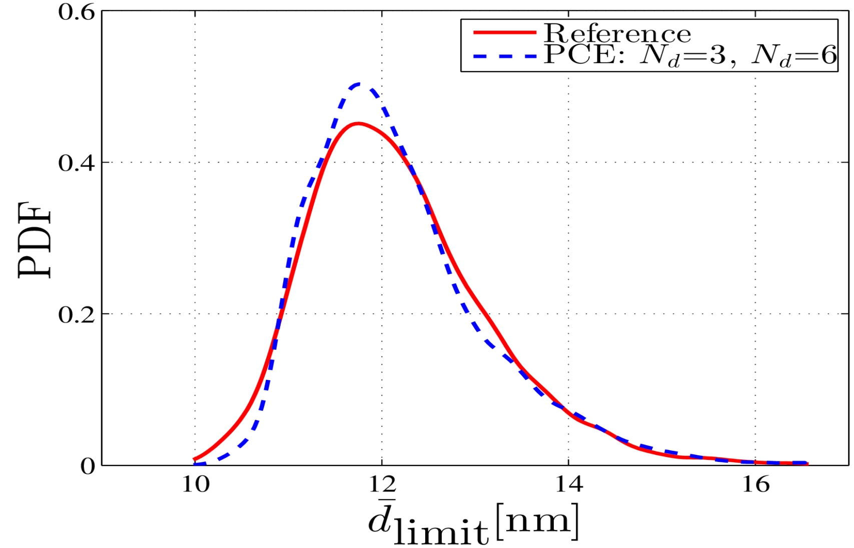


Cantilever beams array
[Boer et *al.* 2013]

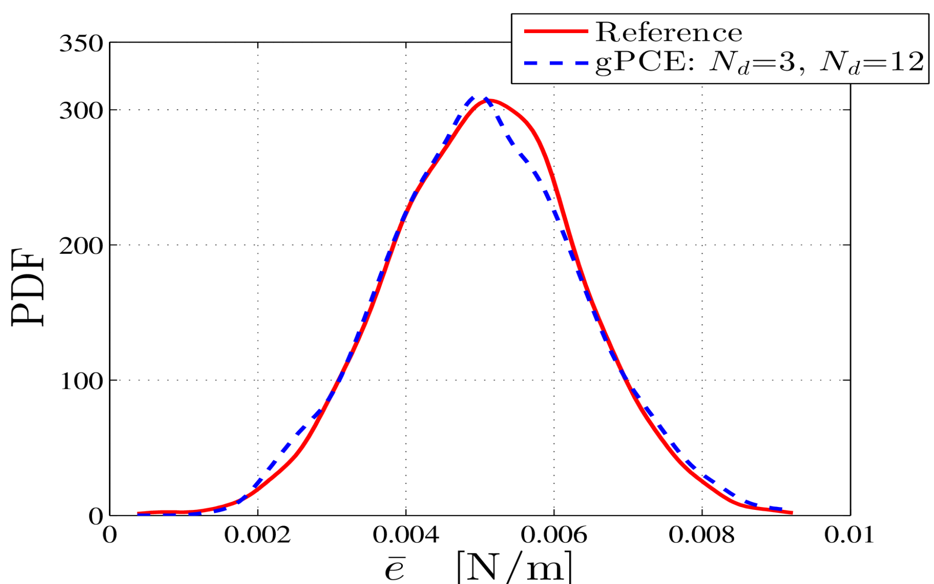
Numerical results

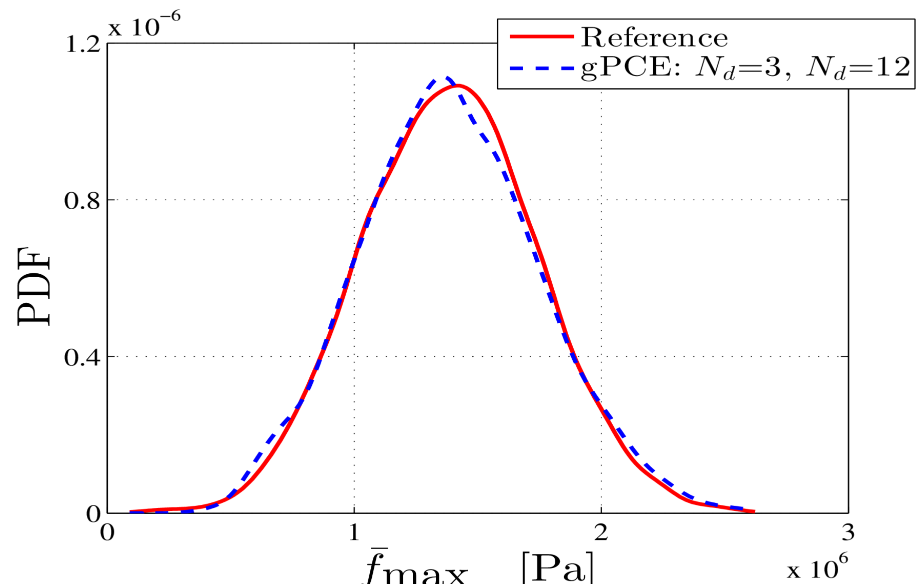
- Direct Monte-Carlo multiscale vs Stochastic-model based multiscale method
- Distribution of contact forces parameters
  - The stochastic model-based method **approximates well the probabilistic distribution** of the apparent contact forces





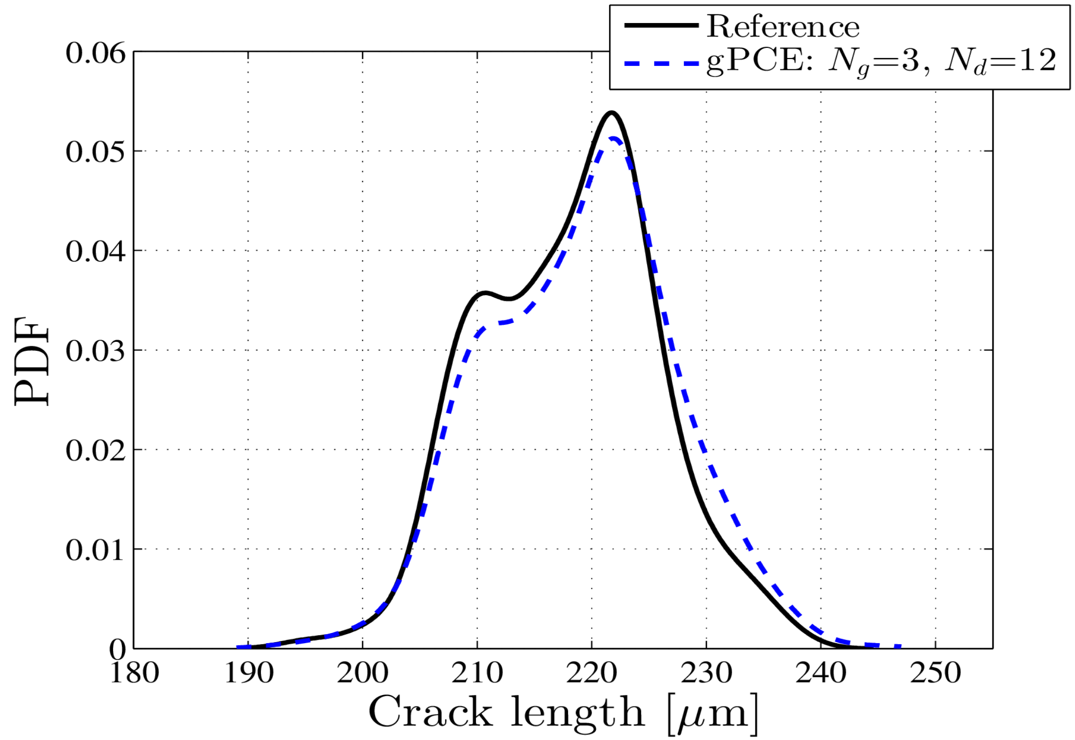
Humidity 85%





Numerical results

- Direct Monte-Carlo multiscale vs Stochastic-model based multiscale method
- Distribution of crack lengths
    - The stochastic model-based method **approximates well the probabilistic distribution** of the crack lengths

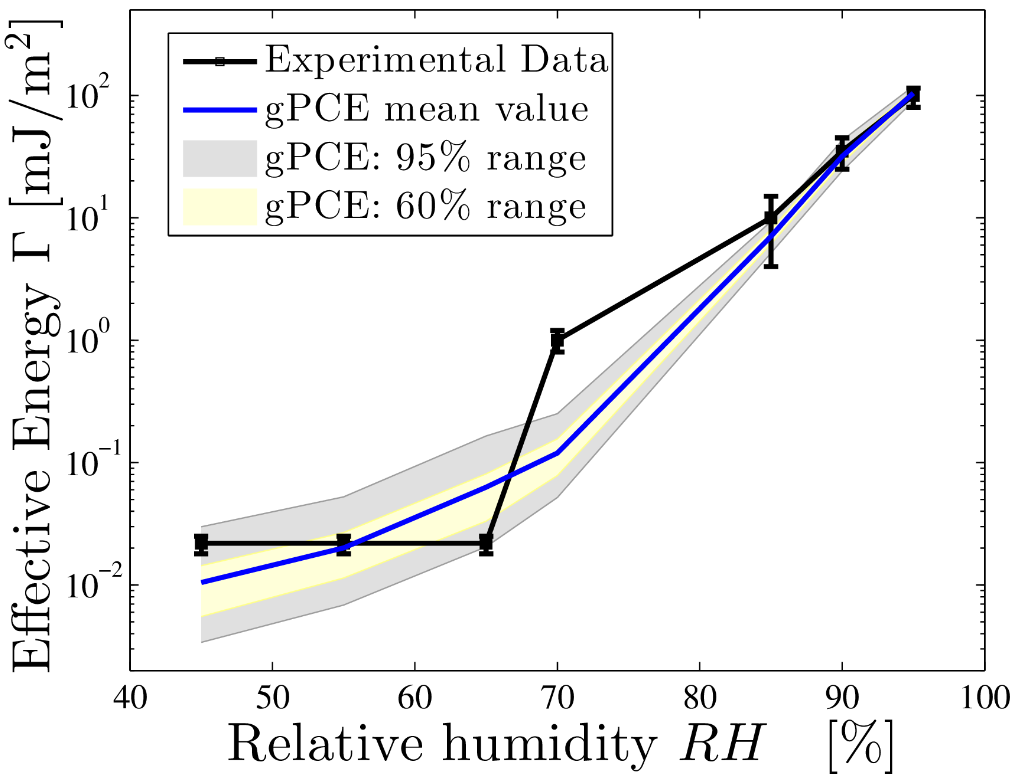


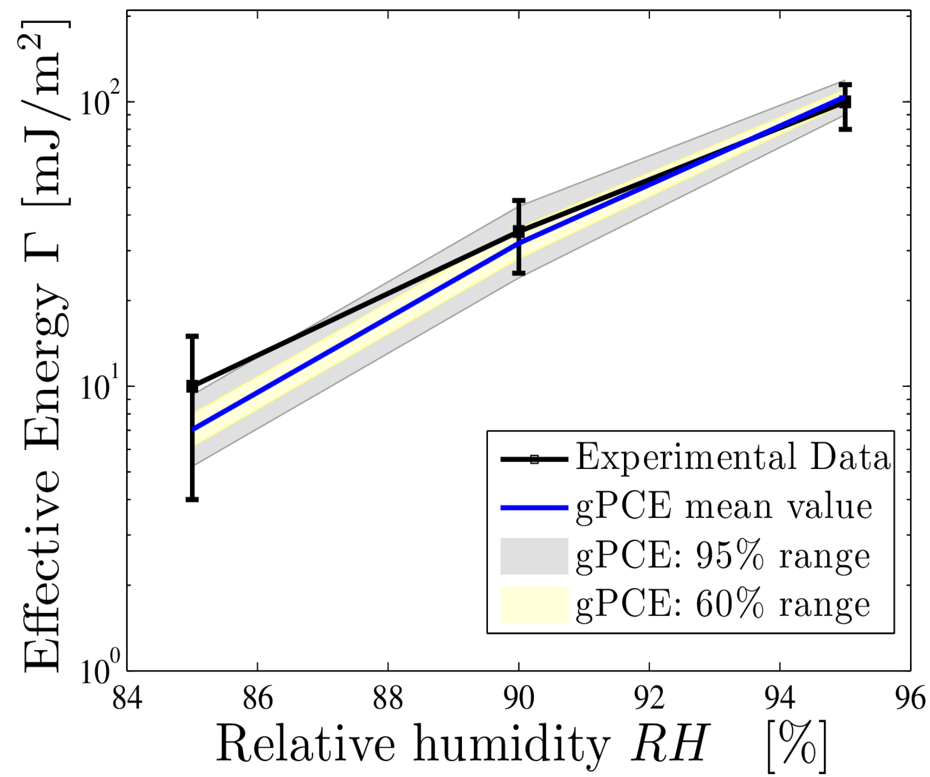
Humidity 85%

- Computational efficiency: **Time** to evaluate **1 realization** in one CPU:
    - Direct Monte-Carlo method: ***~16 hours*** (due to the evaluation of the apparent contact forces)
    - Stochastic model-based method: ***~ 5 minutes*****.**
    - To obtain the distribution: **1000 realizations are required**
- **Good approximation and acceptable computation cost**

Numerical results

- Validation: comparison with experimental results [Boer et al. 2013]
  - Accurate prediction of the experimental results at high humidity levels
  - At low humidity levels:
    - The van der Waals forces need to be accounted for
    - The rough surface needs to be directly measured





$$\Gamma = \frac{3}{2} E \frac{h^2 t^3}{l_s^4},$$

→ Crack lengths

Conclusions & Perspectives

- A **Stochastic model-based multiscale method for stiction problems** taking the surface topology into account by
  - Using spectral density to characterize the AFM surface measurements and generate numerical surfaces
  - Using multi-scale approach, and a semi-analytical contact model
    - To define and evaluate the **meso-scale apparent contact forces**
    - To integrate them as **contact laws to FE model**
  - Applying gPCE to build a stochastic model of the random meso-scale contact forces
    - To reduce efficiently the **computational cost**
- The model is **validated** by a comparison with **experimental results**
- Applying the model to evaluate the **failure percentage** of MEMS designs such as
  - The stiction of MEMS accelerometers under shock
  - The stiction of MEMS gears system →

http://www.sandia.gov/mstc/mems/

Documents can be downloaded at:
www.ltas-cm3.ulg.ac.be

References

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Thank you for your attention