

Modeling of fracture across scales and time



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Pierre Kerfriden
and the team

Motivation: understand and optimise material fracture behavior

Multi-scale Methods - two approaches compared

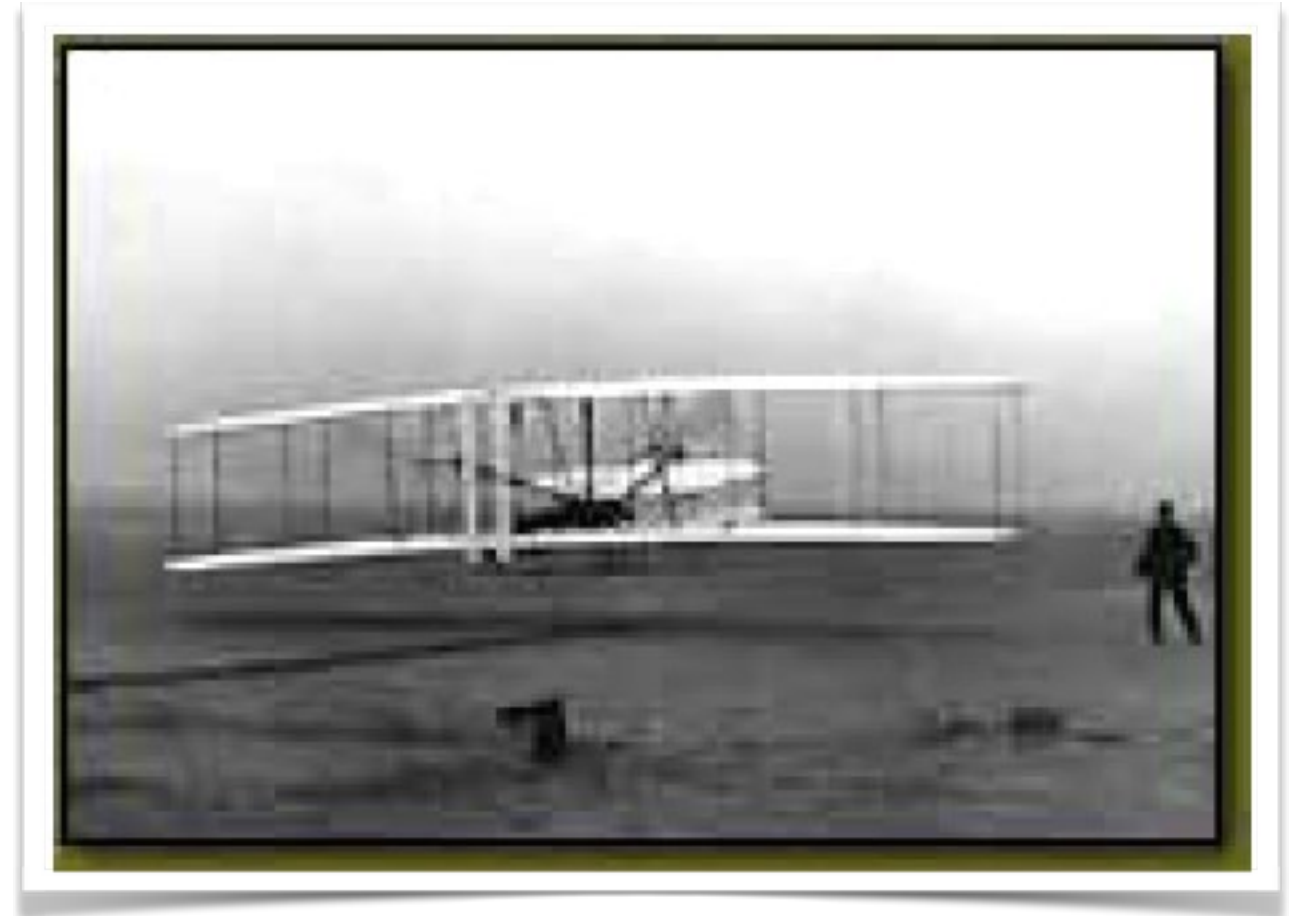
Parallel with medical simulation

Future

Wilbur and Orville Wright, 1903

Wright Flyer

10:35am Dec 17, 1903

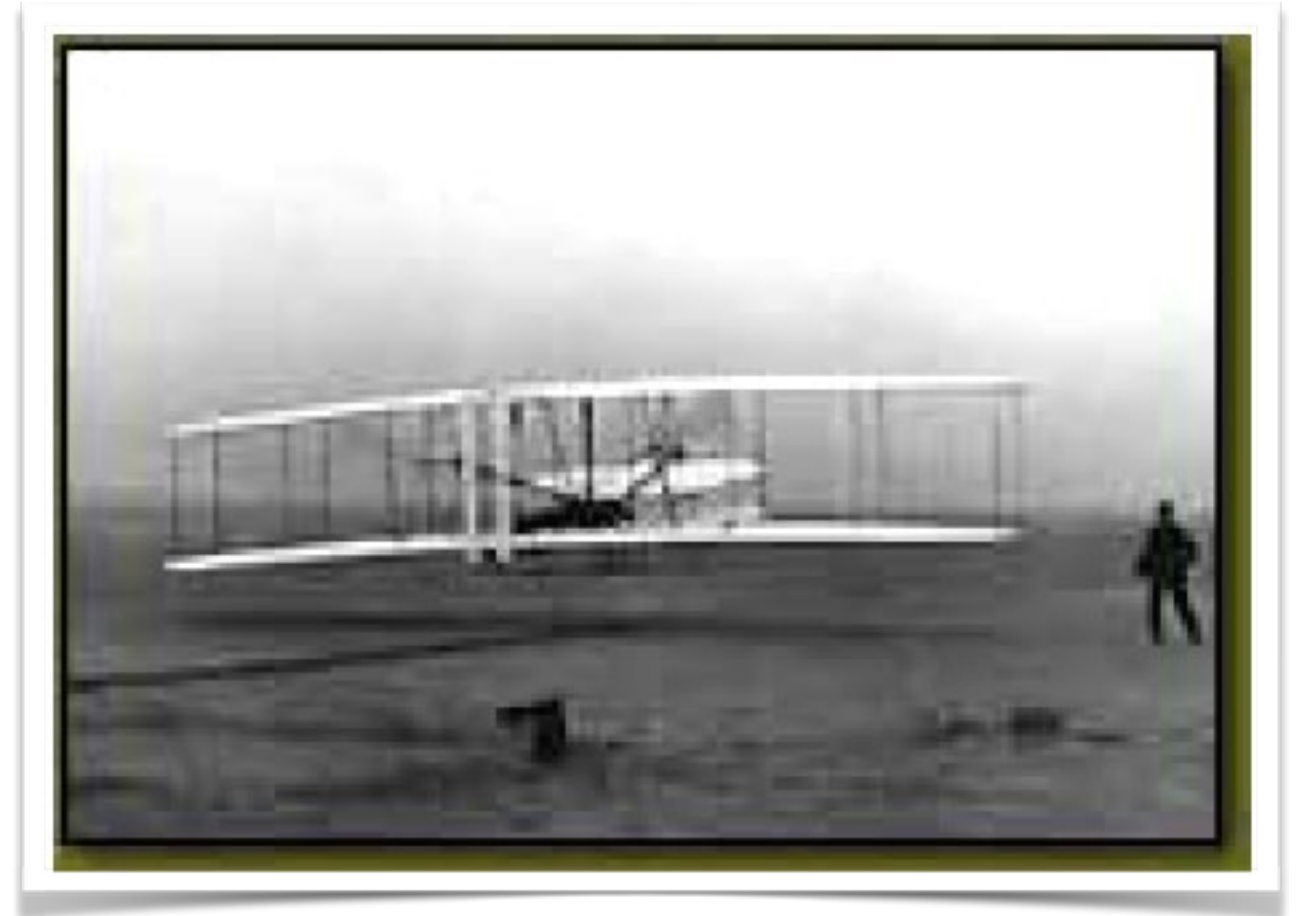


Wilbur and Orville Wright, 1903

On Dec 14 Wilbur won the coin toss, made the first attempt and stalled

Orville made the first flight on Dec. 17

12 seconds & 120 ft



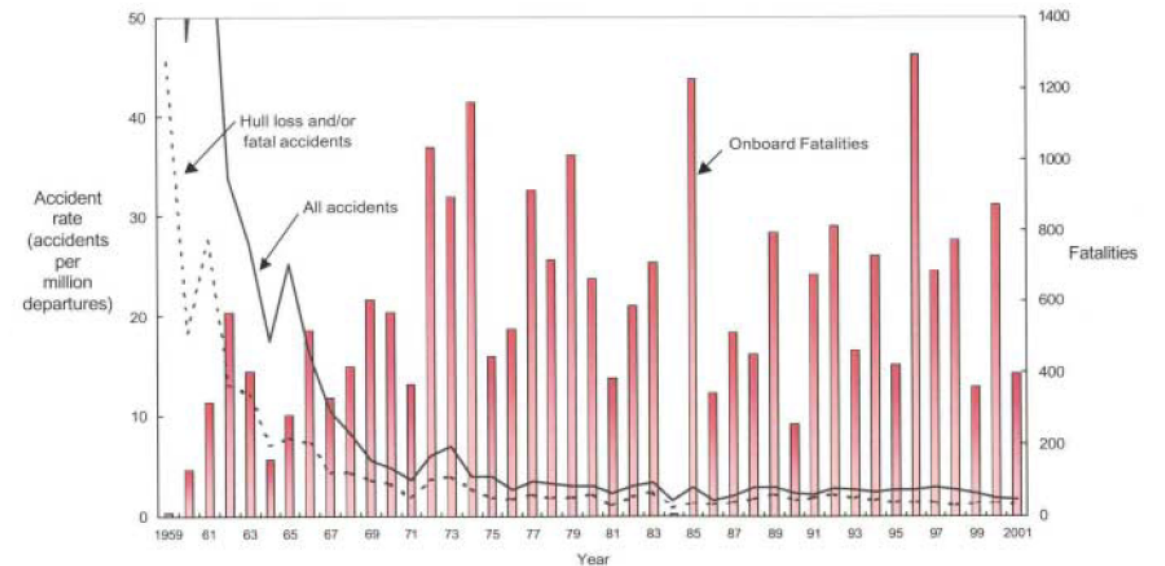
Aircraft safety

20,000 years



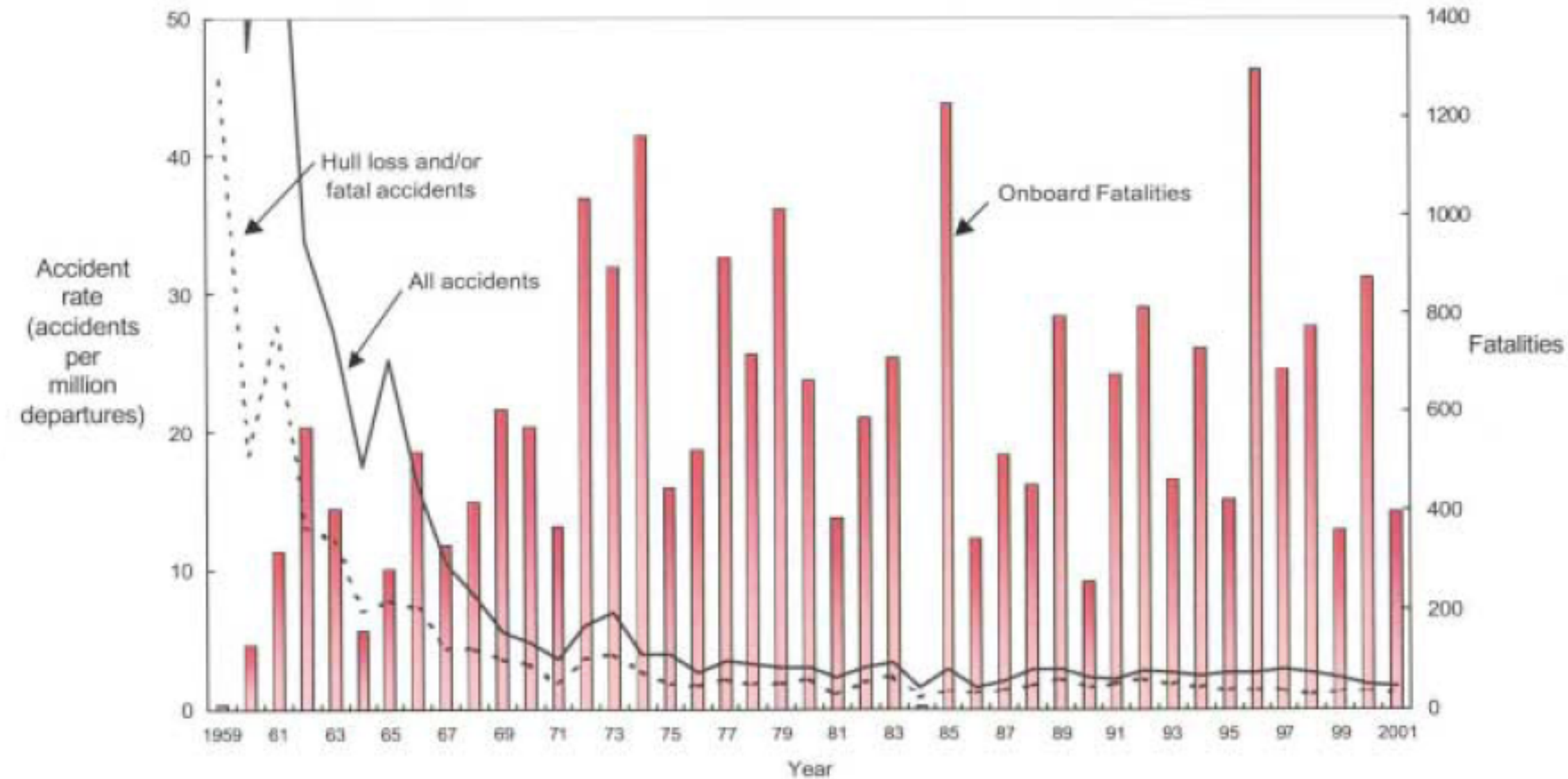
Worldwide statistics

[1959-2001] 1,307
commercial jet aircraft
losses

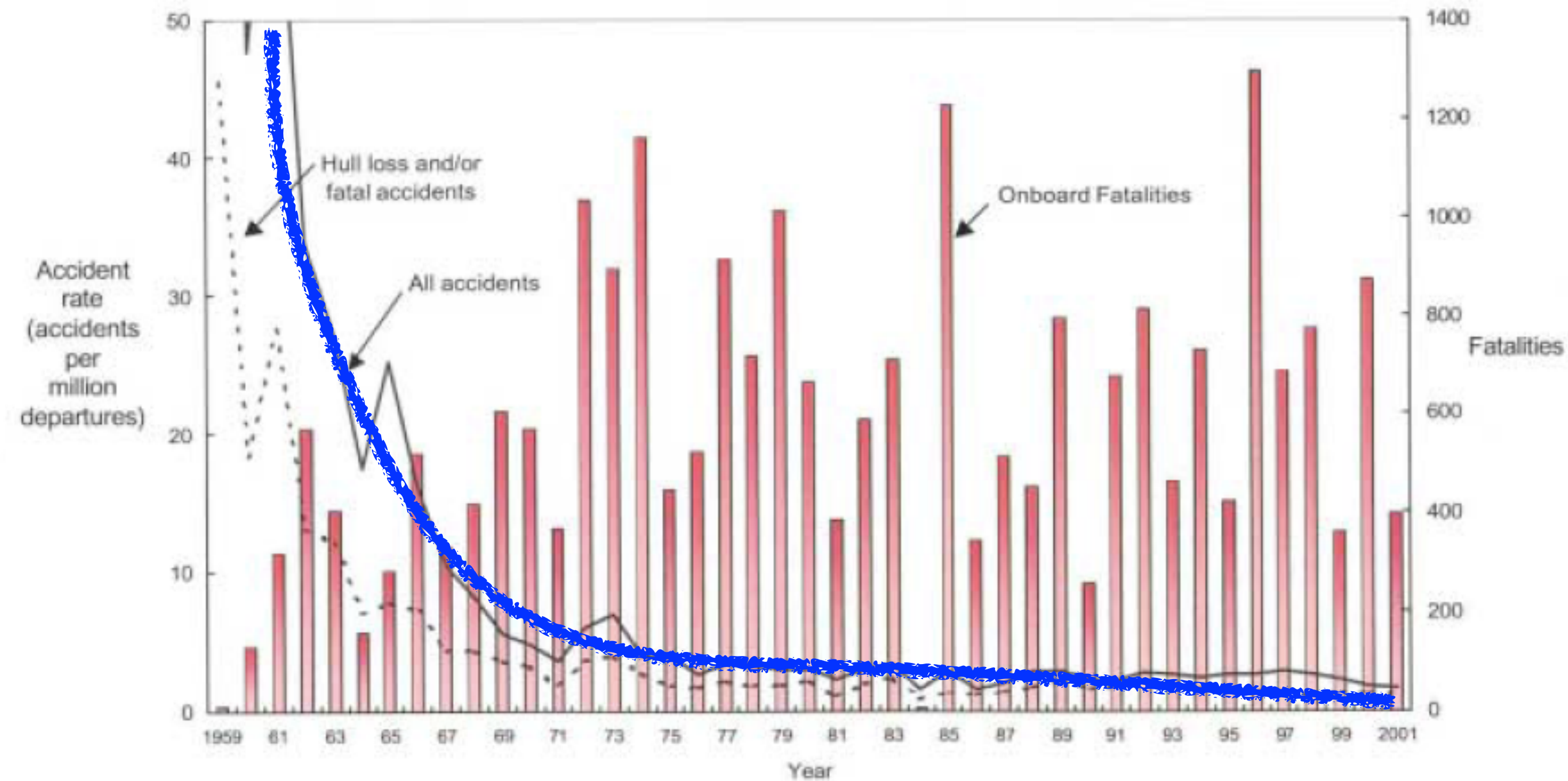


Today:
1 accident per
1,000,000
departures

Accident rates and fatalities/year

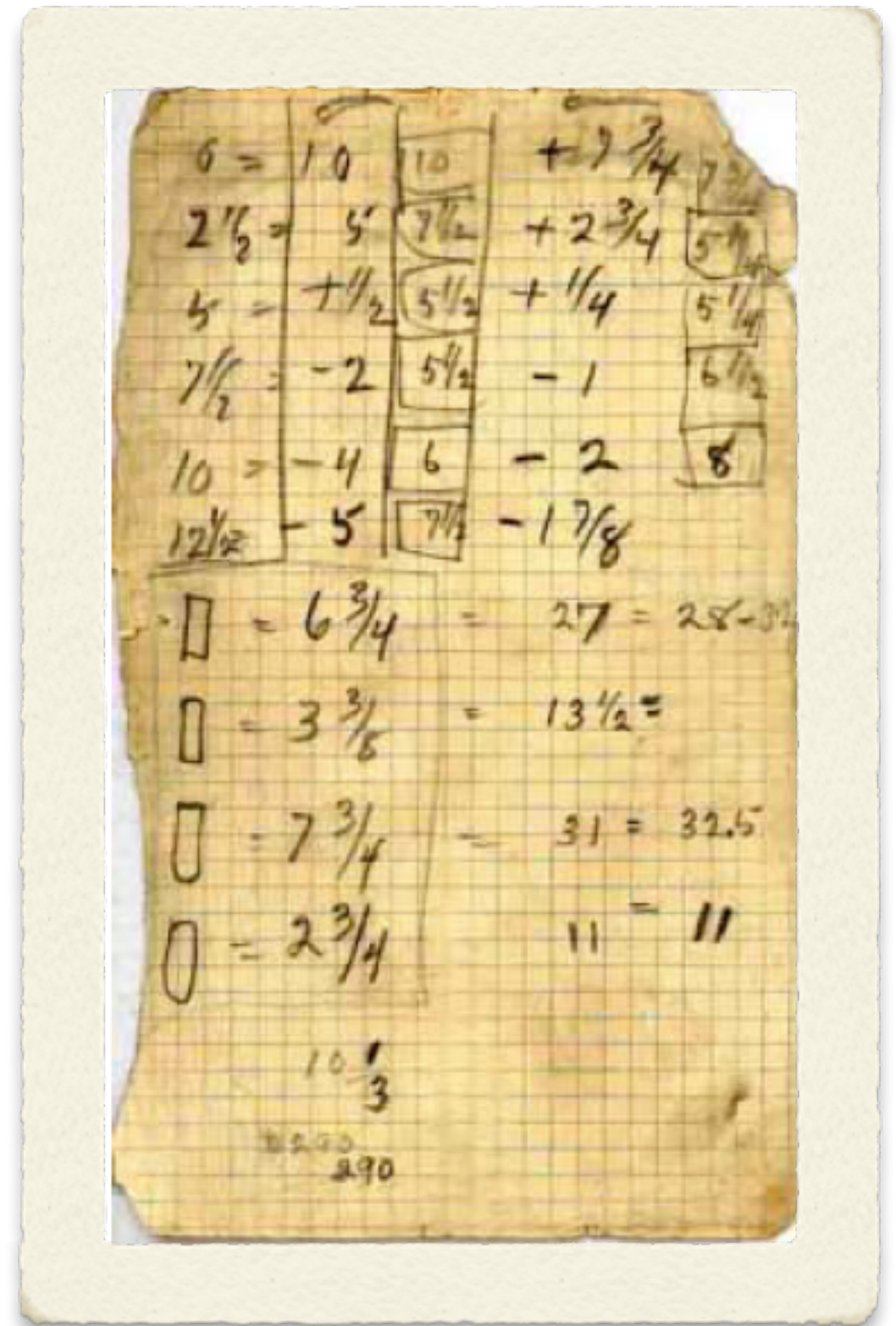
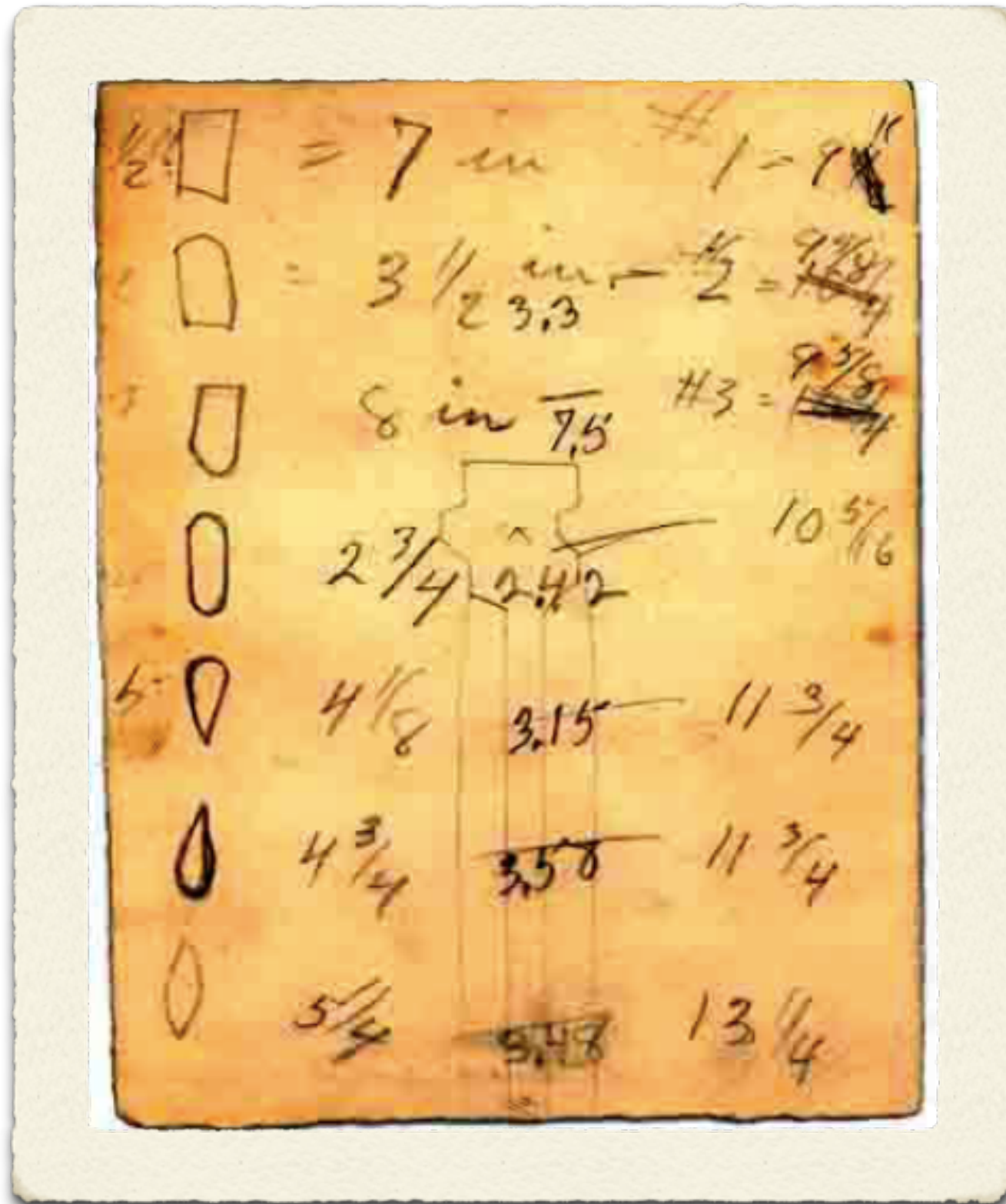


Accident rates and fatalities/year



Source: Flight Safety Foundation/Boeing Commercial Airplane Group

Learning from intuition & theory



Franklin Institute Science Museum. Wilbur Wright's handwriting

Learning from experience

Increased practical understanding of mechanics — in particular fracture and fatigue



Bird strikes



Aloha airlines accident - fatigue cracks at corners

Novel convertible aircraft

Learning from experiments

World's largest wind tunnel (2014)



© AFP/Getty Images



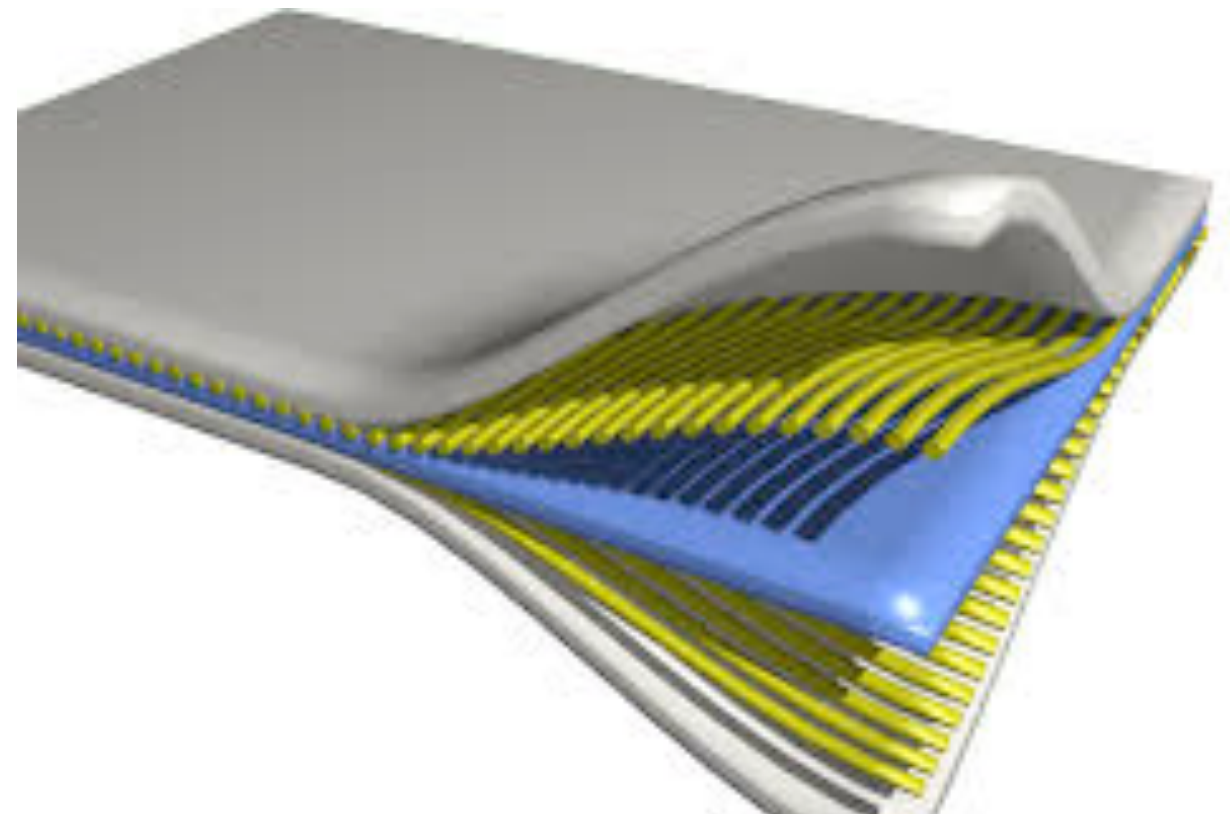
Replica of the 1901 Wright Wind Tunnel
(constructed with assistance from Orville Wright)

teaching...



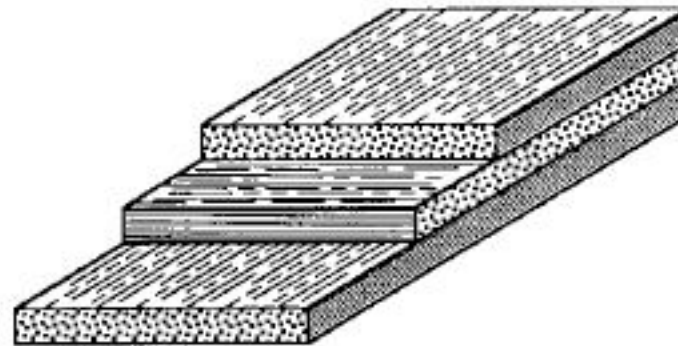
New materials for more payload

Introduction of composite materials have reduced the weight of structures by 20%

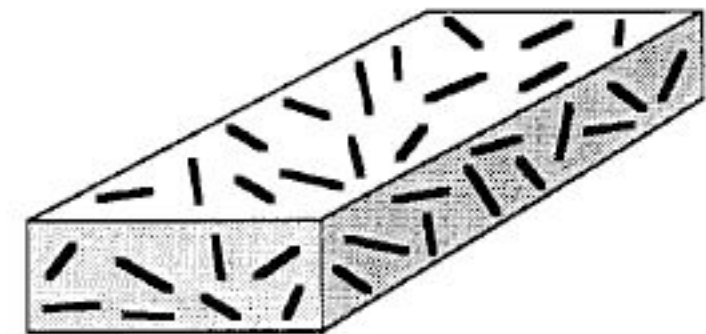


Over 1,000km saving of 8,660kg of fuel
[A340-300]

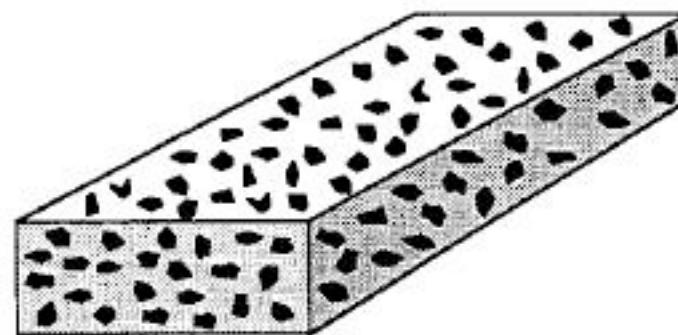
Continuous Fibers



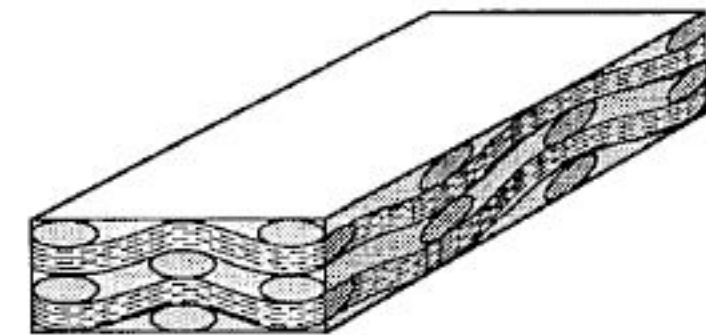
Discontinuous Fibers, Whiskers



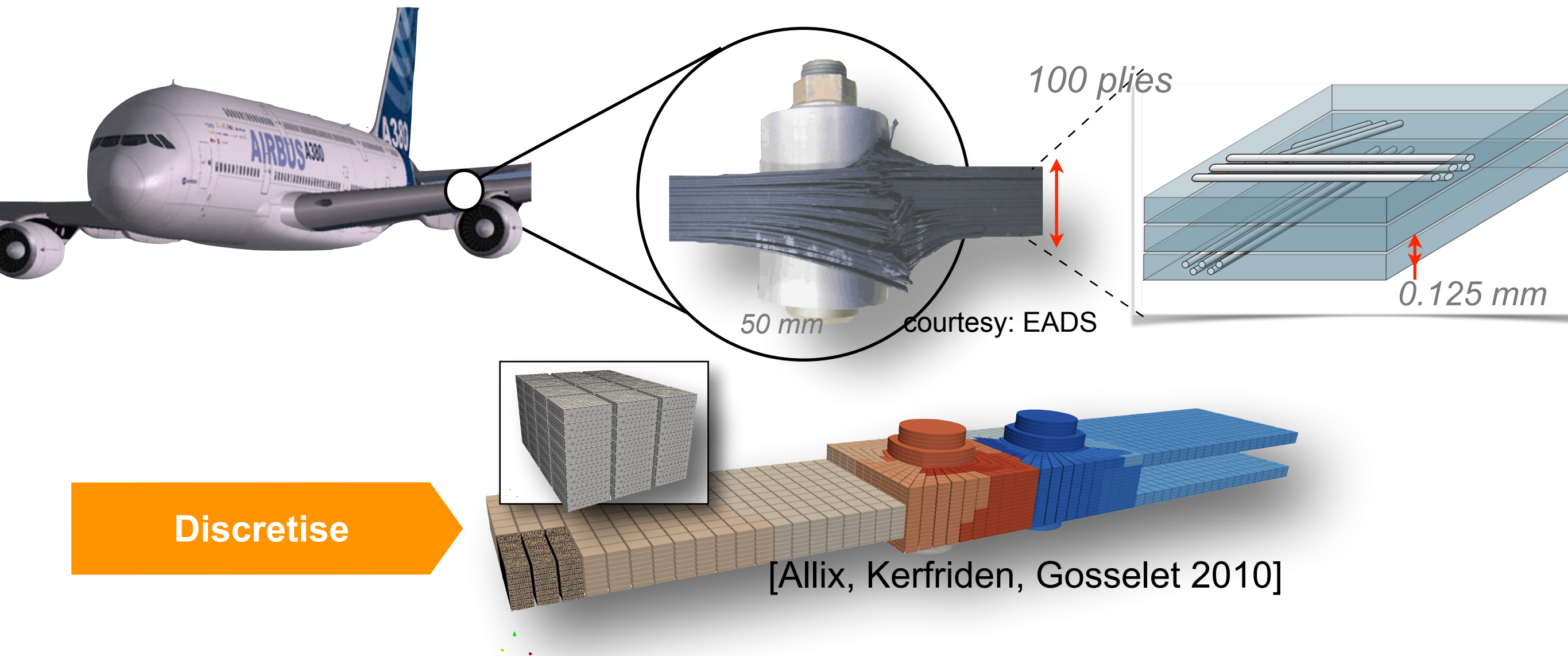
Particles



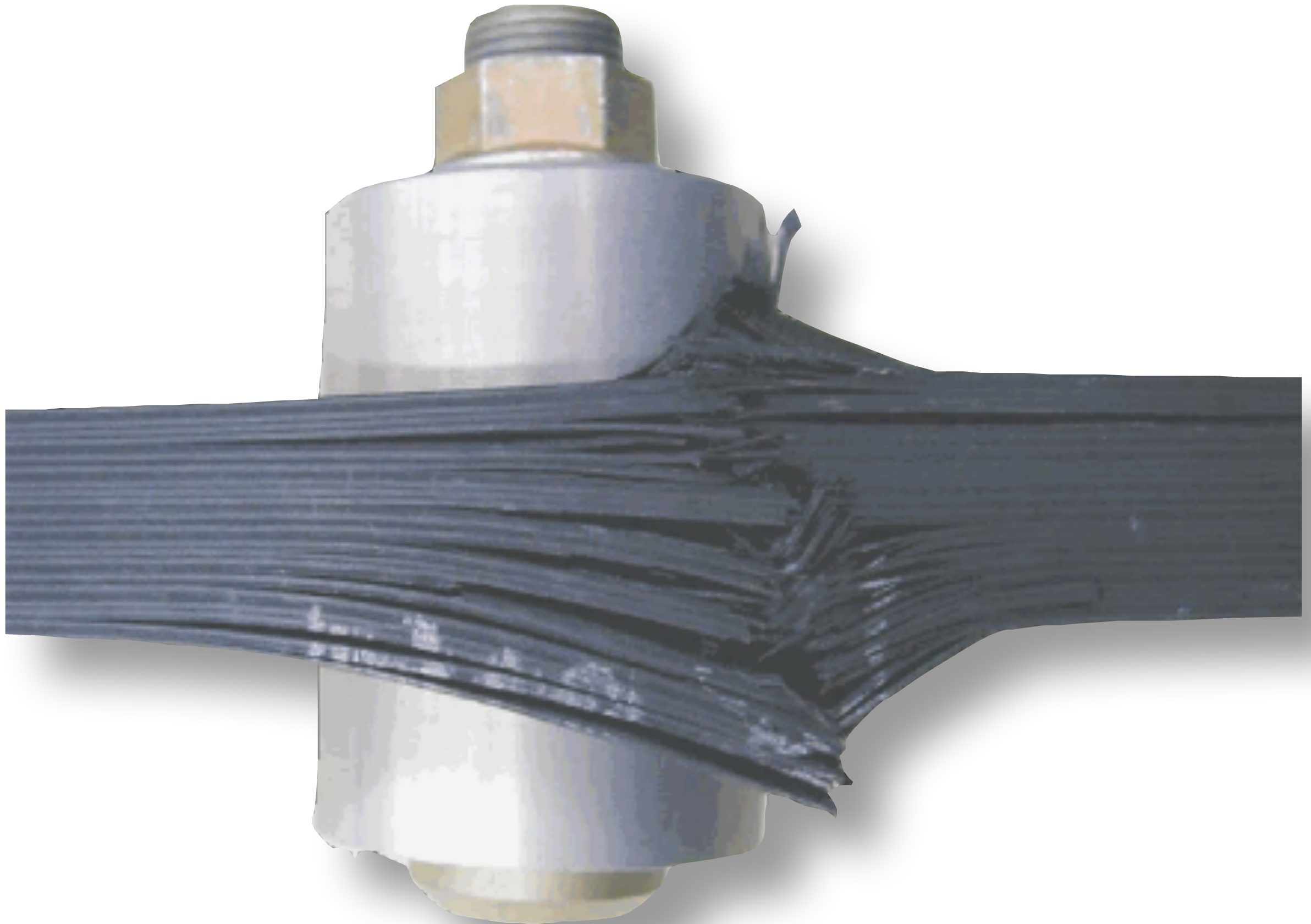
Fabric, Braid, Etc.



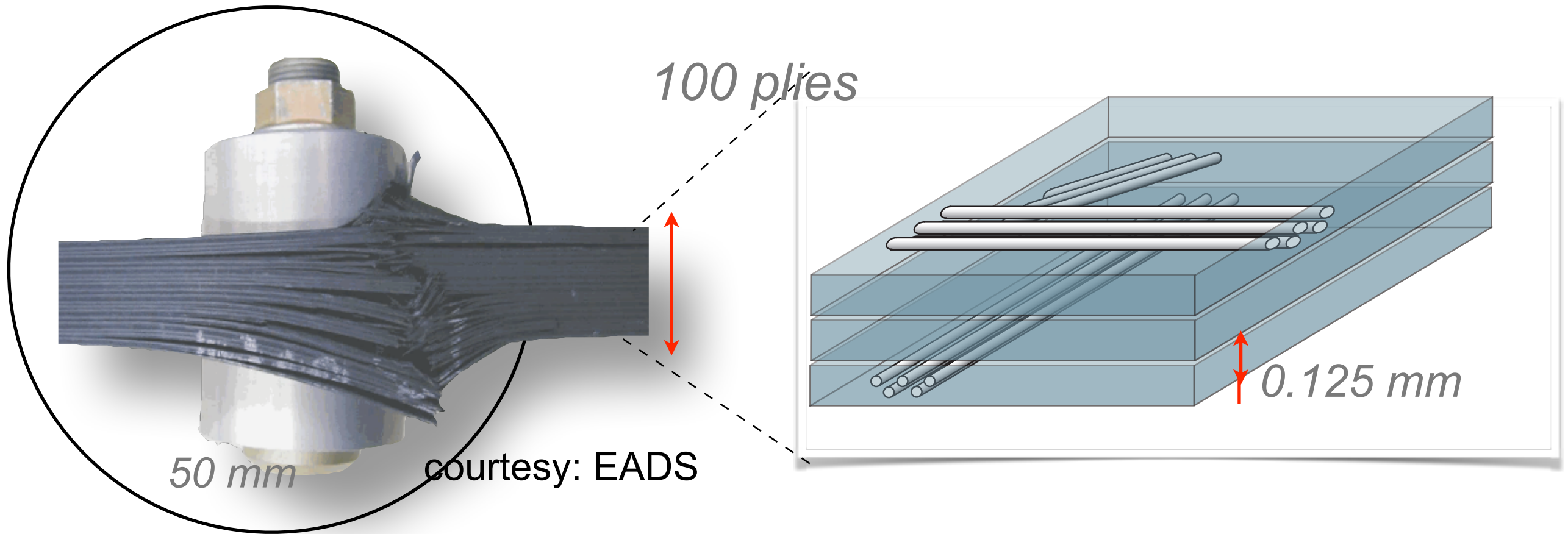
New kinds of experiments for new kinds of models

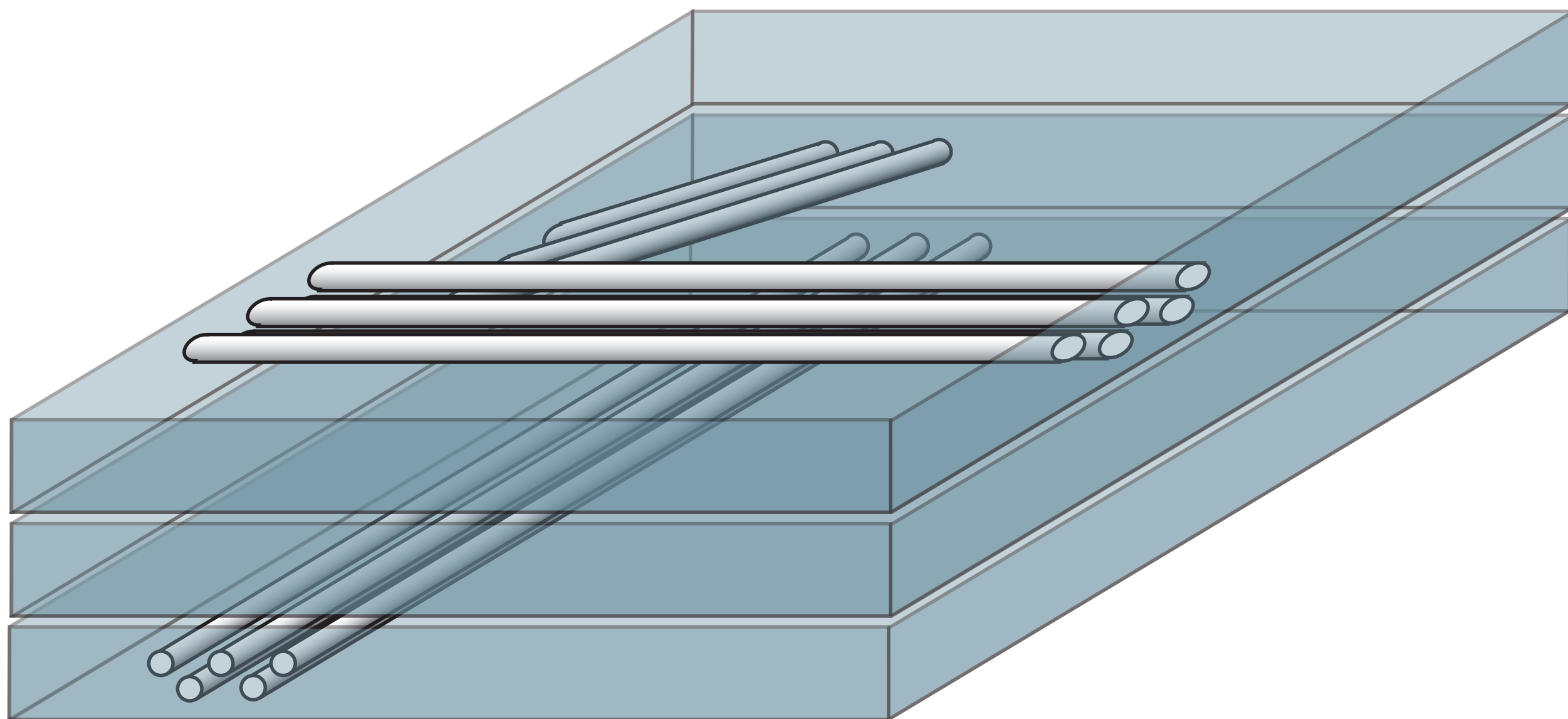


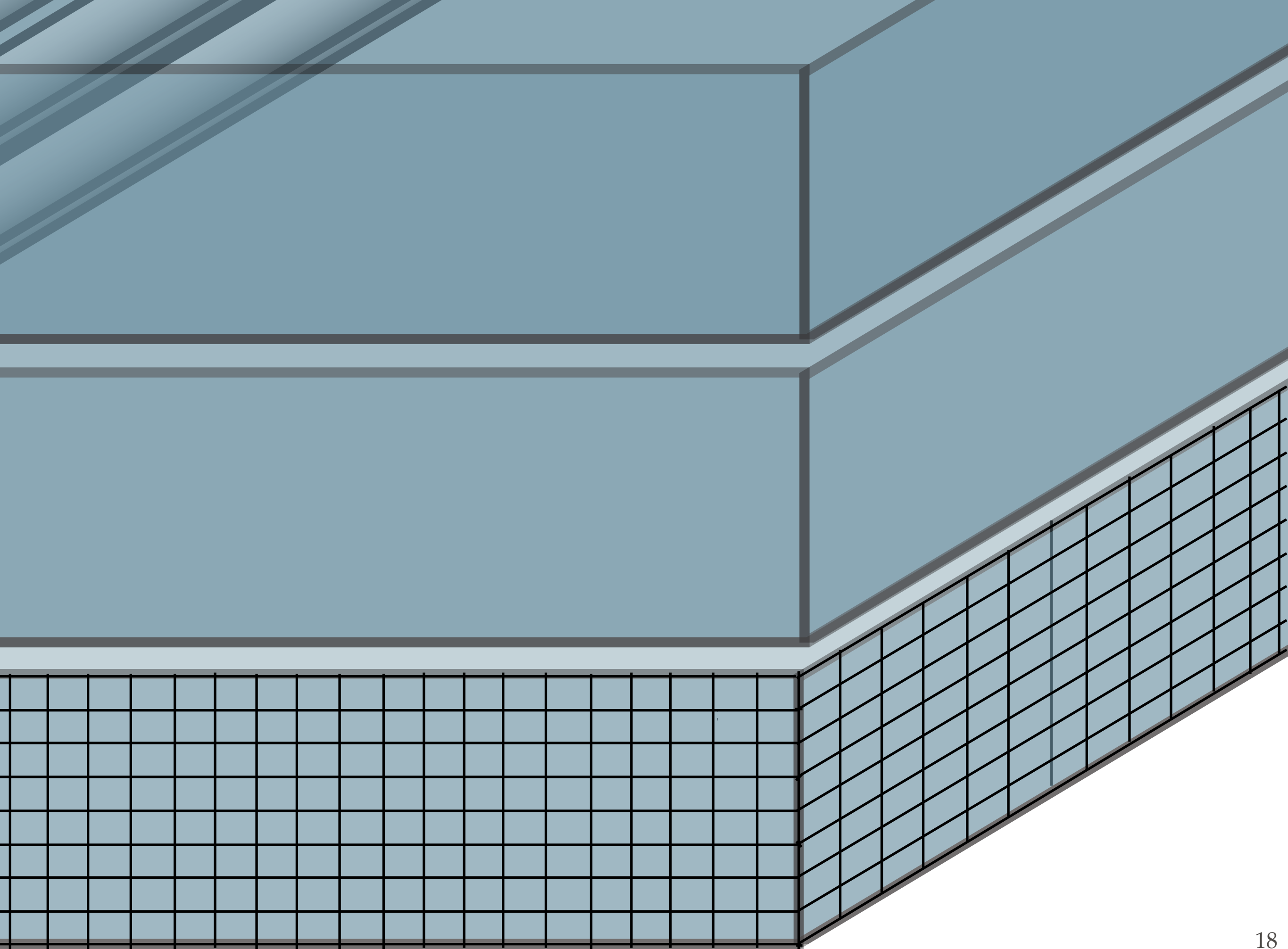
A bolted joint



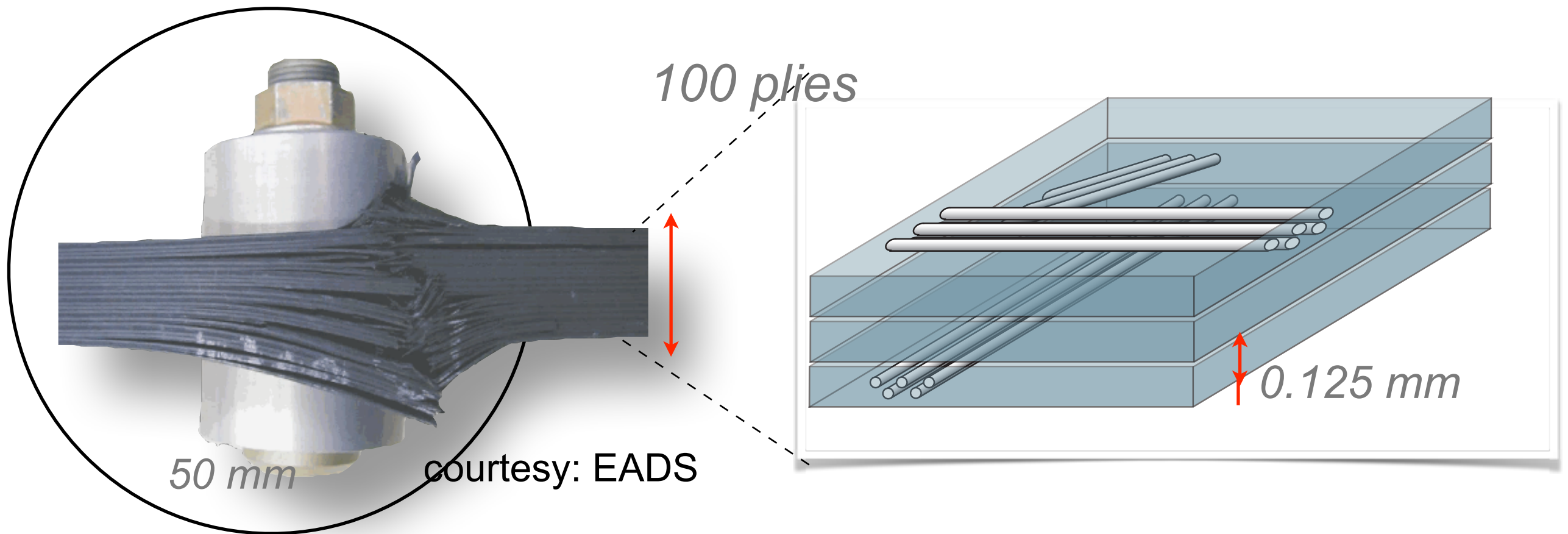
A bolted joint



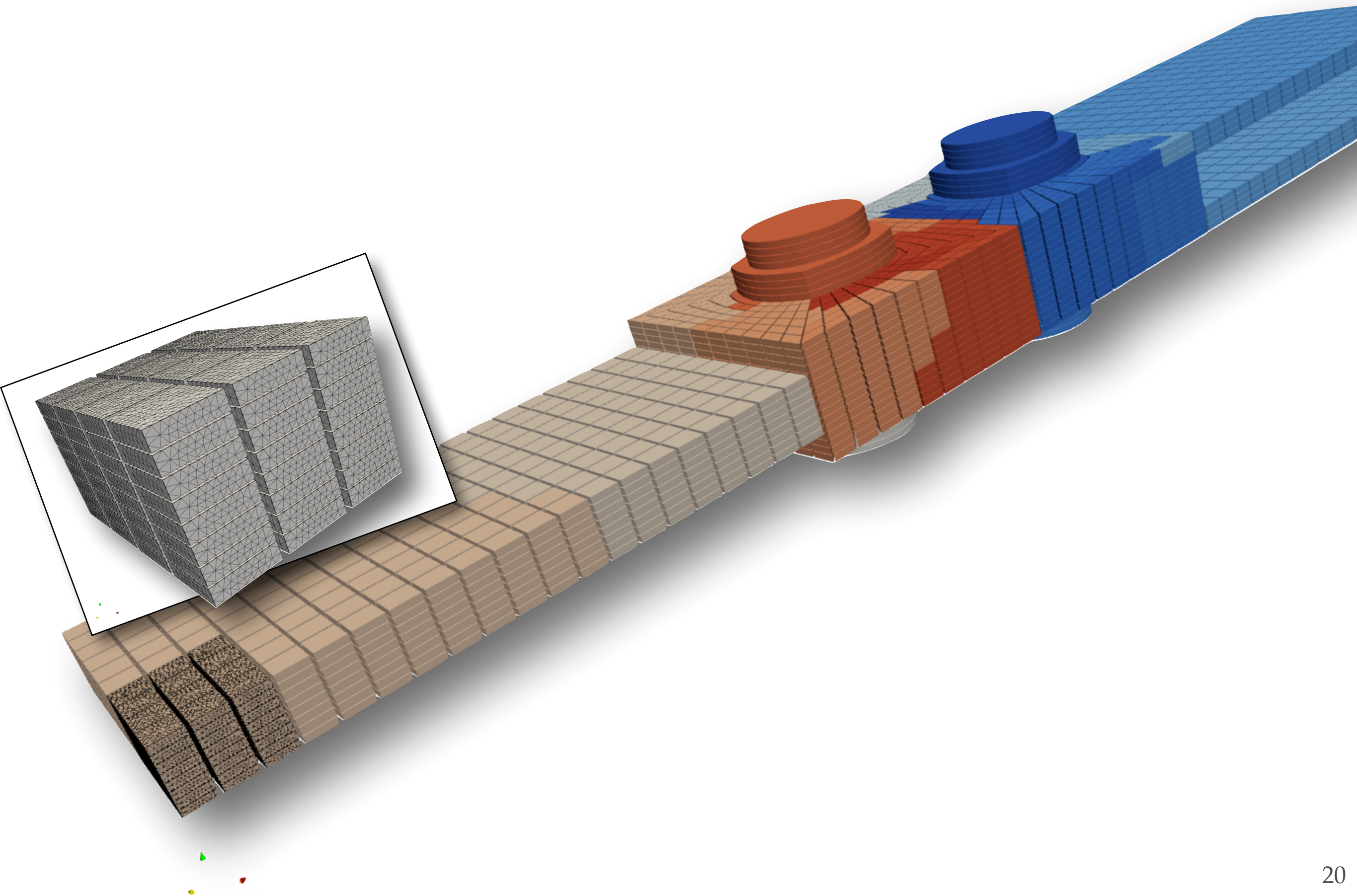


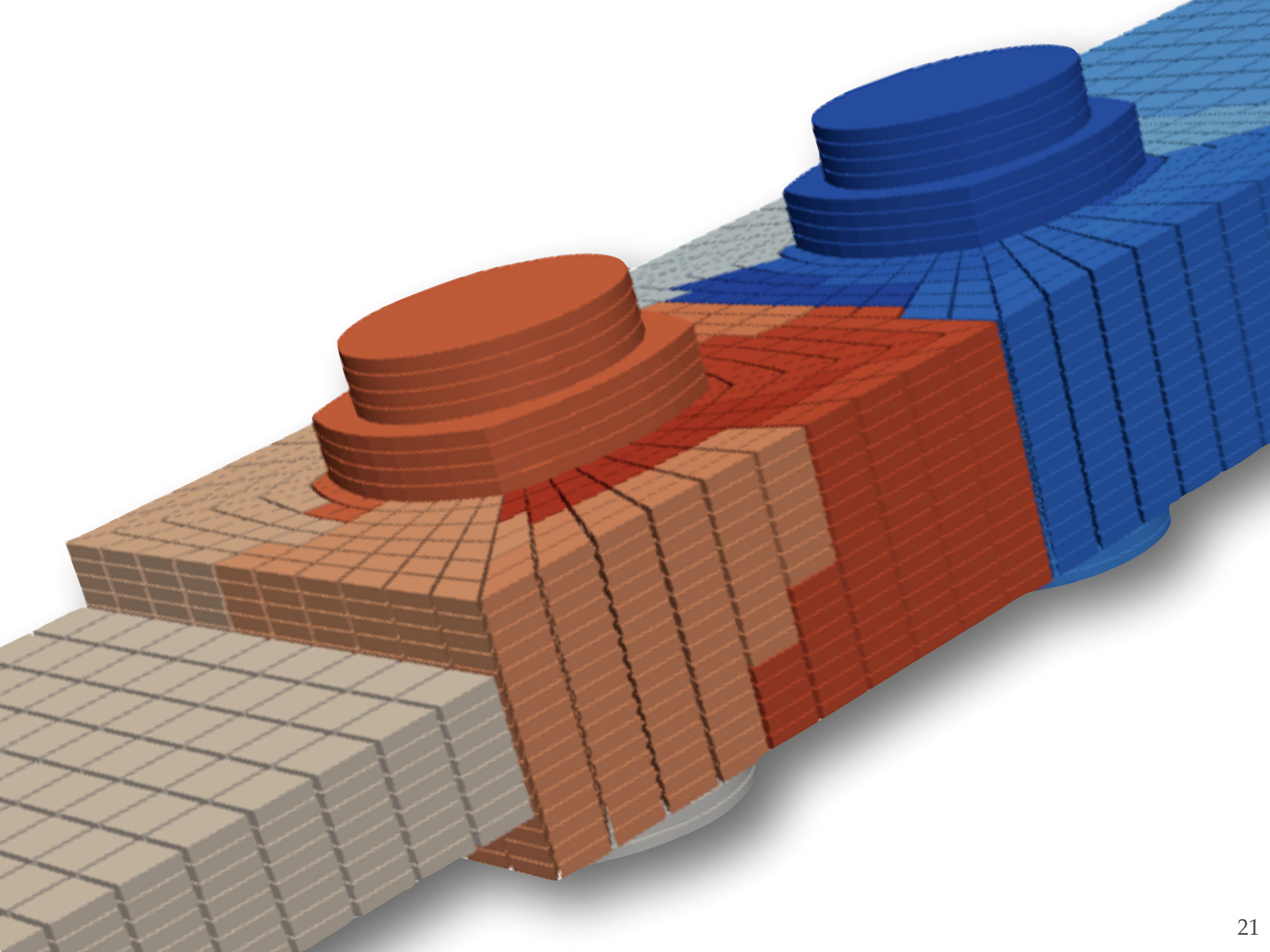


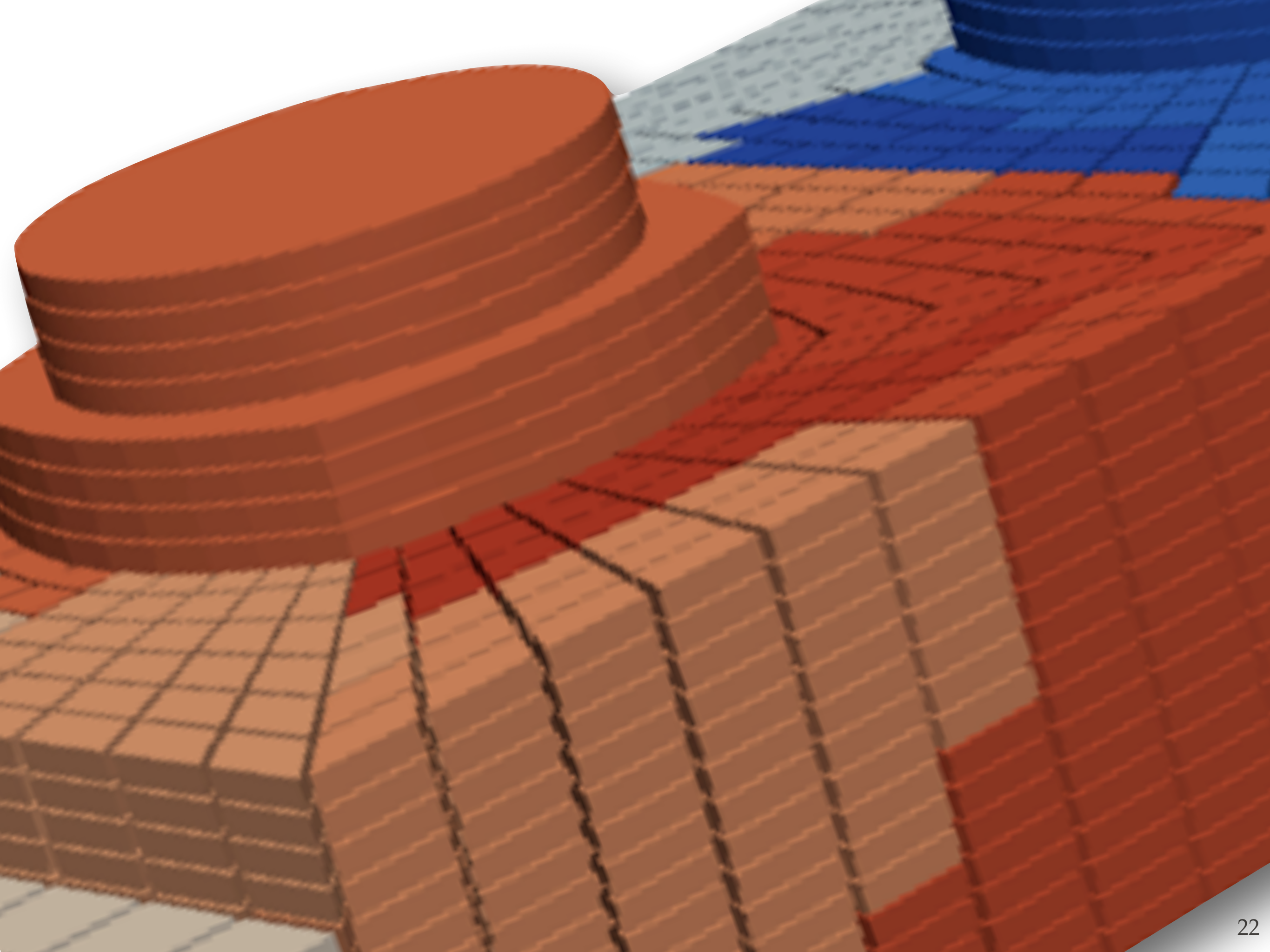
A bolted joint



- 5 elements through the thickness of a ply $\Rightarrow 0.025\text{mm}/\text{element}$
- 50mm bolted joint area $\Rightarrow 2,000$ elements
- 50mm x 50mm x 100 plies $\Rightarrow 2,000 \times 2,000 \times (100 \times 5)$
 $\Rightarrow$ **2 billion elements**







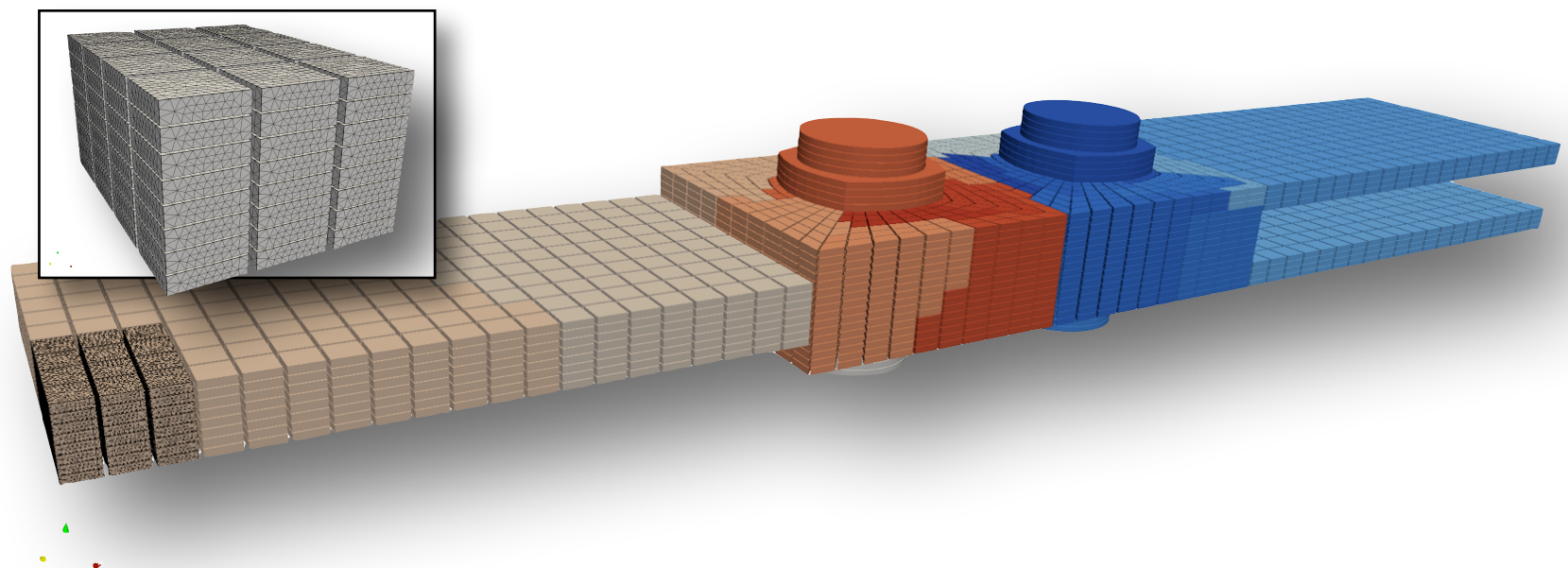
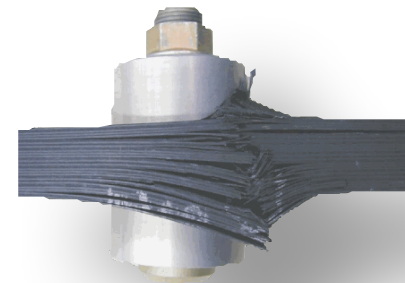
A380 giant



Large structures

whose behaviour is governed by
small-scale effects

=> intractable problem size



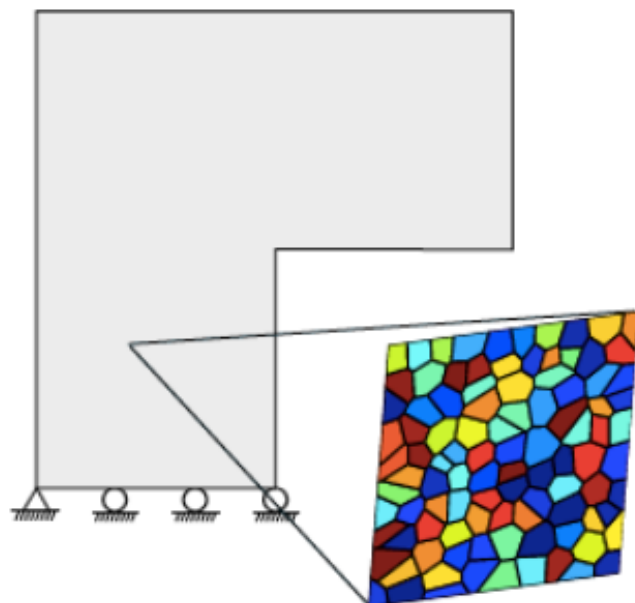
How can the problem size
be reduced but the
accuracy controlled?

Challenge

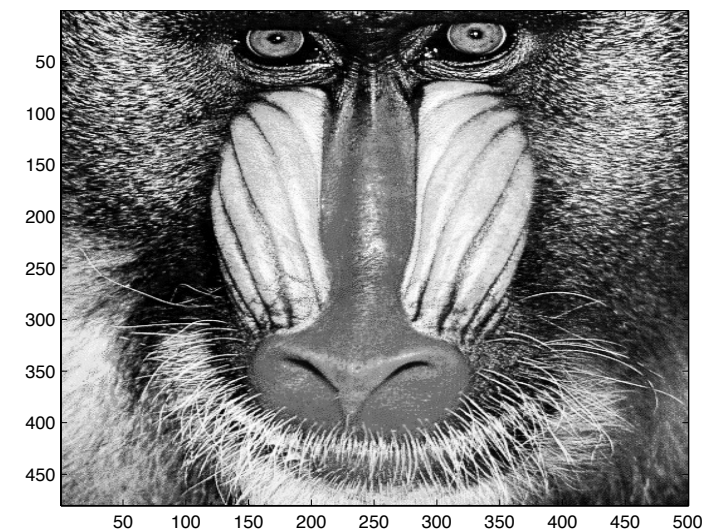
- Reduce the problem size
- Preserve essential features

Reduce computational
expense
Control the error

Physics based model
reduction a.k.a. **Multiscale
Methods**



Algebraic based model
reduction a.k.a. **Machine
Learning**

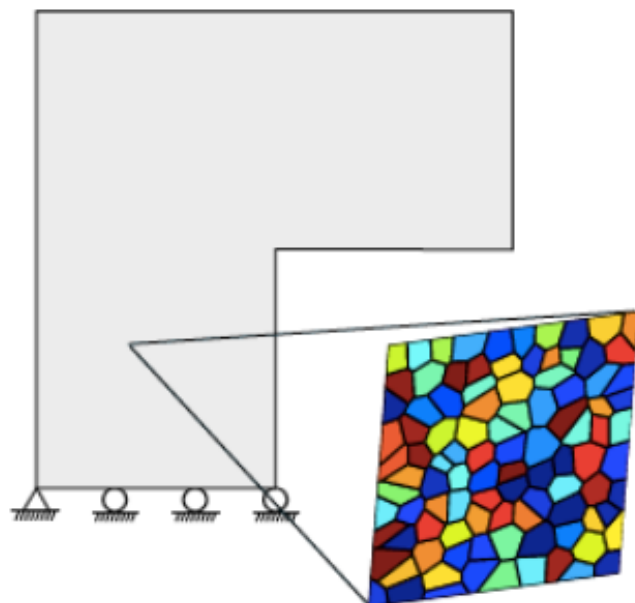


Challenge

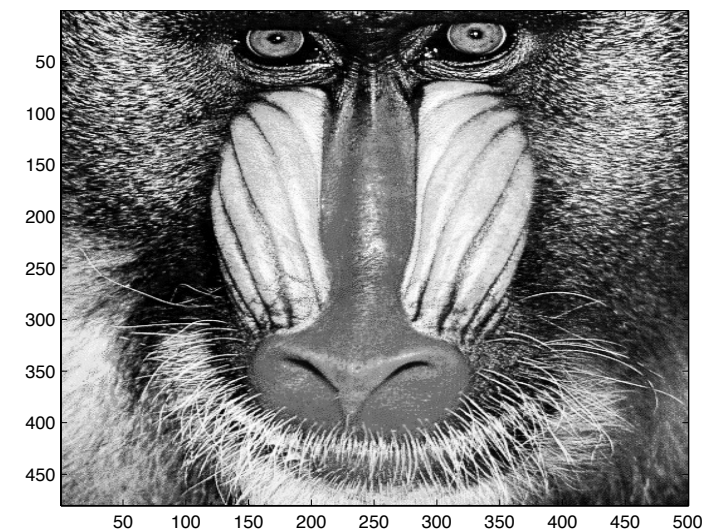
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Physics based model
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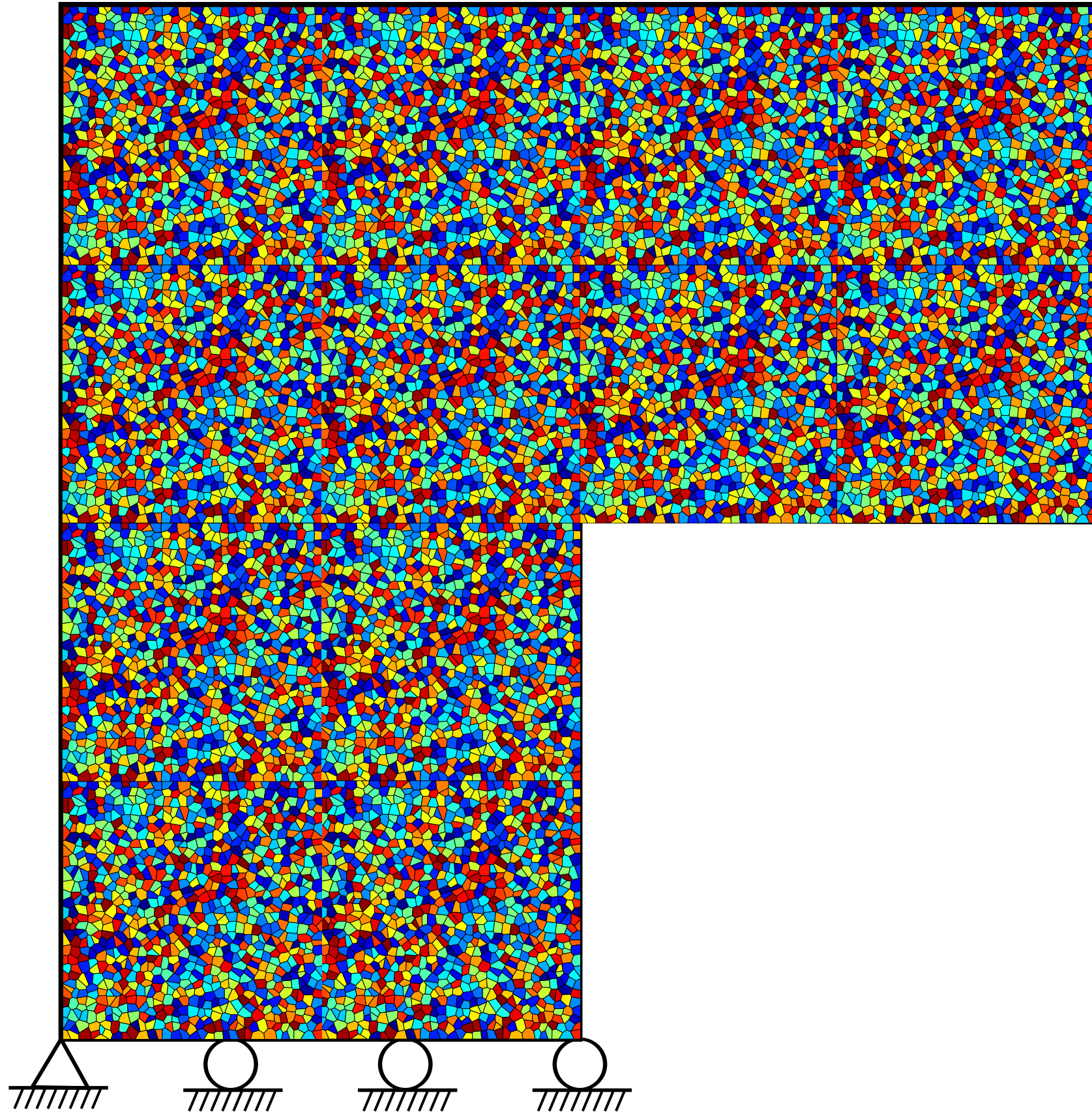
Algebraic based model
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Learning

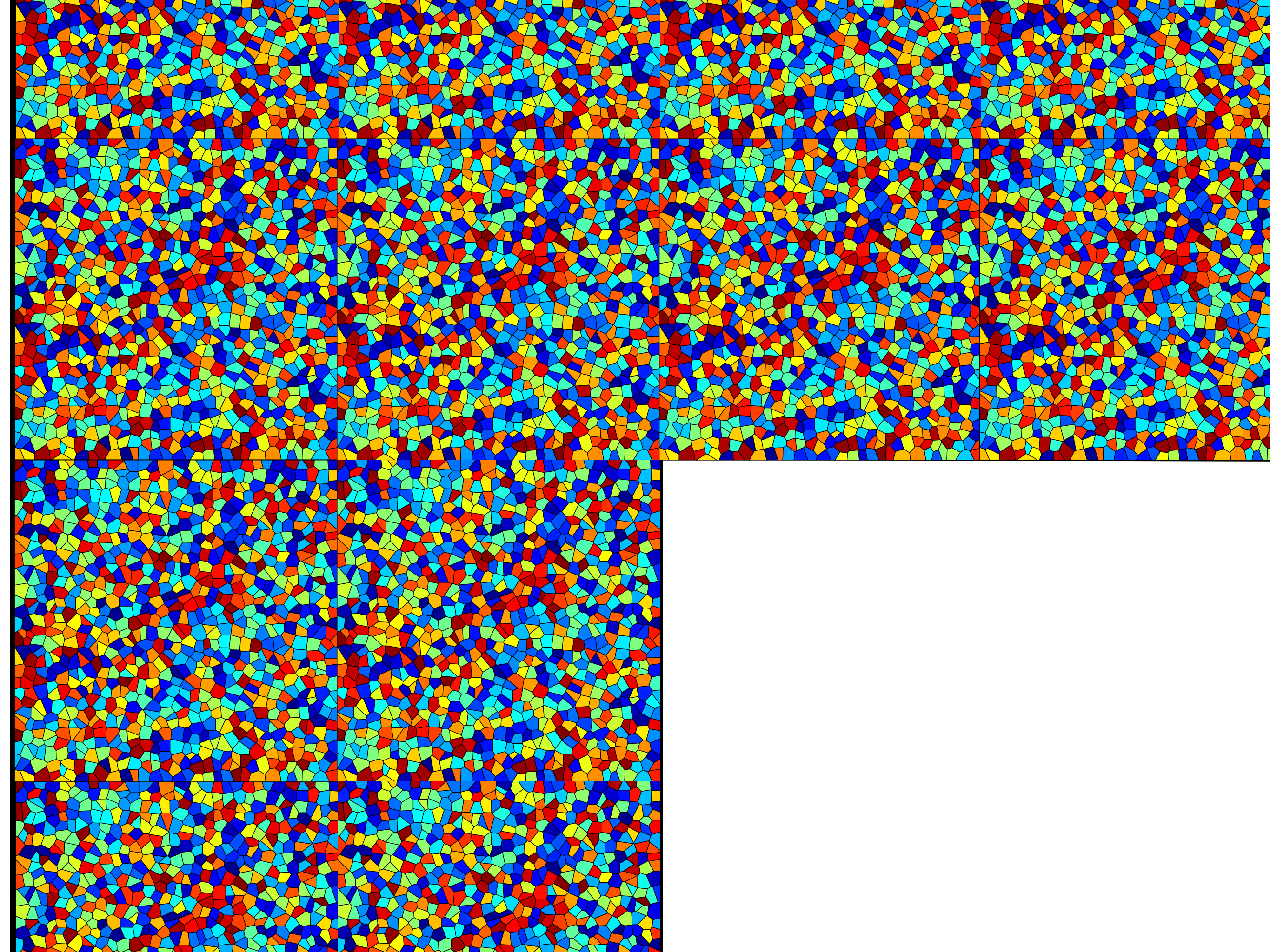


Physics-based
model reduction methods

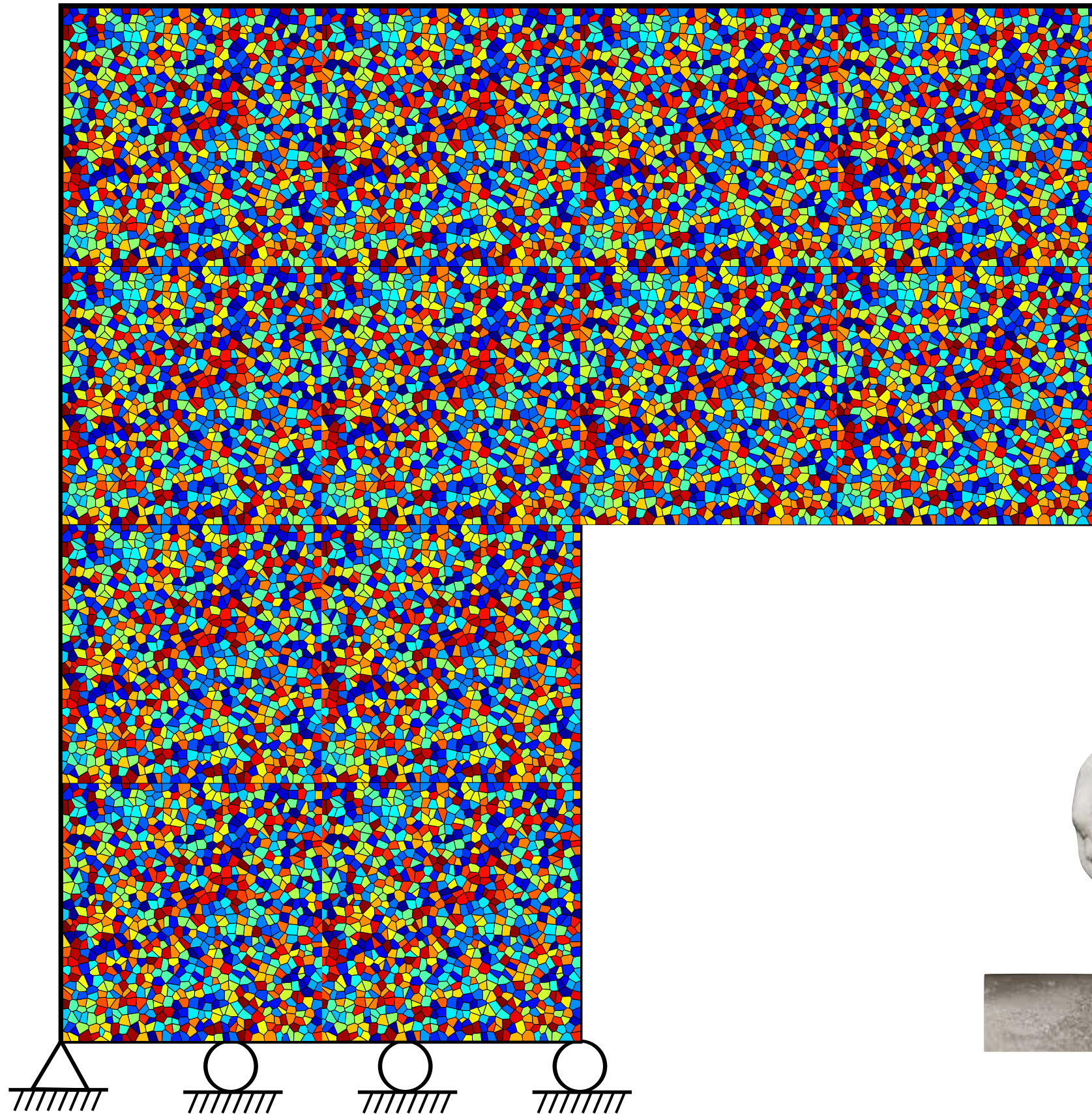
multi-scale methods

Full-scale



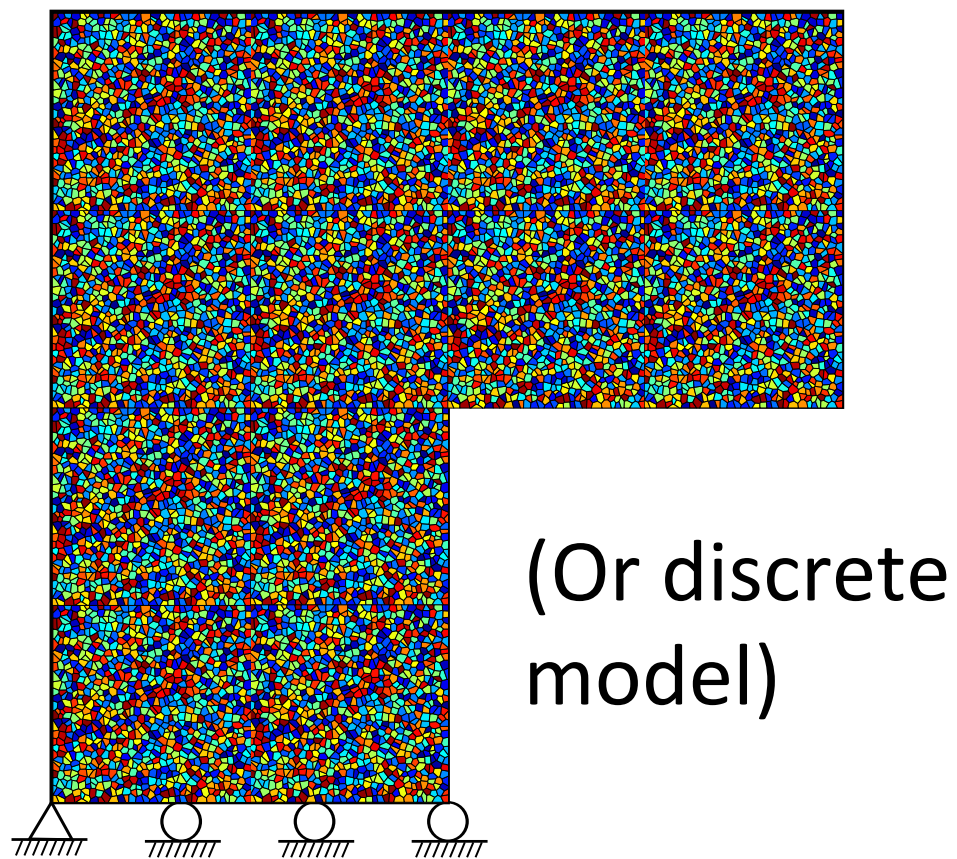


Full-scale

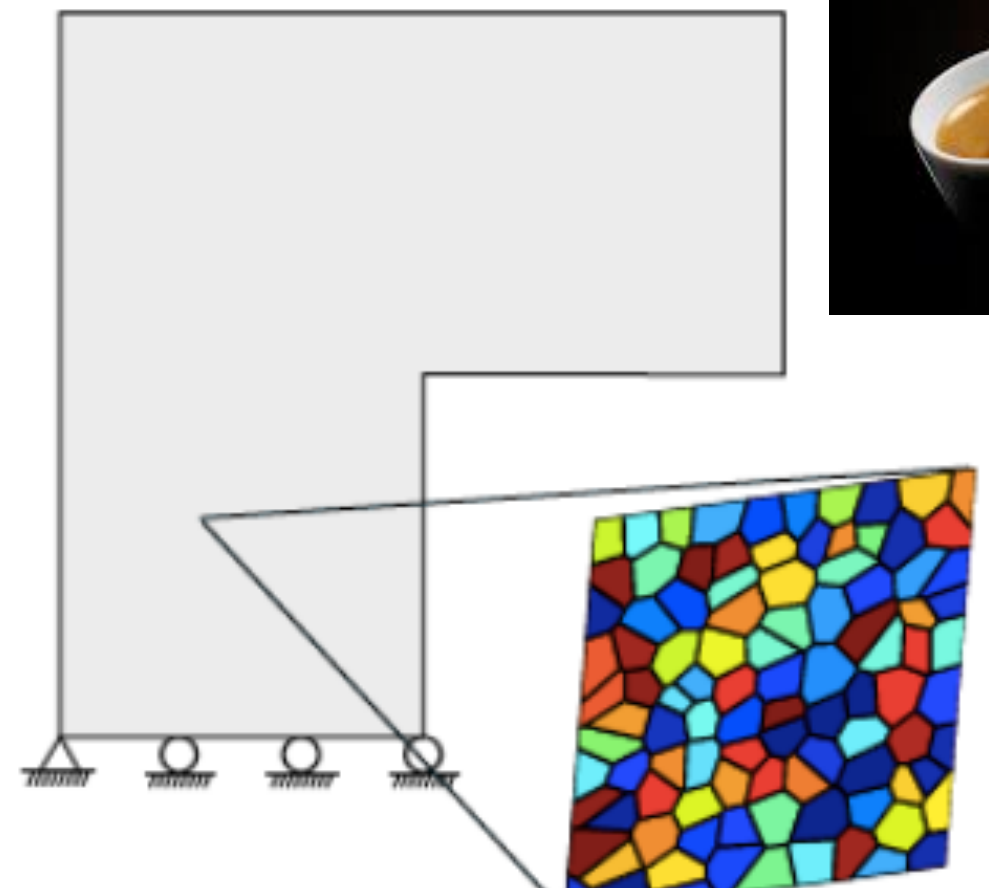
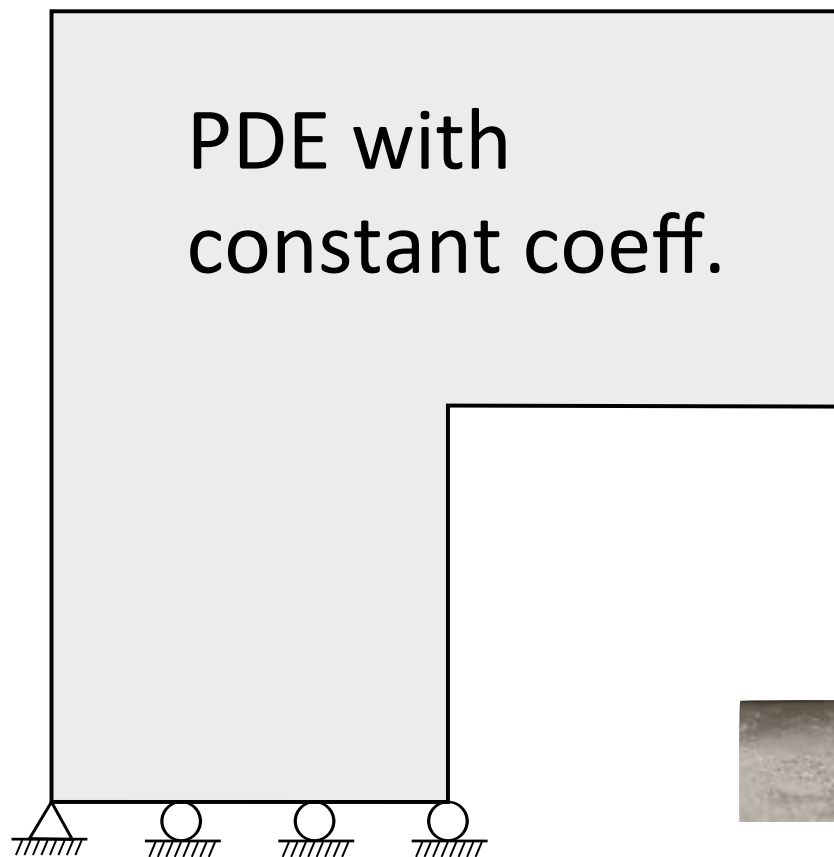


Multi-scale methods

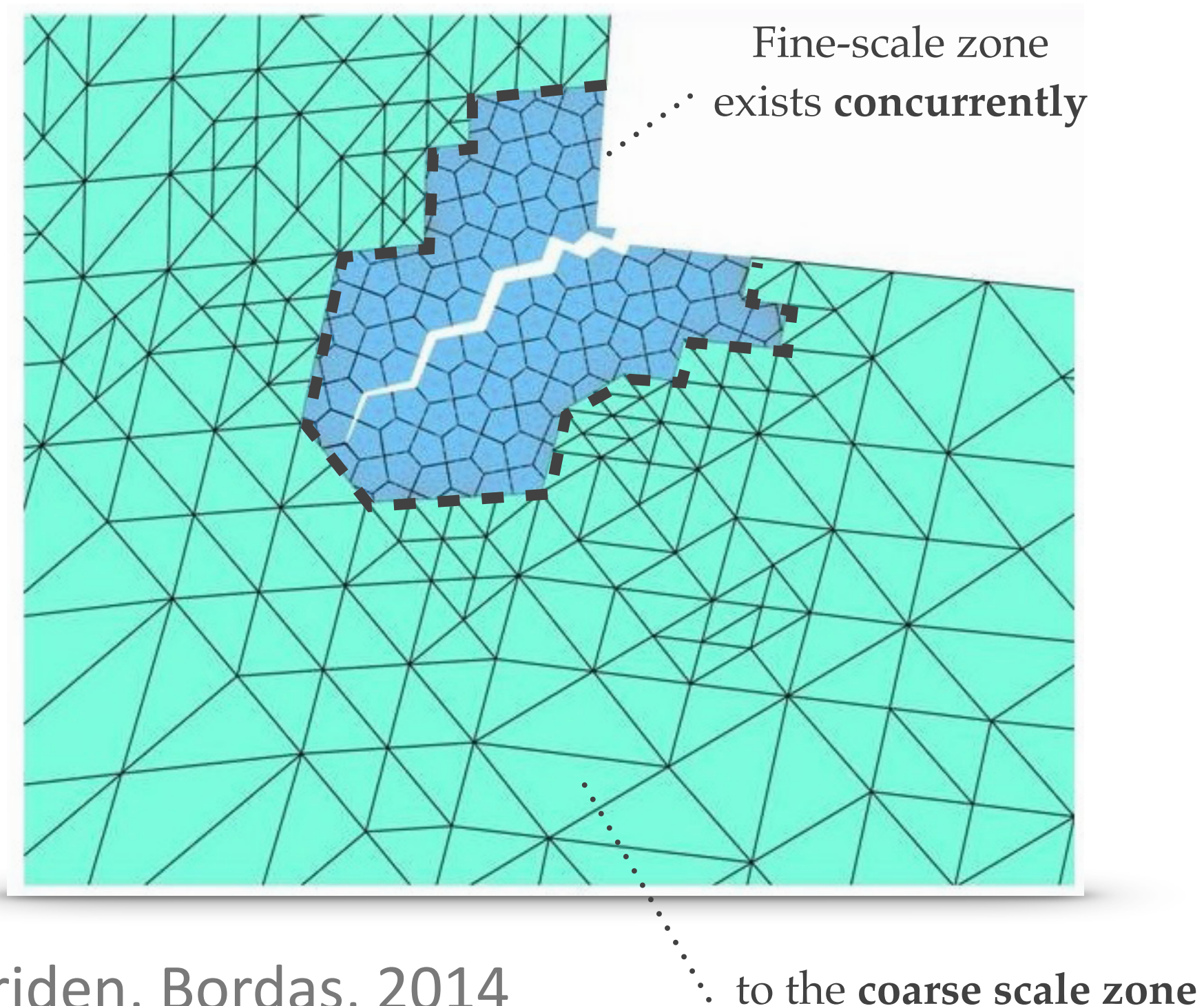
Replace the heterogeneous fine-scale model by an equivalent smoother model at the scale where the predictions are required



↓ Homogenisation

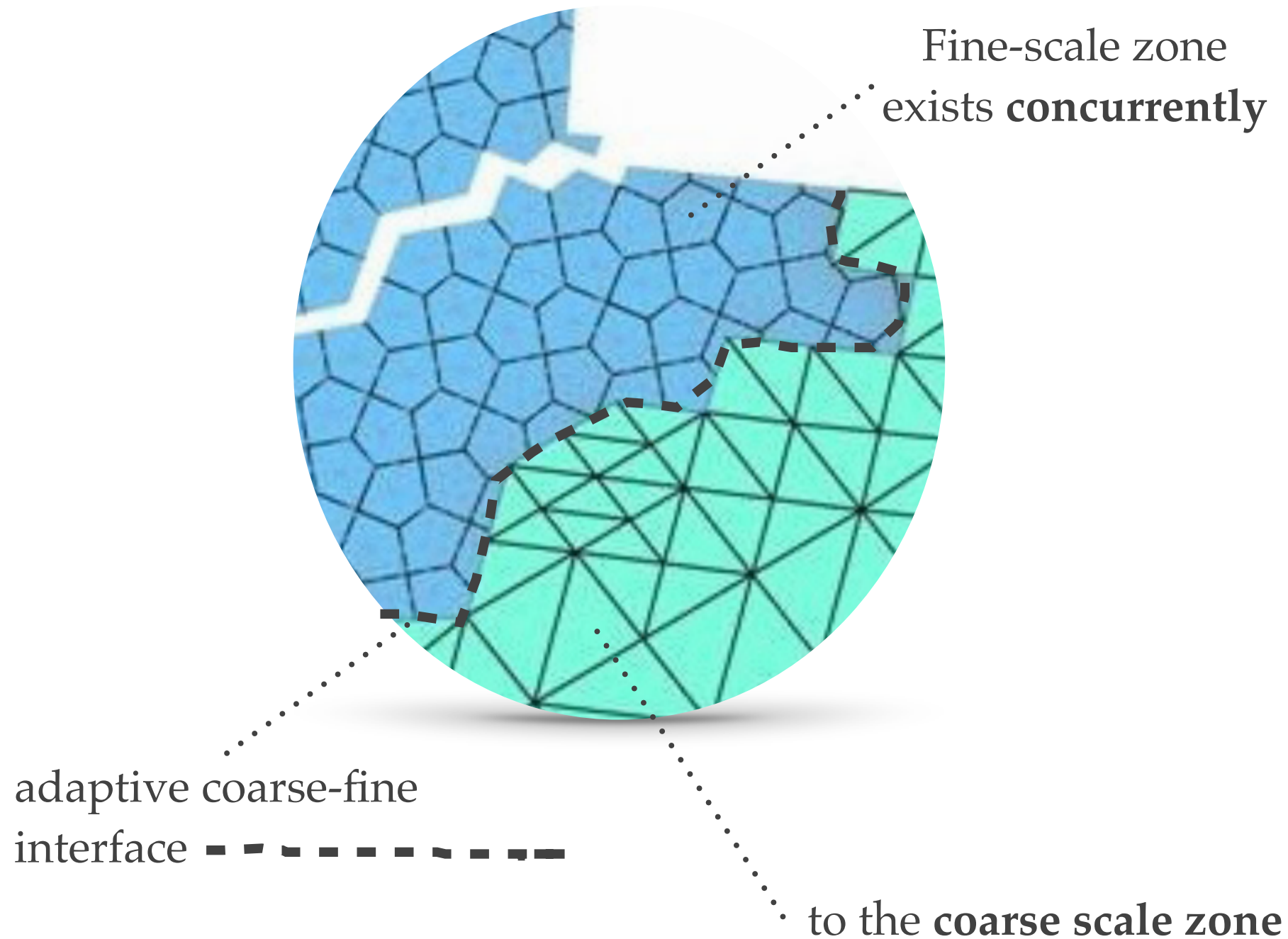


Concurrent methods



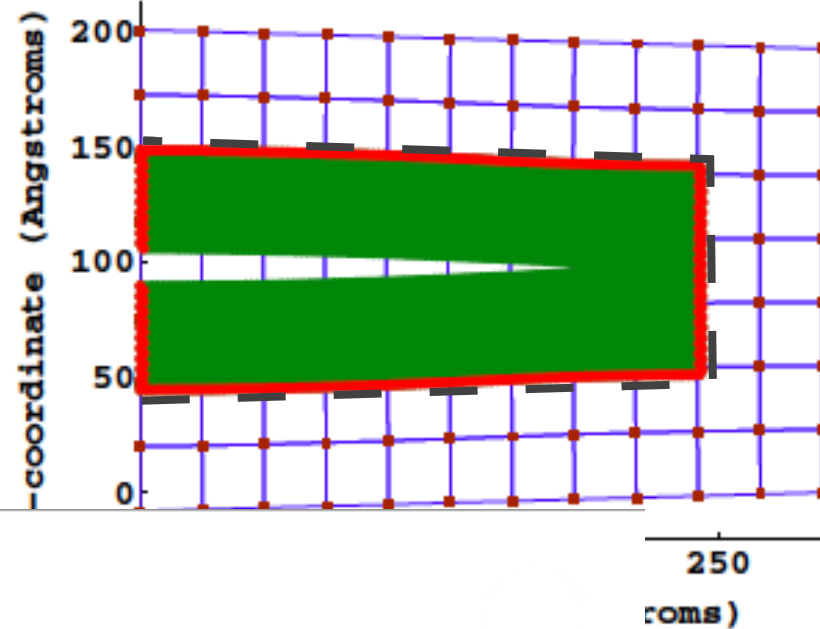
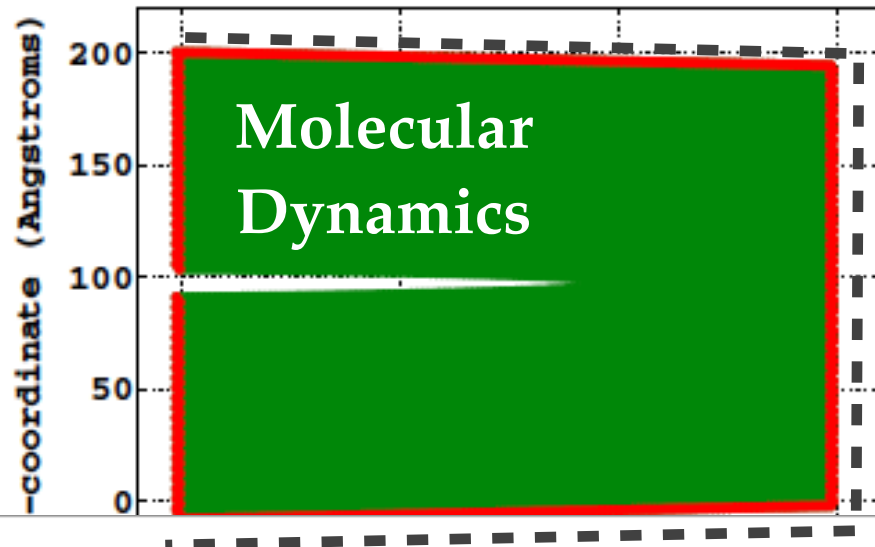
Akbari, Kerfriden, Bordas, 2014

Concurrent methods

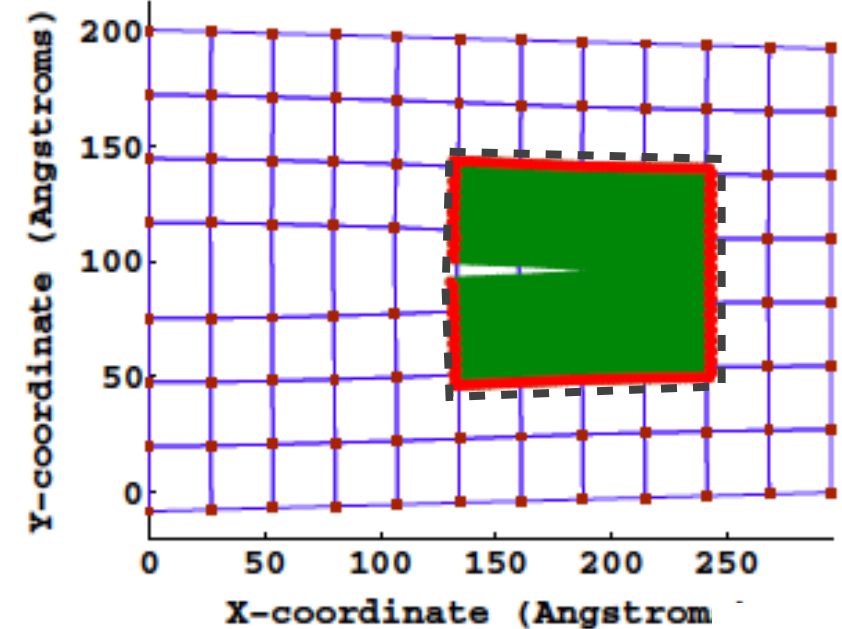


Concurrent methods

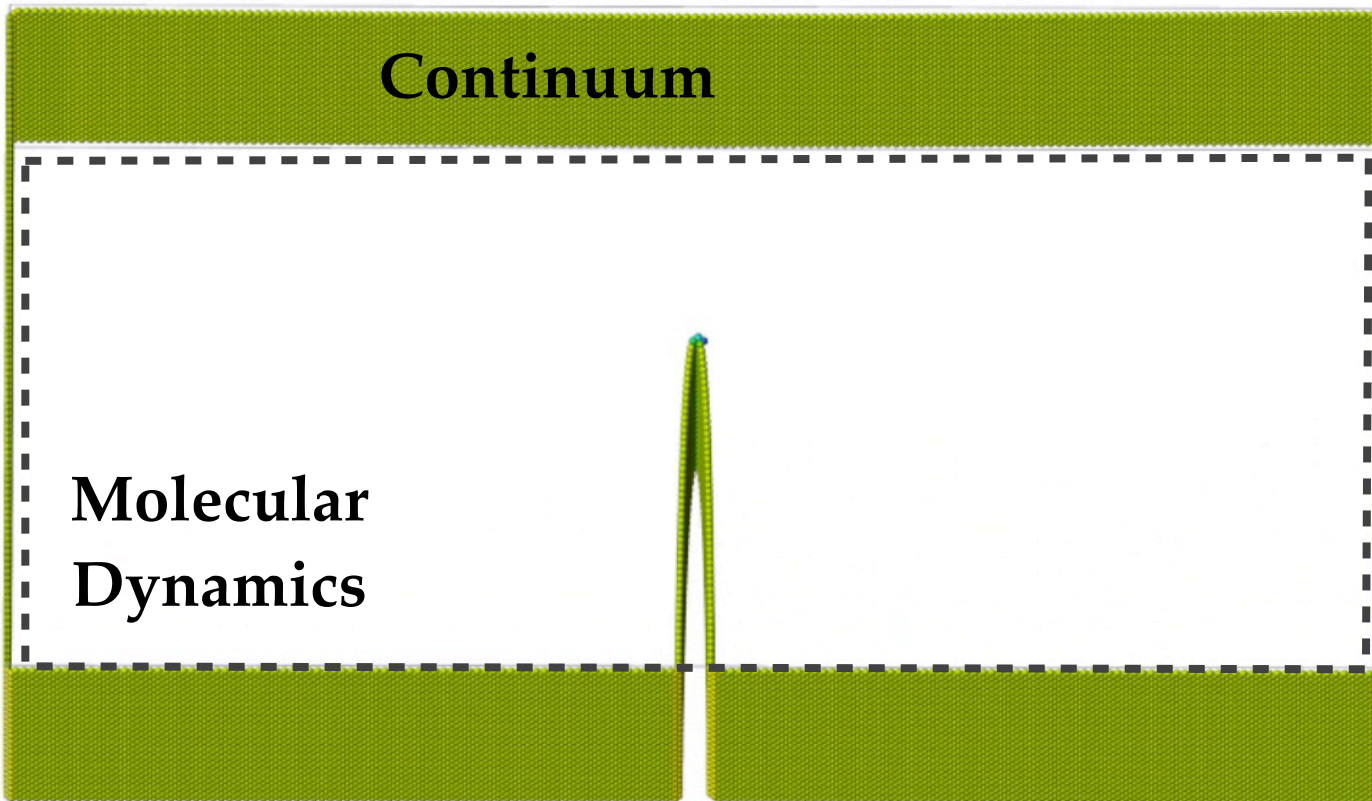
Continuum



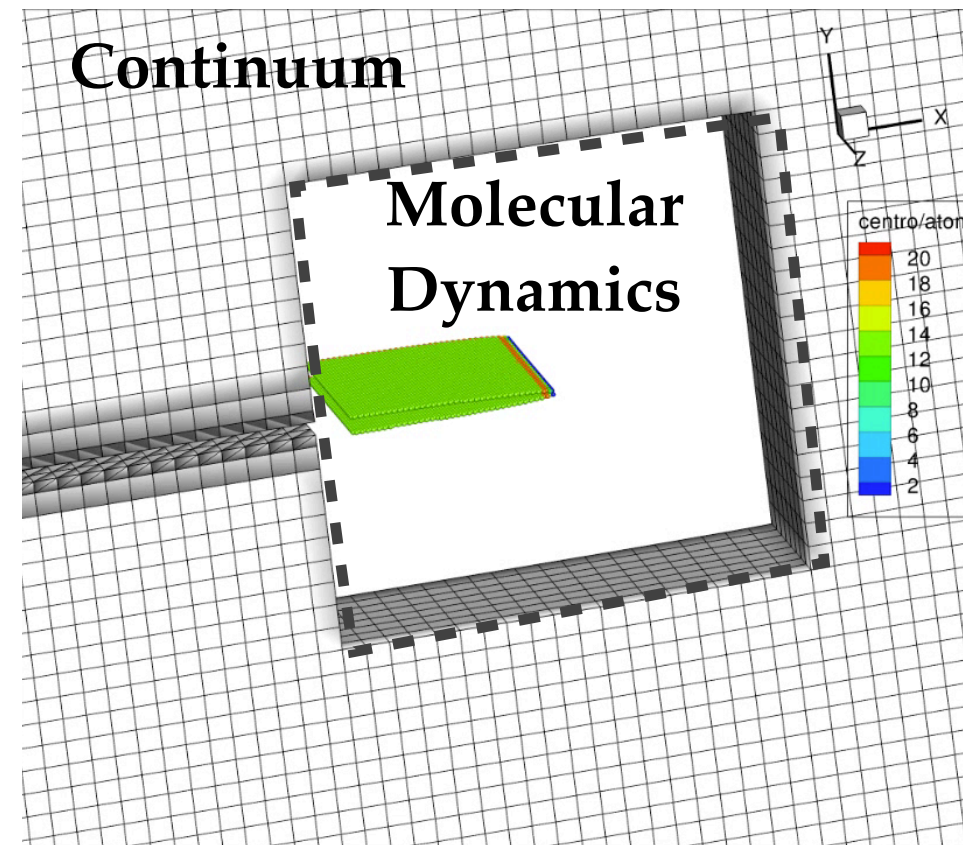
Coarse-graining



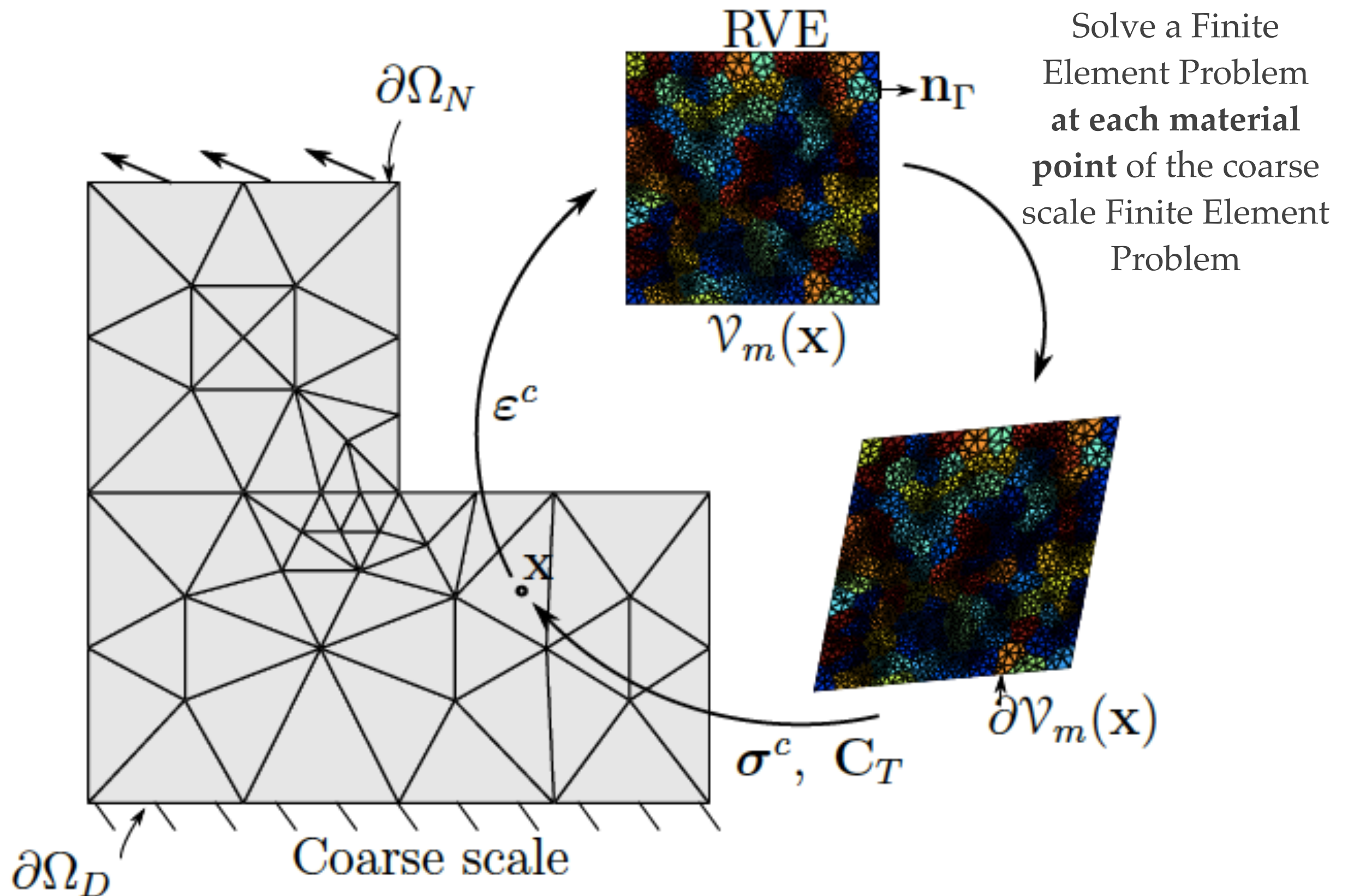
Continuum



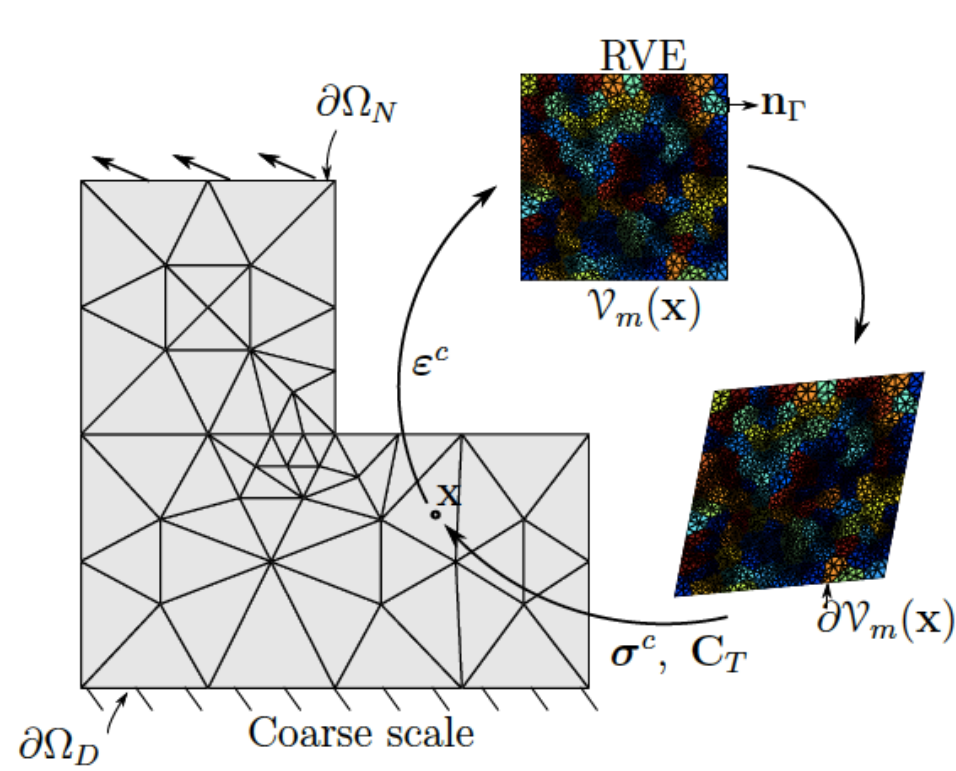
Continuum



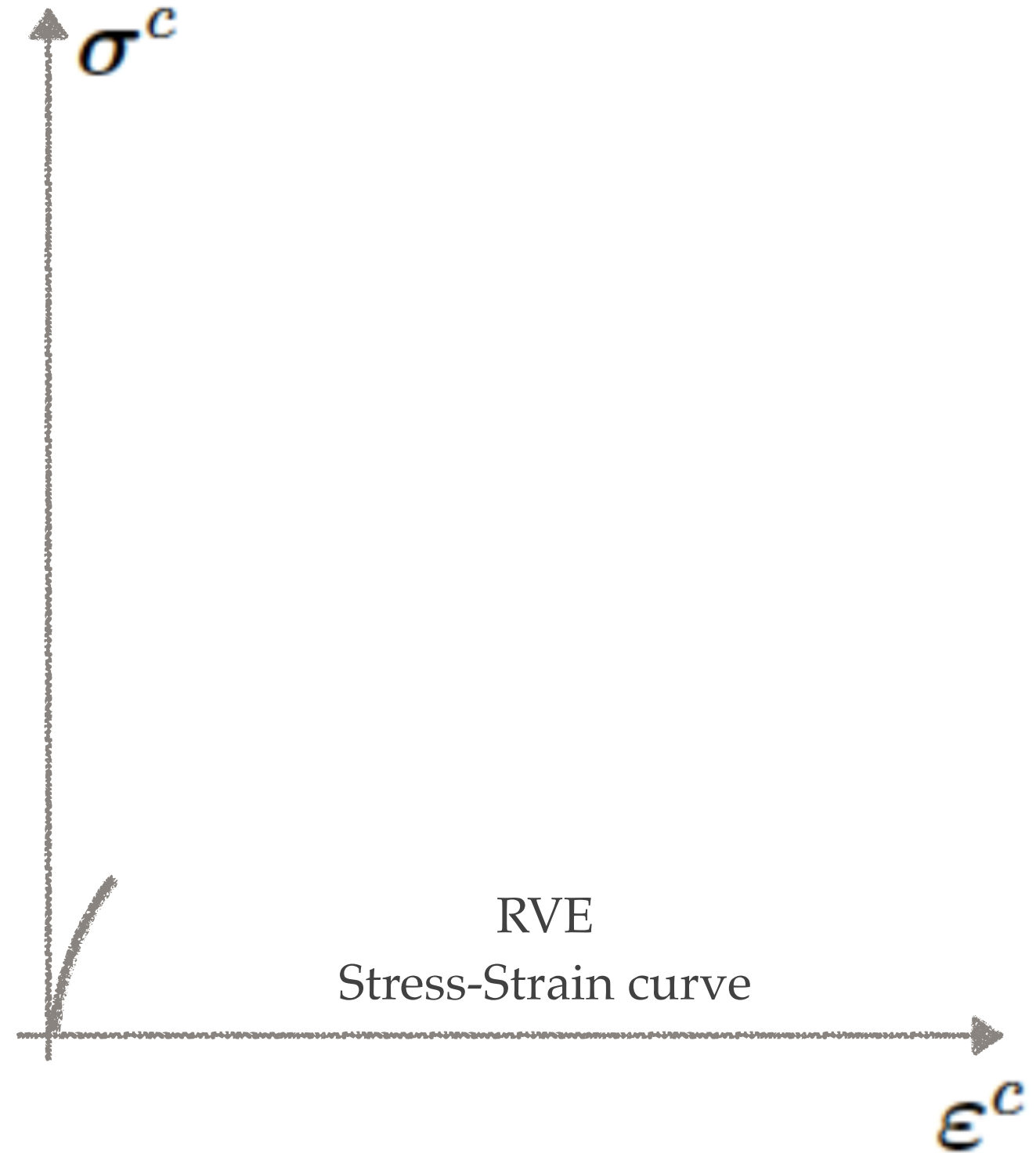
Hierarchical methods FE²



Hierarchical methods FE²

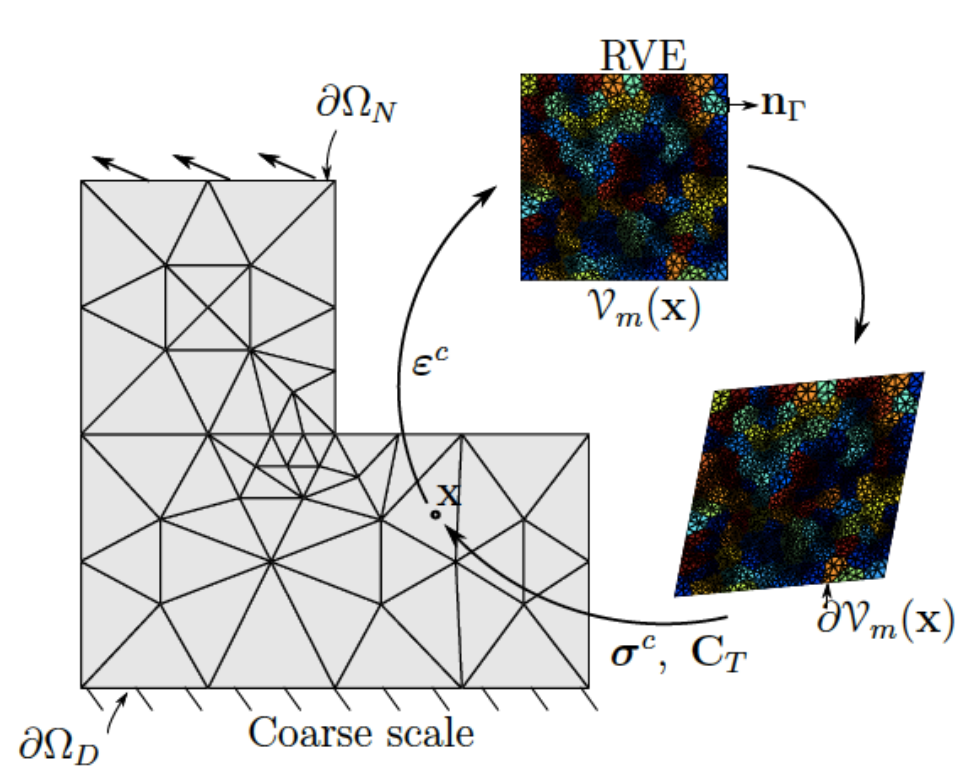


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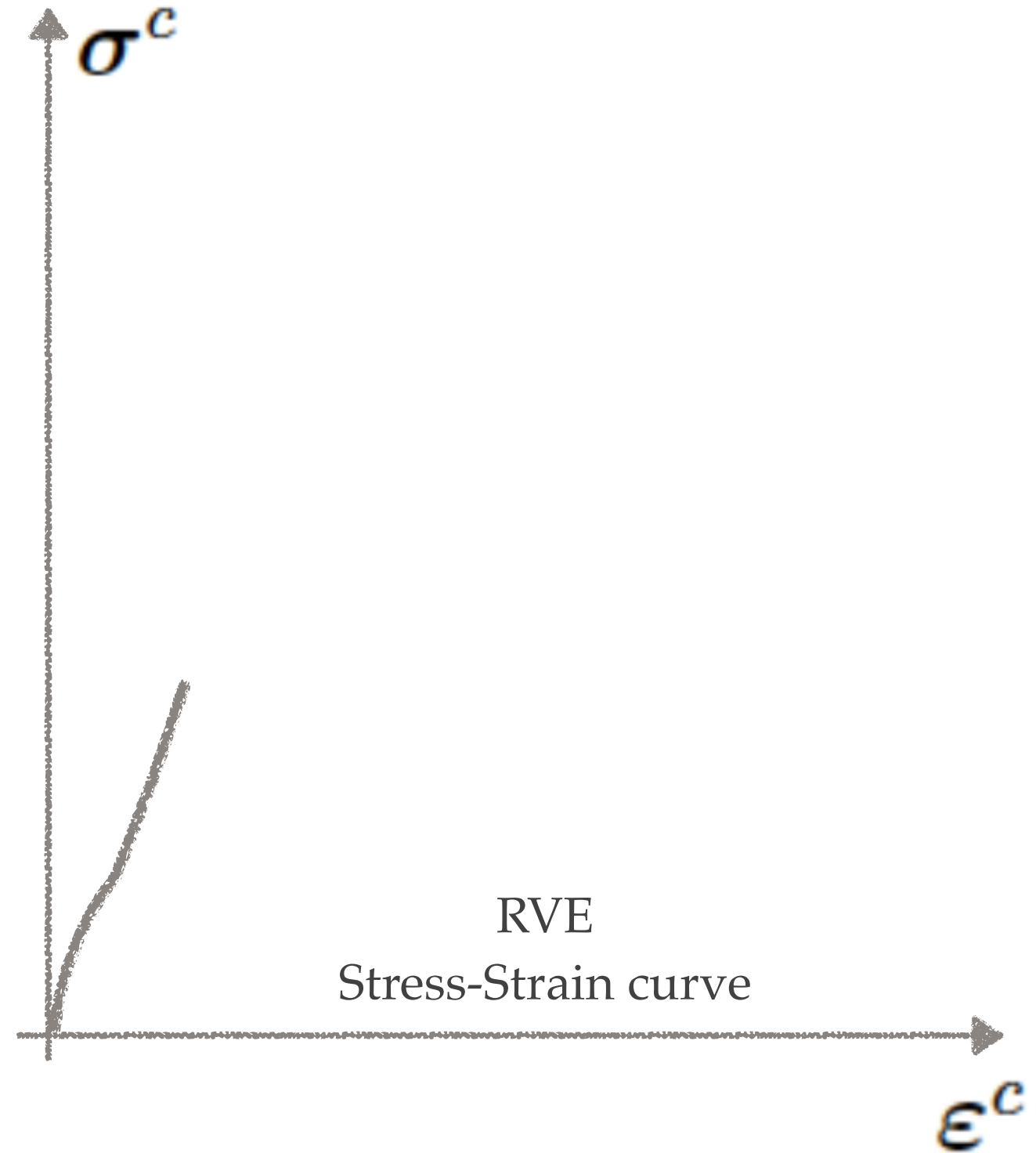


Feyel, Chaboche, 2000 - Akbari, Kerfriden, Bordas, 2014

Hierarchical methods FE²

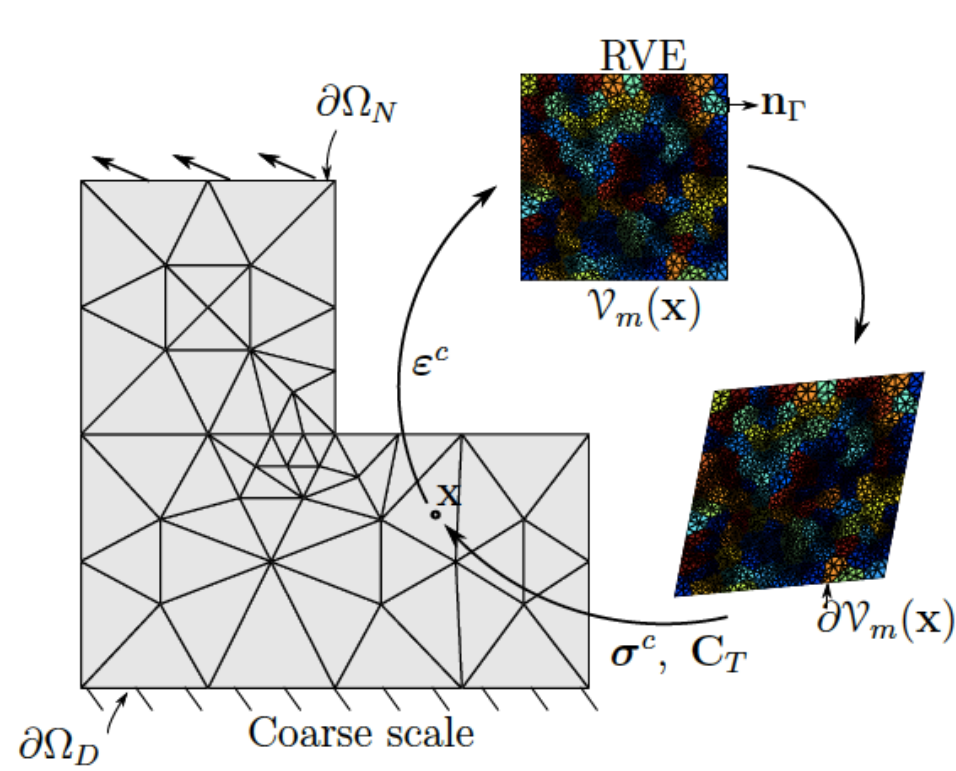


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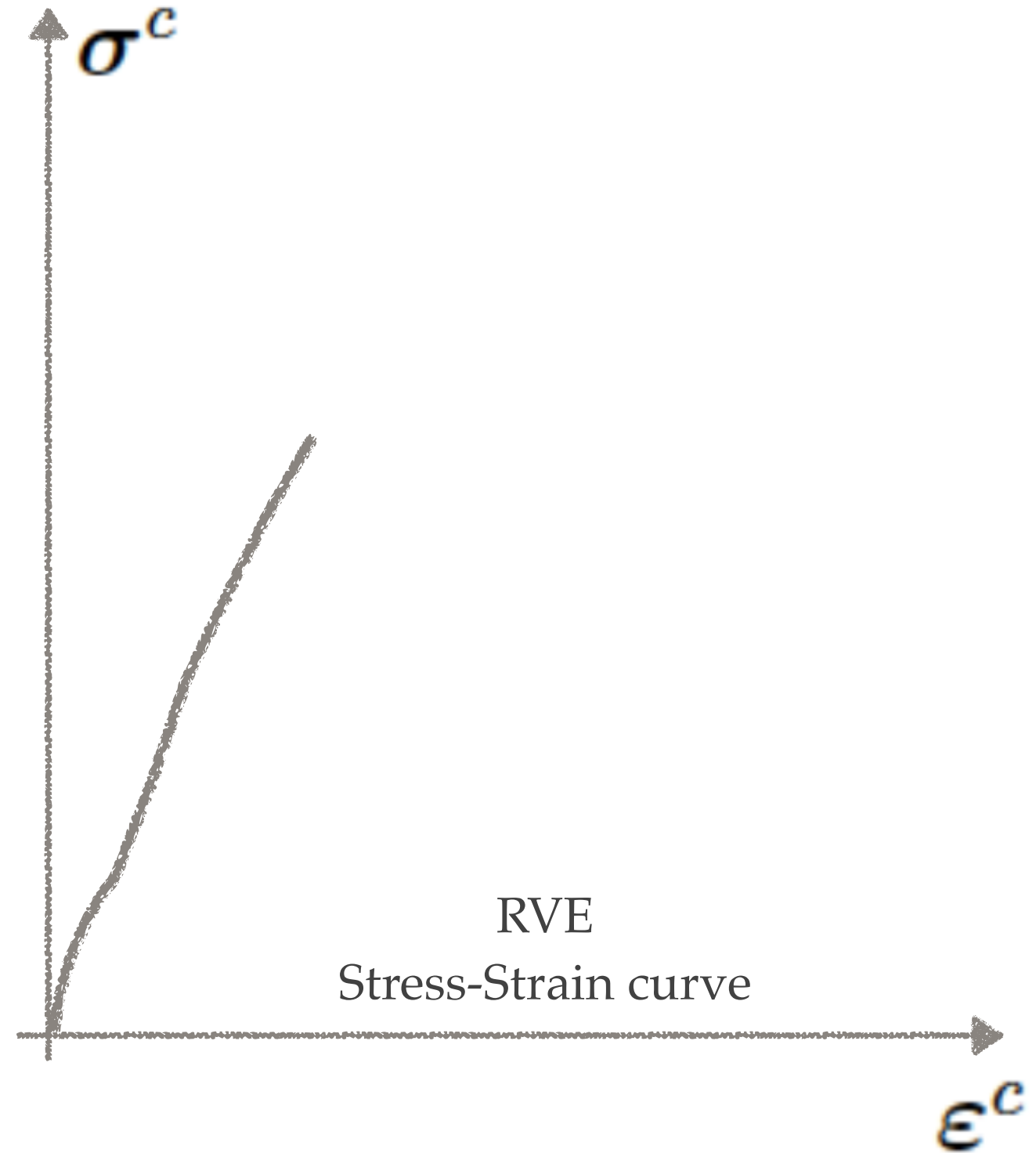


Feyel, Chaboche, 2000 - Akbari, Kerfriden, Bordas, 2014

Hierarchical methods FE²

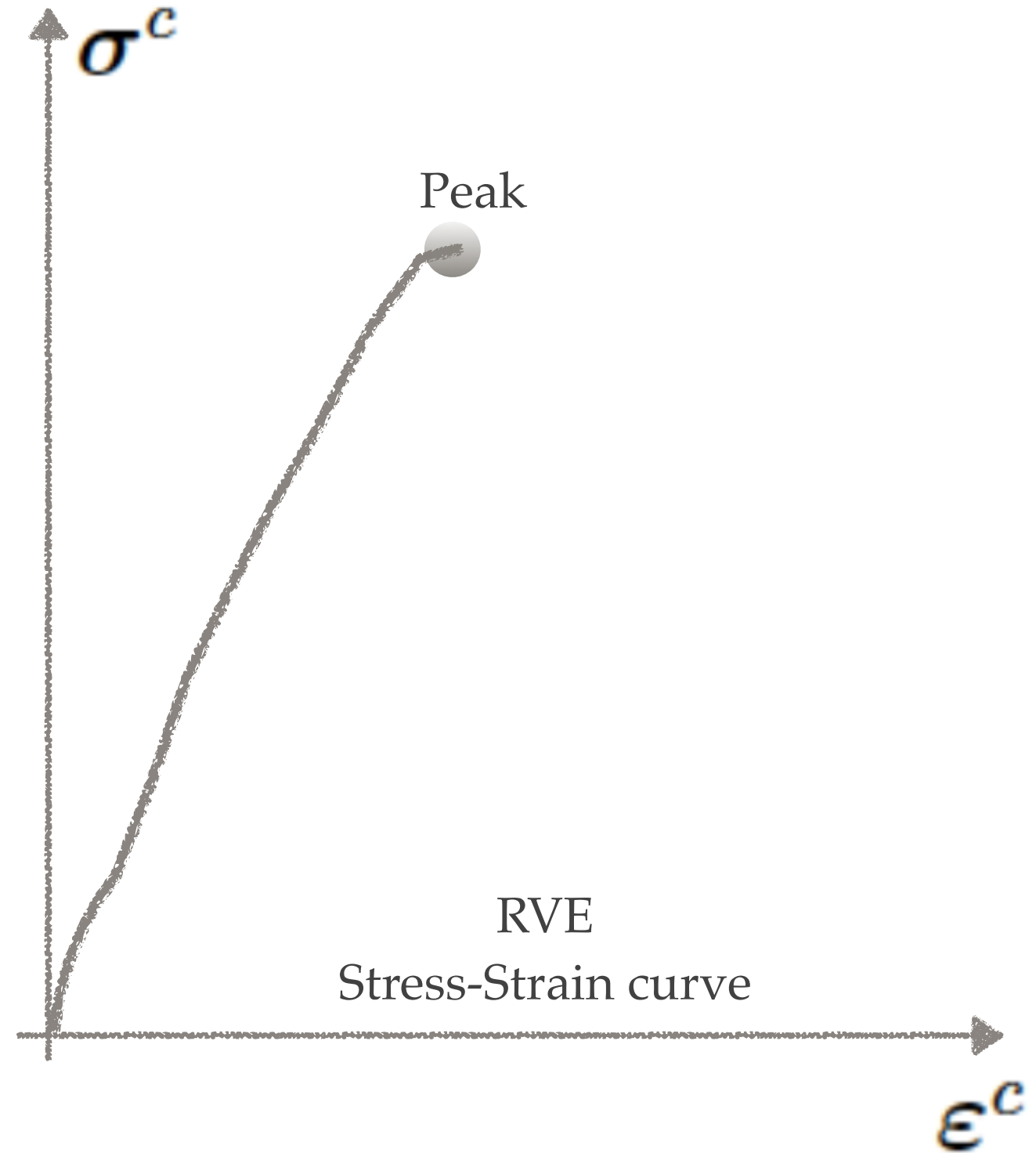
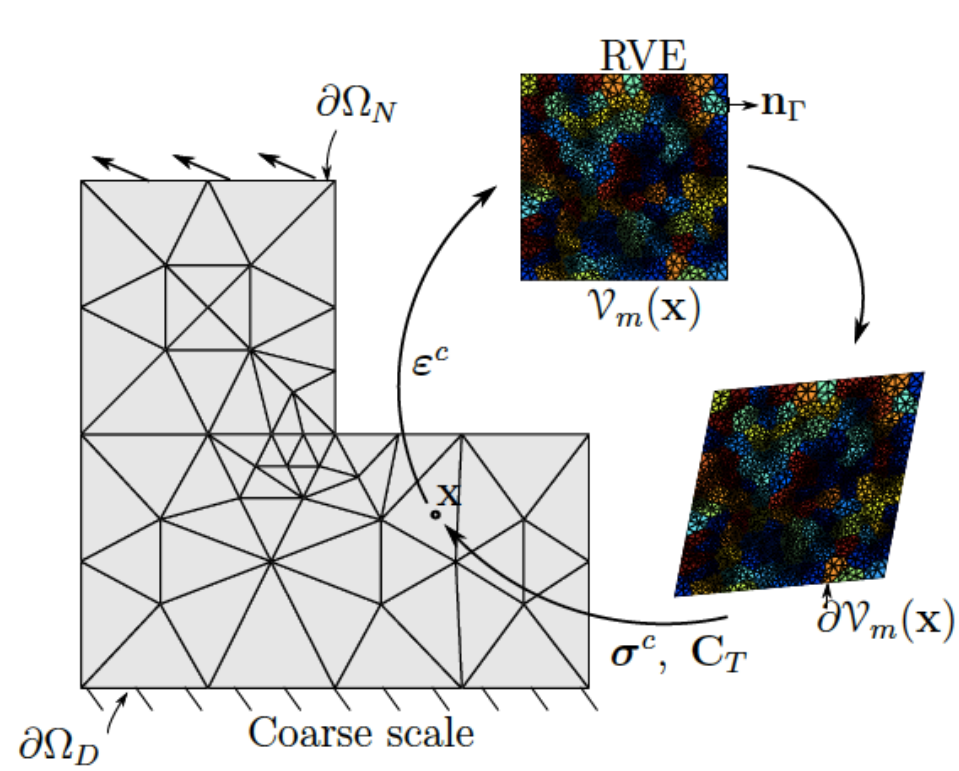


Loading



Feyel, Chaboche, 2000 - Akbari, Kerfriden, Bordas, 2014

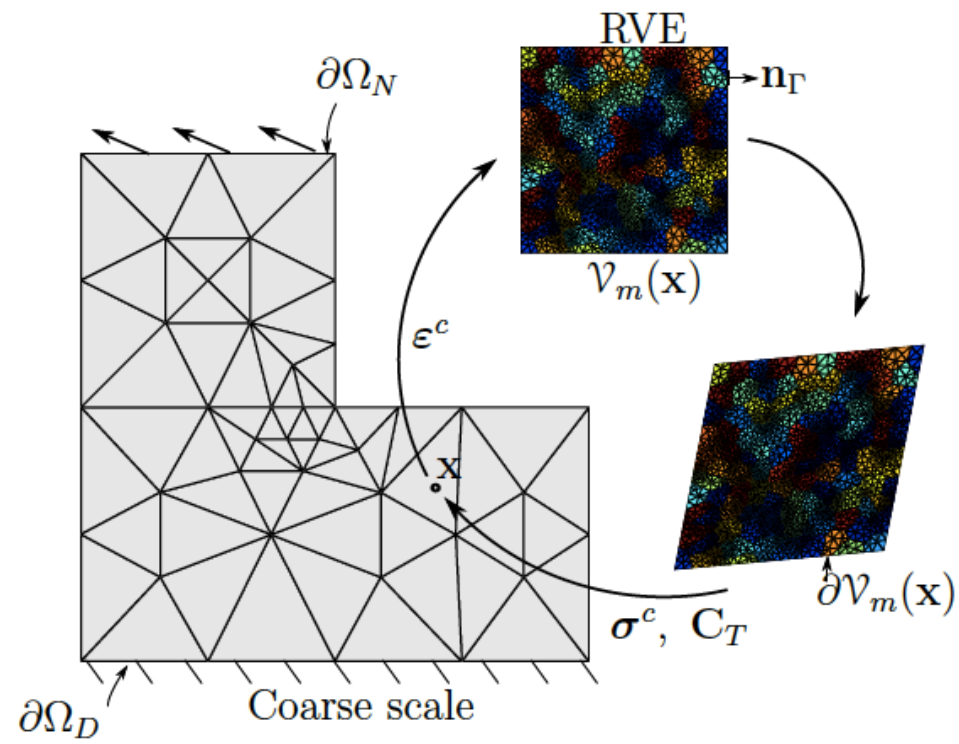
Hierarchical methods FE²



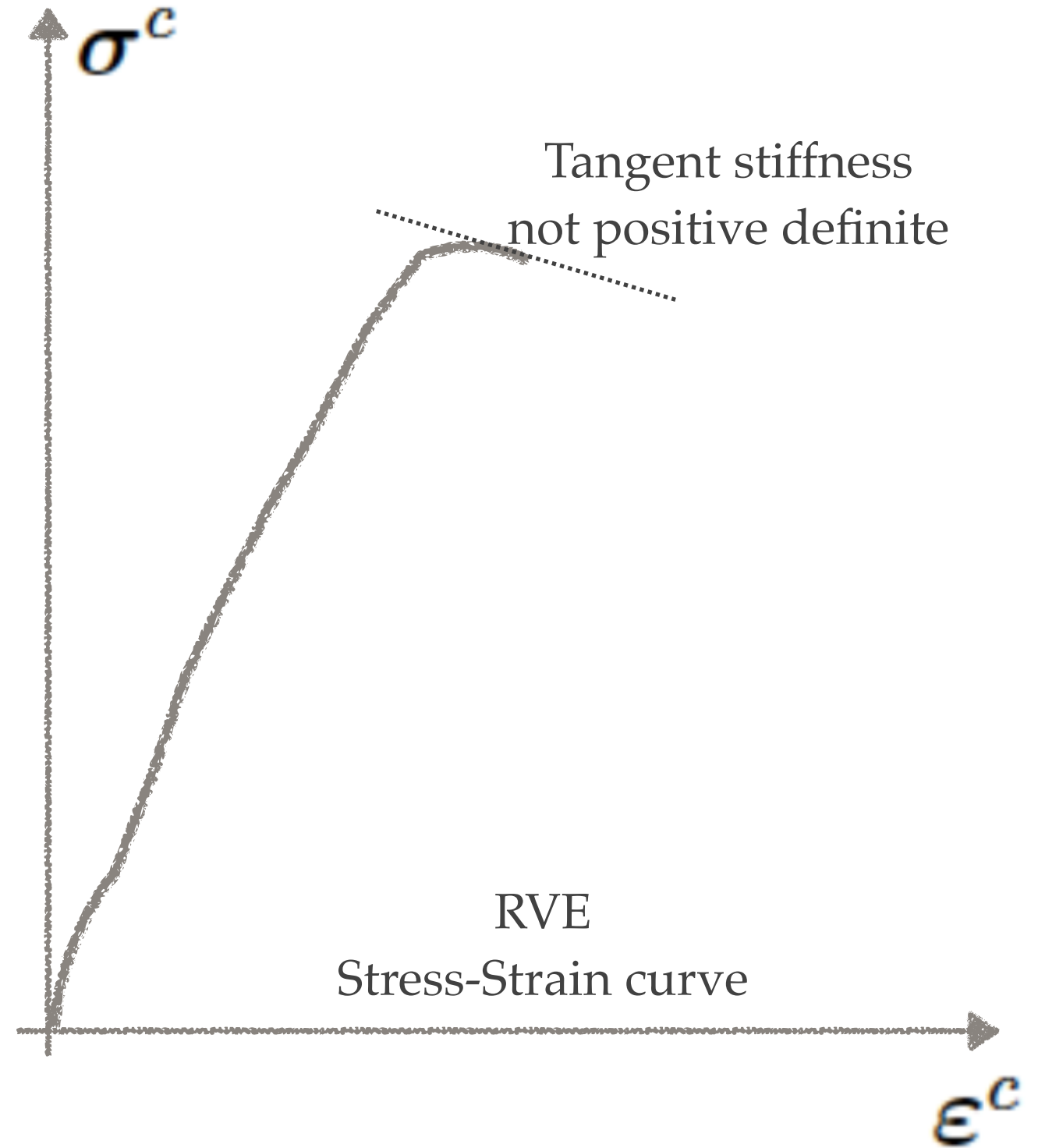
Peak

Feyel, Chaboche, 2000 - Akbari, Kerfriden, Bordas, 2014

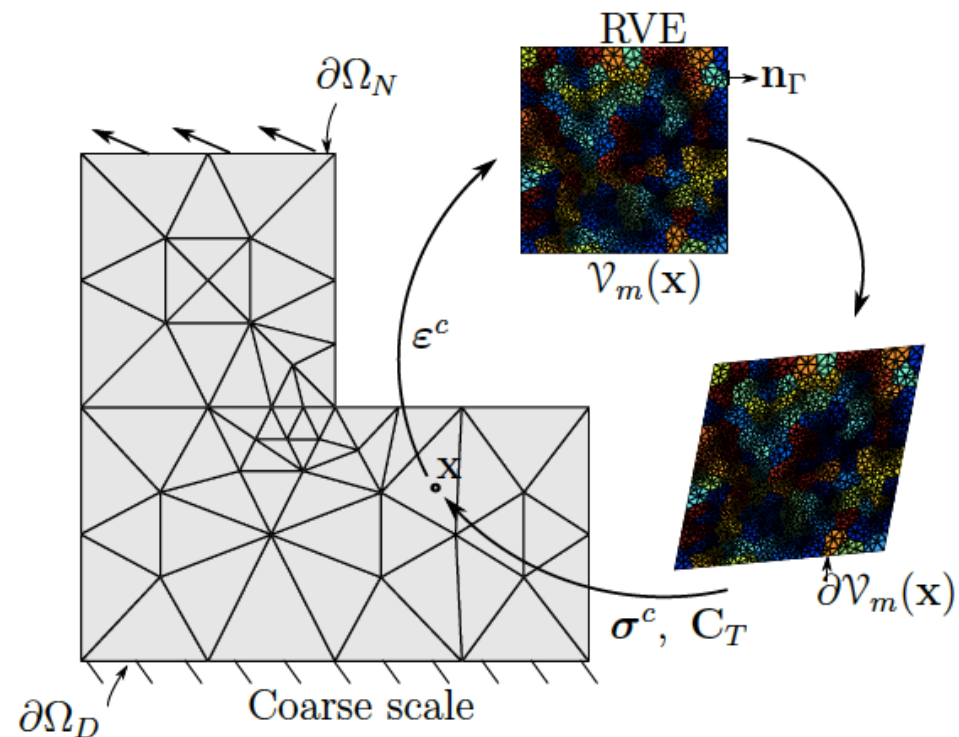
Hierarchical methods FE²



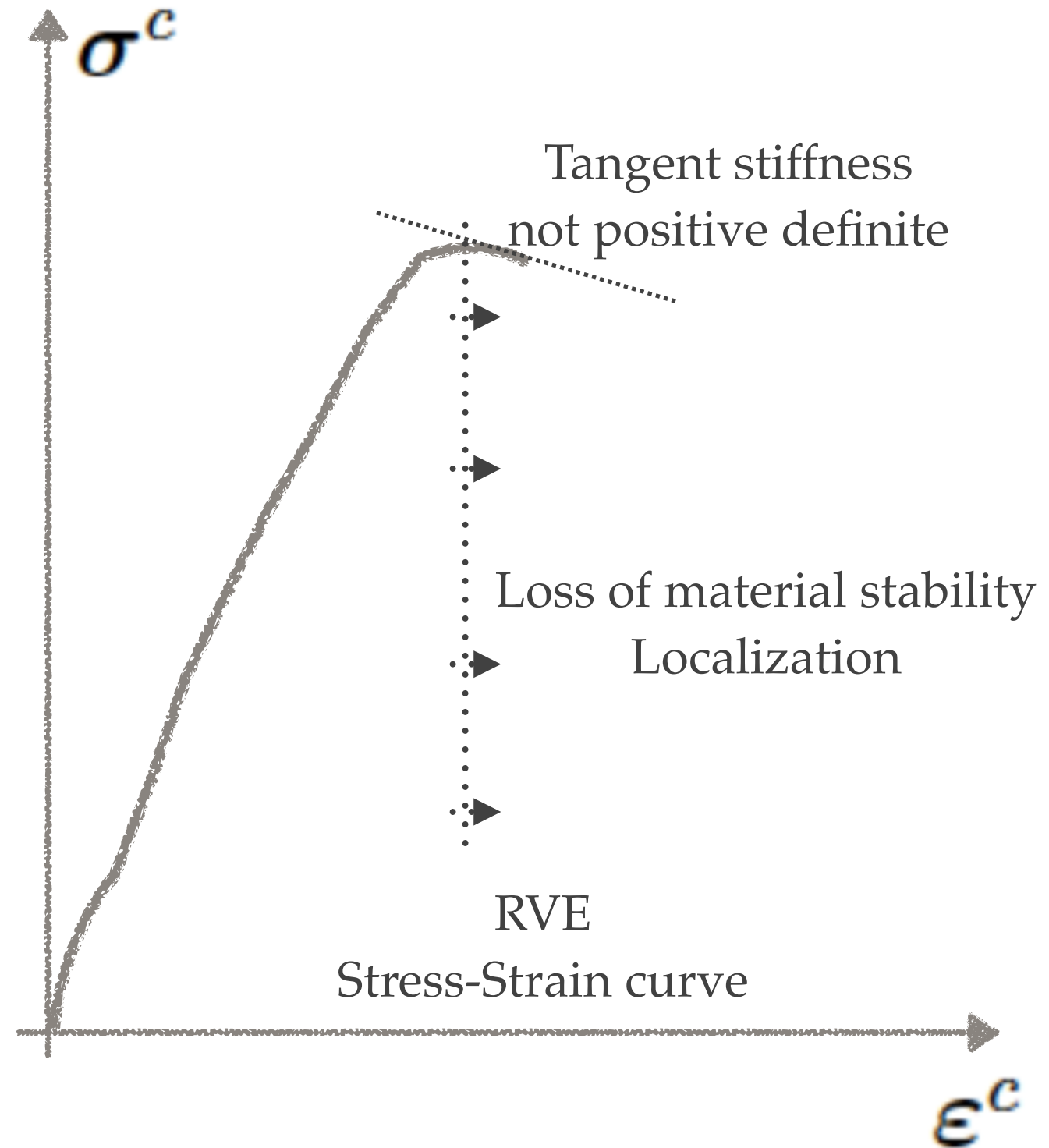
Unloading



Hierarchical methods FE²

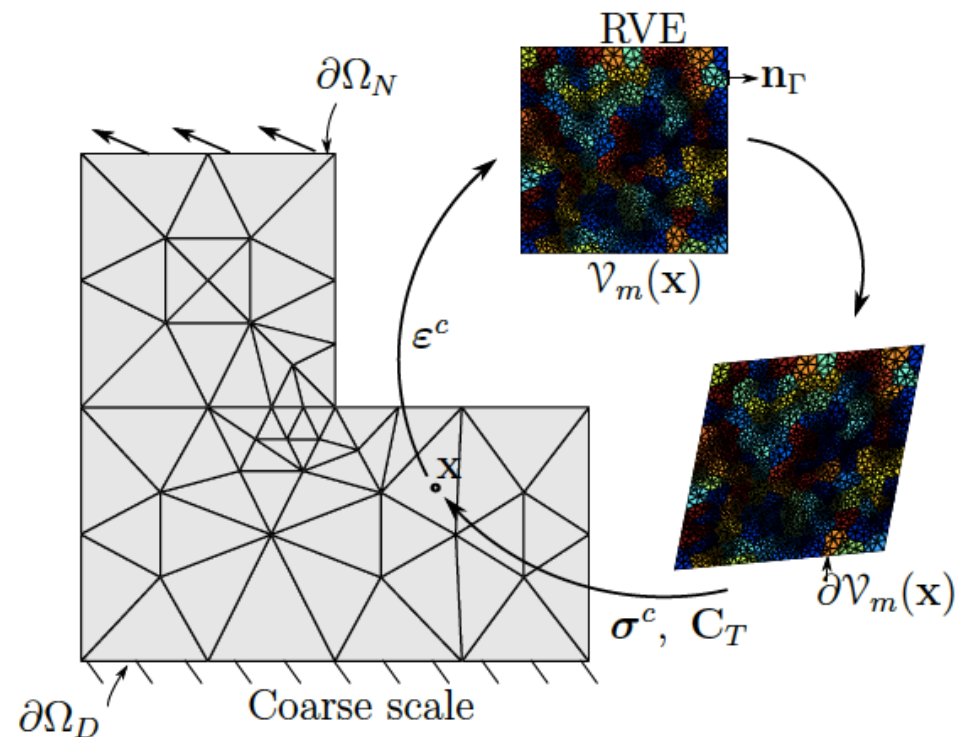


Unloading
RVE does not exist

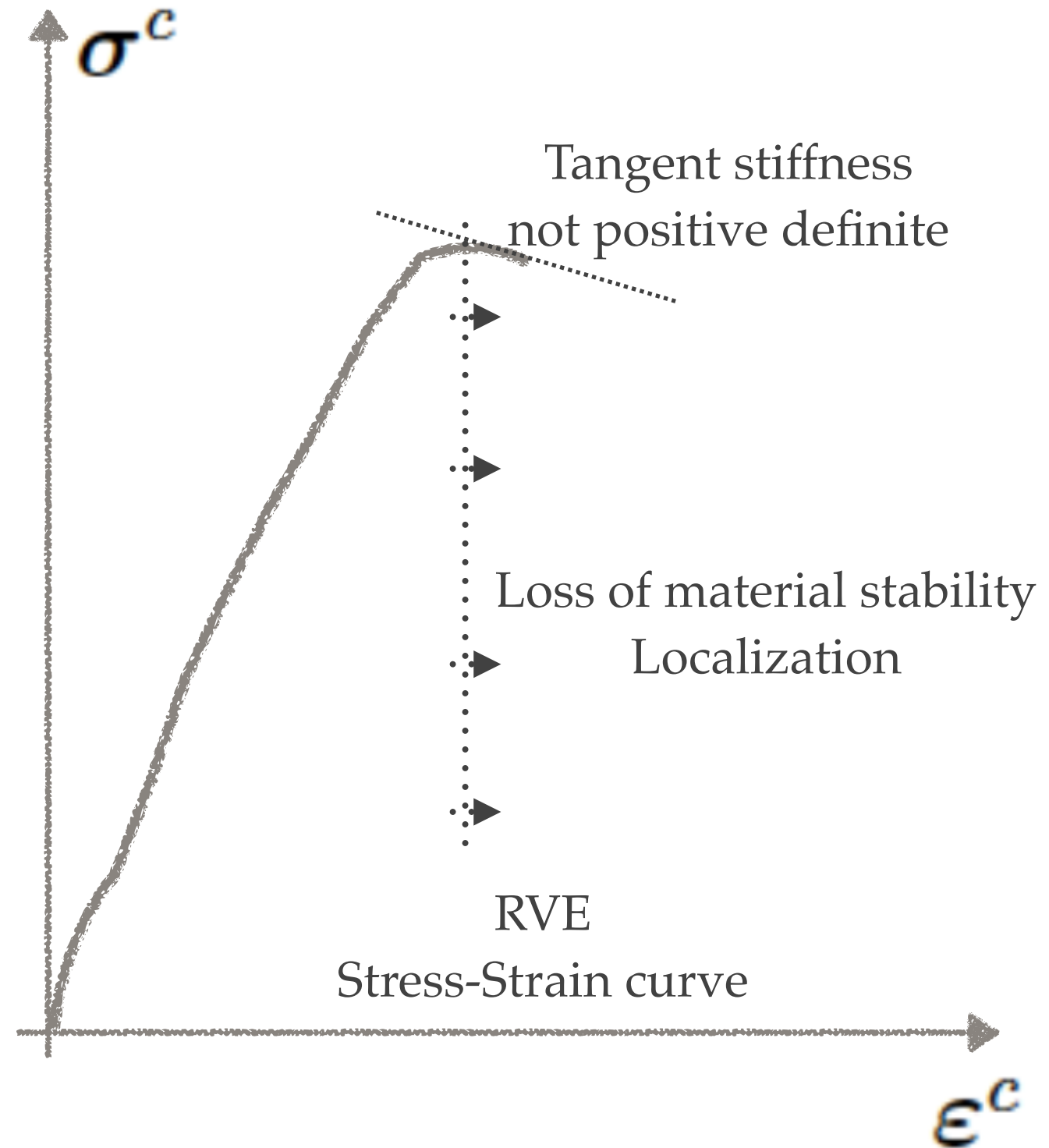


Feyel, Chaboche, 2000 - Akbari, Kerfriden, Bordas, 2014

Hierarchical methods FE²

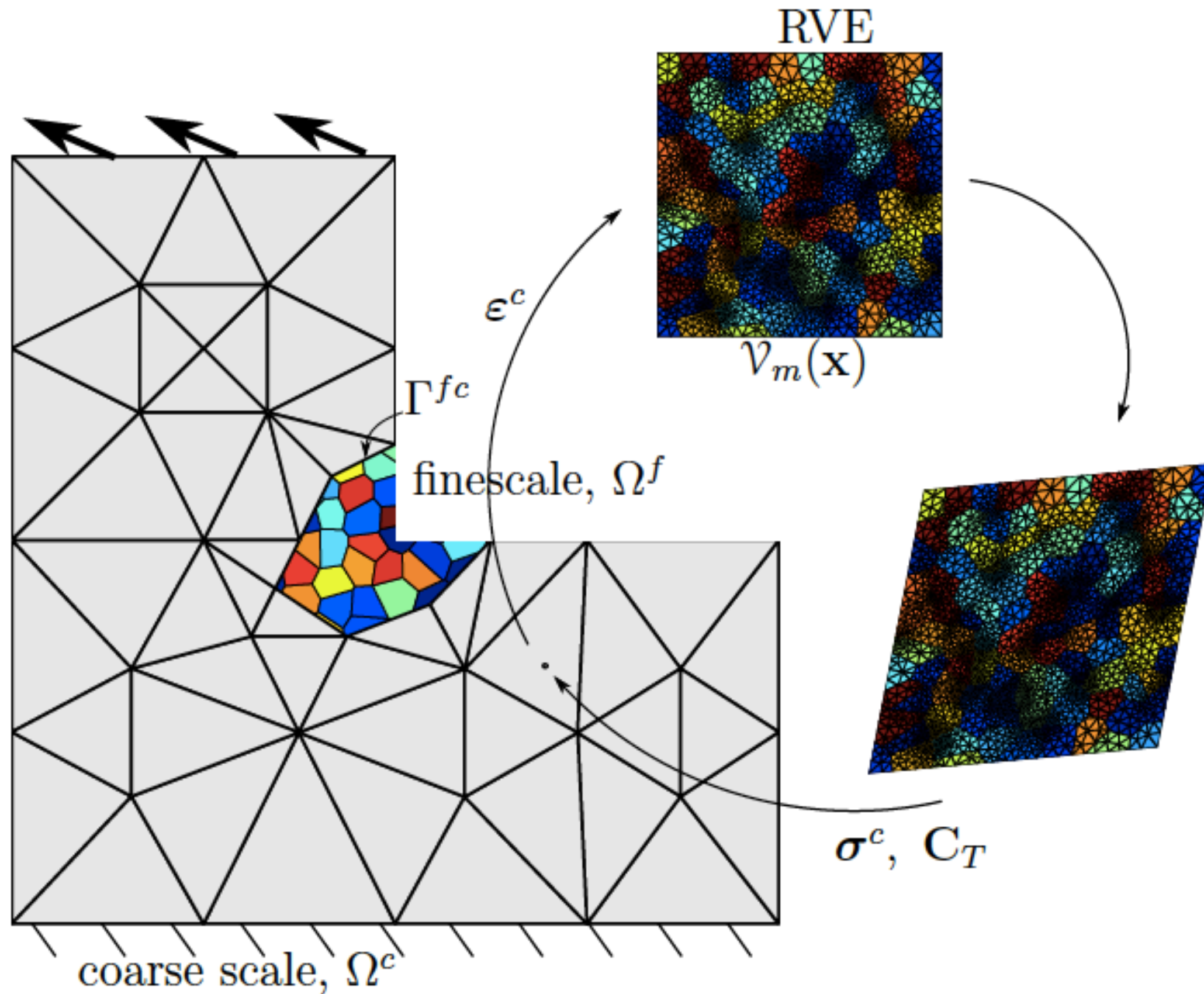


Unloading
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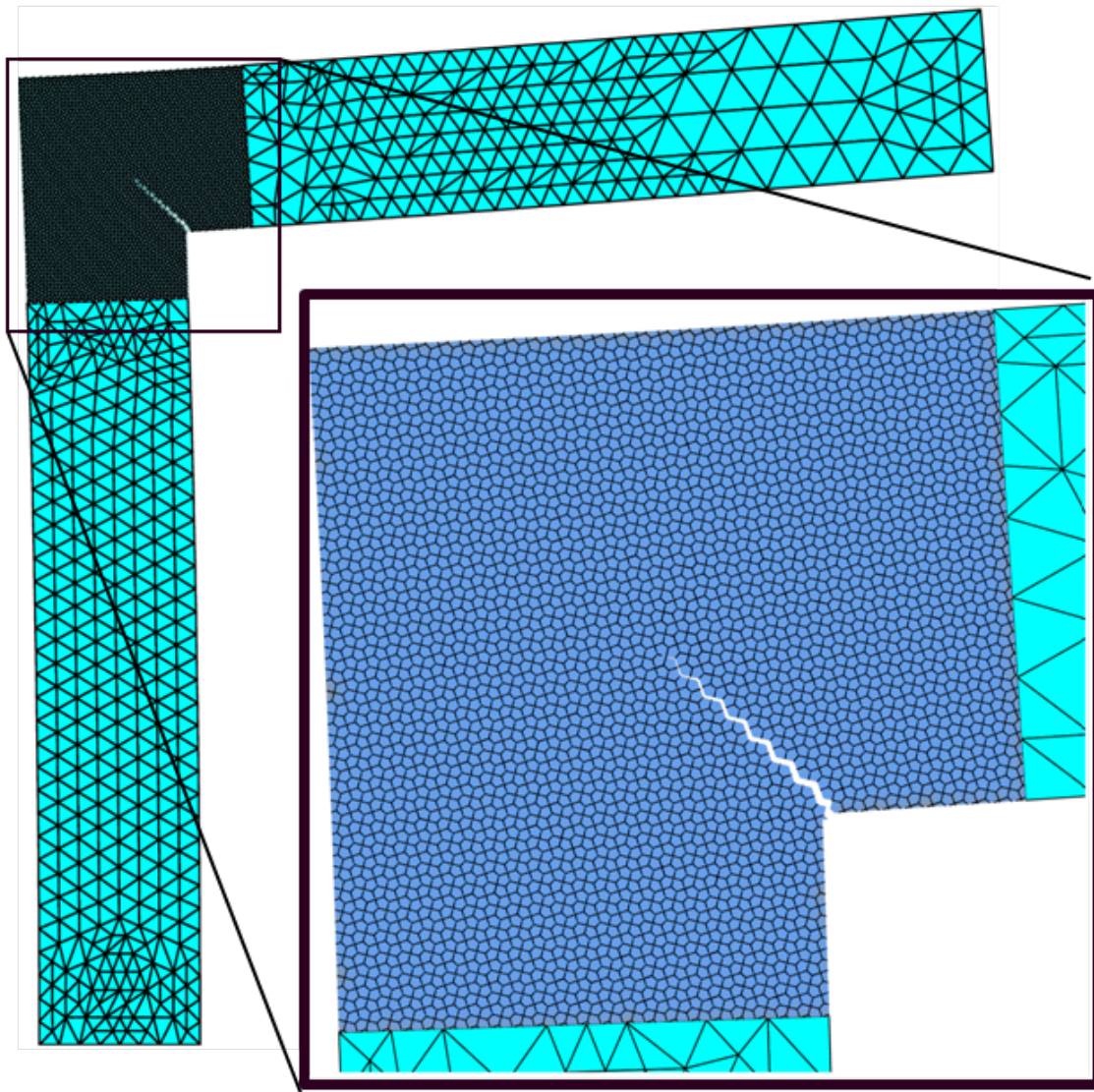
Feyel, Chaboche, 2000 - Akbari, Kerfriden, Bordas, 2014

Hybrid methods

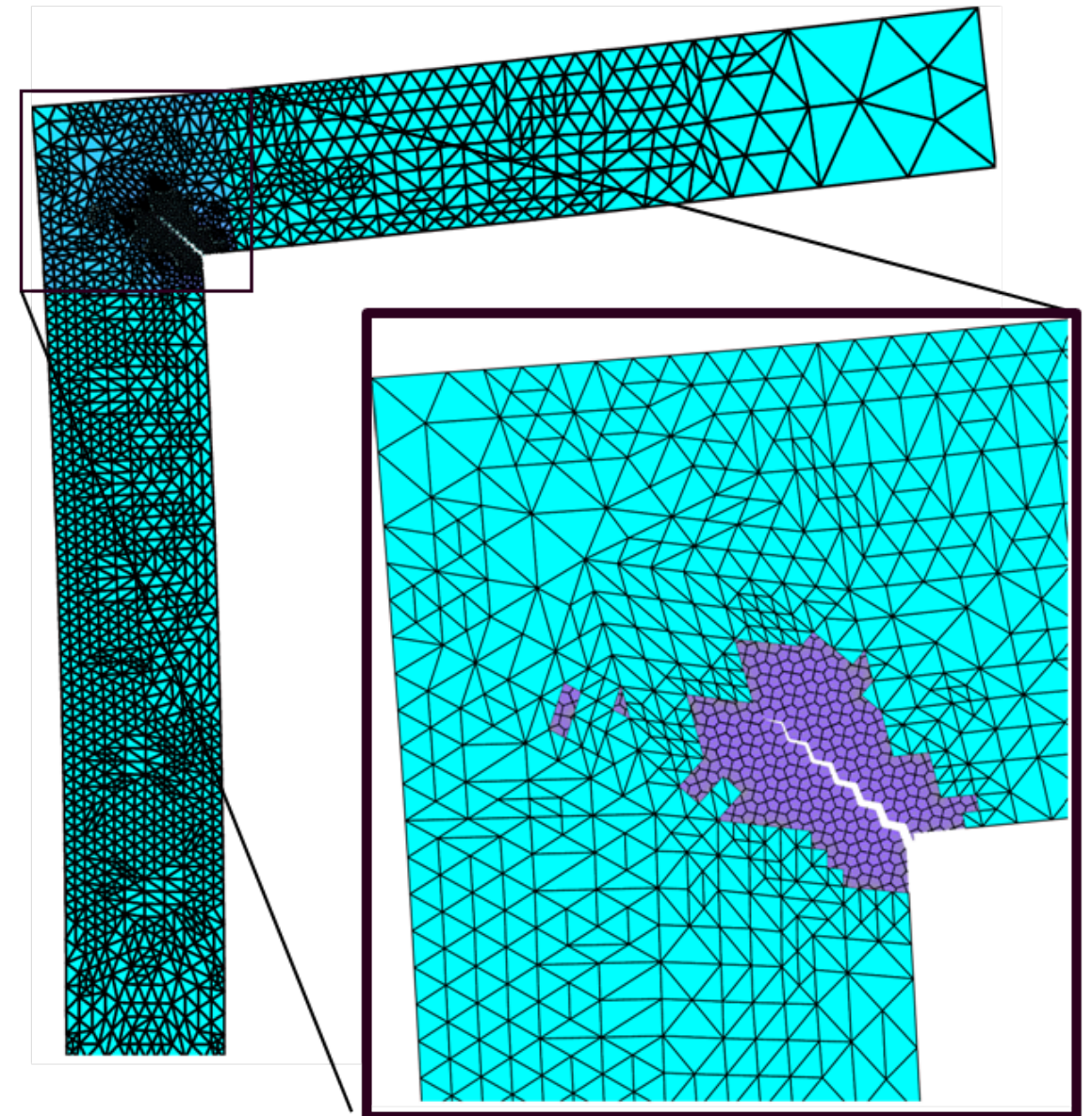


Example

Direct Numerical Solution



Adaptive Multiscale method



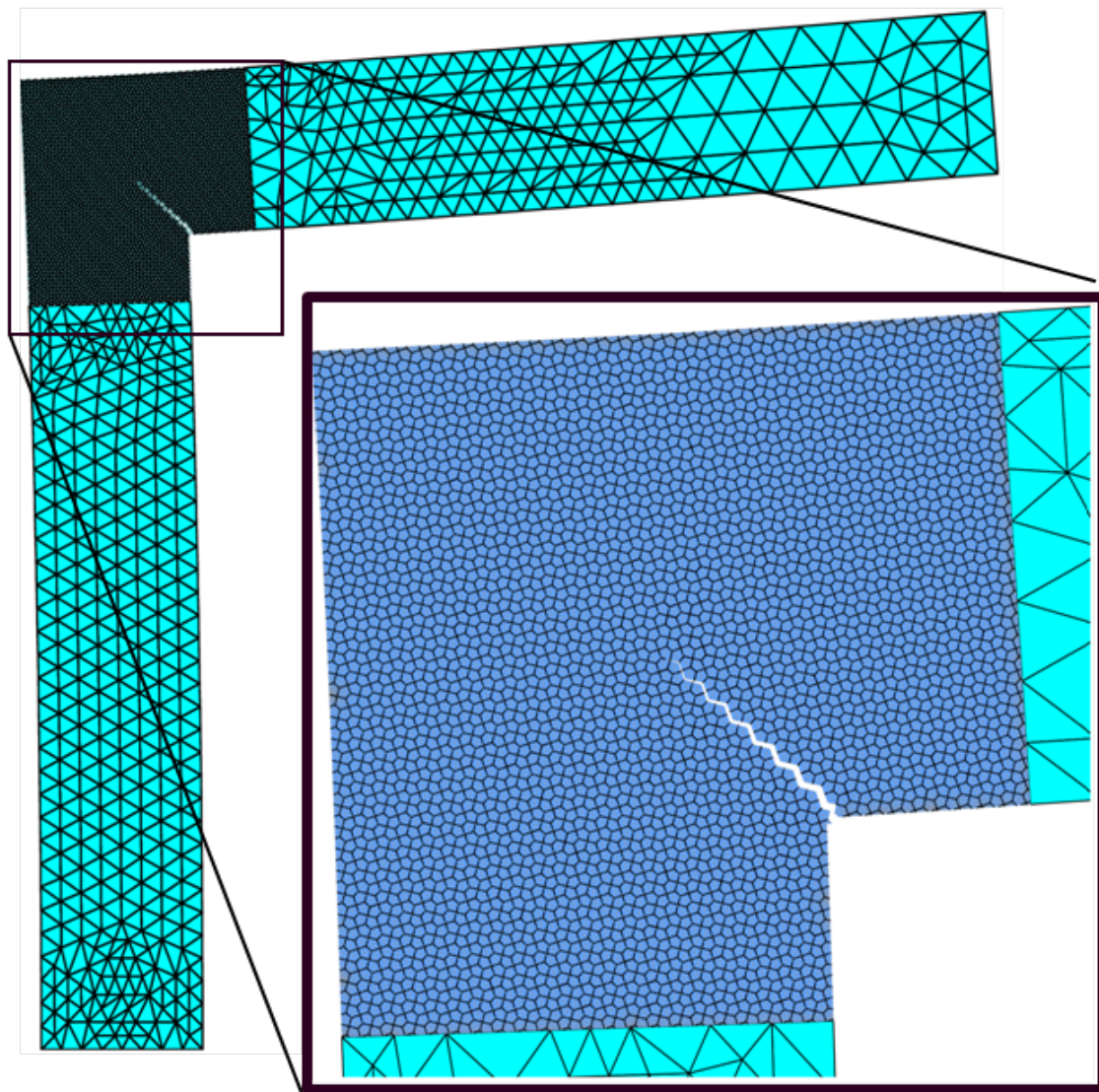
Example



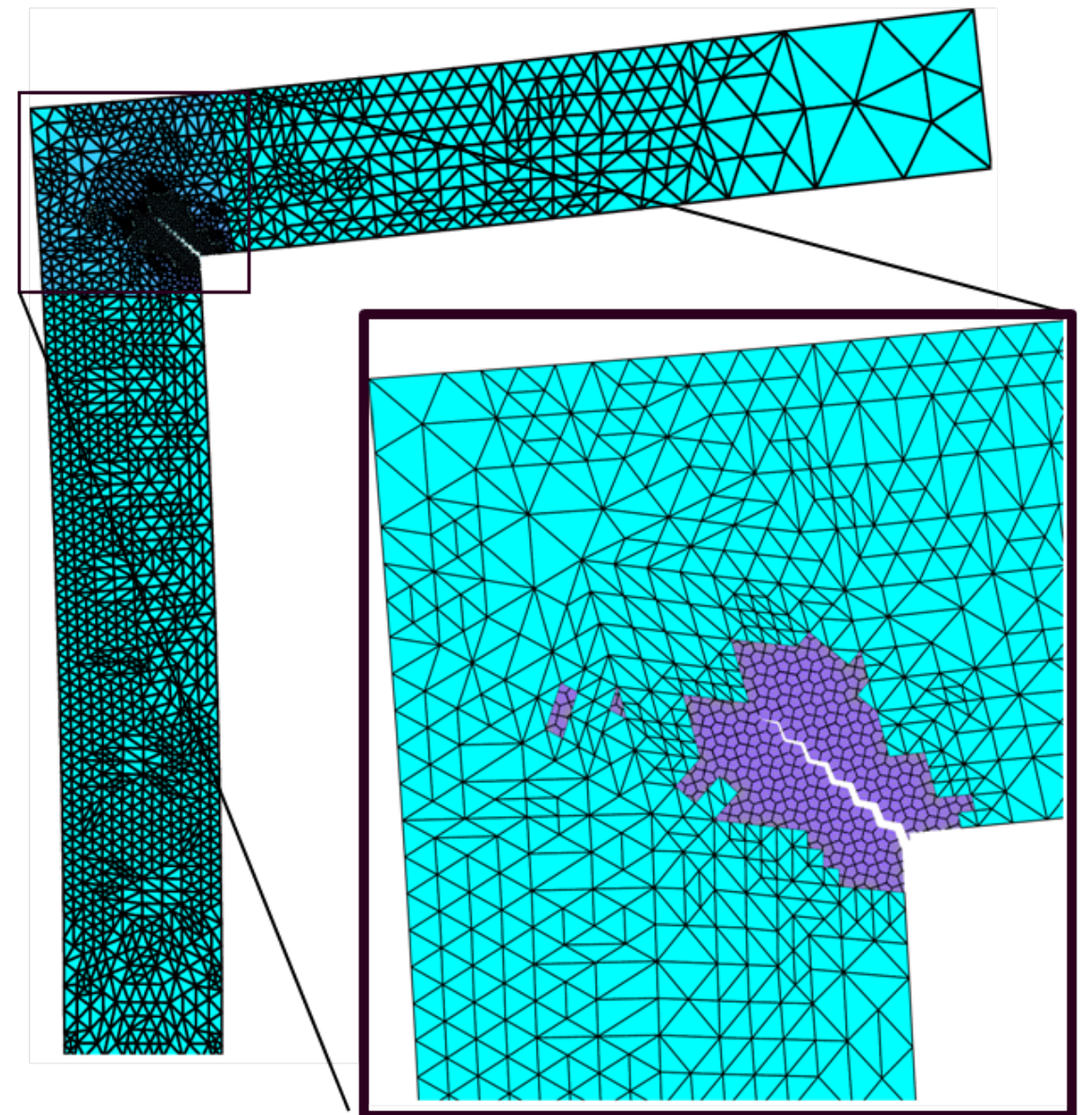
20-100 times fewer unknowns in 2D ~ 1000 times fewer in 3D



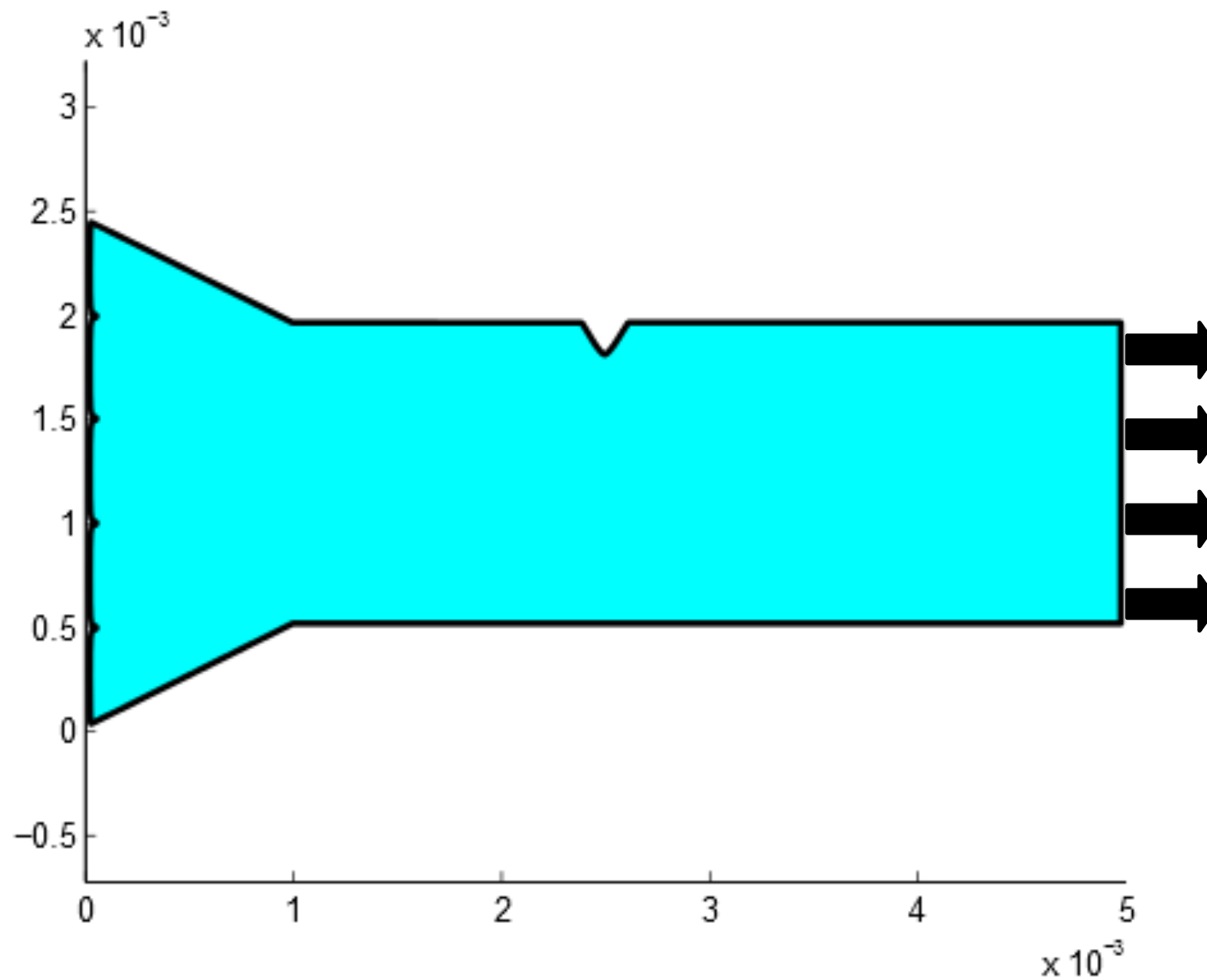
Direct Numerical Solution



Adaptive Multiscale method



Results: uni-axial tension

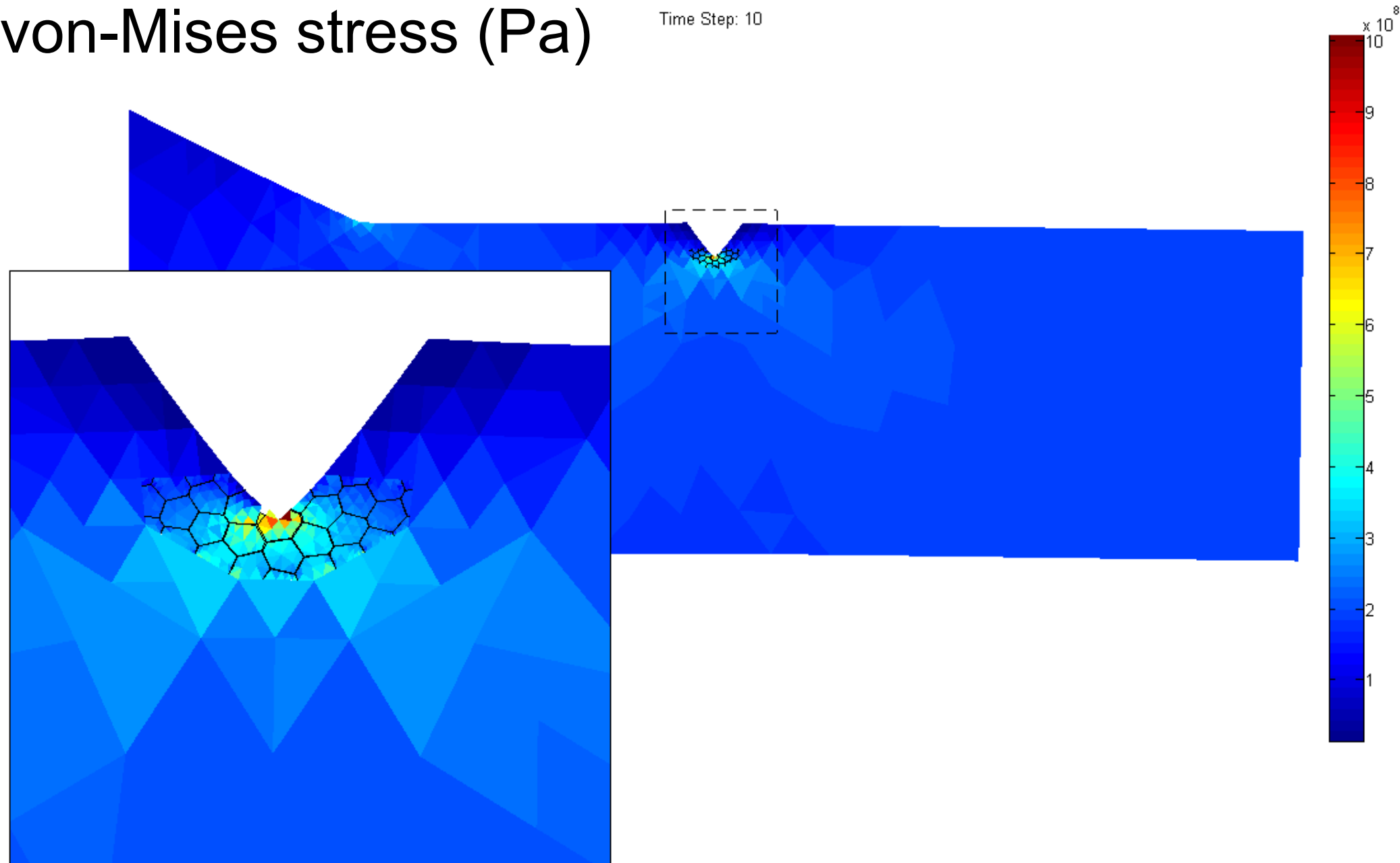


❖ Sizes are in mm

Results: uni-axial tension

von-Mises stress (Pa)

Time Step: 10



❖ 100X (magnification of displacement)

Results: uni-axial tension

von-Mises stress (Pa)

Time Step: 20

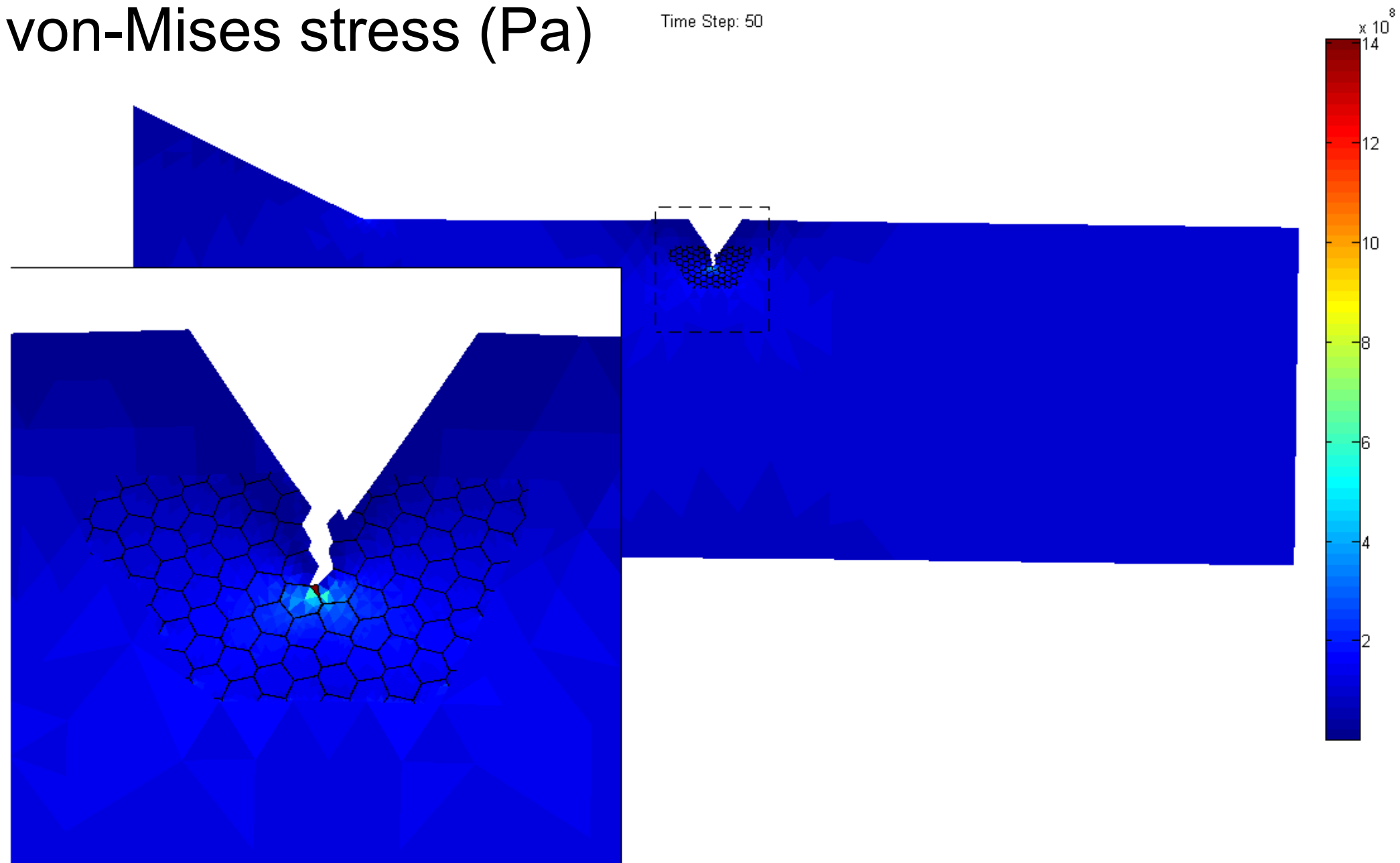


❖ 100X (magnification of displacement)

Results: uni-axial tension

von-Mises stress (Pa)

Time Step: 50

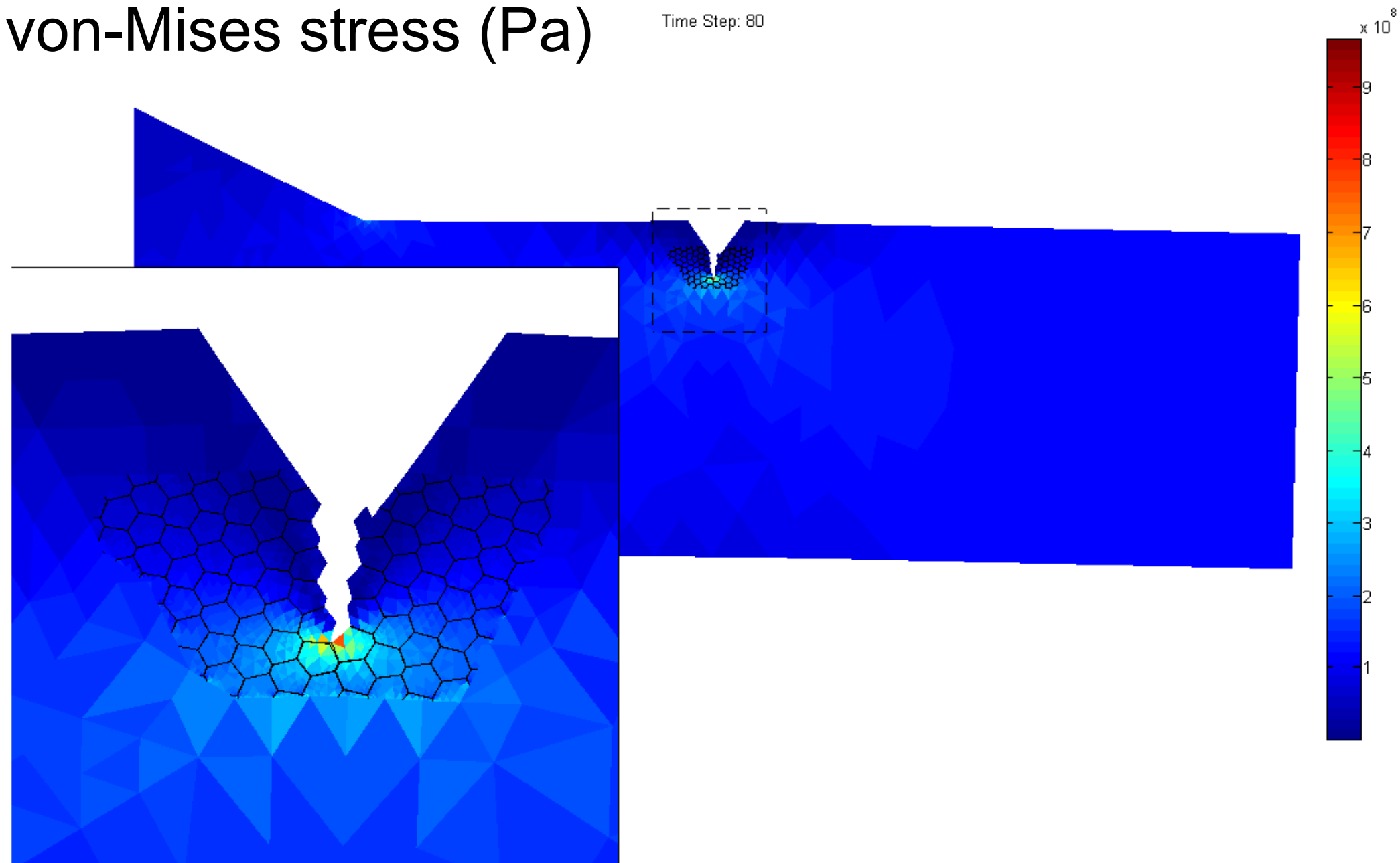


❖ 100X (magnification of displacement)

Results: uni-axial tension

von-Mises stress (Pa)

Time Step: 80

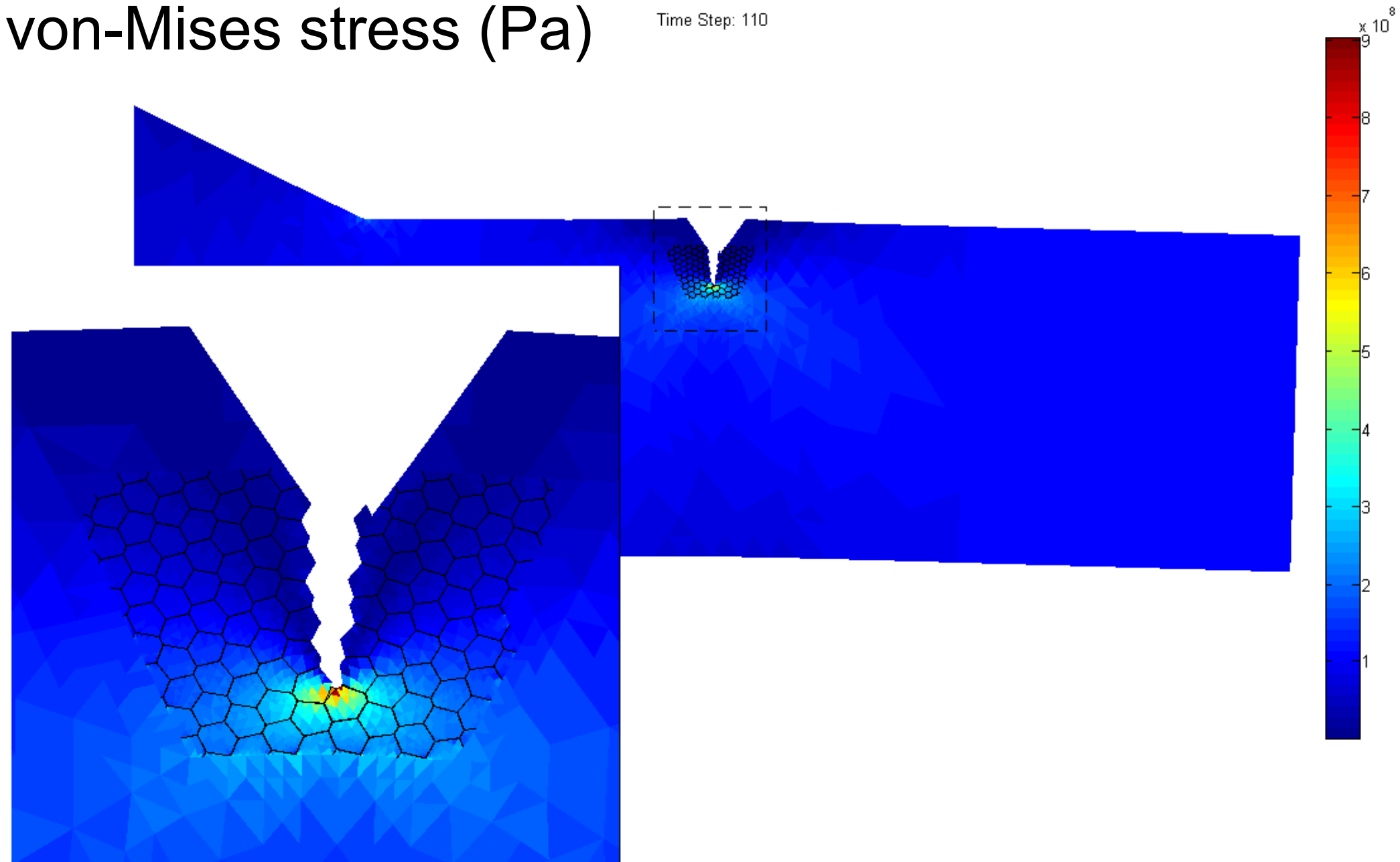


❖ 100X (magnification of displacement)

Results: uni-axial tension

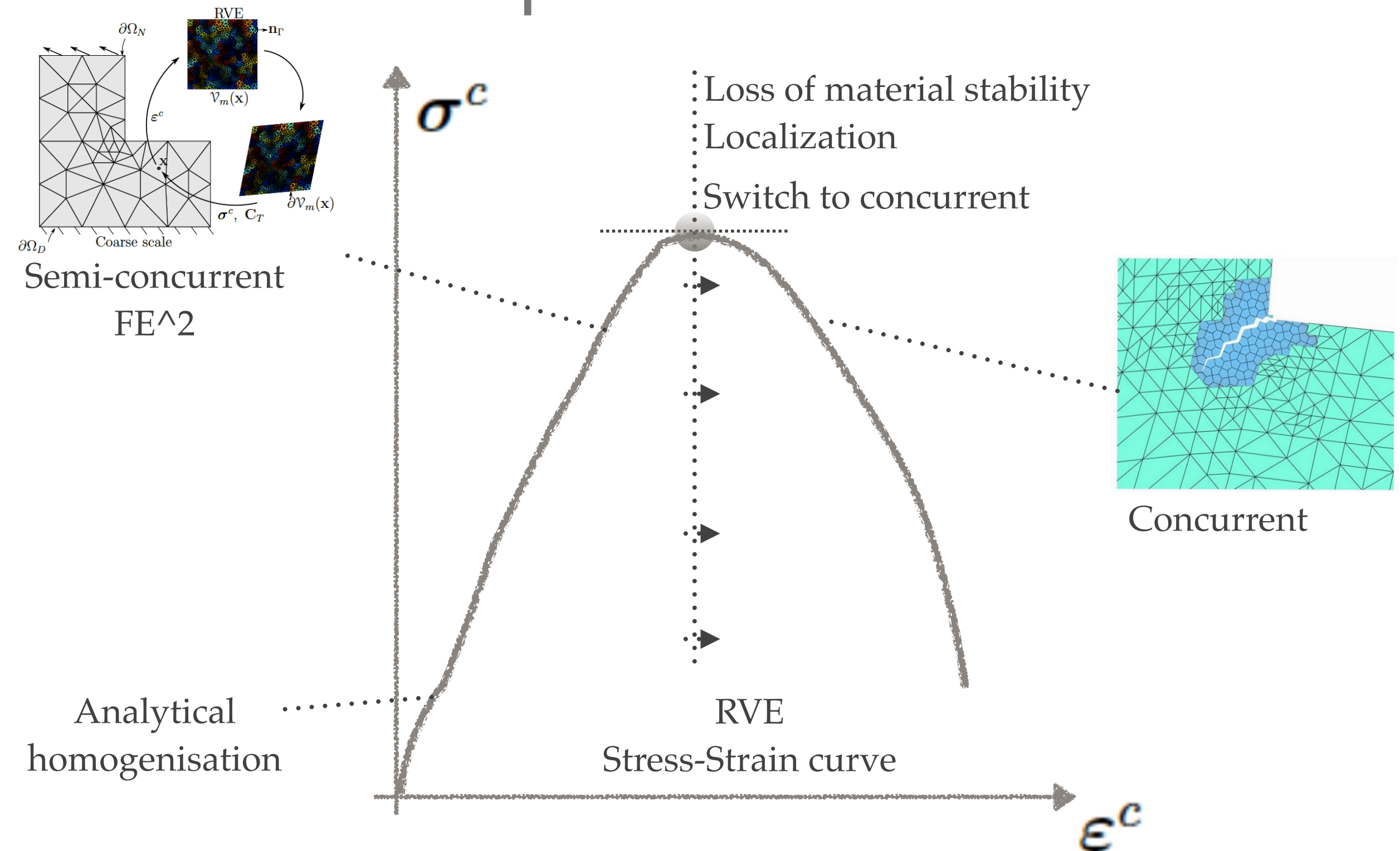
von-Mises stress (Pa)

Time Step: 110



❖ 100X (magnification of displacement)

Adaptive multi-scale



Open problem

- model selection and error control

Possible approach

- machine learning and statistical inference, e.g. Bayesian statistics

Open problem

- statistical variability at the fine scale (geometry, material parameter)

Possible approach

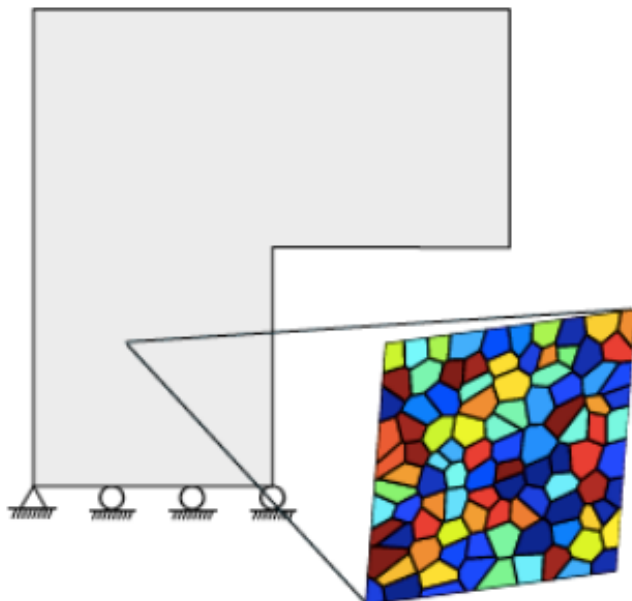
- identification through small-scale experiments (costly, difficult to characterize interfaces)
- Monte Carlo

Challenge

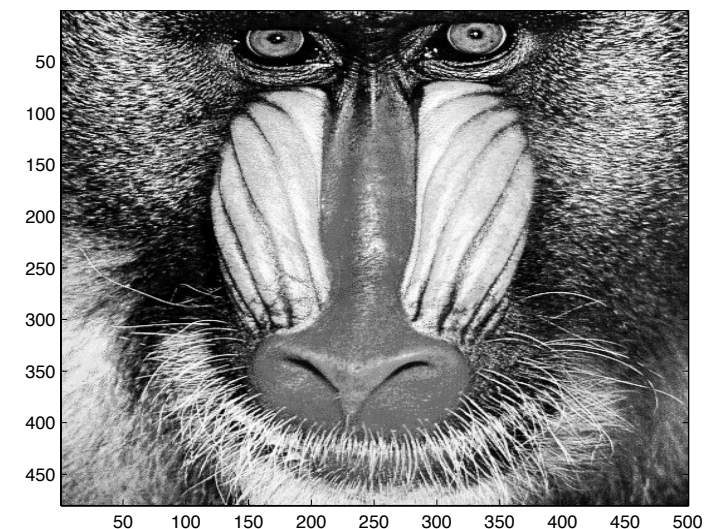
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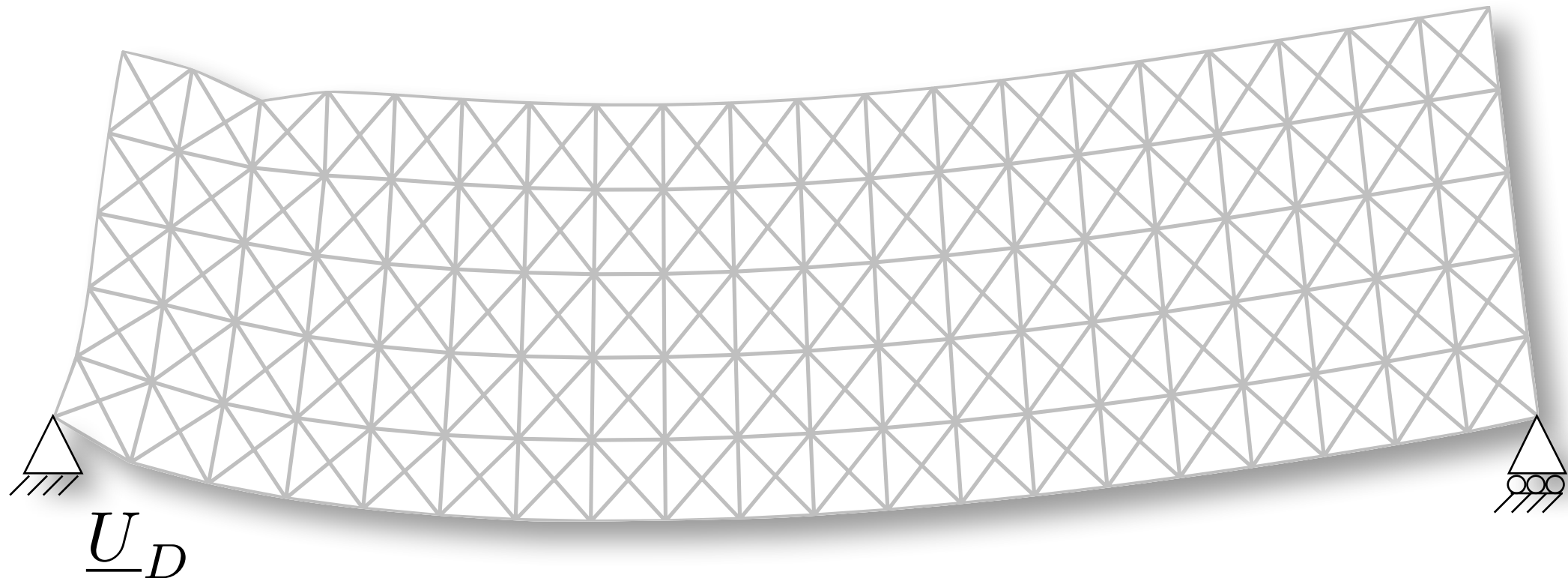
Algebraic model reduction methods

Use precomputed solutions to accelerate online simulations

Example - parametric problems

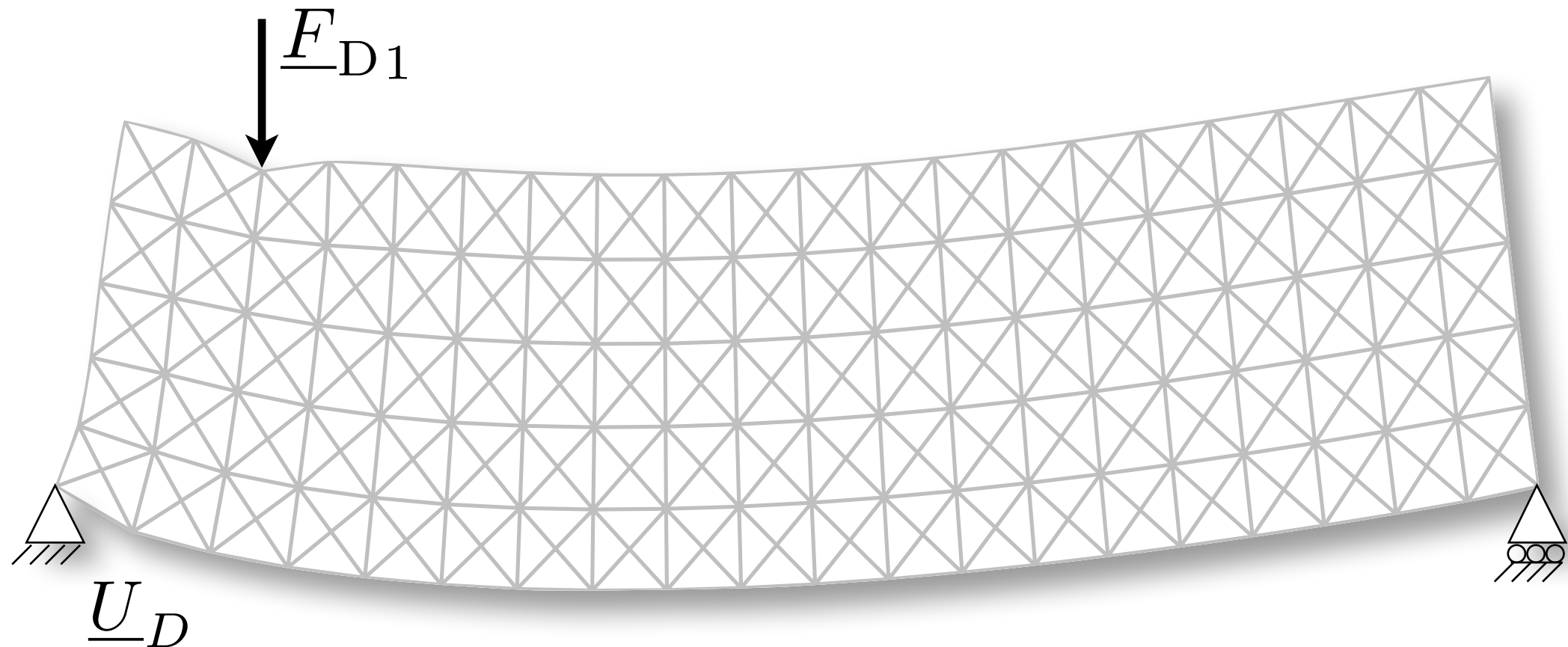
Method of separated representation

Lattice beam problem



Aim: accelerate the simulation using
pre-computations

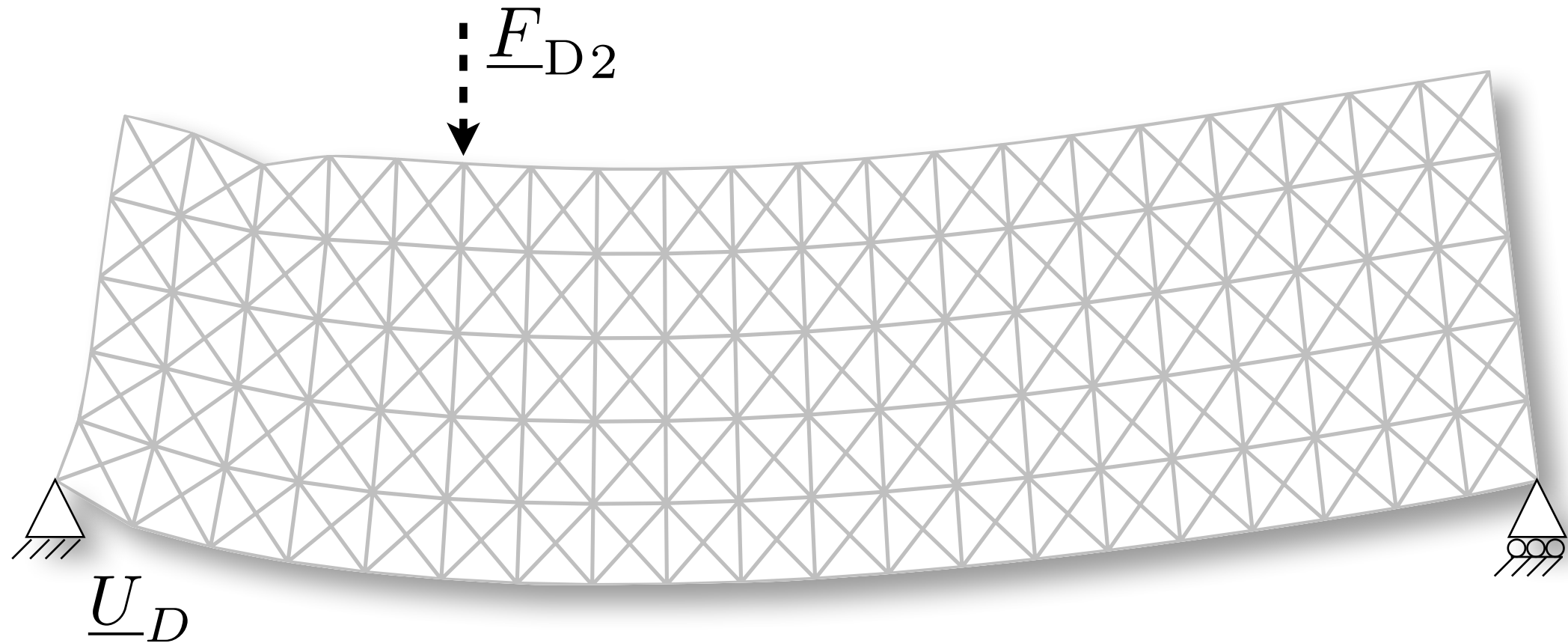
Lattice beam problem



$$\underline{\underline{\mathbf{S}}} = \left(\underline{\mathbf{S}}^1 \right.$$

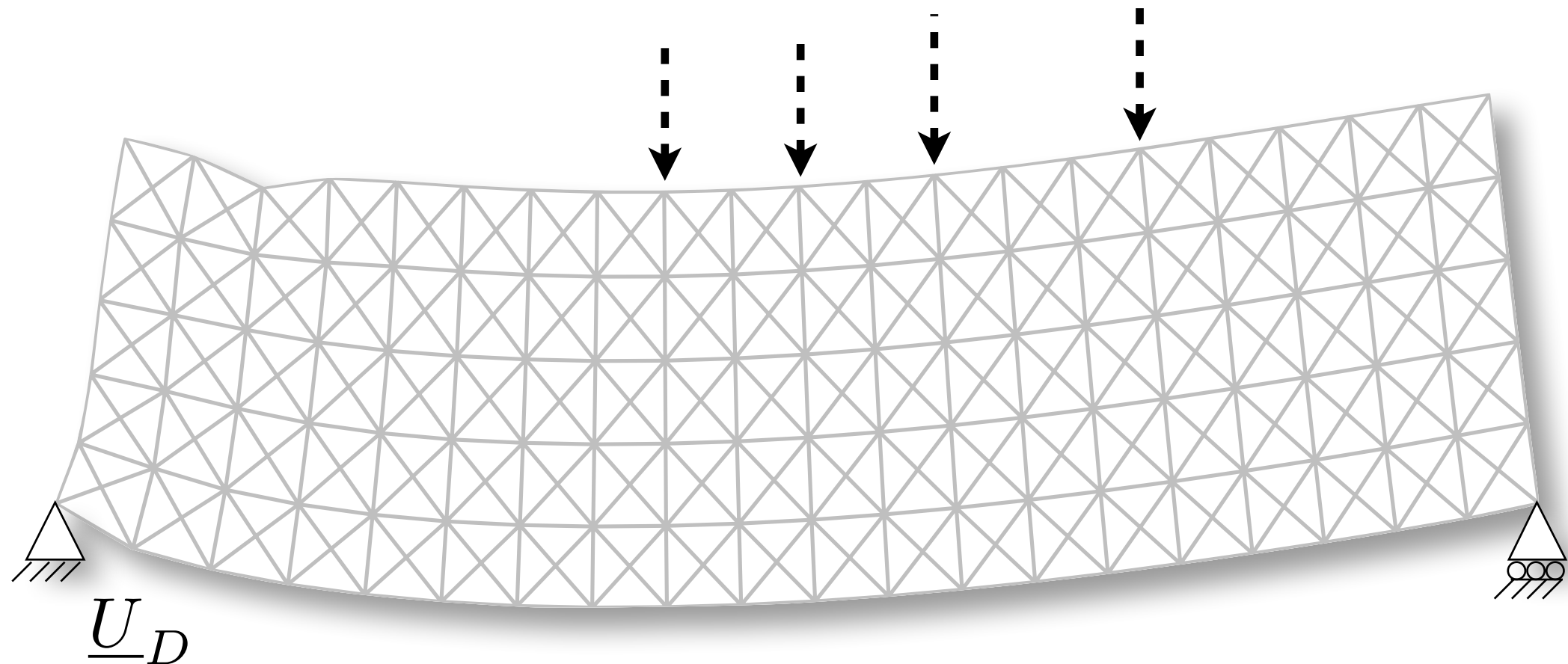
Compute solutions for several loading conditions

Lattice beam problem



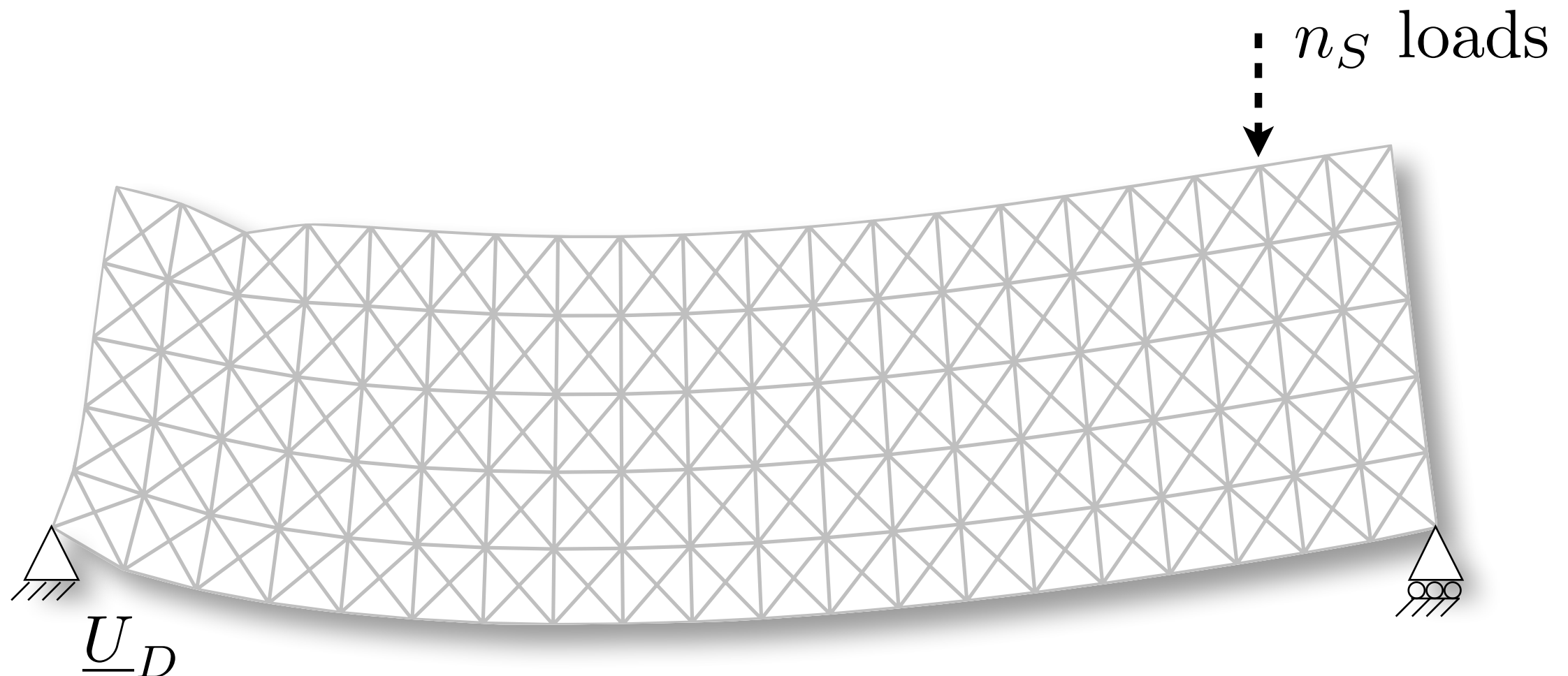
$$\underline{\underline{\mathbf{S}}} = \left(\underline{\underline{\mathbf{S}}}^1 \quad \underline{\underline{\mathbf{S}}}^2 \right)$$

Lattice beam problem



$$\underline{\underline{\mathbf{S}}} = \left(\underline{\underline{\mathbf{S}}}^1 \quad \underline{\underline{\mathbf{S}}}^2 \quad \dots \right)$$

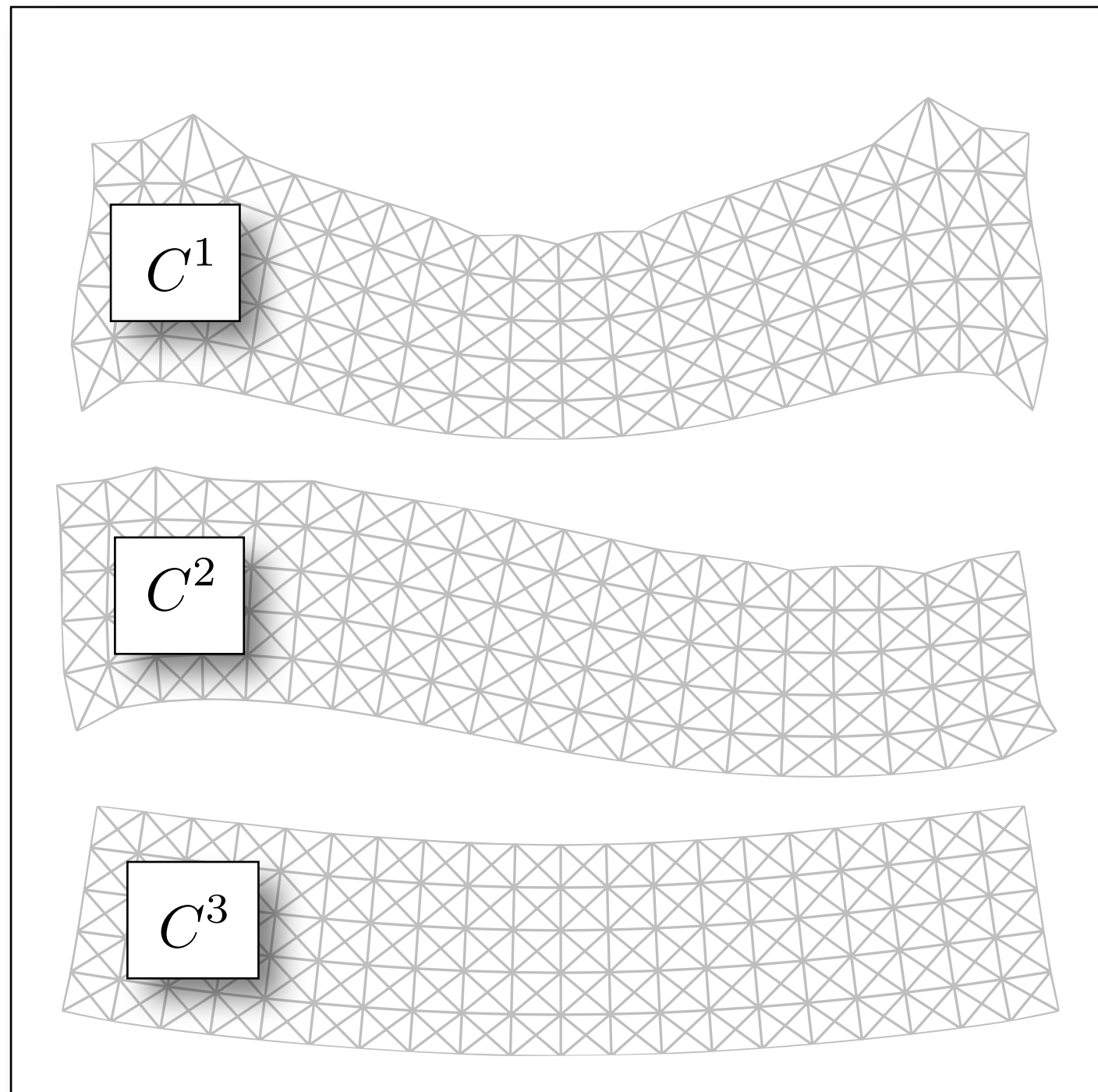
Lattice beam problem



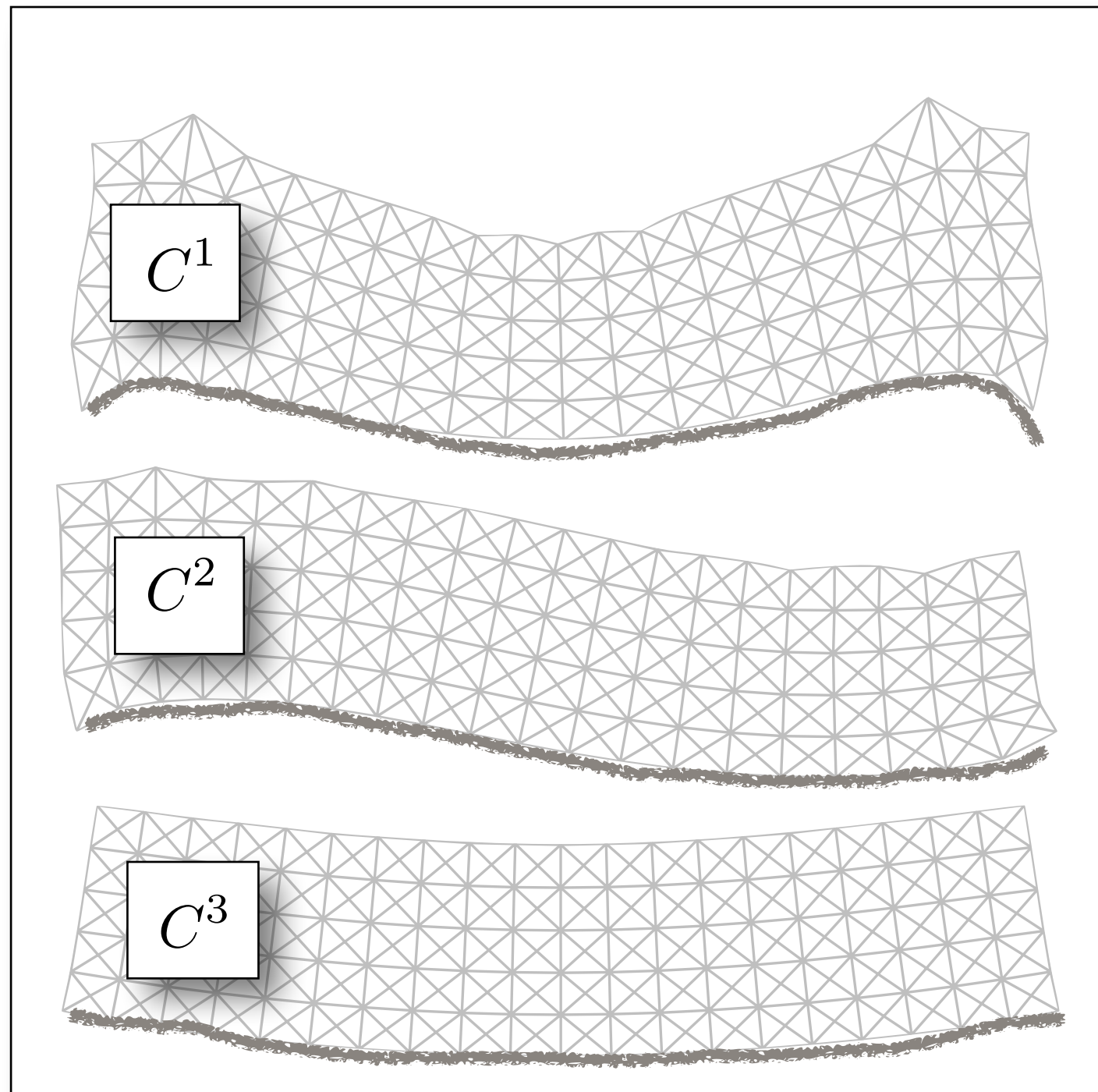
$$\underline{\underline{\mathbf{S}}} = \left(\underline{\mathbf{S}}^1 \quad \underline{\mathbf{S}}^2 \quad \dots \quad \underline{\mathbf{S}}^{n_S} \right)$$

Perform singular value decomposition - POD
to obtain “most energetic modes”

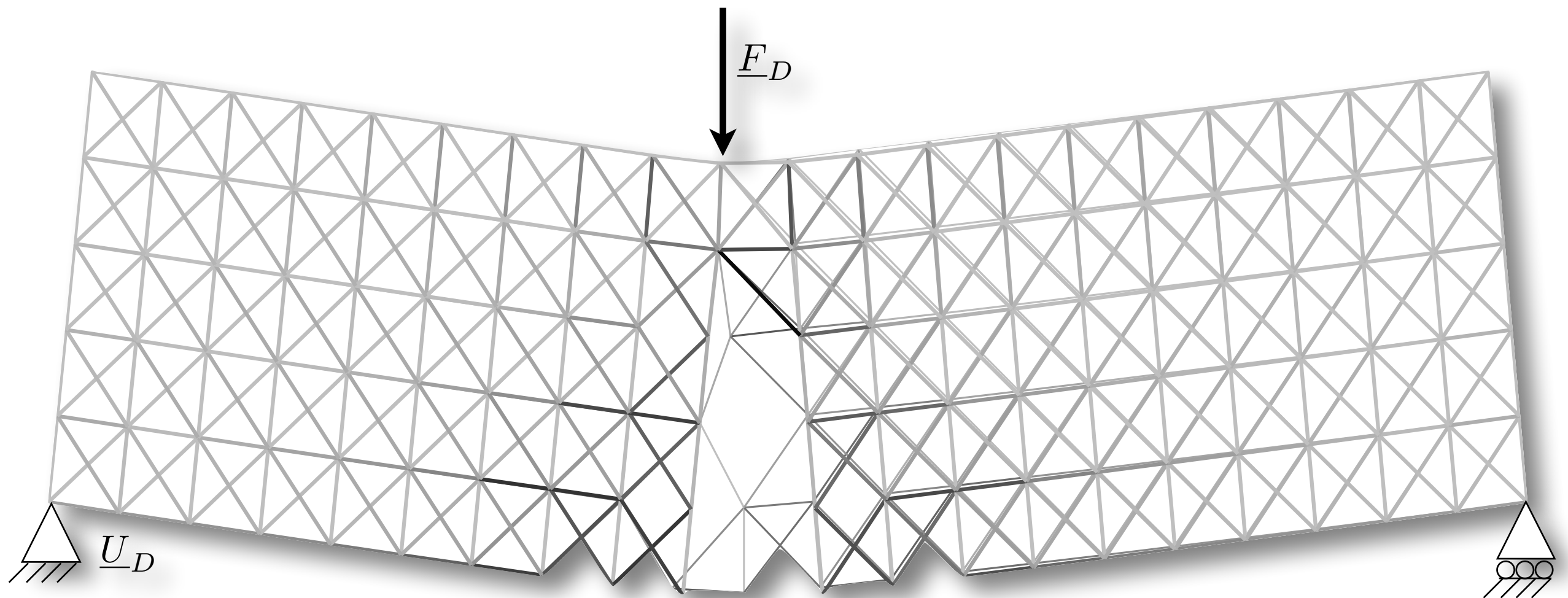
Reduced basis



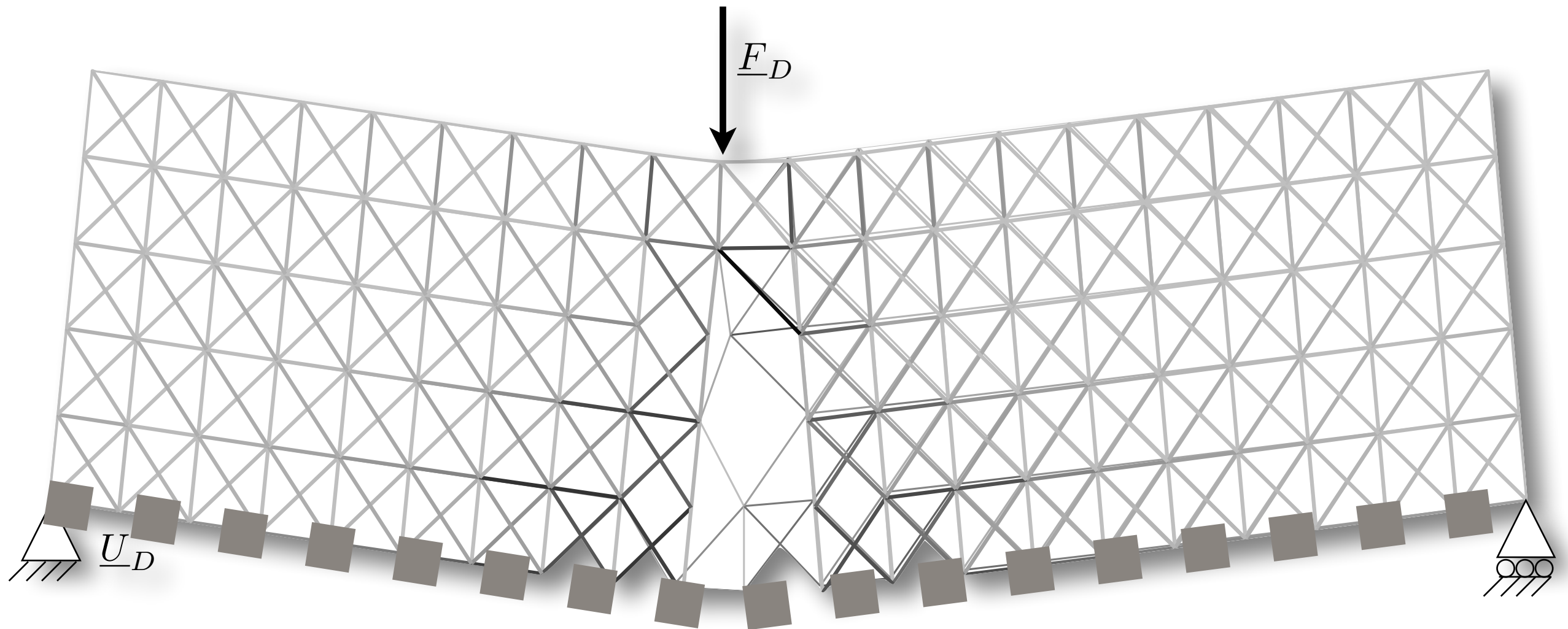
Reduced basis

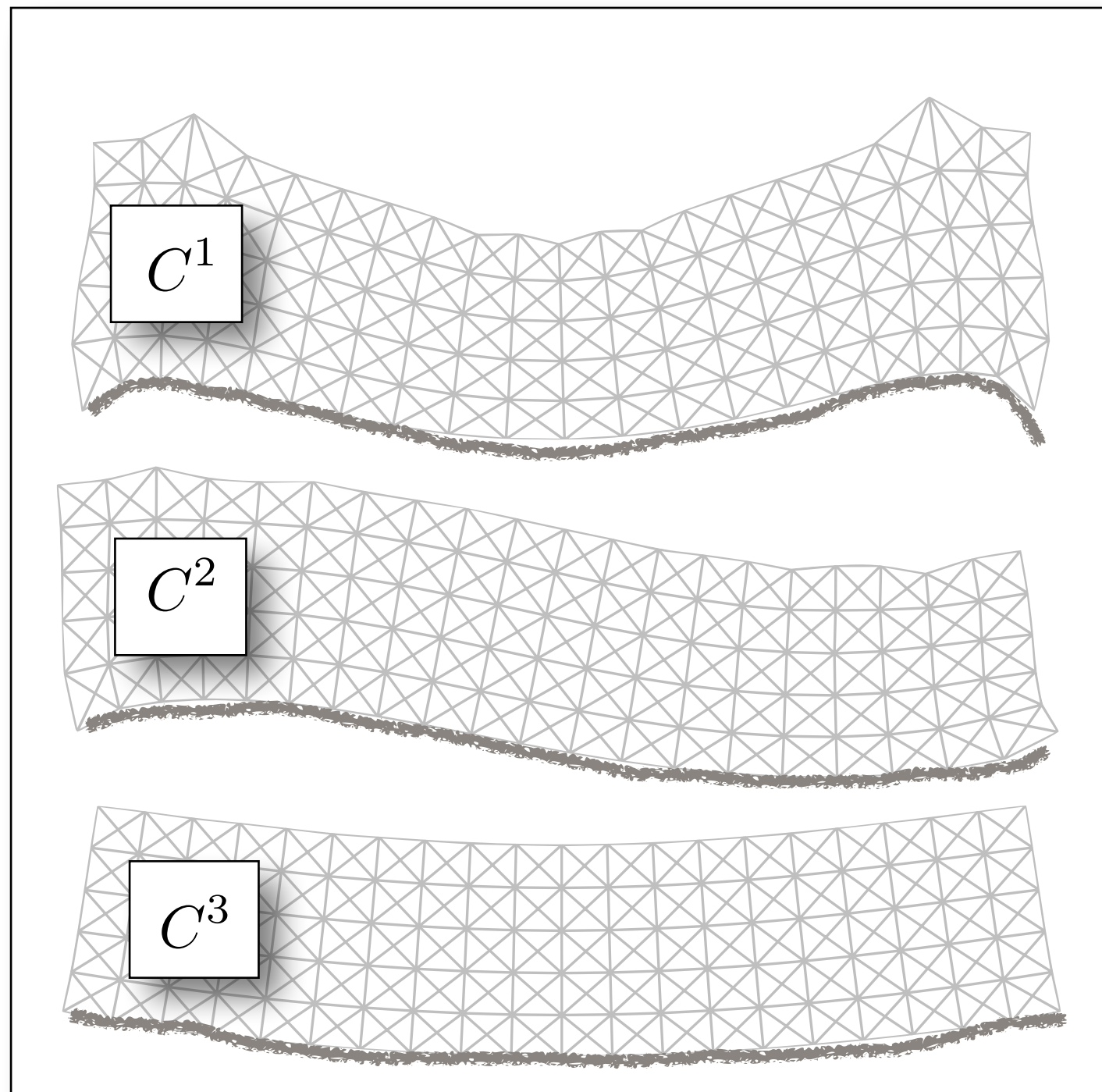


Beyond the elastic limit



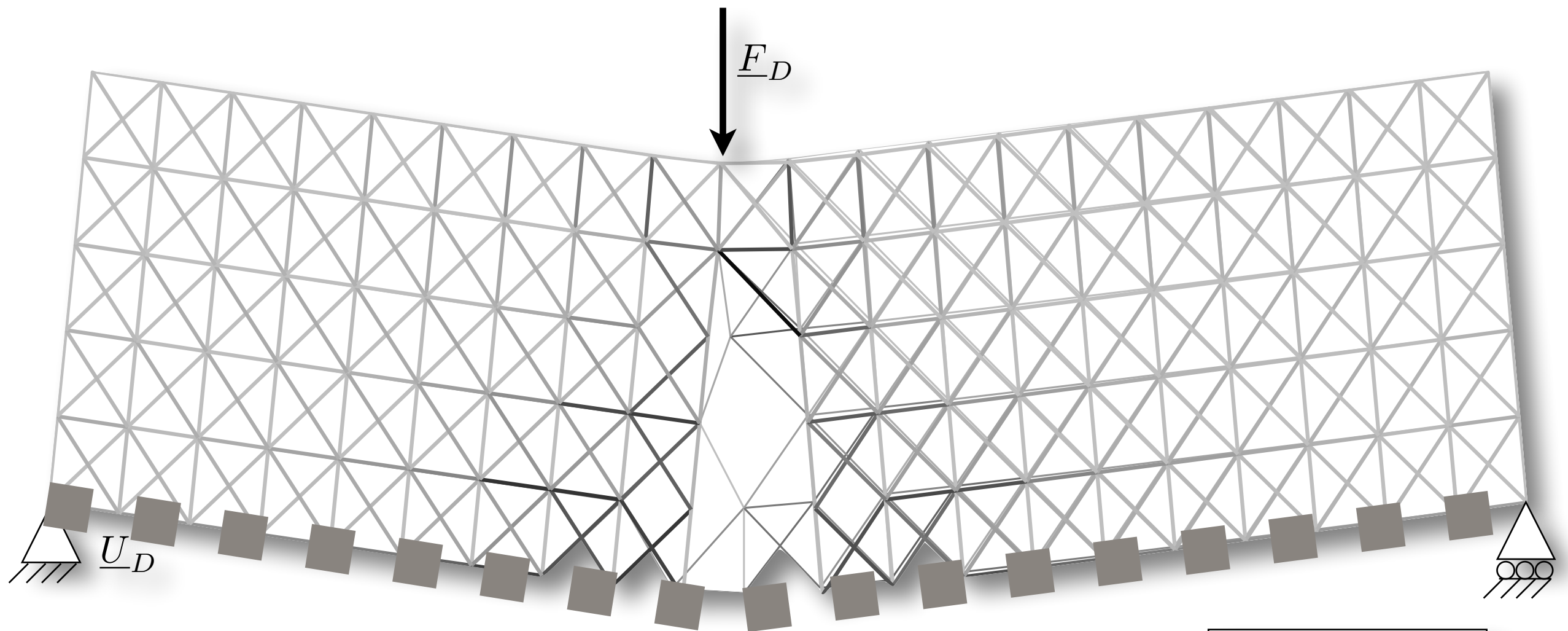
Beyond the elastic limit



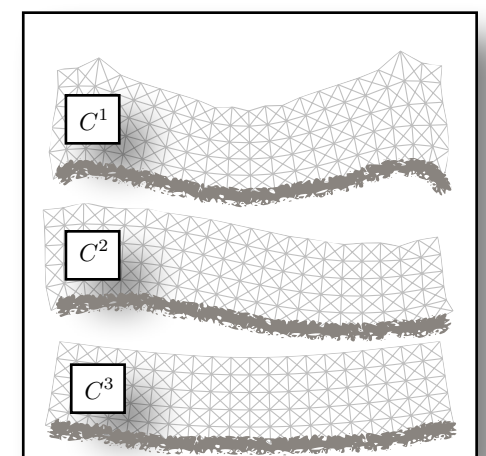


Smooth

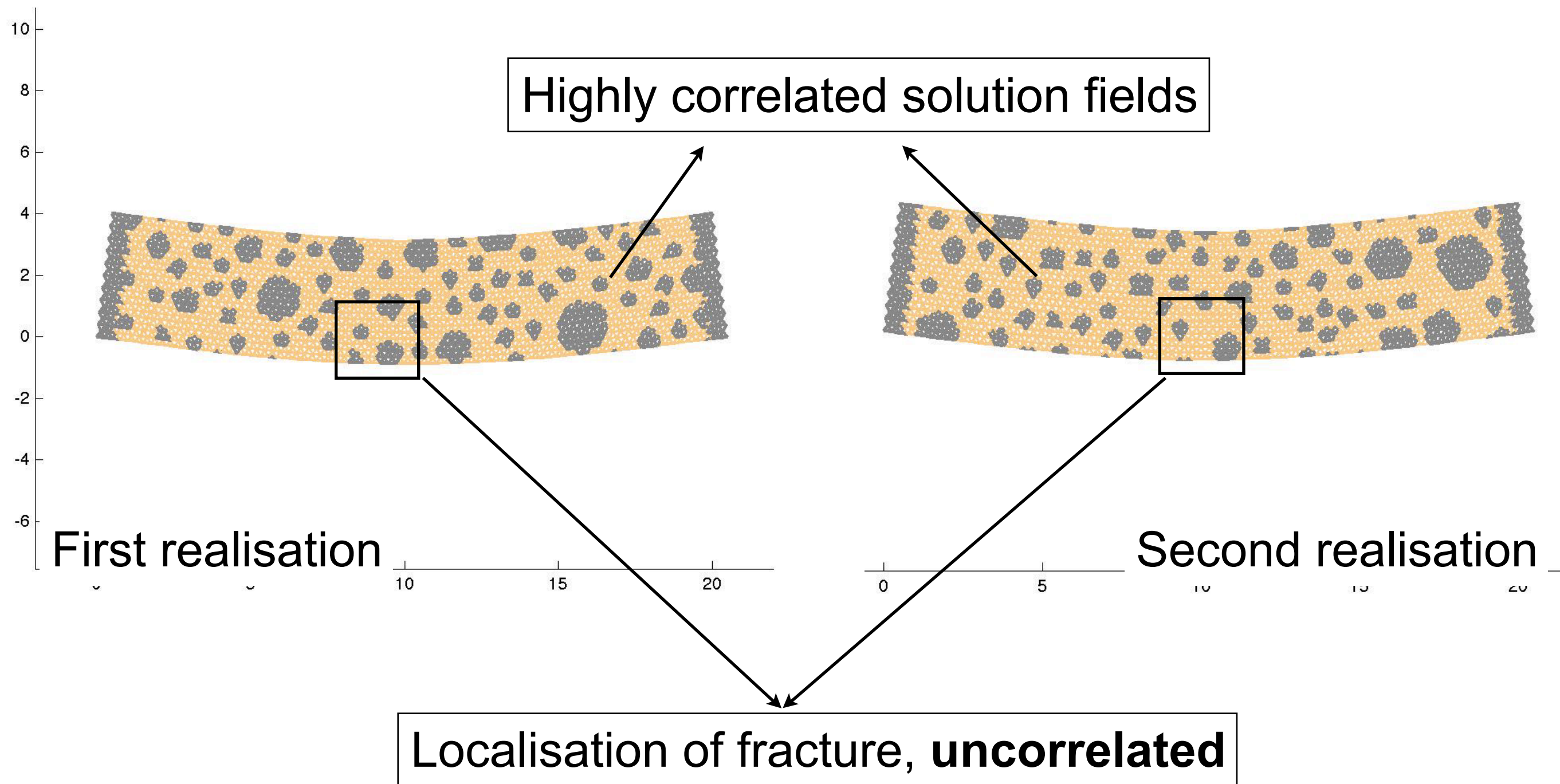
Kink



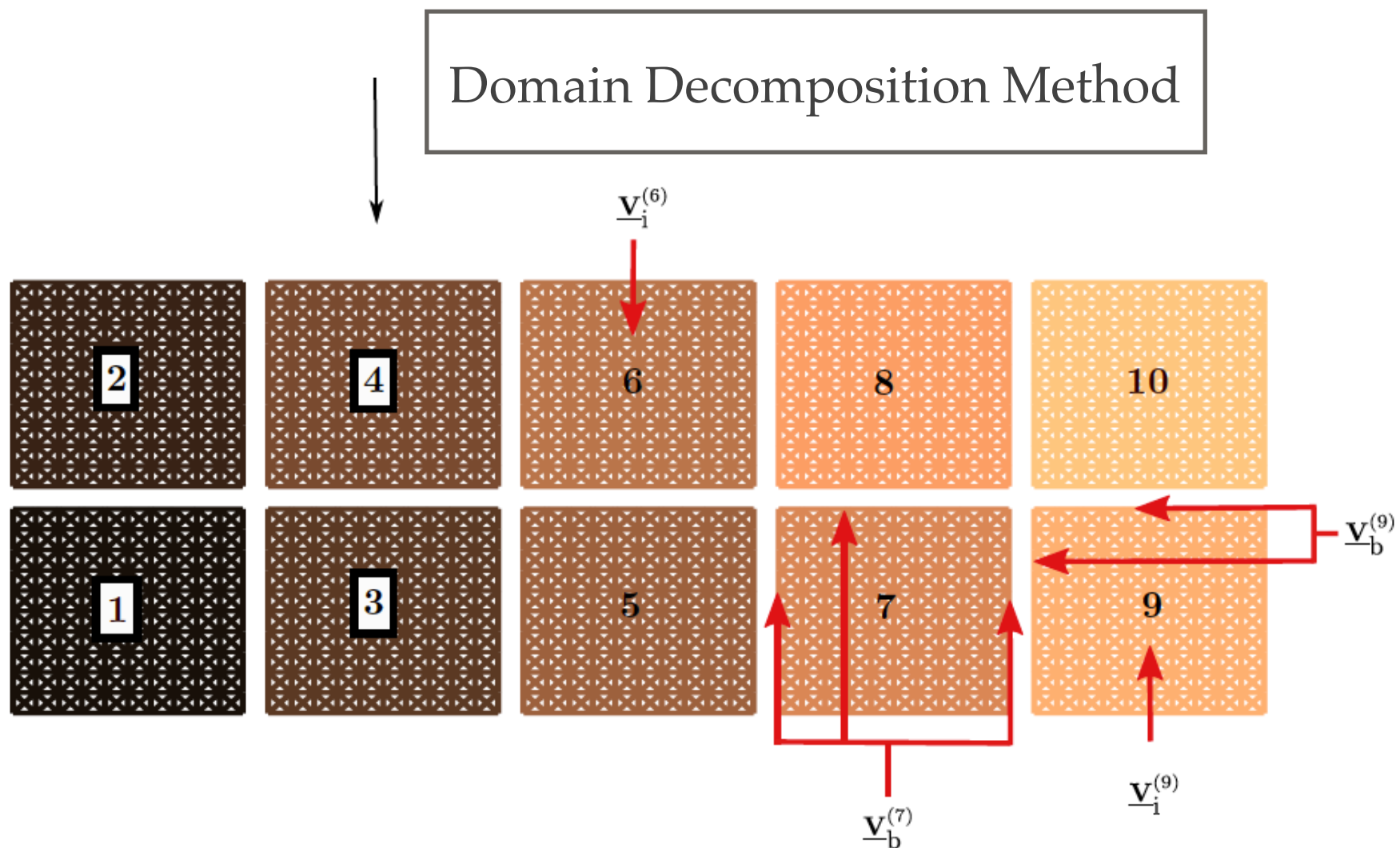
This solution is not in the snapshot !



Parametric / stochastic multiscale fracture mechanics



Partitioned POD/DDM

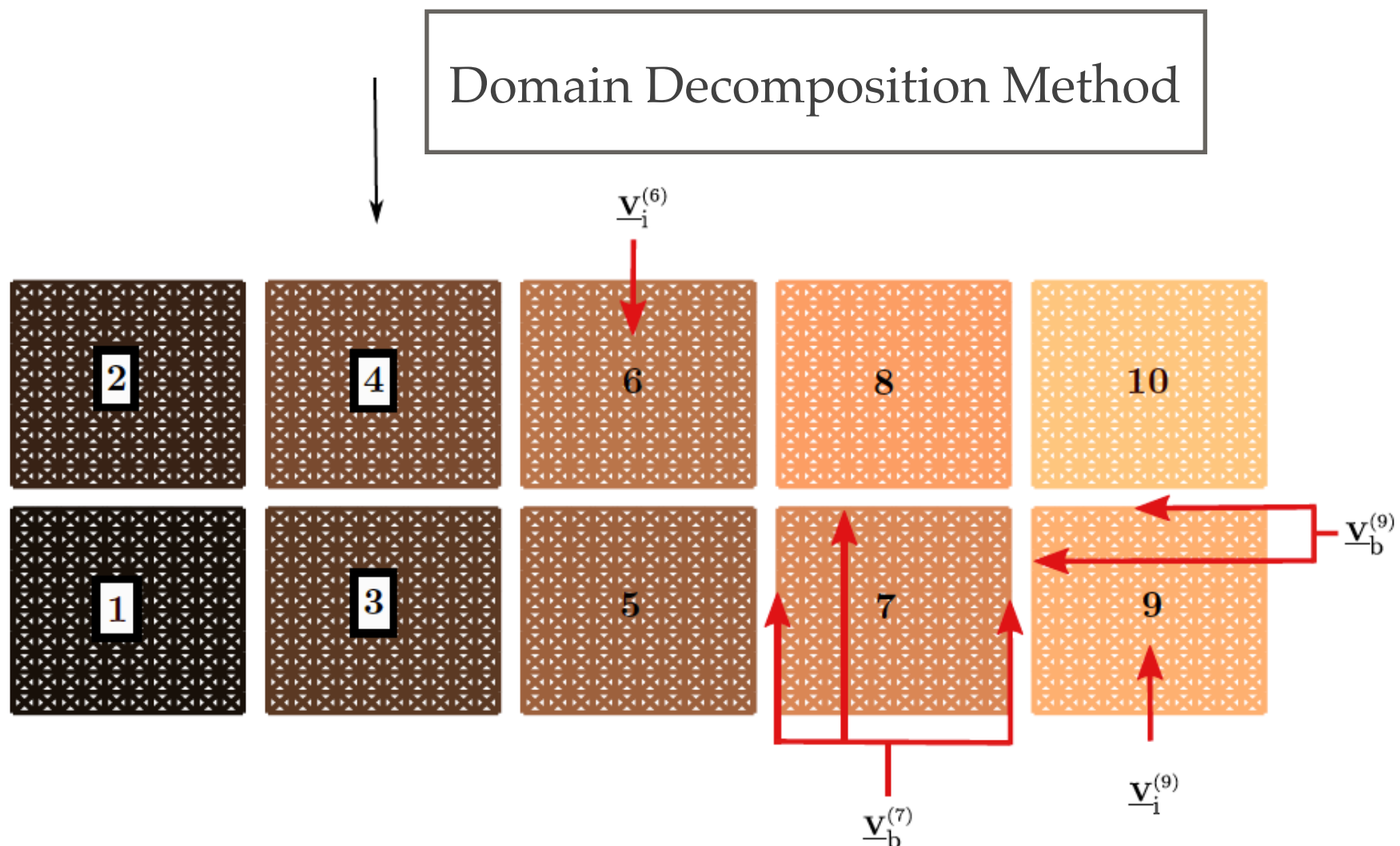


Partitioned POD/DDM



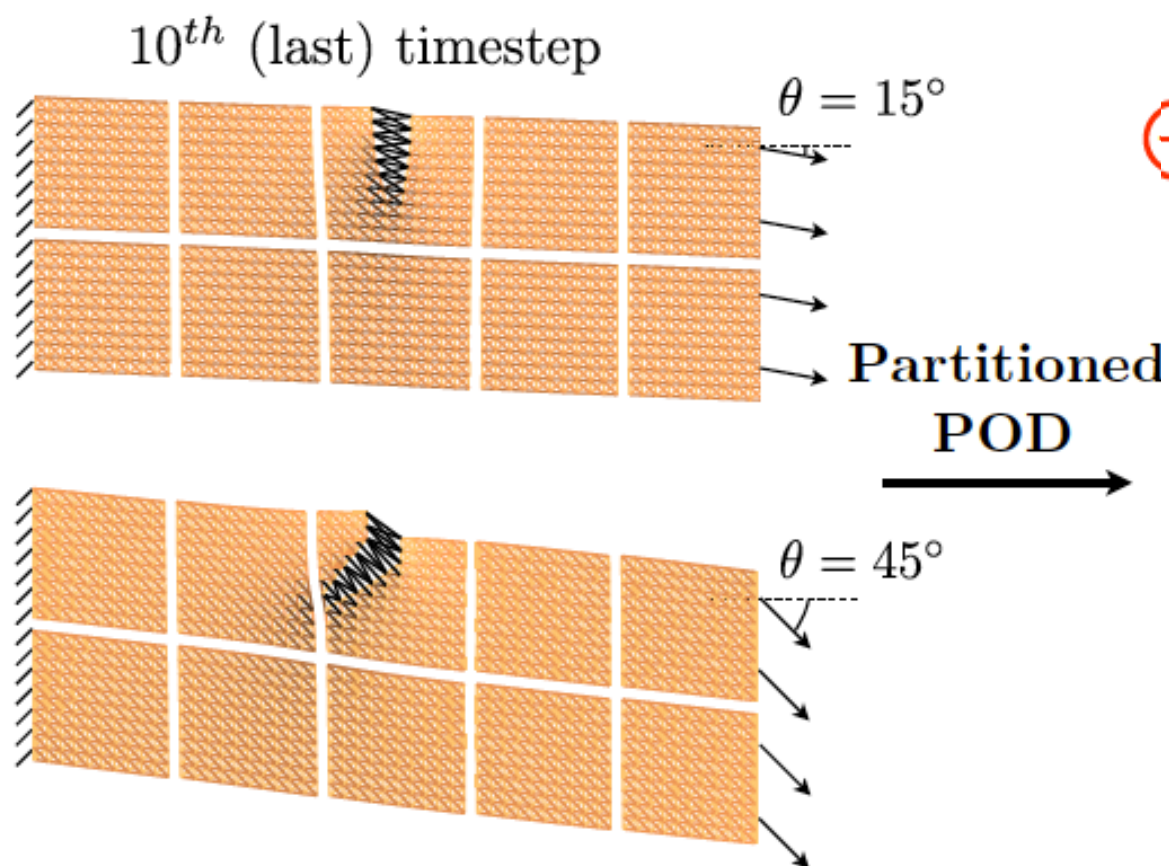
Domain Decomposition Method

Partitioned POD/DDM

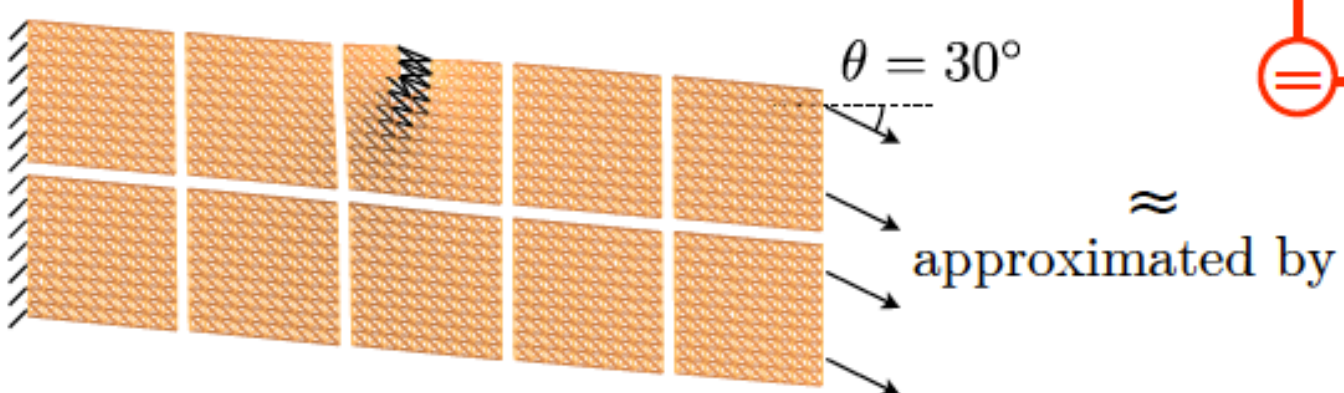


Compute particular realisations

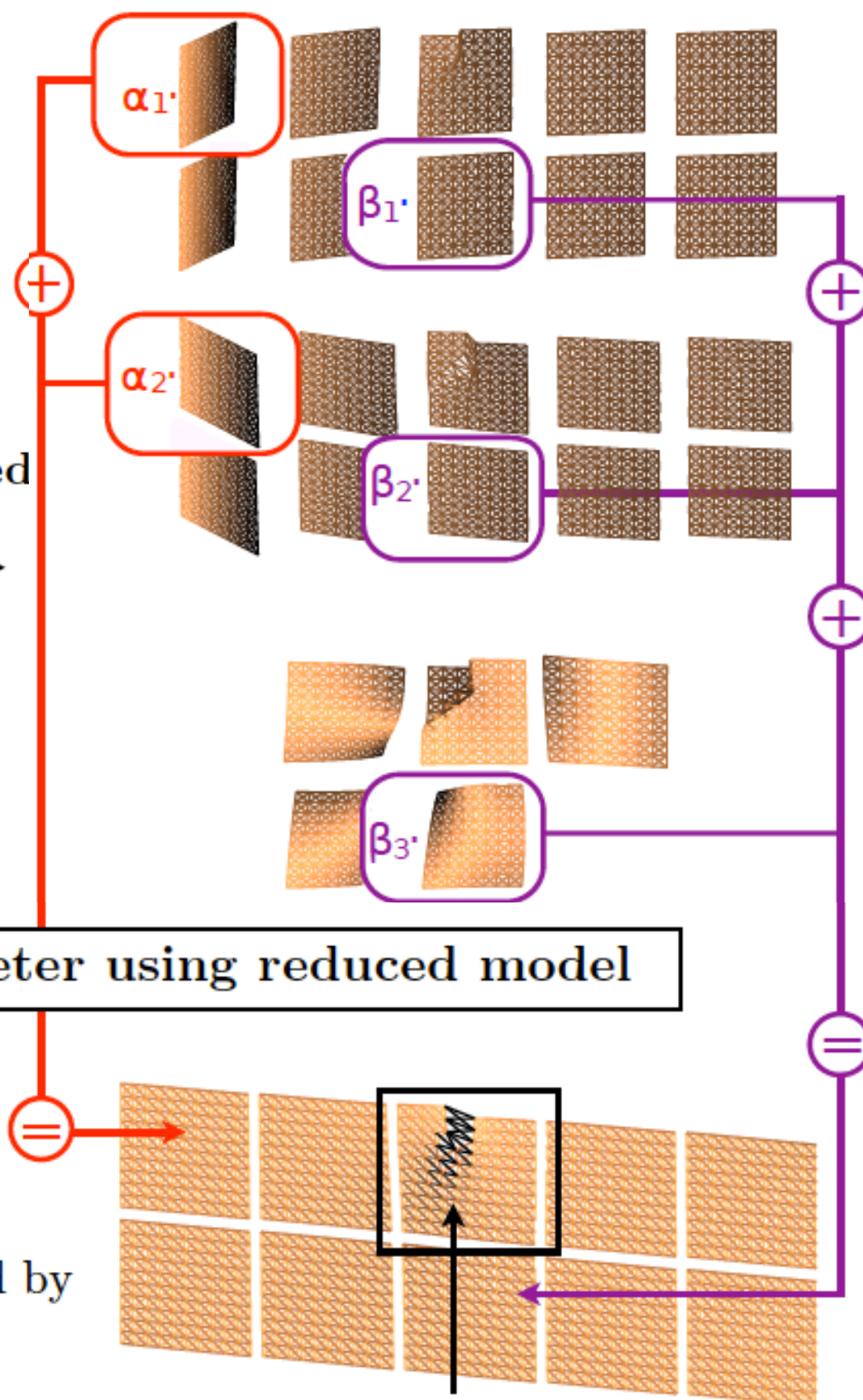
(cost intensive) using domain decomposition (snapshots)



Solution for arbitrary parameter using reduced model

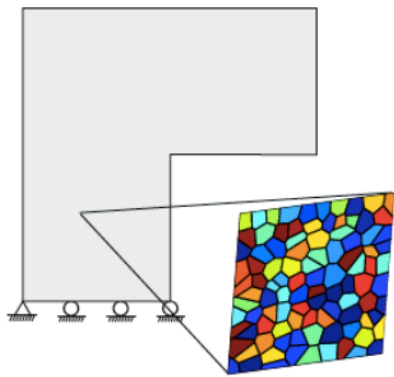


Partitioned reduced basis



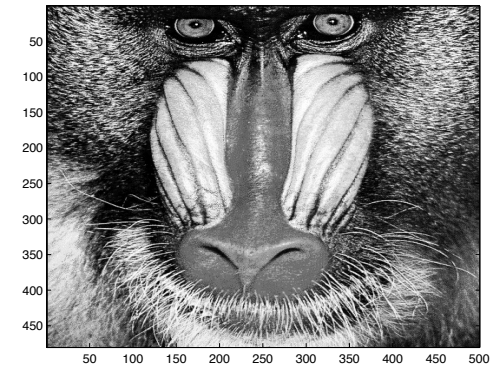
- Decompose the structure into subdomains
- Perform a reduction in the highly correlated region
- Couple the reduced to the non-reduced region by a primal Schur complement

Locally non correlated:
no reduction



Challenges

Reduce the problem size
Preserve essential features



Reduce computational expense - Control the error

**Physics based model reduction
a.k.a. Multiscale Methods**

**Algebraic based model
reduction a.k.a. Machine
Learning**

**Representative volume
elements do not exist after the
onset of fracture**

**The problem is not reducible in
the fracture process zone**

**Adaptive Multi-scale
Methods: hierarchical - semi-
concurrent - concurrent**

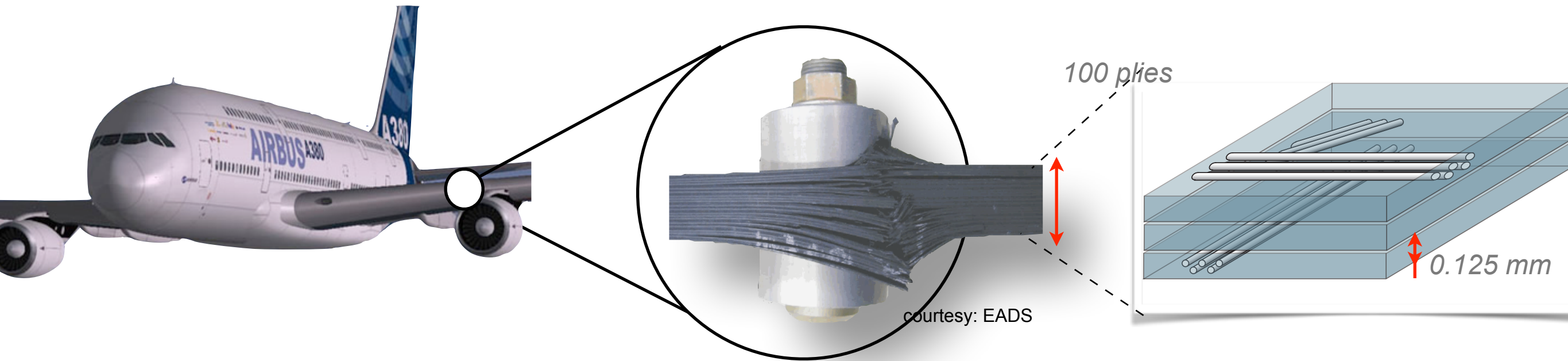
**Adaptive Domain
Decomposition Proper
Orthogonal Decomposition**

Open problems

- how to define the reduced area?
- precomputation time (offline)

Future?

Material complexity

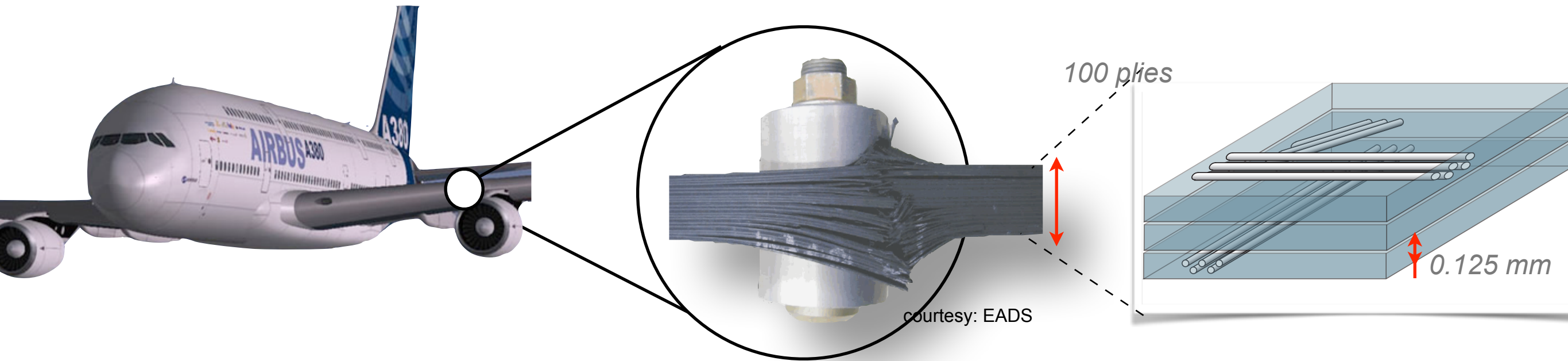


Heterogeneous & multi-functional materials

Can we optimise the material microstructure given macroscopic objective functions

Experiments required to attain sufficient confidence in their behavior are increasingly costly

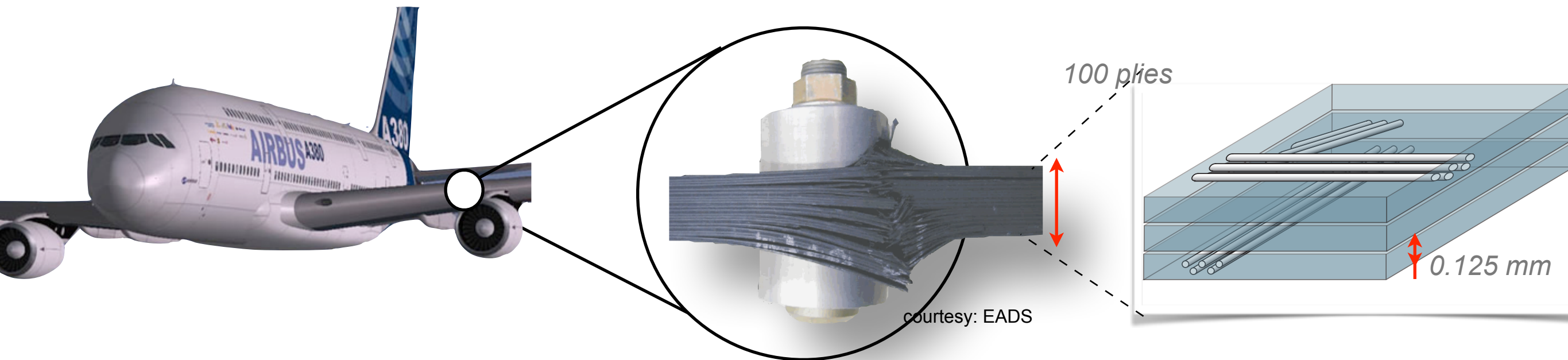
Material complexity



Factor-of-Safety or probabilistic based methods cannot handle unknown unknowns

Lack of similitude between testing (experimental) and operating conditions — also encountered in geophysics, medicine...

Challenges



- Move away from **heuristics** and experience-based engineering
- Develop **fundamental understanding** of physical processes (degradation, ...)

Digital twin concept

Actual aircraft

Digital aircraft model

Life prediction and
extension

Situation awareness

High fidelity modeling
and simulation

Certification and
design methods

**Requires real-time data
assimilation, and model
update...**

Parallel with medicine

Medicine

The average drug developed by a major pharmaceutical company costs at least \$4 billion, and it can be as much as \$11 billion.

Mechanics

The development cost of the A380

11 billion euros...

of the dreamliner...

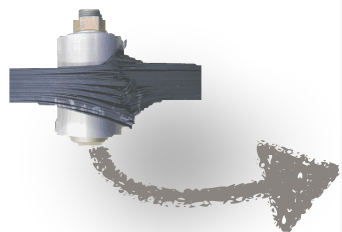
\$32 billion

Mechanics

Macro (wing) - Micro
(carbon fibres)

Environmental effects
(Temperature,
irradiation...)

Experimental condition
dissimilarities



Medicine

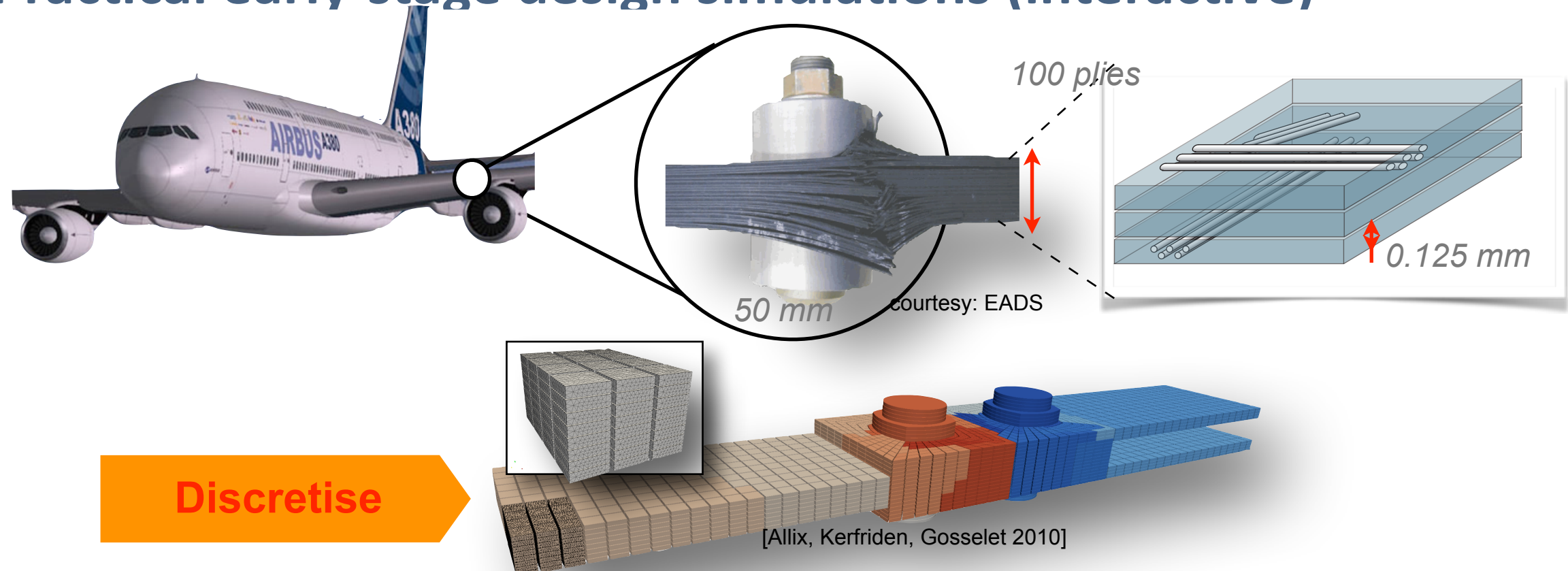
Macro (Body,
Physiology) to micro
(microbes, needle/
scalpel...)

Patient's environment,
living conditions,
habits...

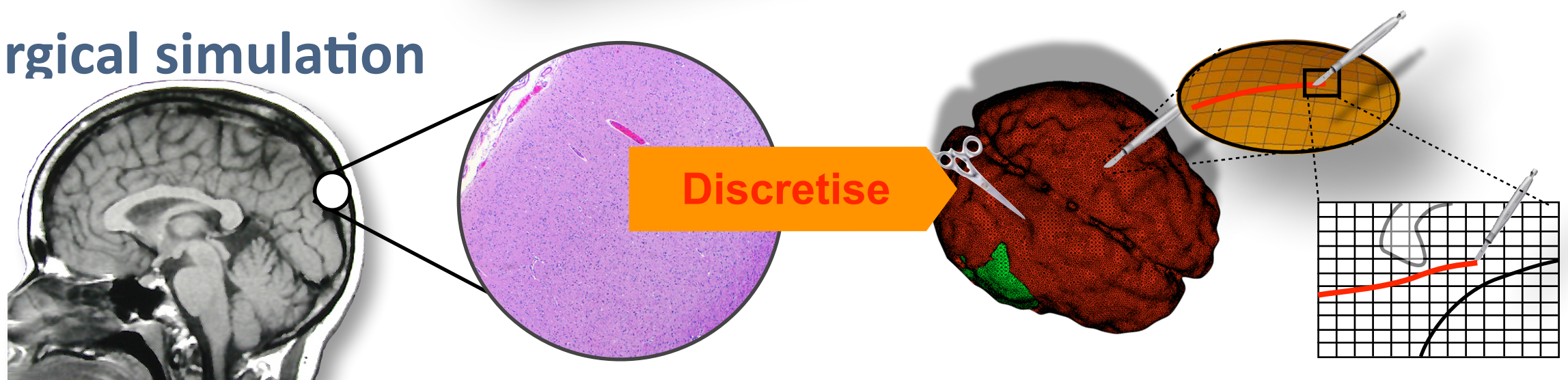
Organ properties
depend strongly on age,
gender, ...

Patient/plane-specific simulation

Practical early-stage design simulations (interactive)

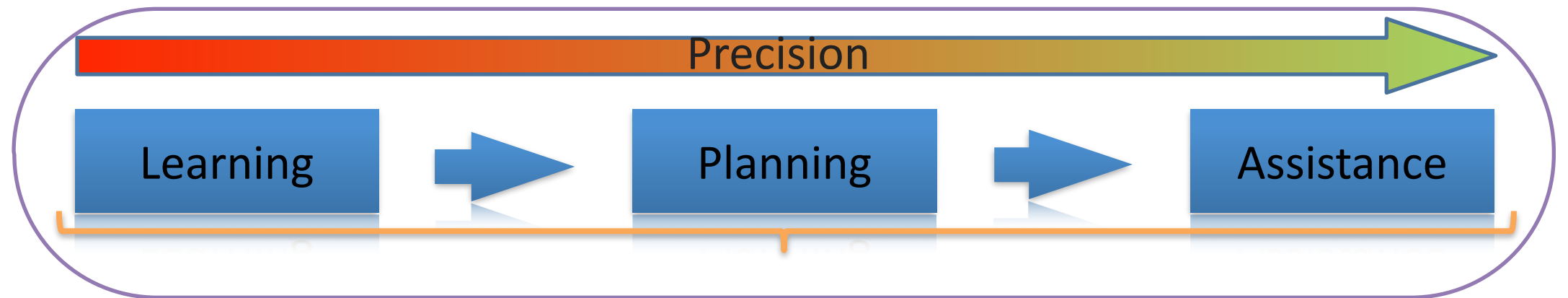


Surgical simulation

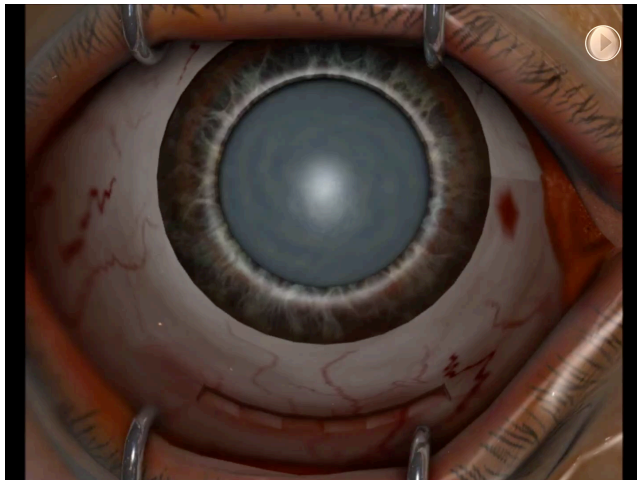


- Reduce the problem size while controlling the error (in QoI) when solving very large (multiscale) mechanics problems

Surgical simulation

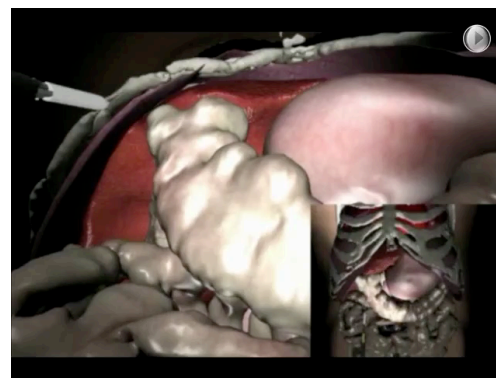


Cataract Surgery



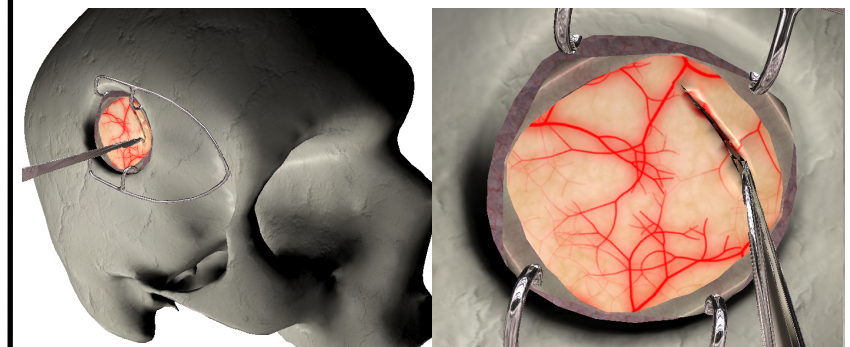
Inria

Abdominal minimally invasive surgery simulation (Inria, Shacra)



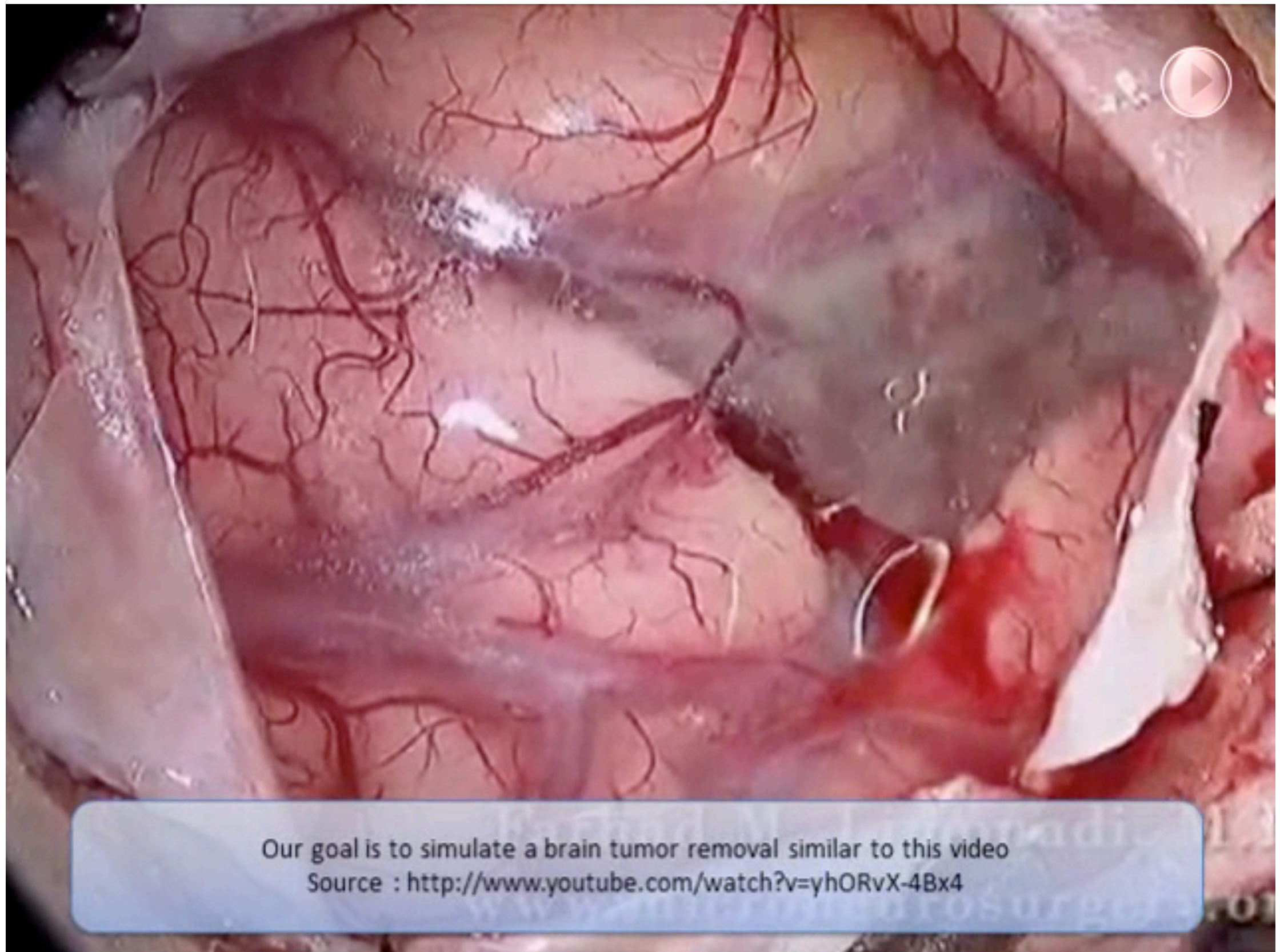
Inria

First implicit, interactive method for cutting with contact



[Courtecuisse et al., MICCAI, 2013 and Medical Image Analysis, 2014]

... not exactly brain surgery



Conclusions

- **Understanding and optimisation of fracture of heterogeneous materials**
 - multi-scale methods are being developed
 - these methods are expensive
 - model selection remains an open problem
 - variability of the material properties exacerbate these difficulties
 - taking into account realistic situations remains elusive
 - coupling with sensing systems may be the future

... mechanical twinning

real-time simulations could also help engineers gain insight into complex non-intuitive phenomena by allowing to probe, quickly, the parameter space and design space



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thanks for your attention

Partners and Funding



UNIVERSIDAD DE CHILE



UNIVERSIDAD
POLITECNICA
DE VALENCIA



Rolls-Royce®



Gracias por su atención
Merci de votre attention
Thank you for your attention
Danke für Ihre Aufmerksamkeit
Gracie per la vostra attenzione