Modelling (evolving) discontinuities

Multi-scale fracture and model order reduction Pierre Kerfriden, Lars Beex, Jack Hale, Olivier Goury, Daniel Alves Paladim, Elisa Schenone, Davide Baroli, Thanh Tung Nguyen

Advanced discretisation techniques Danas Sutula, Xuan Peng, Haojie Lian, Peng Yu, Qingyuan Hu, Sundararajan Natarajan, Nguyen-Vinh Phu

Error estimation Pierre Kerfriden, Satyendra Tomar, Daniel Alves Paladim, Andrés Gonzalez Estrada

Biomechanics applications Alexandre Bilger, Hadrien Courtecuisse, Bui Huu Phuoc

and all the others!

Stéphane P.A. Bordas stephane.bordas@alum.northwestern.edu http://legato-team.eu

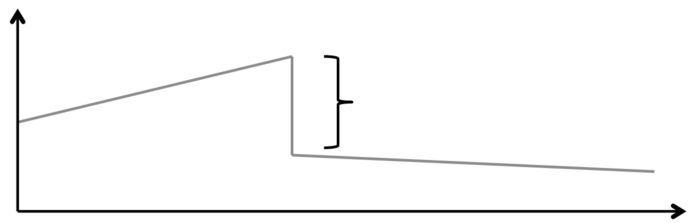
CISM Course, Udine, Italy, 2017 June 5-9

Organised by Gernot Beer & Stéphane Bordas

Classification of discontinuities

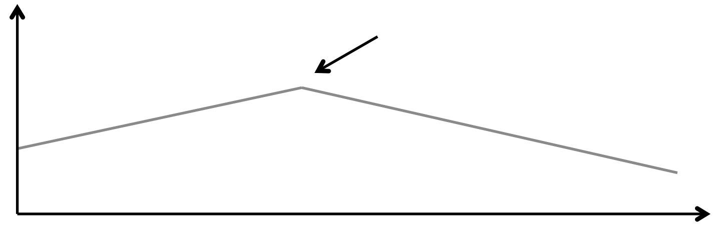
Strong discontinuities

- The primal field of the solution is discontinuous, e.g. cracks lead to strong discontinuities in the displacement field.



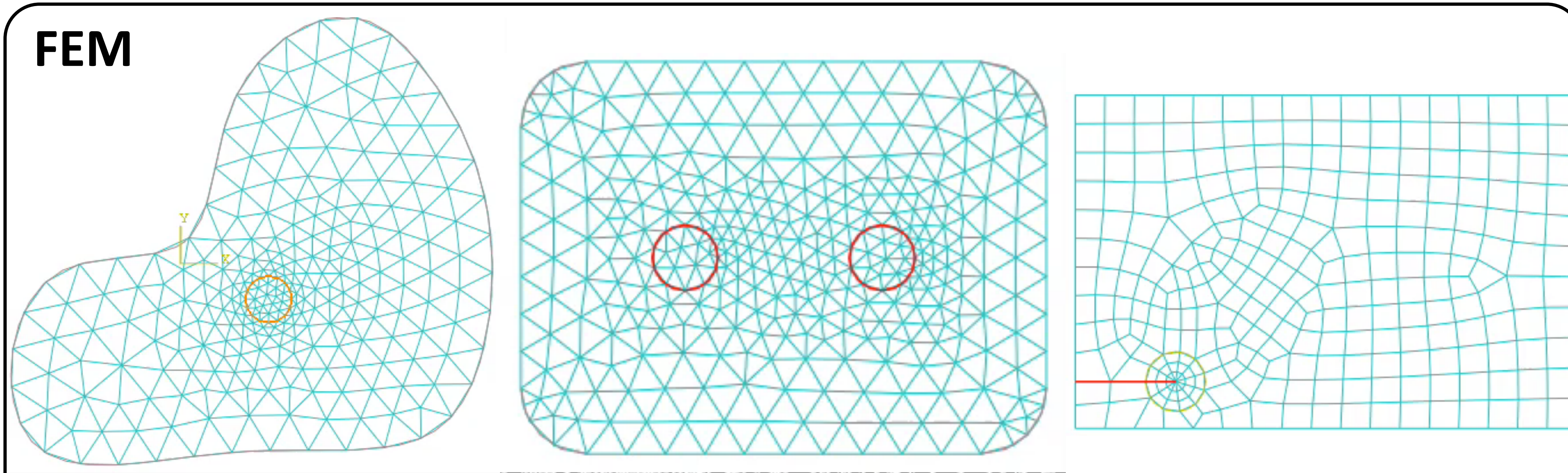
Weak discontinuities

- The first derivative of the solution is discontinuous, e.g. discontinuities in the strain field through a material interface.

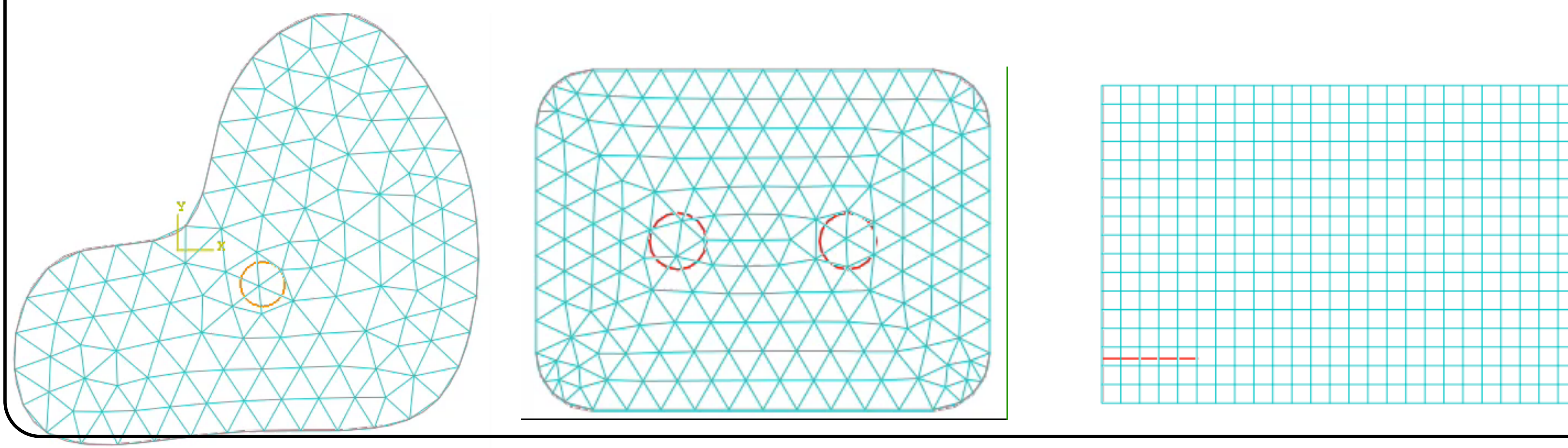


Mechanics of interfaces - or free boundary problems (Avner Friedman)

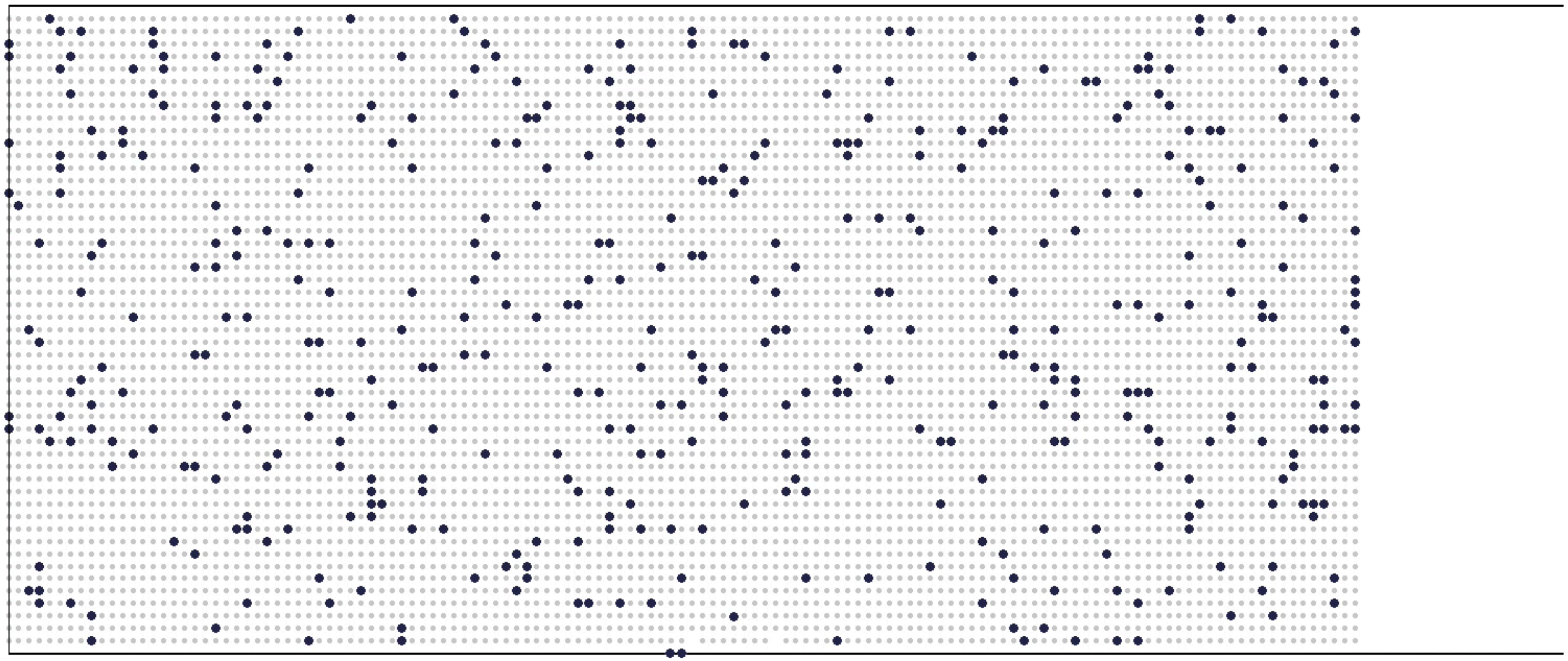
FEM



XFEM



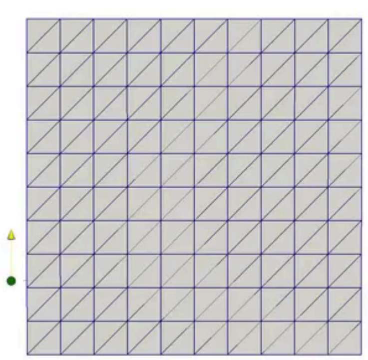
Thrombus formation in an artery

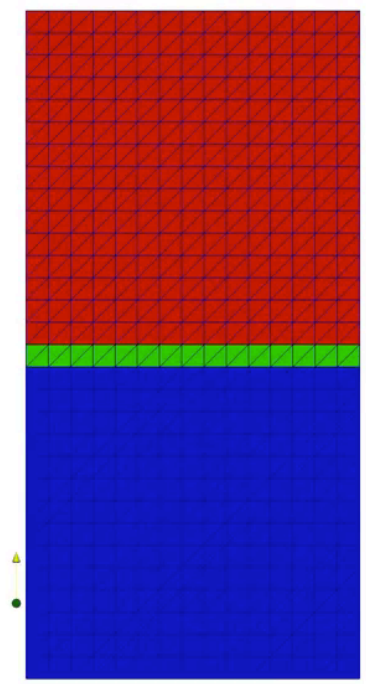


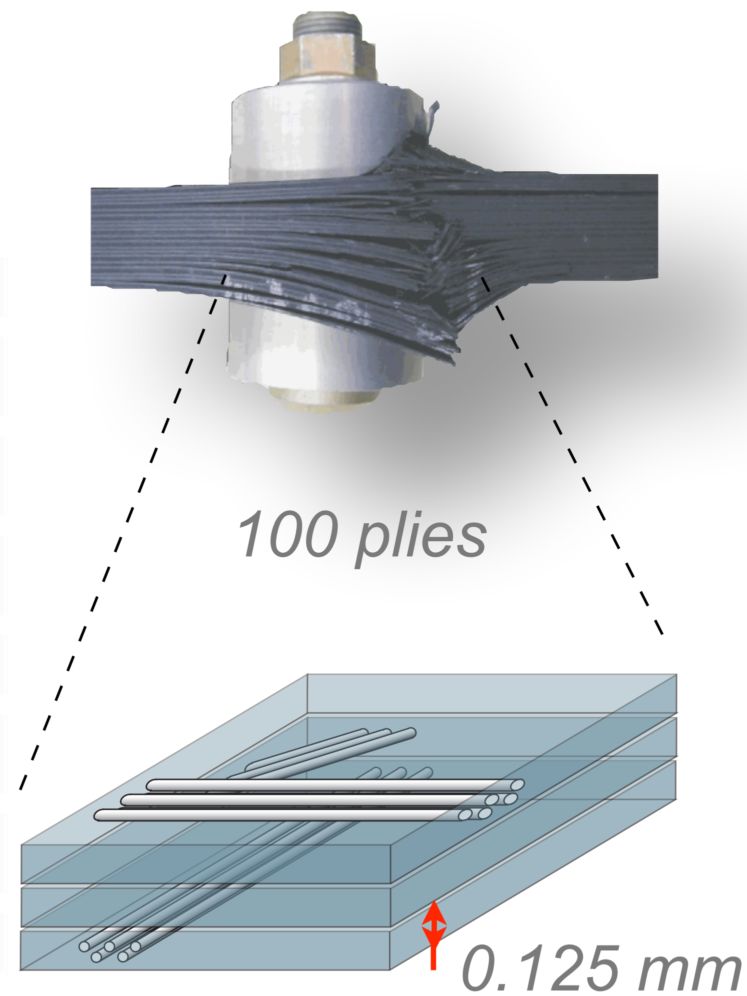
IJNMBE2017 Moh

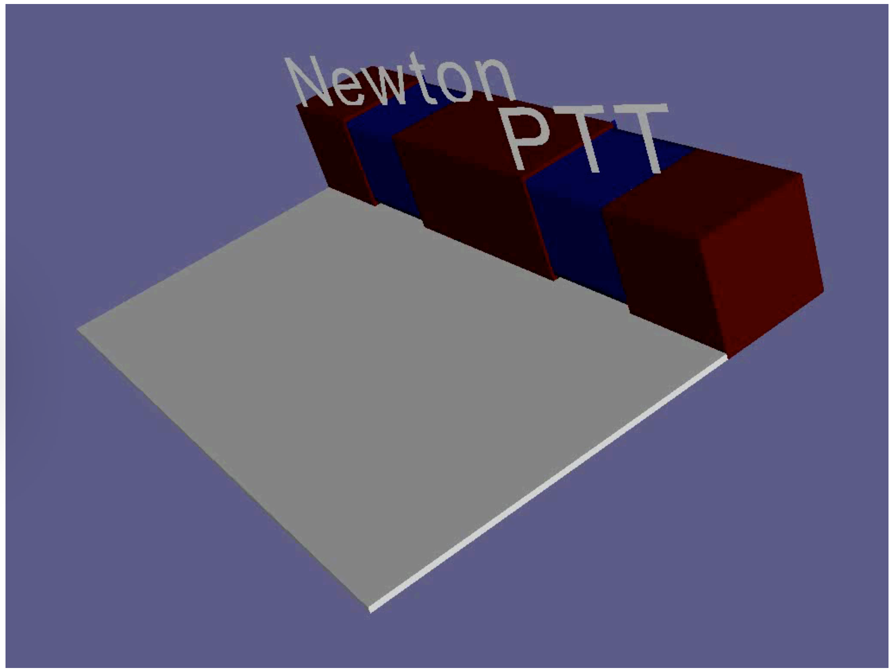
Interfaces in practical engineering simulations

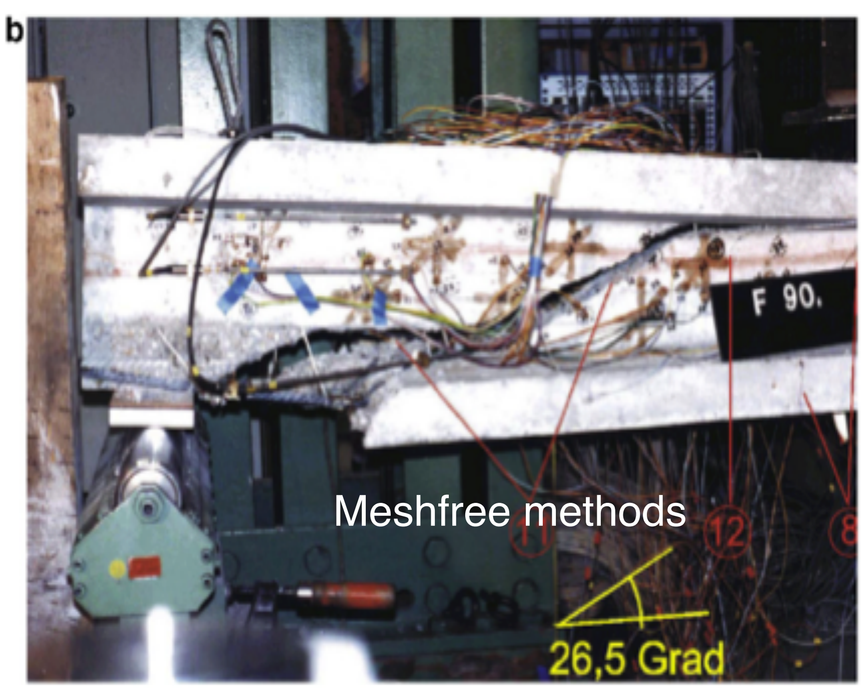
Interfaces between phases

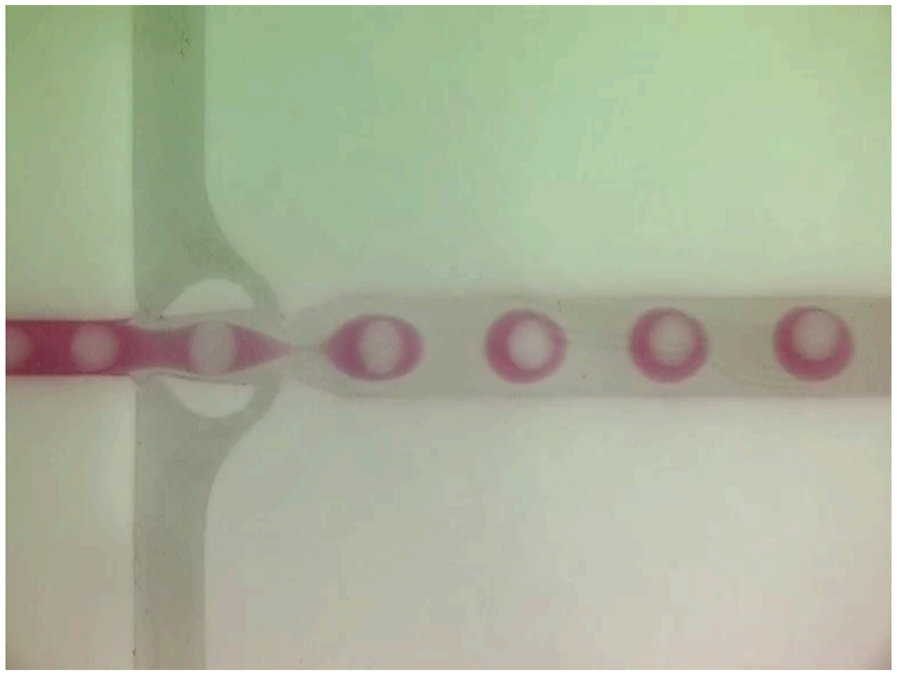






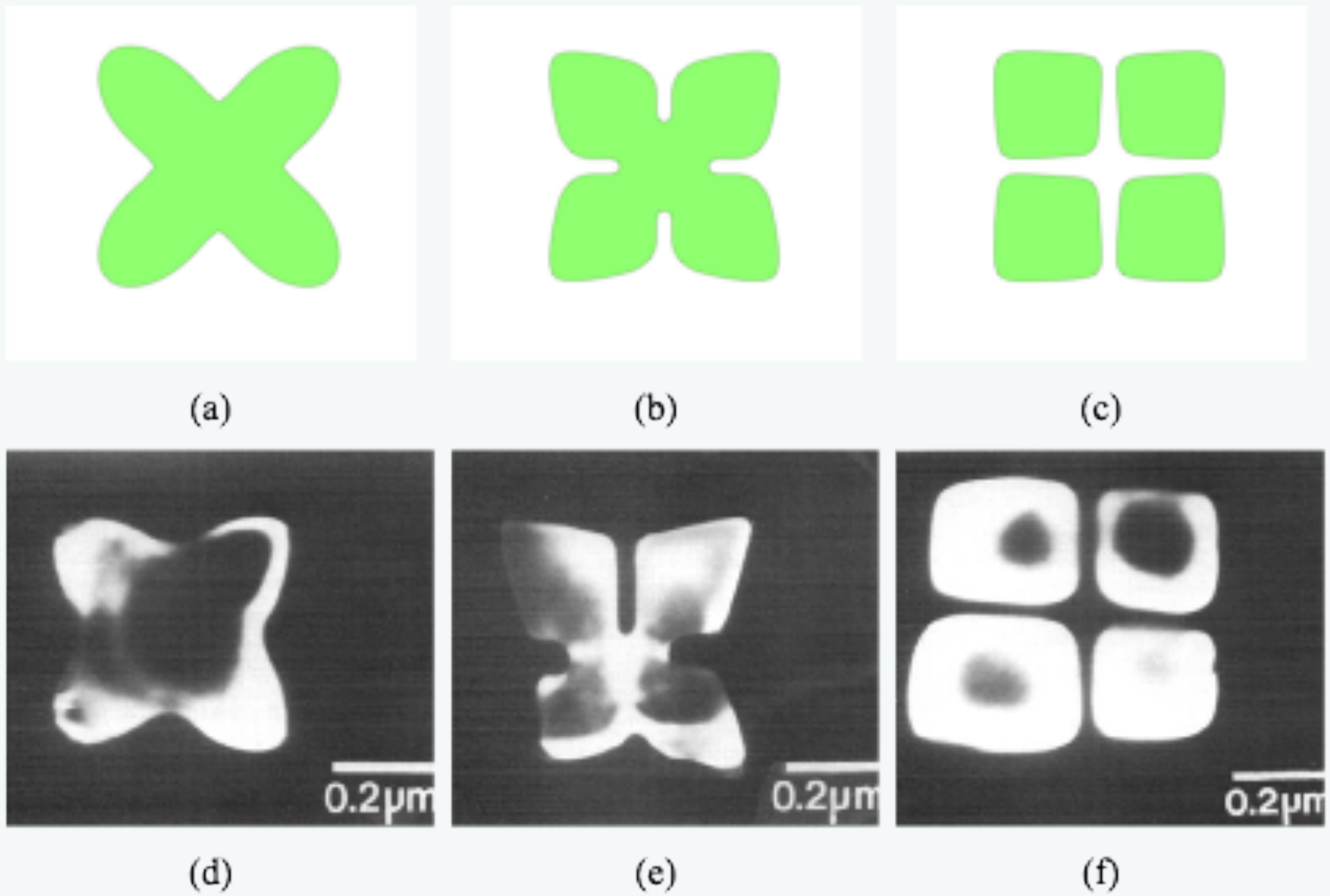






CMECH 2007, EFM2008 CAS 2009, with Timon Rabczuk and Goangseup Zi

Equilibrium of nano-inhomogeneities



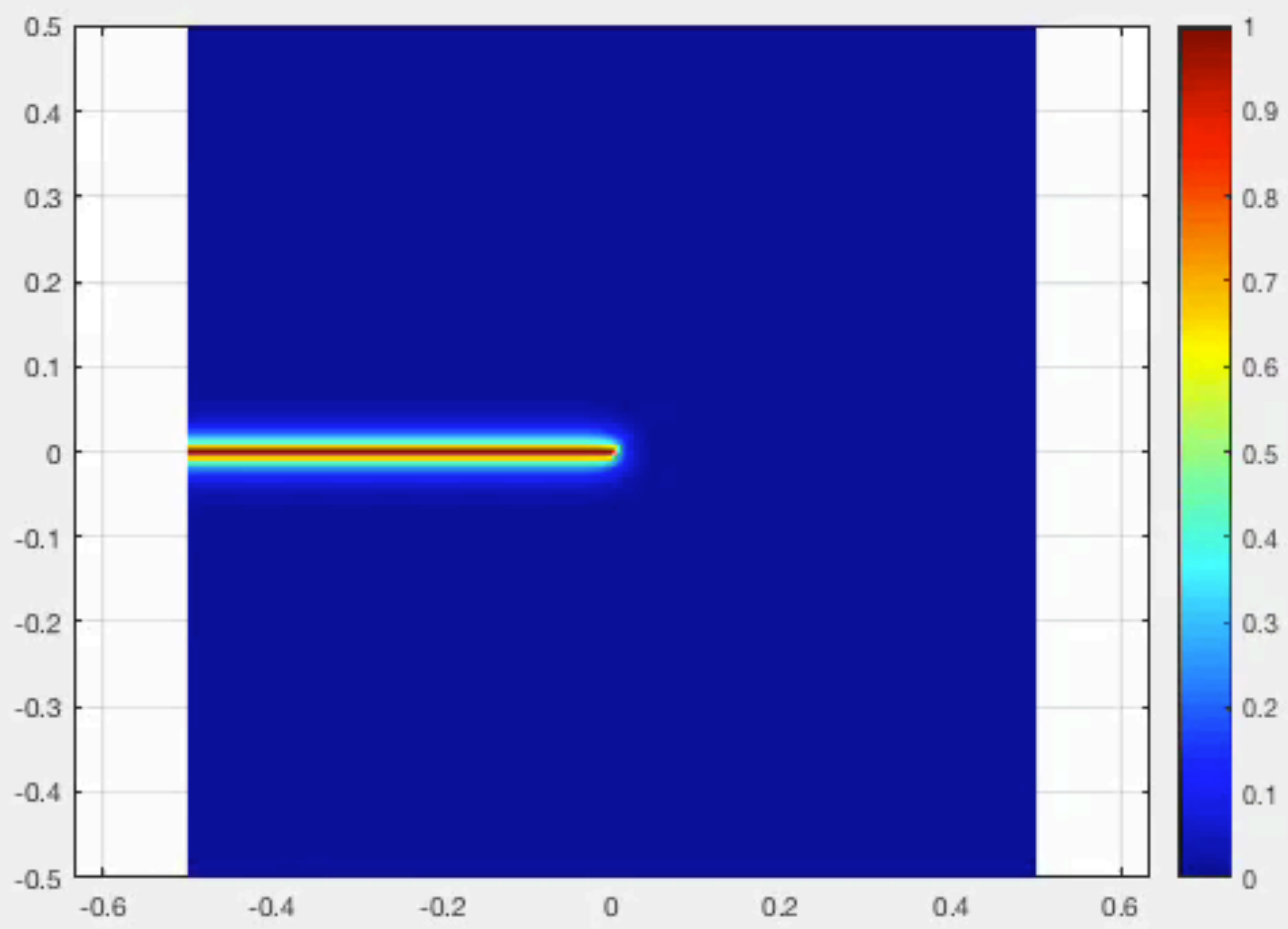
JMPS2015 http://orbilu.uni.lu/bitstream/10993/11024/1/manuscript%20-%20JMPS-D-12-00428.pdf
CMECH2013 http://orbilu.uni.lu/bitstream/10993/11022/1/Manuscript_XZHAO_CMECH_revision.pdf

Keloids

Keloids

Keloids

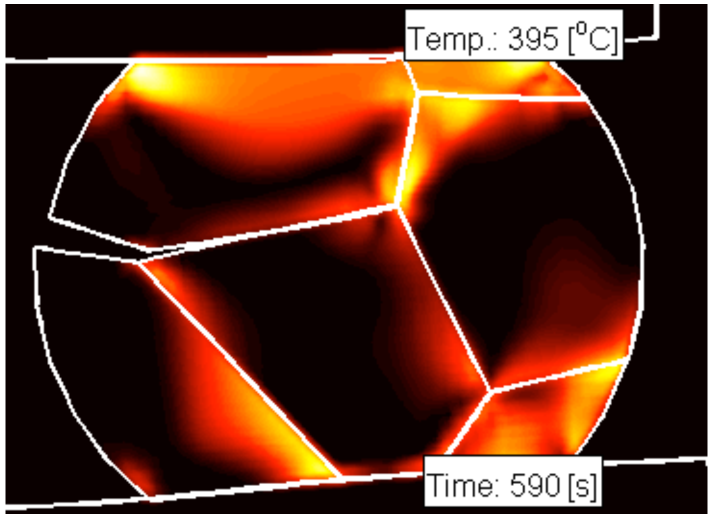
Cracks are interfaces: phase field modelling of fracture



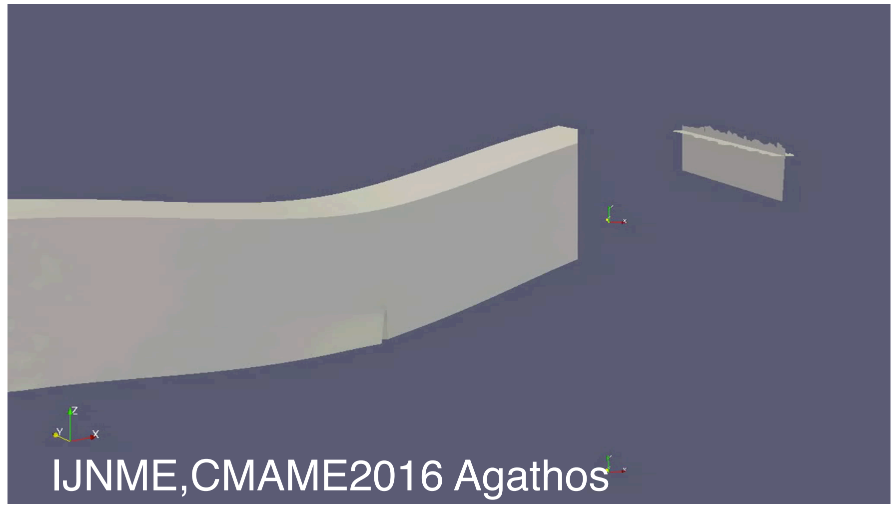
2017 Nguyen-Vinh Phu

Cracks and cuts create interfaces

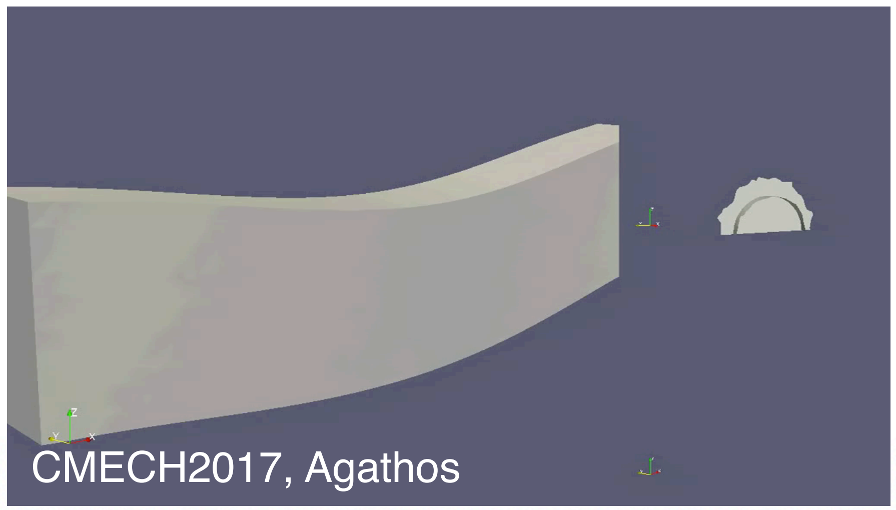
CRACKS & CUTS



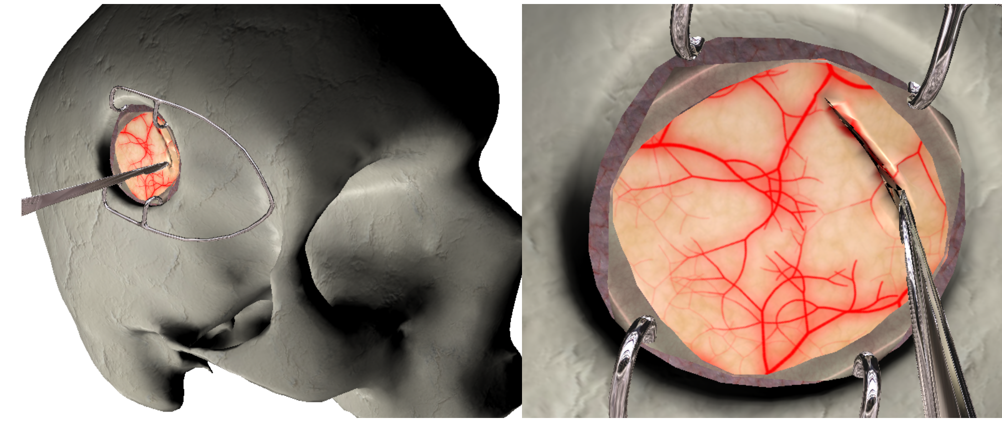
IJNME2011, CMS2012, Menk



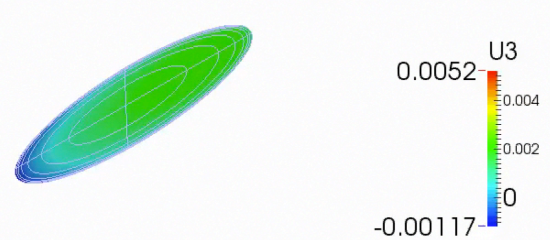
IJNME,CMAME2016 Agathos



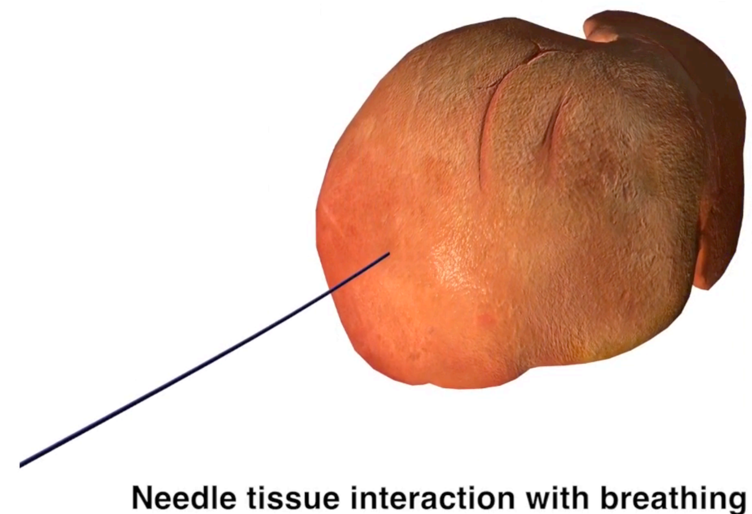
CMECH2017, Agathos



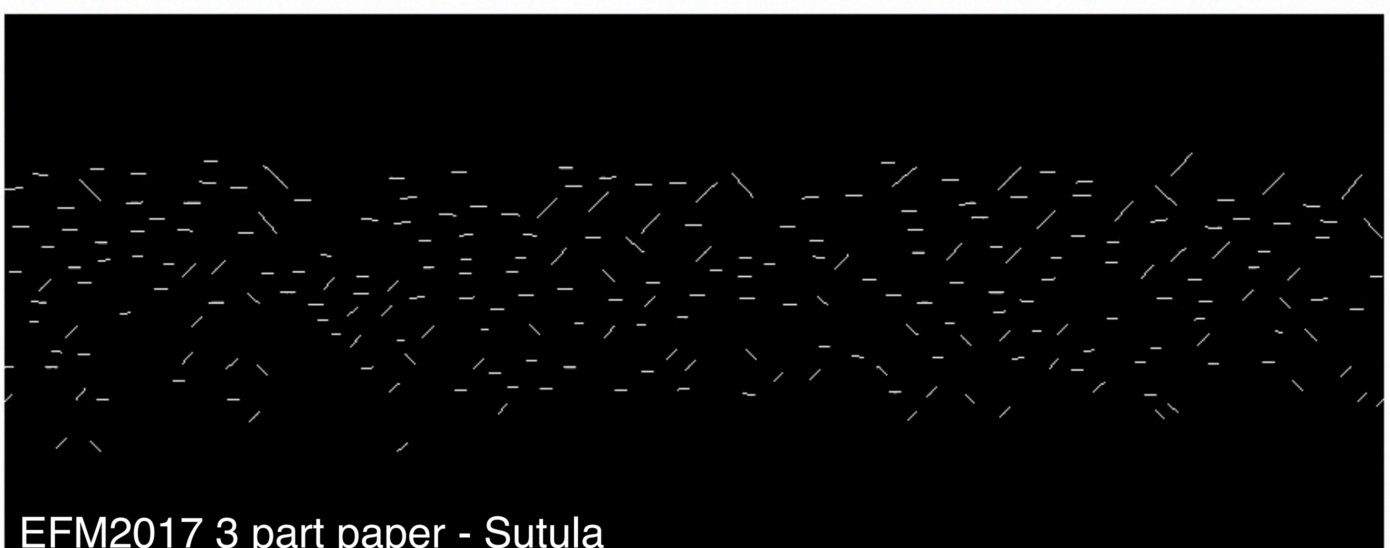
Real-time simulation of cutting during brain surgery
Med. Im. Anal. 2014 Courtecuisse



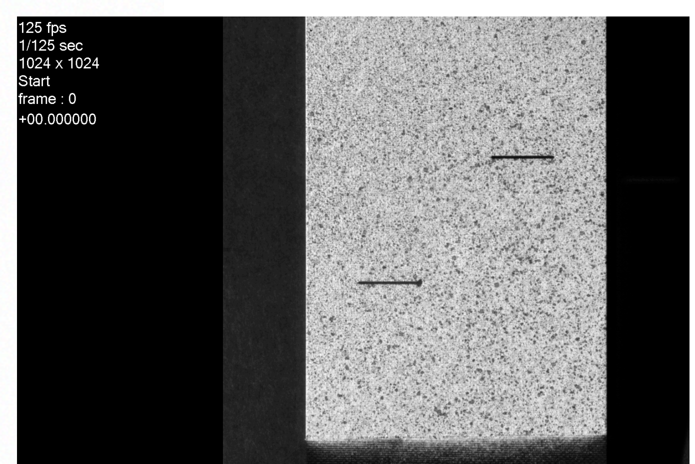
CMAME2016 Peng



IEEE J. Biomed. Engng. 2017 Bui



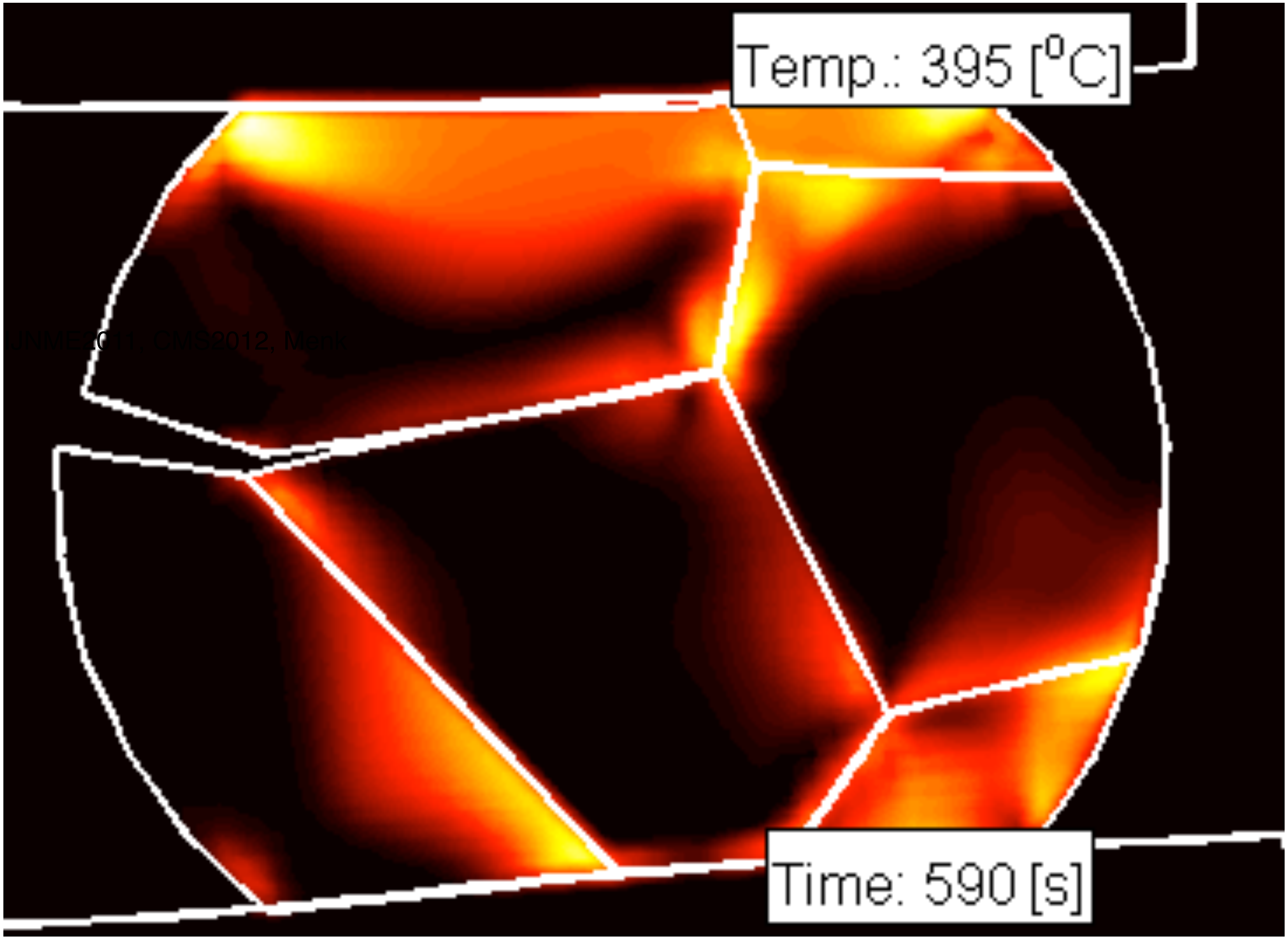
EFM2017 3 part paper - Sutula



COST 2014, Cahill

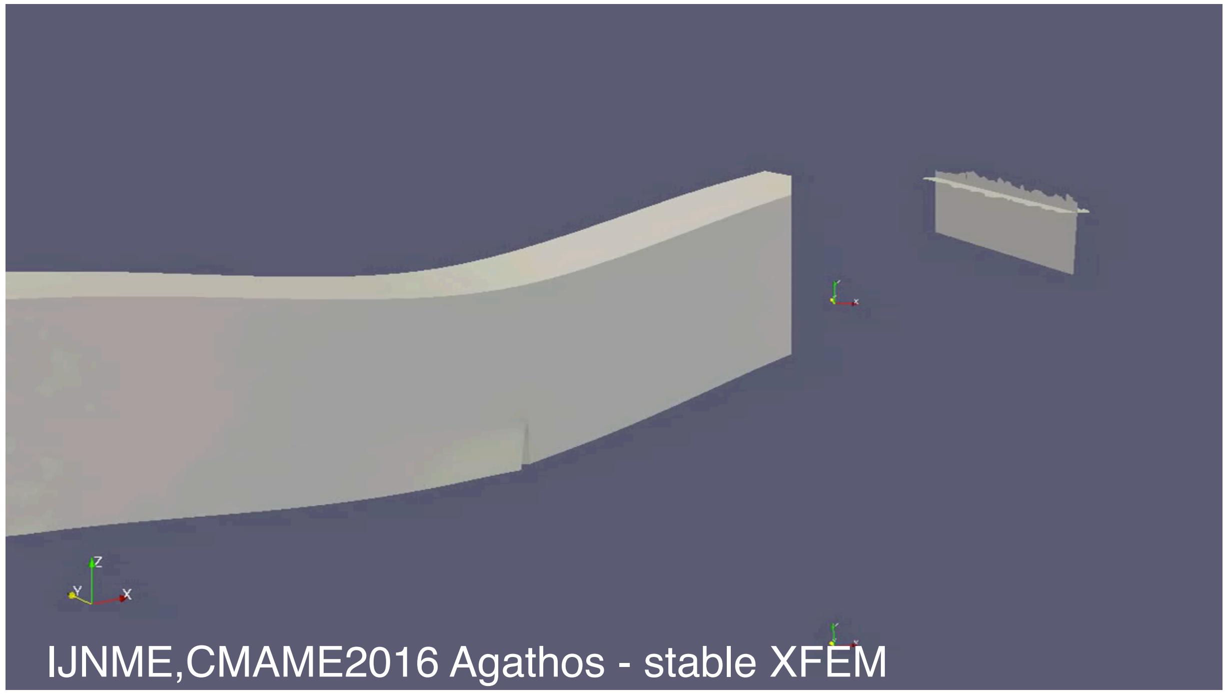
Cracks and cuts create interfaces

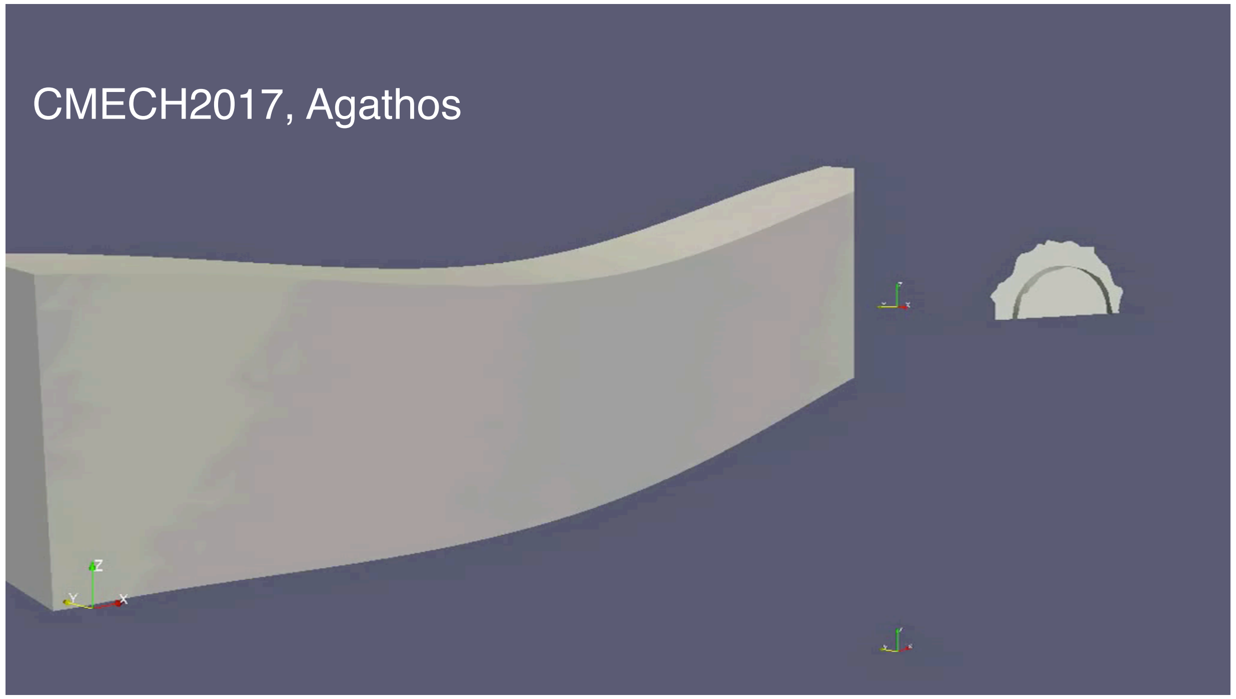
CRACKS & CUTS



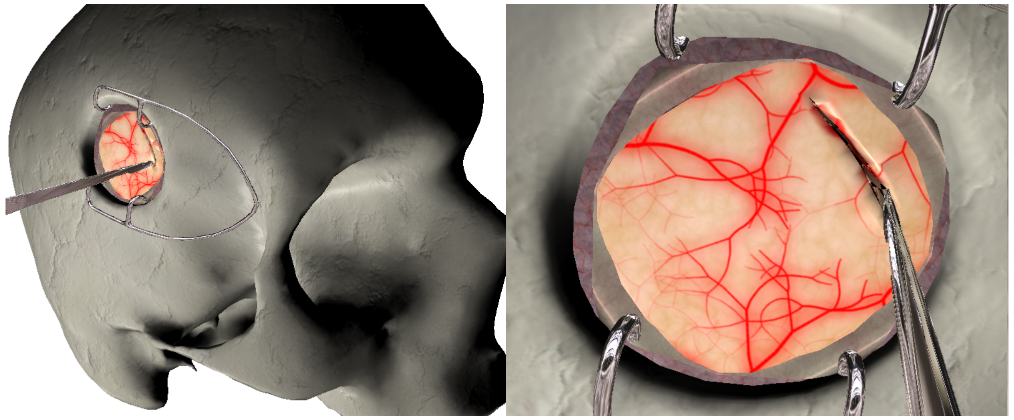
IJNME2011, CMS2012, Menk

Cracks and cuts create interfaces

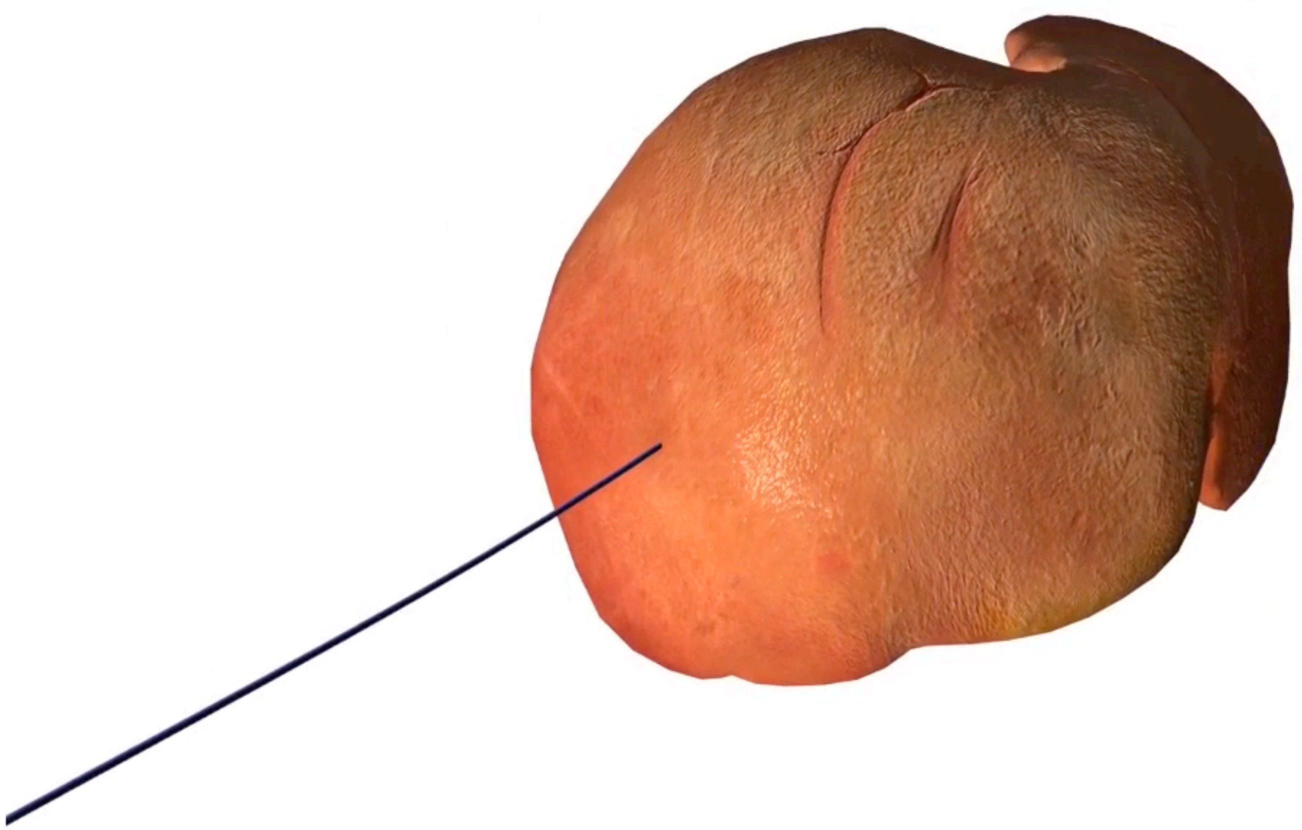




Cracks and cuts create interfaces



Real-time simulation of cutting during brain surgery - Med. Im. Anal. 2014 Courtecuisse

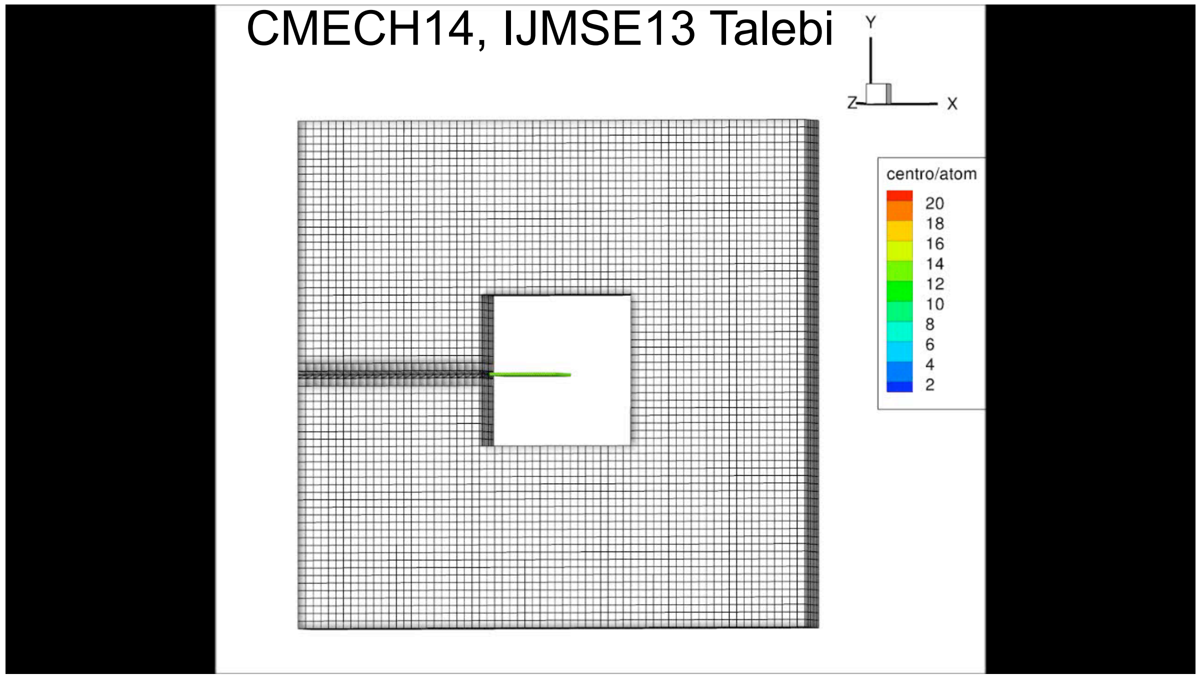


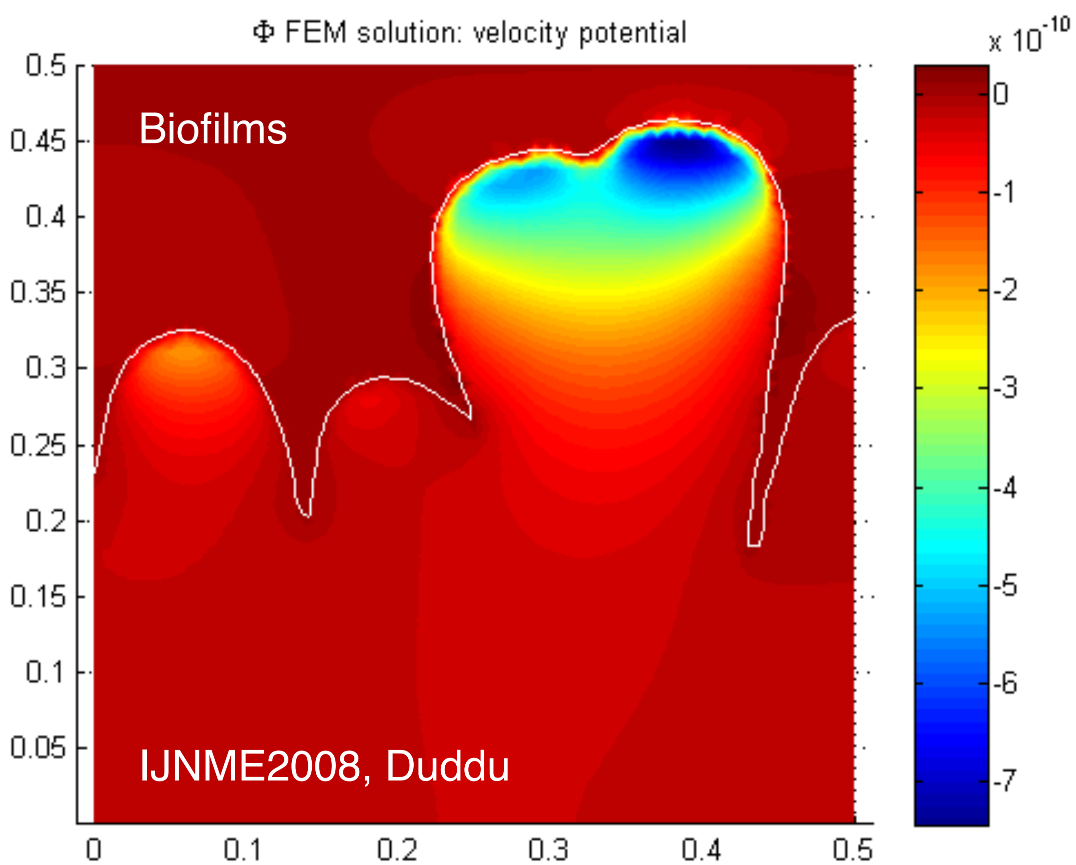
Needle tissue interaction with breathing motion

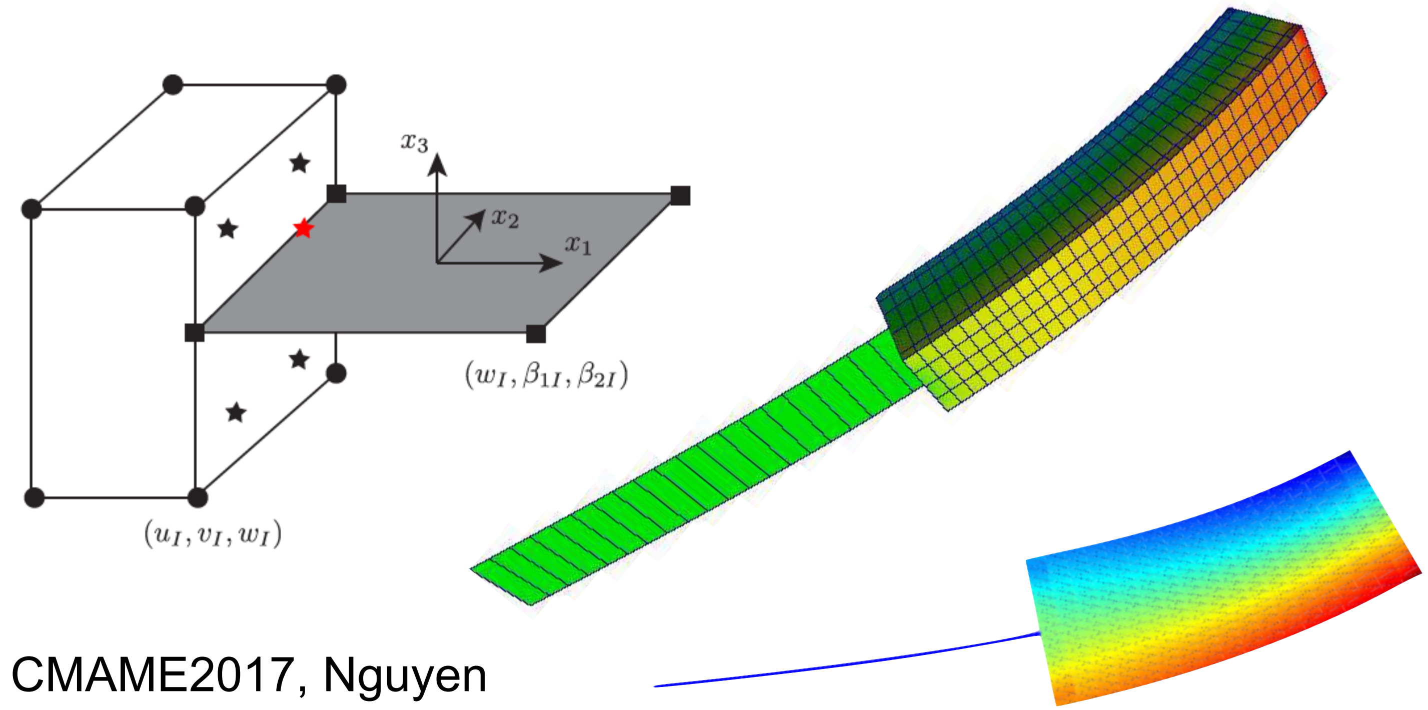
IEEE J. Biomed. Engng. 2017 Bui

Interfaces between different models, scales or PDEs

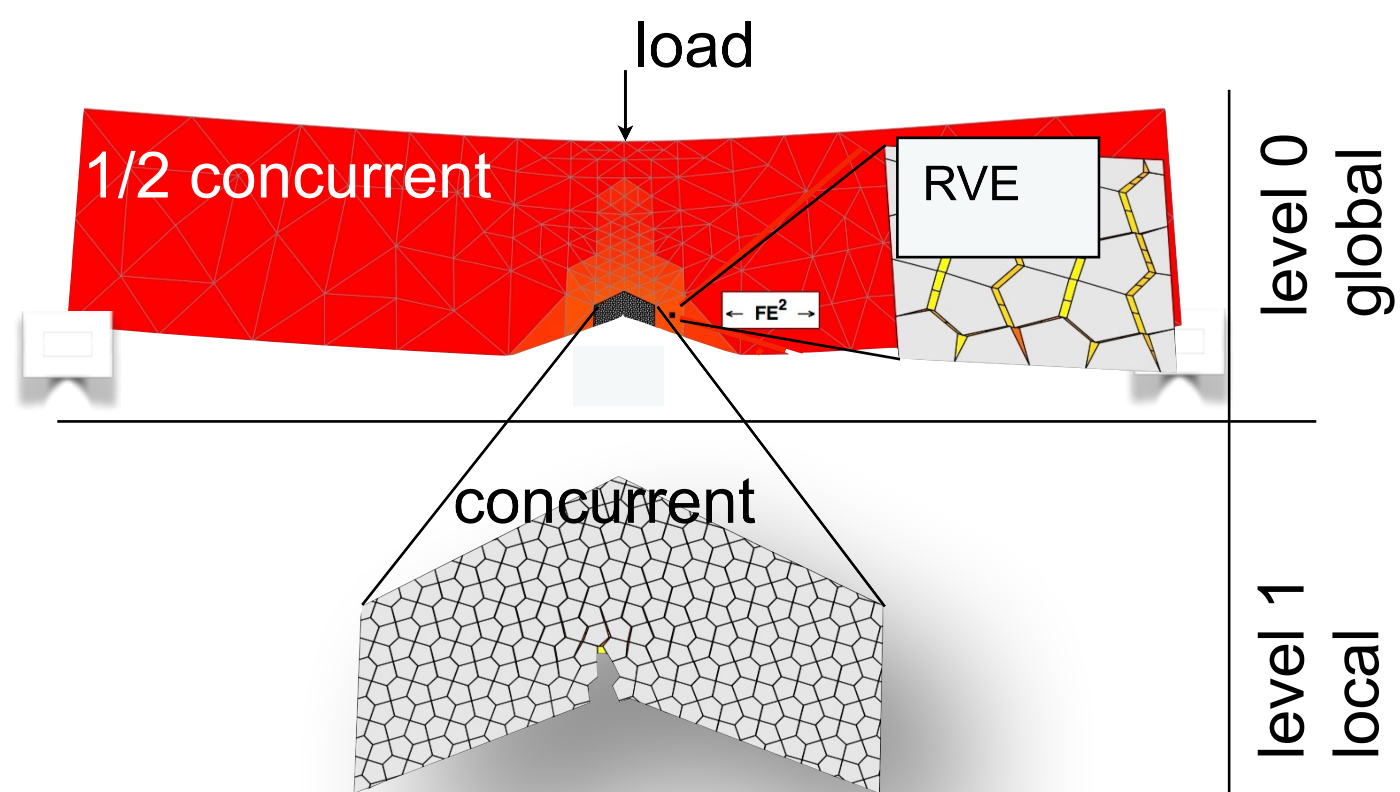
MODELS







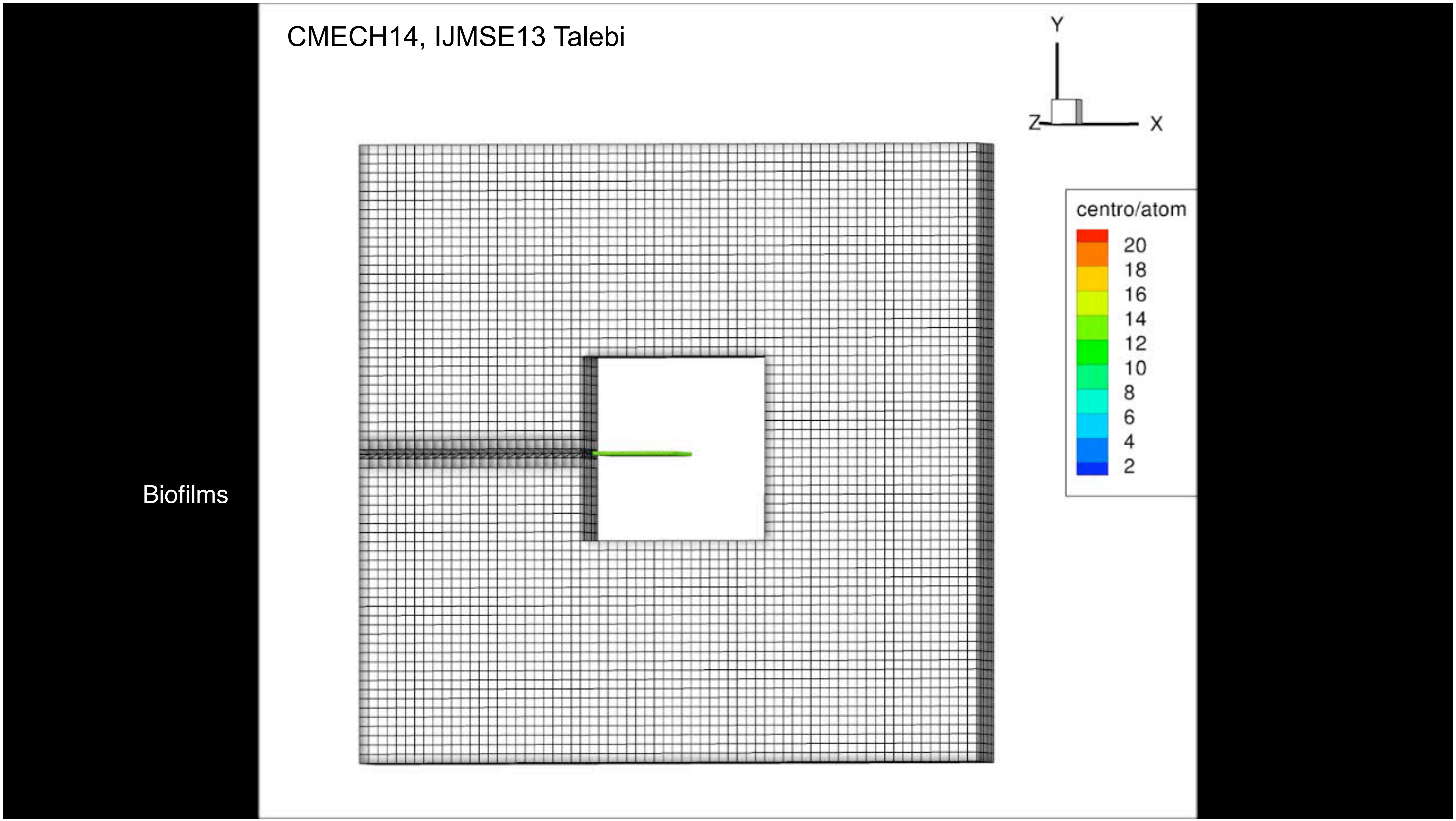
CMAME2017, Nguyen



PhilMag15, Akbari
CMAME13,CMECH16, Goury
NMPDES13,CMAME15, Chi

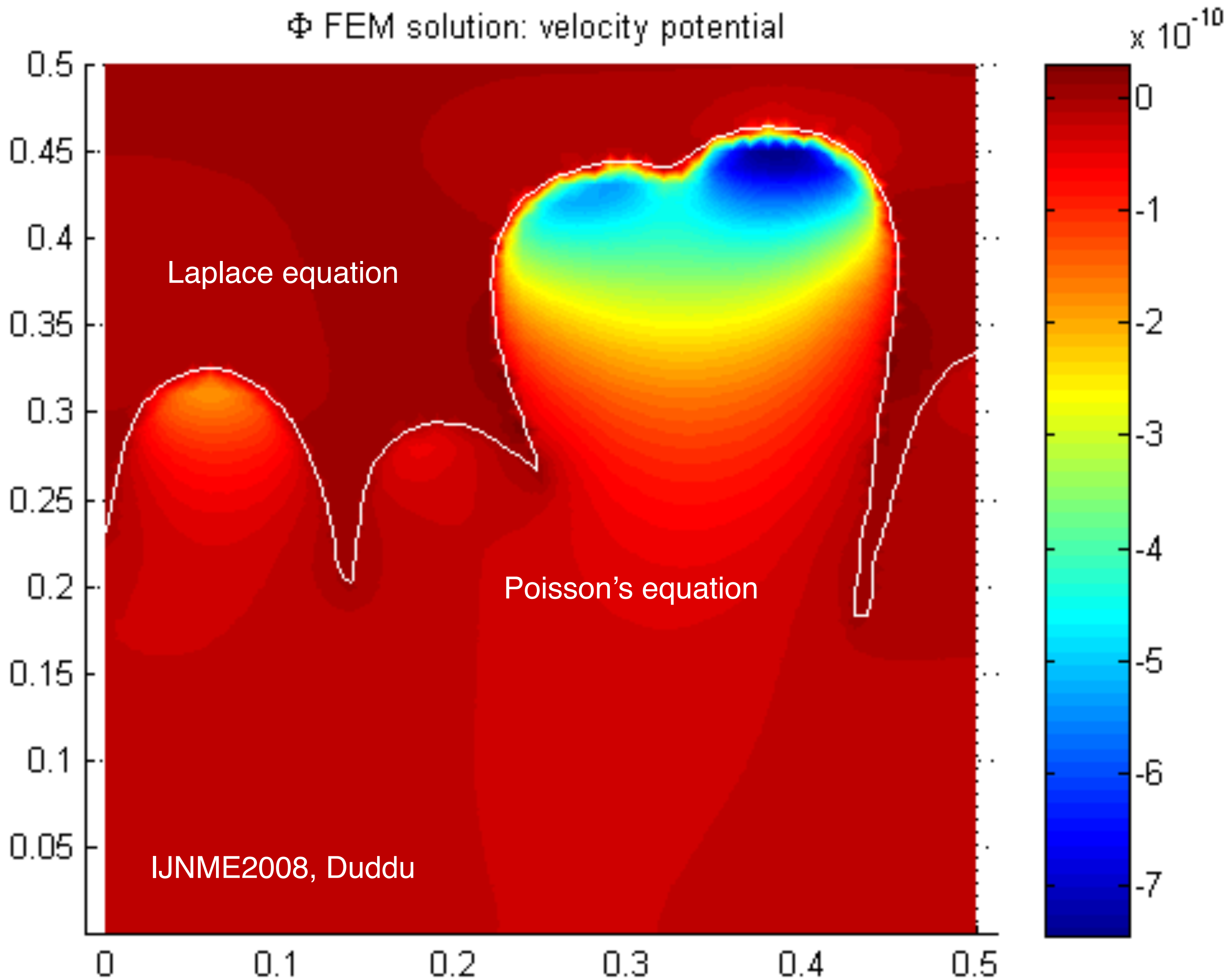
Interfaces between different models, scales or PDEs

MODELS

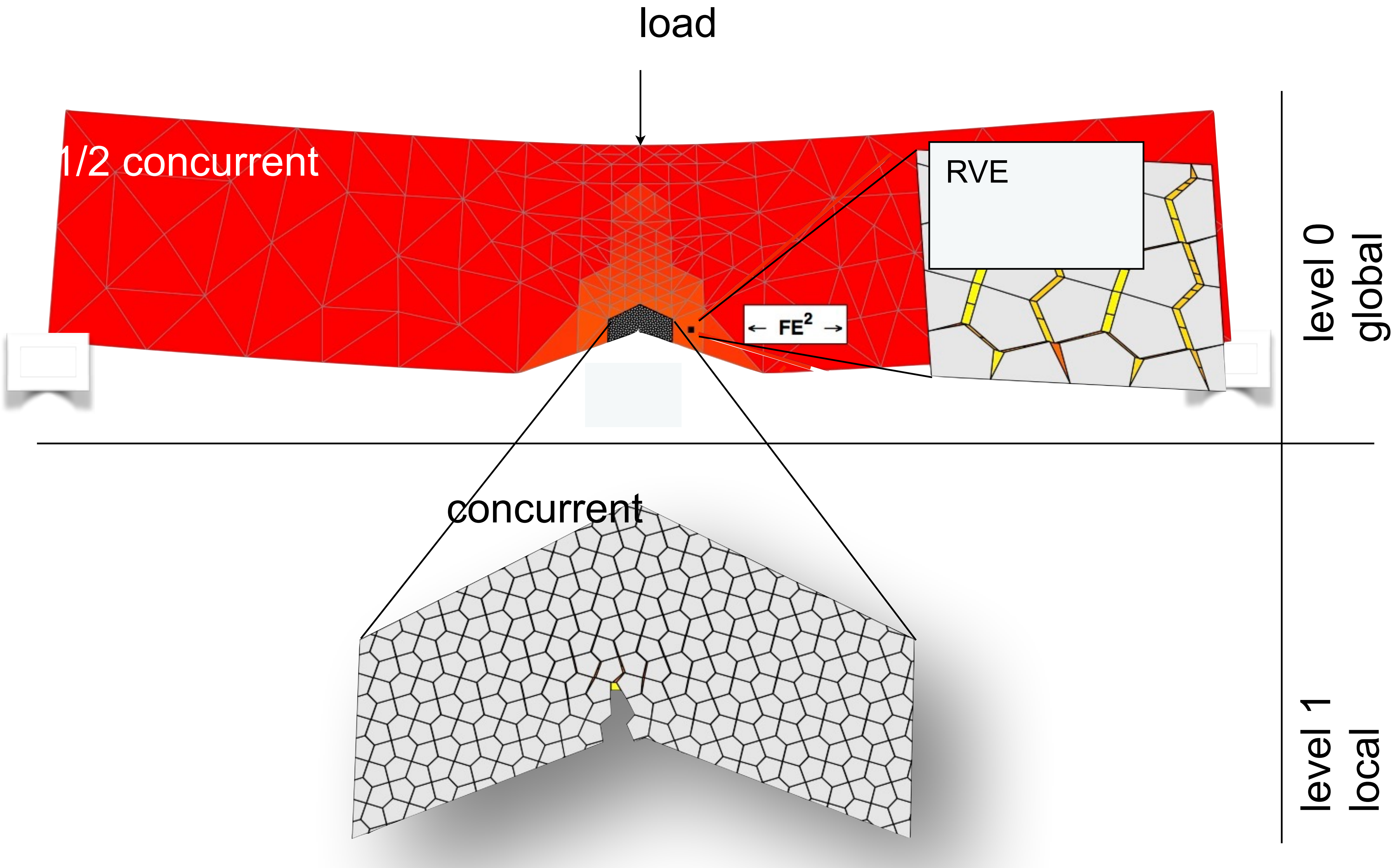


Interfaces between different models, scales or PDEs

MODELS

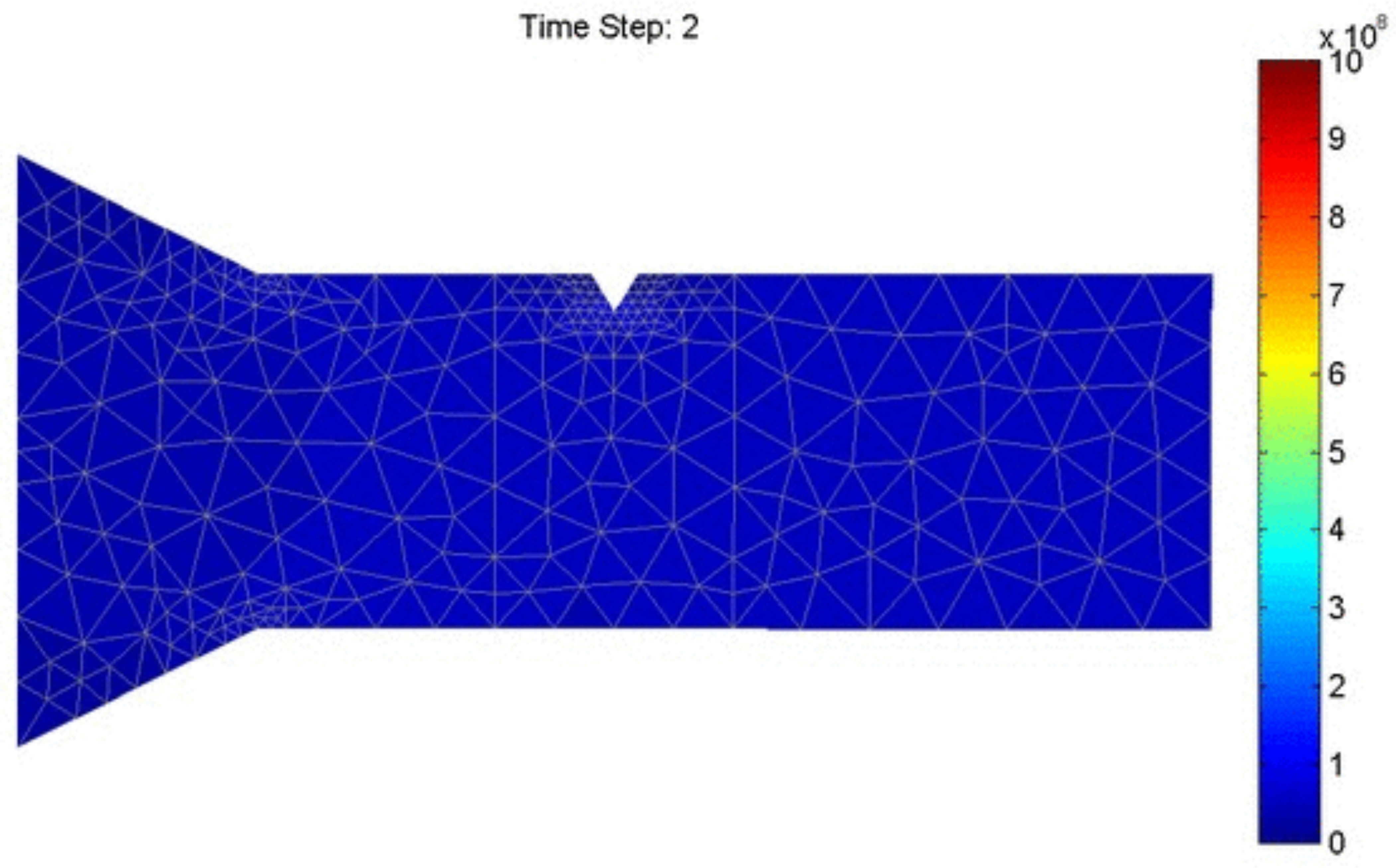


Interfaces between different models, scales or PDEs

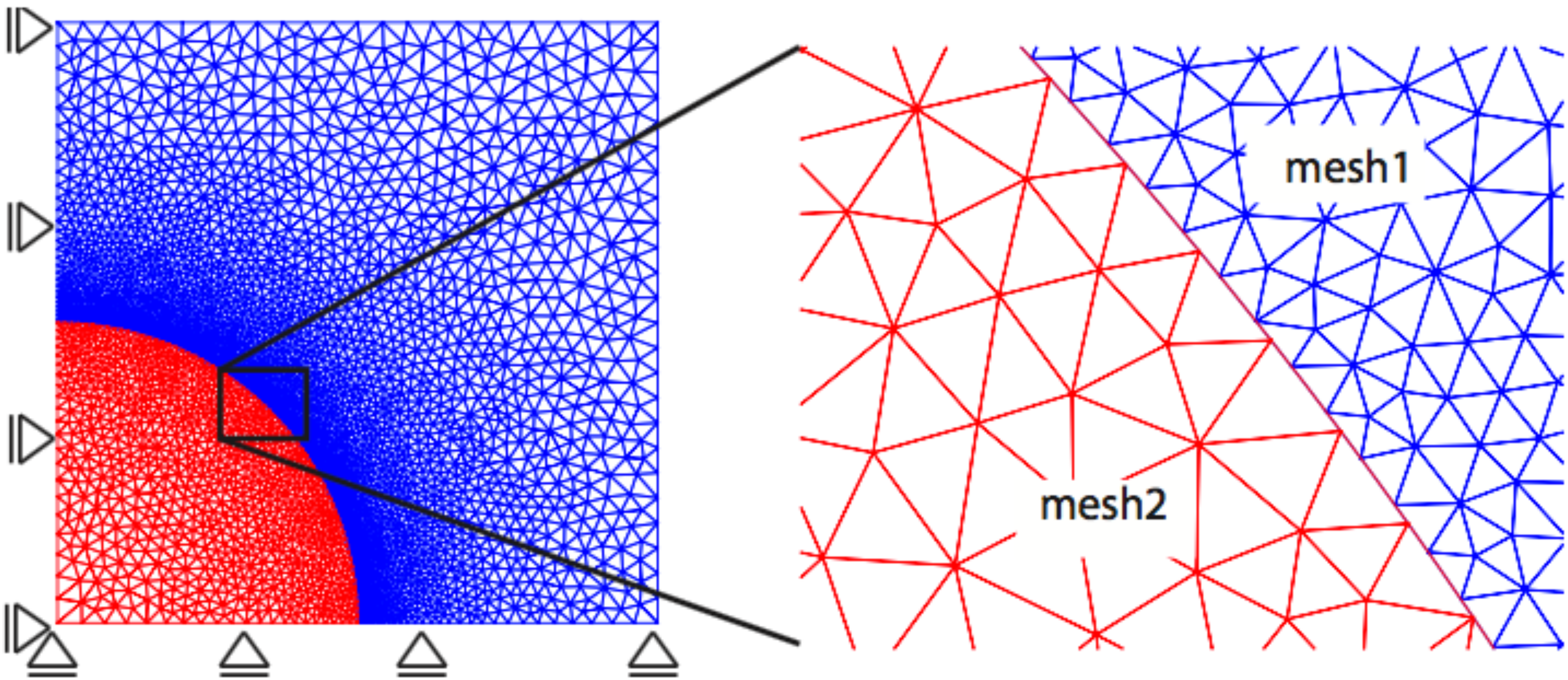


PhilMag15, Akbari
CMAME13,CMECH16, Goury
NMPDES13,CMAME15, Chi

Interfaces between different models, scales or PDEs



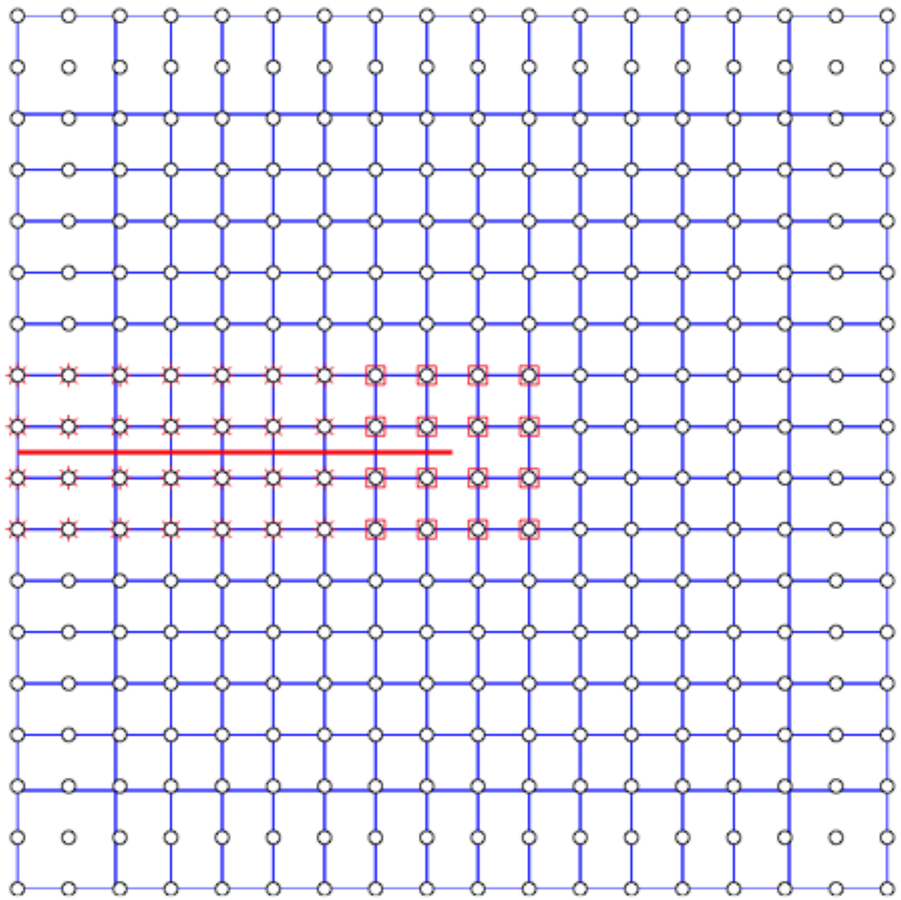
Interfaces between different discretisations



CMECH2014, CAD2014, CMECH2016, MatCompSim2016, CMAME2017, Nguyen-Vinh Phu
http://publications.uni.lu/bitstream/10993/13726/1/phu-meshless.pdf
https://orbilu.uni.lu/bitstream/10993/15234/1/bordasphu.pdf

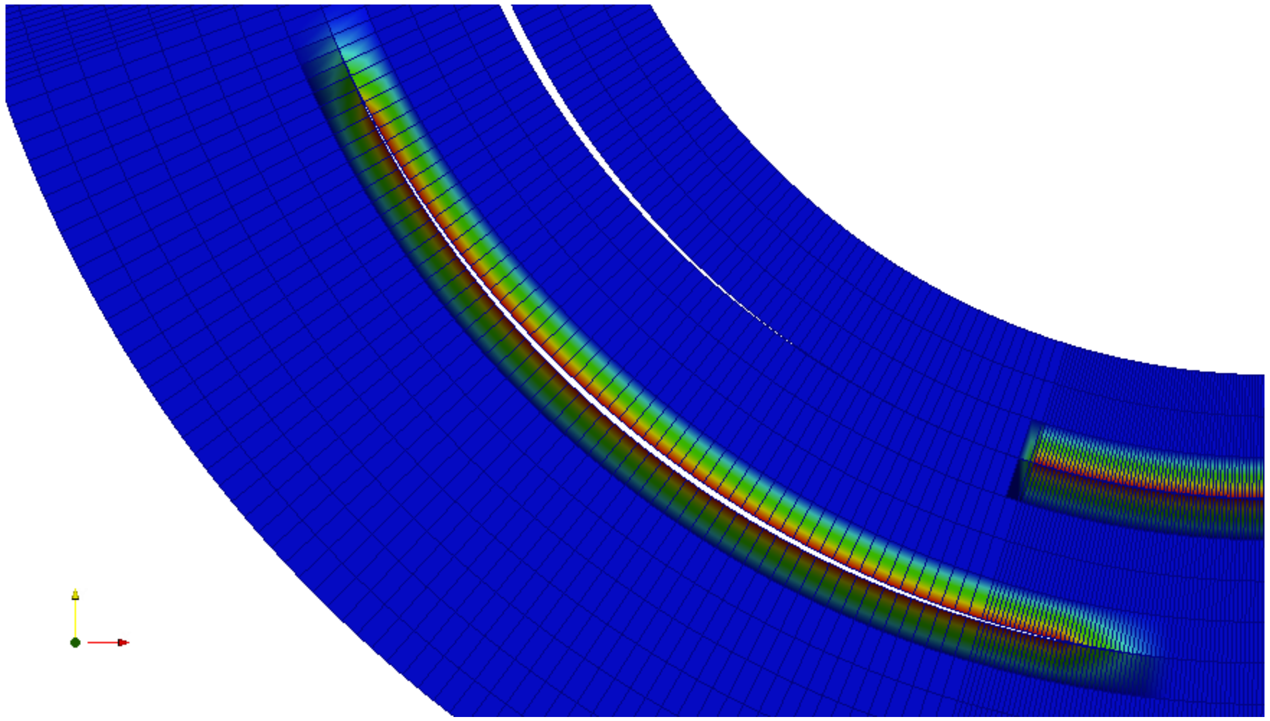
Discontinuities modeling

PUM enriched methods



- IGA: link to CAD and accurate stress fields
- XFEM: no remeshing

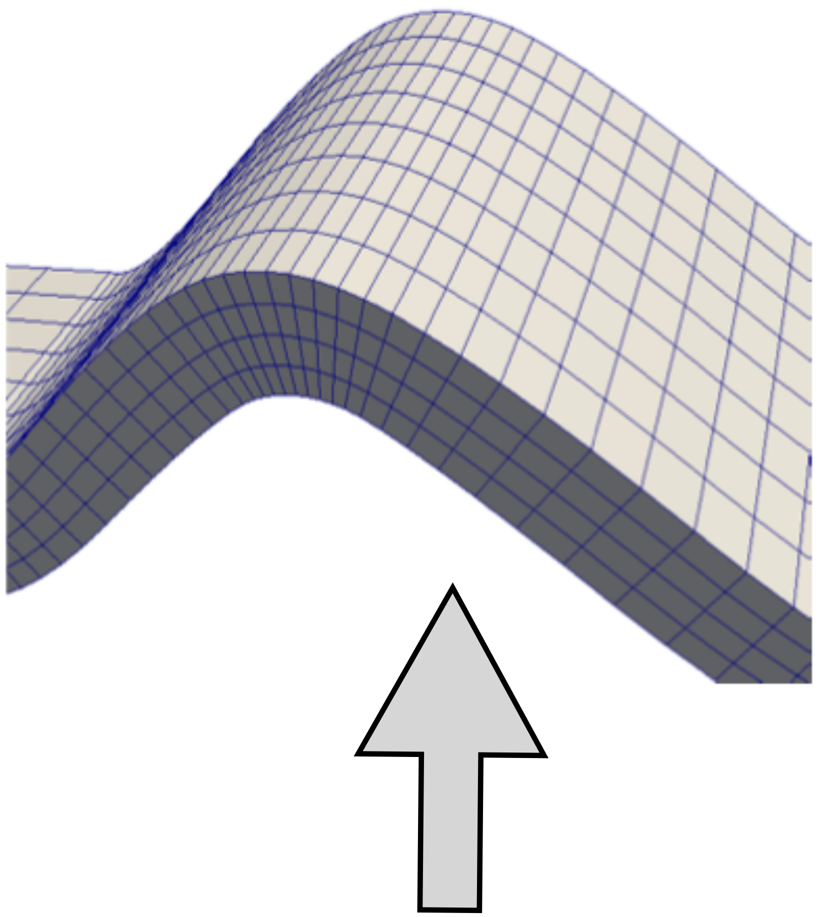
Mesh conforming methods



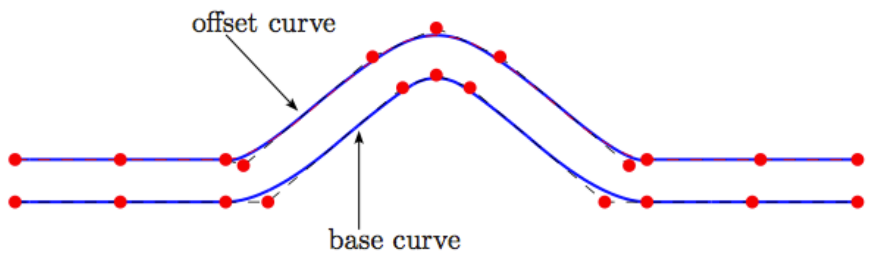
- IGA: link to CAD and accurate stress fields
- Apps: delamination

Isogeometric cohesive elements: advantages

- Direct link to CAD
- Exact geometry
- Fast/straightforward generation of interface elements
- Accurate stress field
- Computationally cheaper

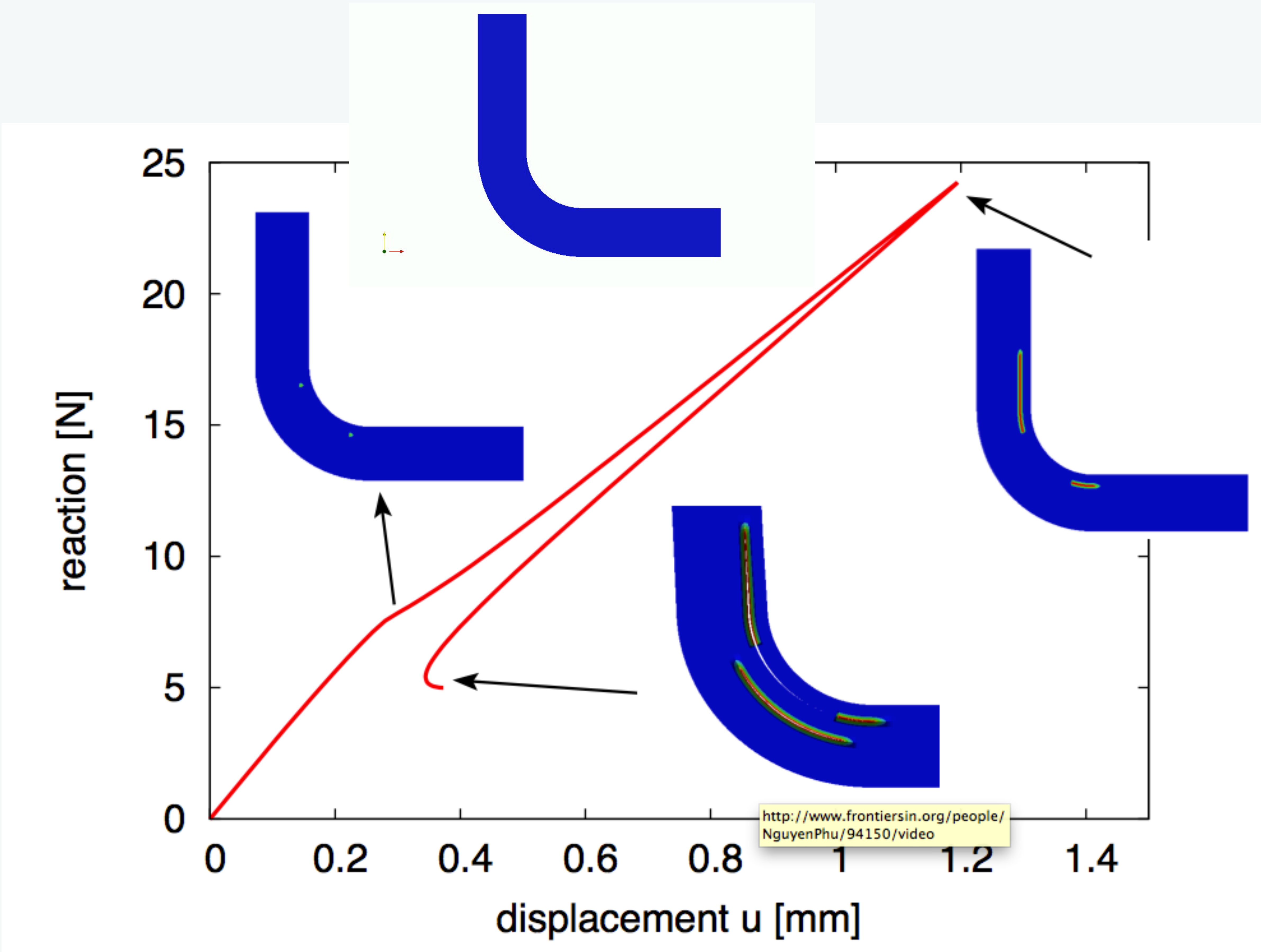


- 2D Mixed mode bending test (MMB)
- 2 x 70 quartic-linear B-spline elements
- Run time on a laptop 4GBi7: 6 s
- Energy arc-length control

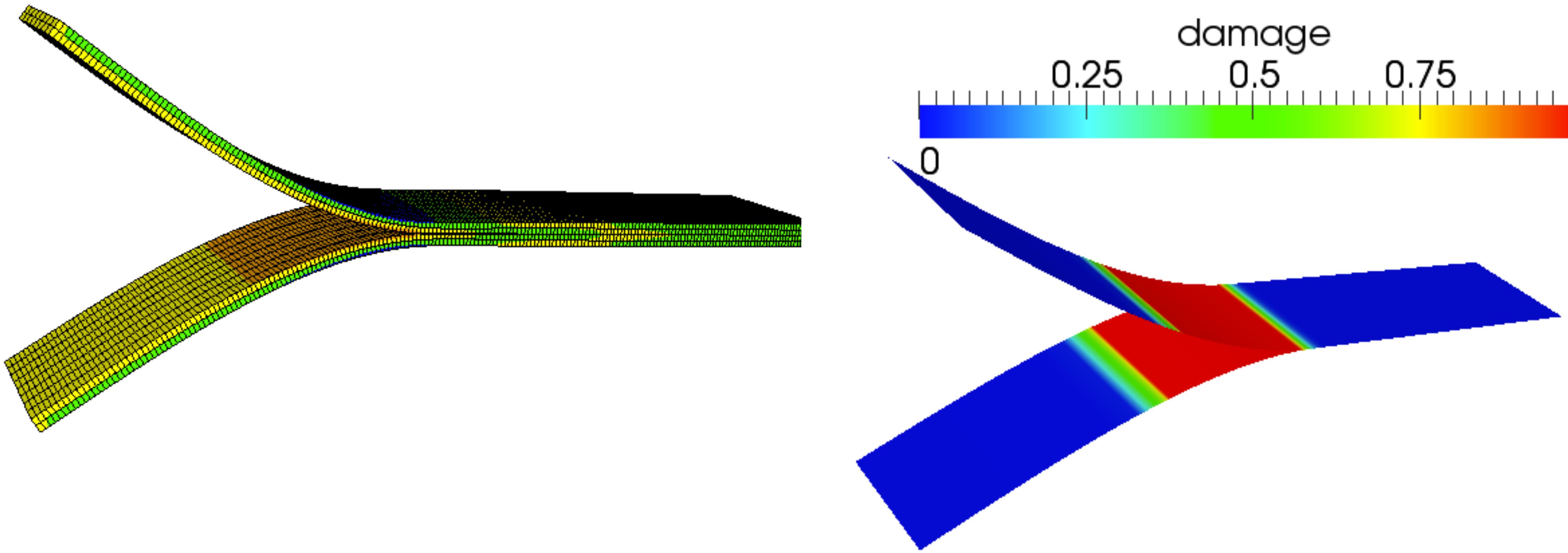


V. P. Nguyen and H. Nguyen-Xuan. High-order B-splines based finite elements for delamination analysis of laminated composites. Composite Structures, 102:261–275, 2013.

Isogeometric cohesive elements: 2D example

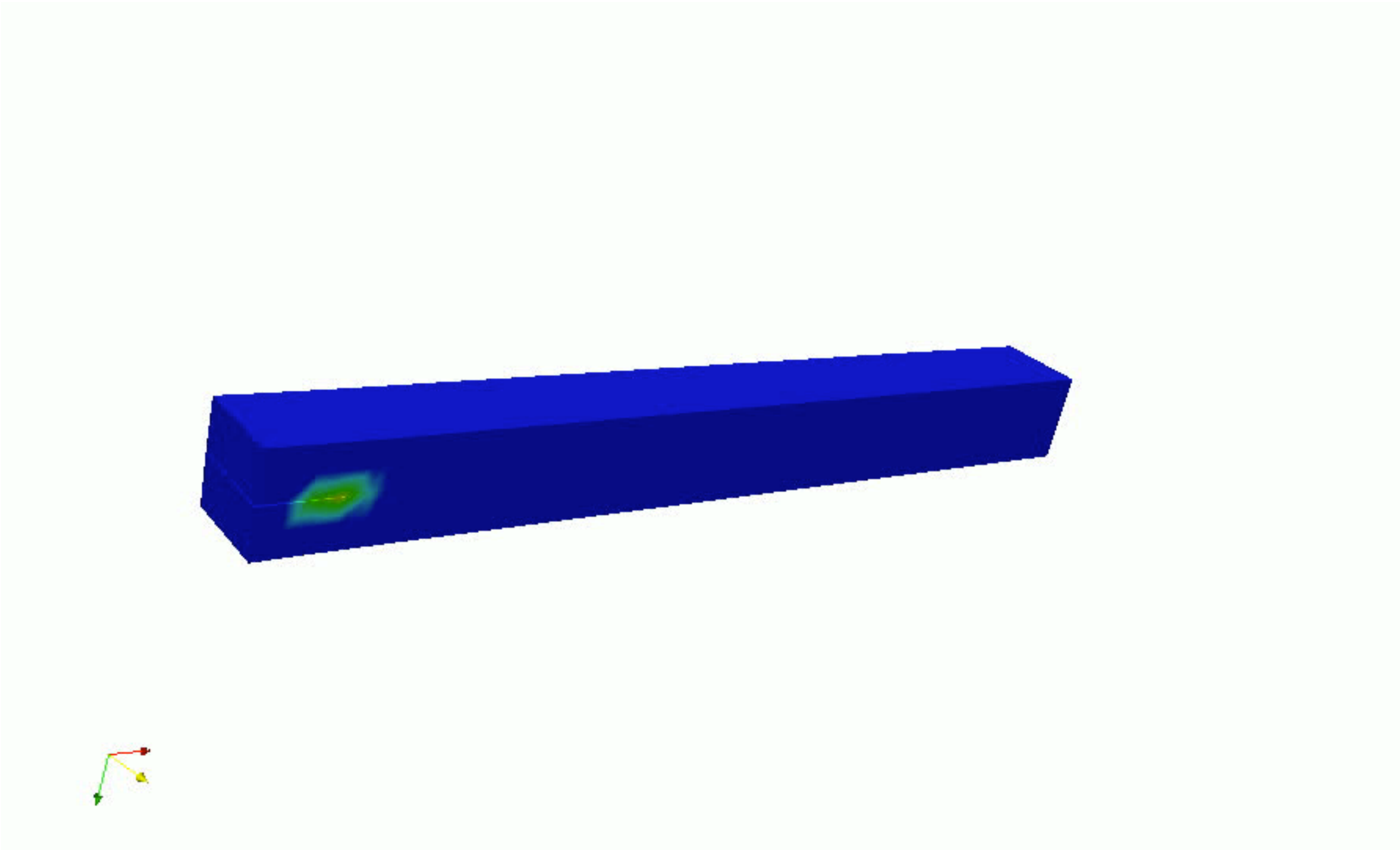


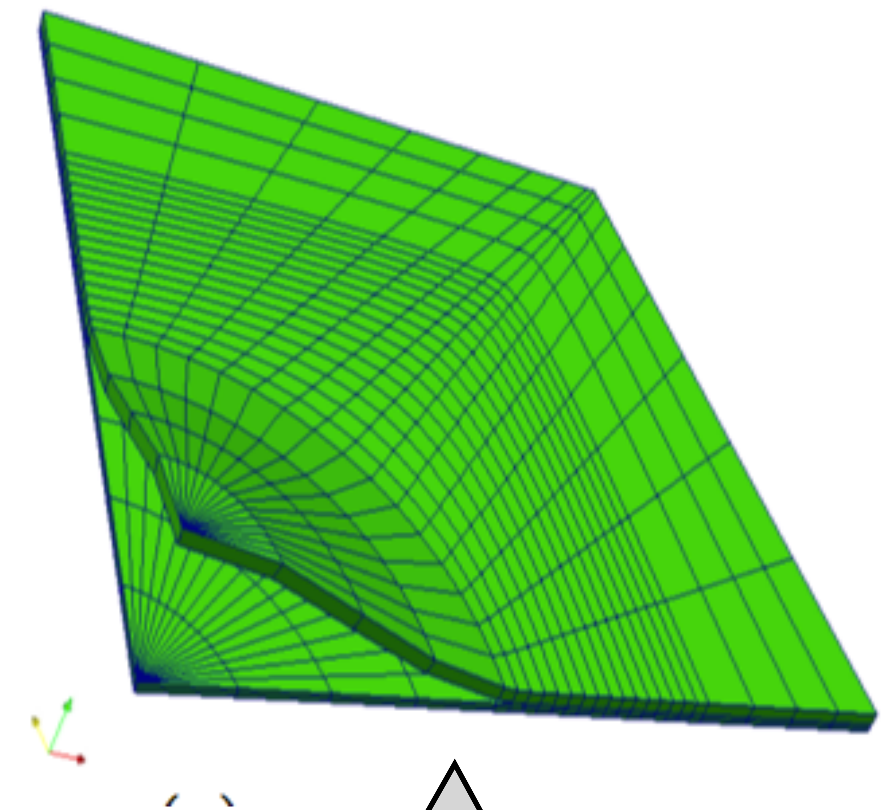
Isogeometric cohesive elements: 3D example with shells



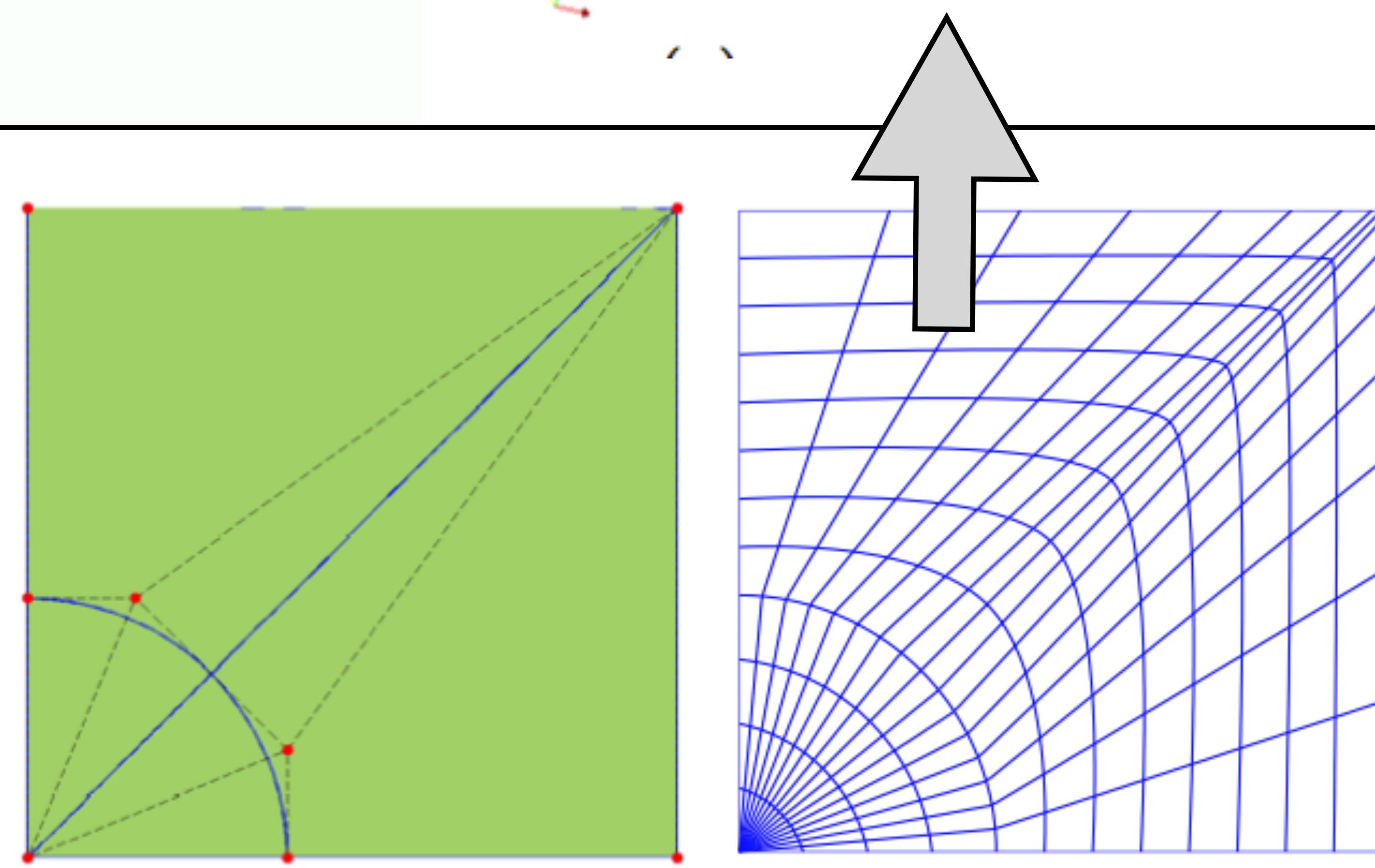
- Rotation free B-splines shell elements (Kiendl et al. CMAME)
- Two shells, one for each lamina
- Bivariate B-splines cohesive interface elements in between

Isogeometric cohesive elements: 3D examples





- cohesive elements for 3D meshes the same as 2D
- large deformations



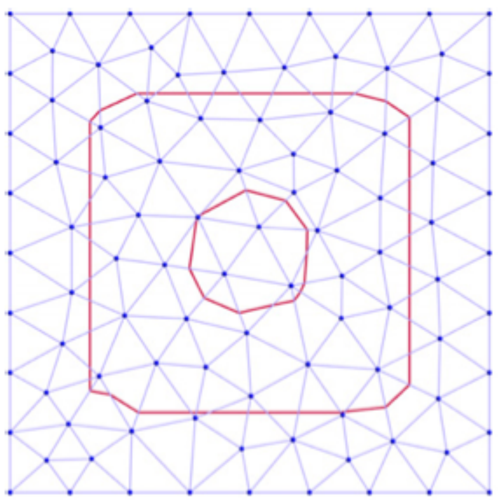
Streamlining the CAD-analysis transition

Coupling, or decoupling?

Decoupling CAD and Analysis.

Separate field and boundary discretisation

- Immersed boundary method (Mittal, *et al.* 2005)
- Fictitious domain (Glowinski, *et al.* 1994)
- Embedded boundary method (Johansen, *et al.* 1998)
- Virtual boundary method (Saiki, *et al.* 1996)
- Cartesian grid method (Ye, *et al.* 1999, Nadal, 2013)

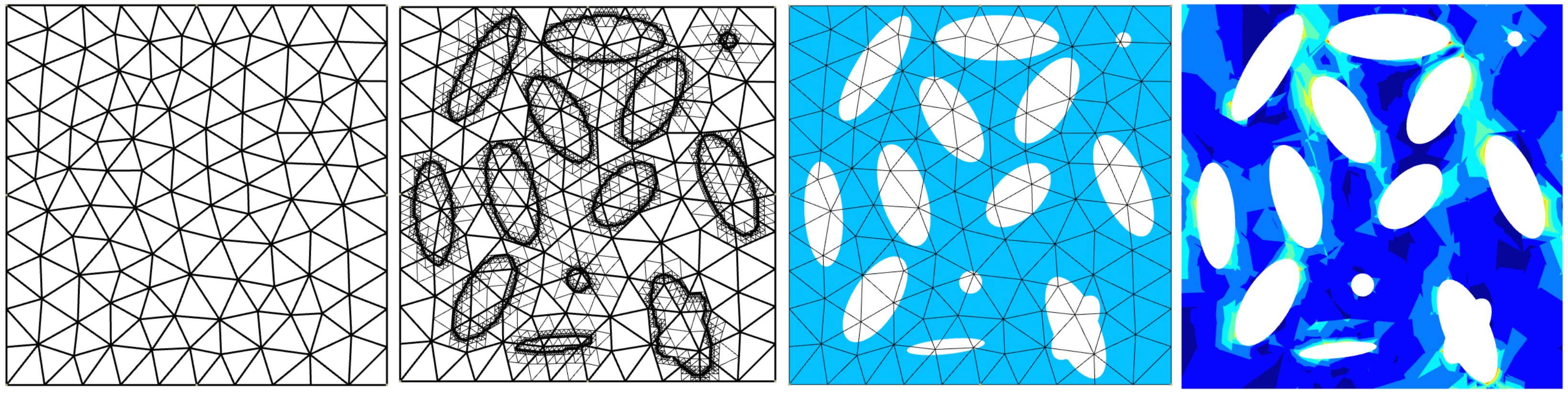


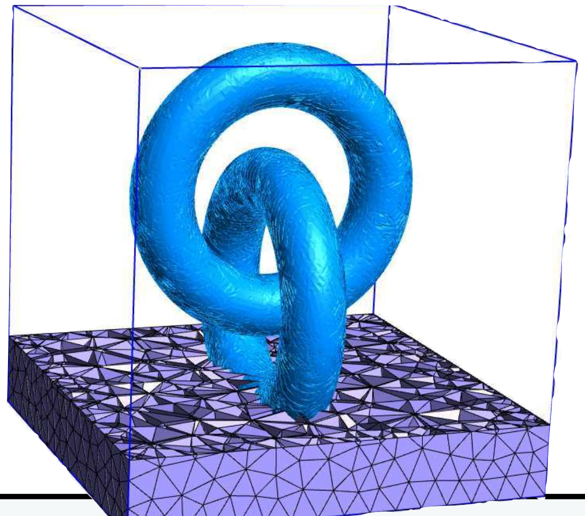
✓ Easy adaptive refinement + error estimation (Nadal, 2013)

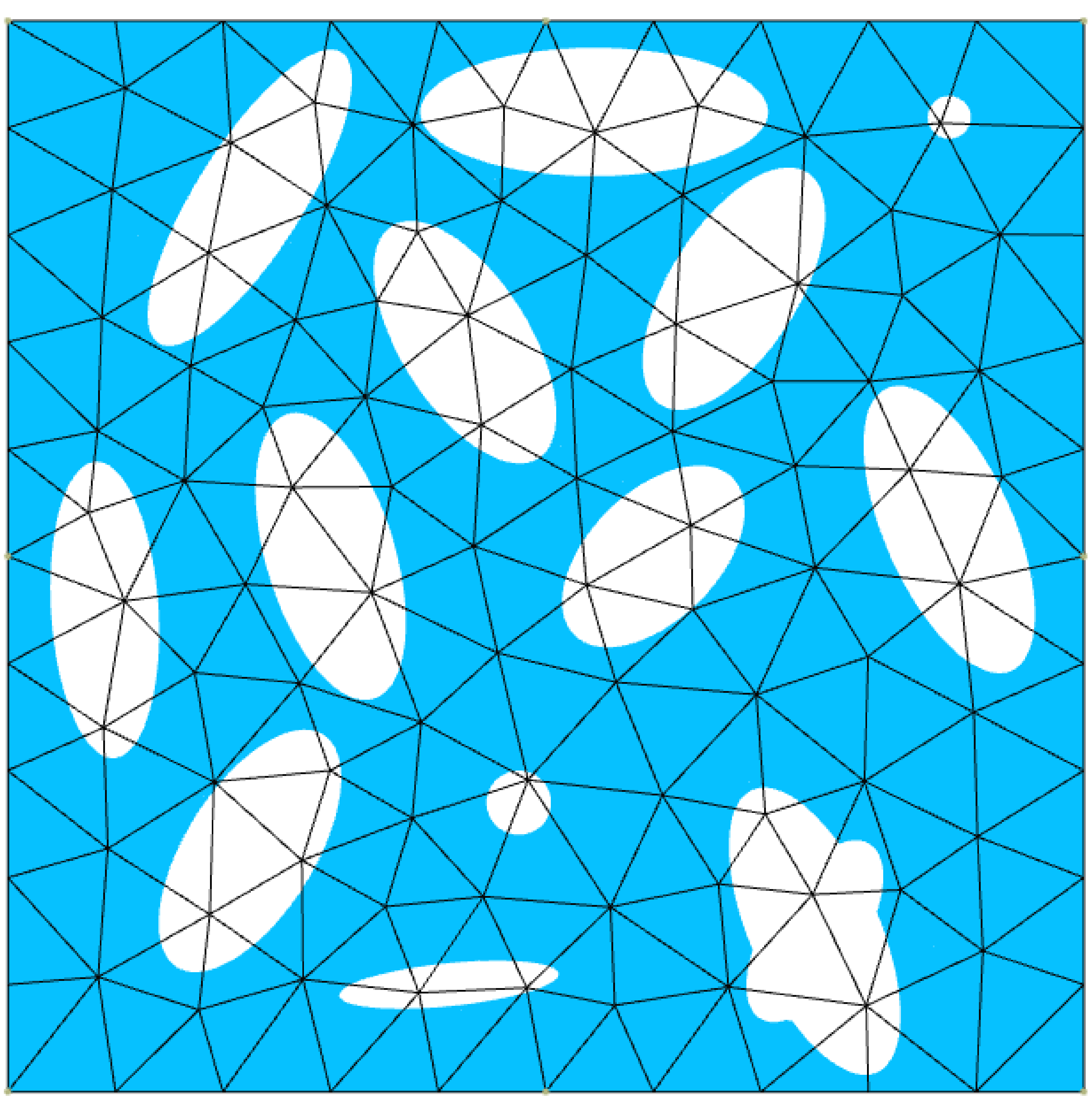
✓ Flexibility of choosing basis functions

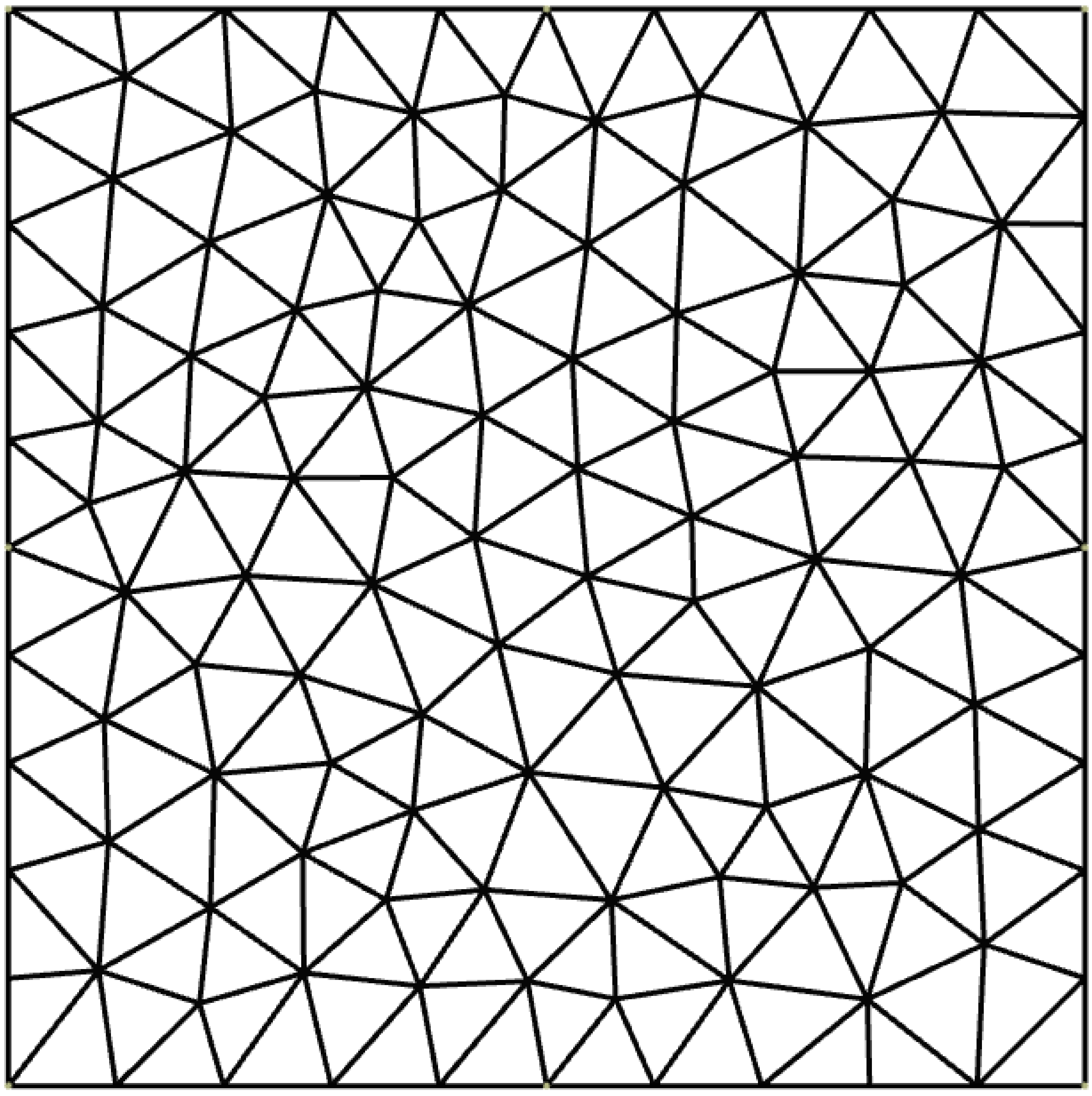
- Accuracy for complicated geometries? BCs on implicit surfaces?

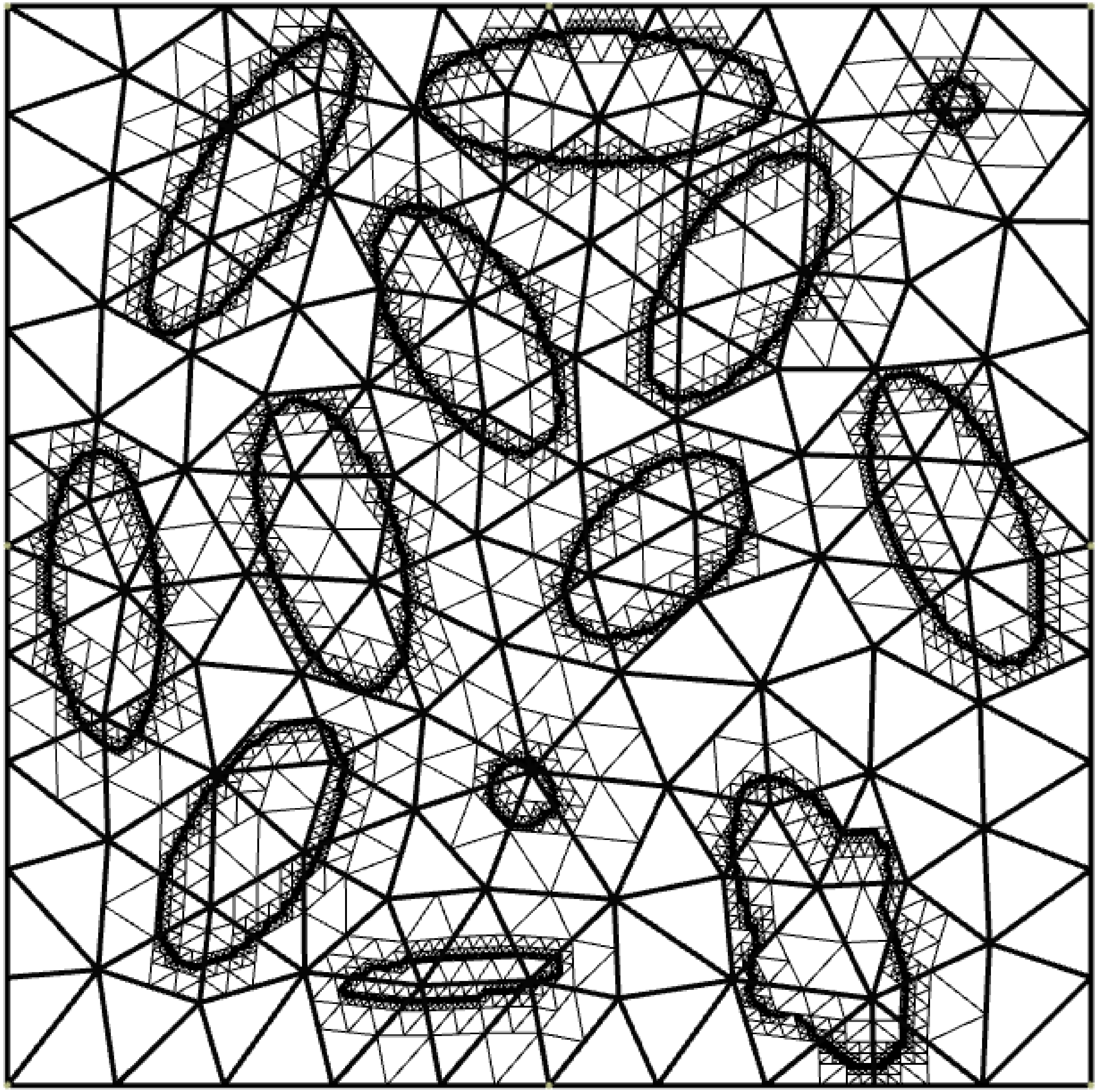
➡ An accurate and implicitly-defined geometry from arbitrary parametric surfaces including corners and sharp edges (CMAME2011, Moumnassi)

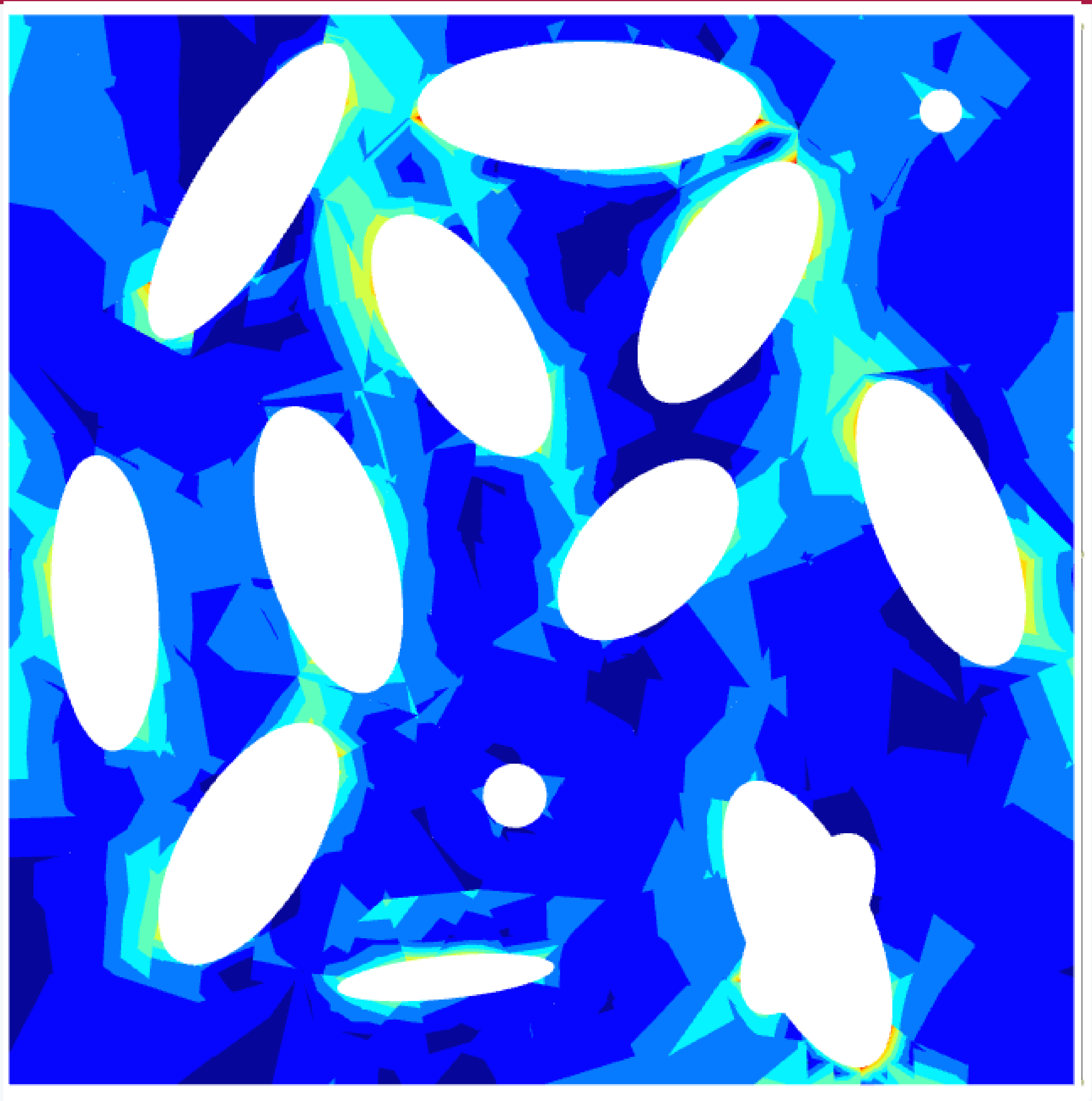






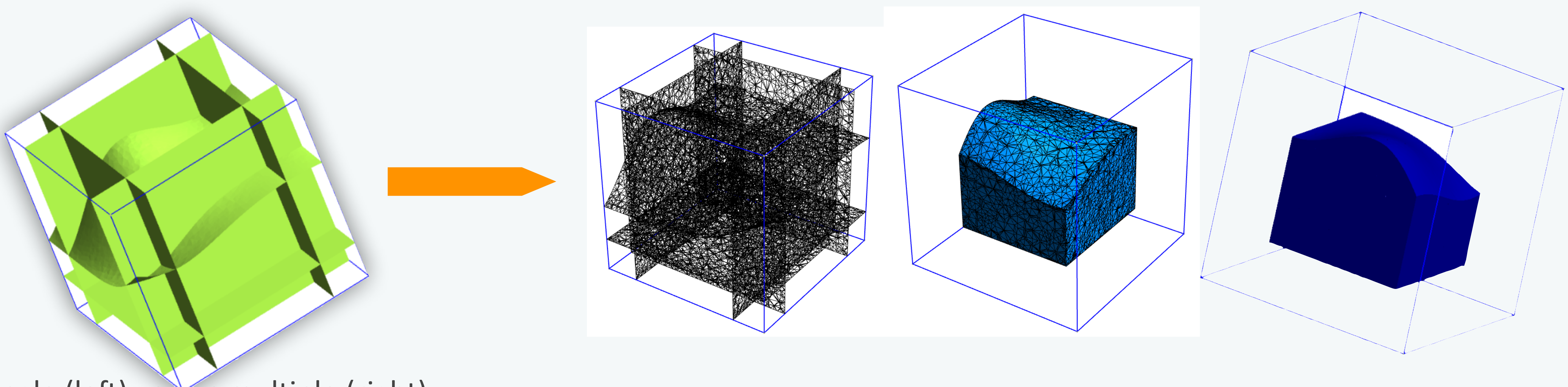




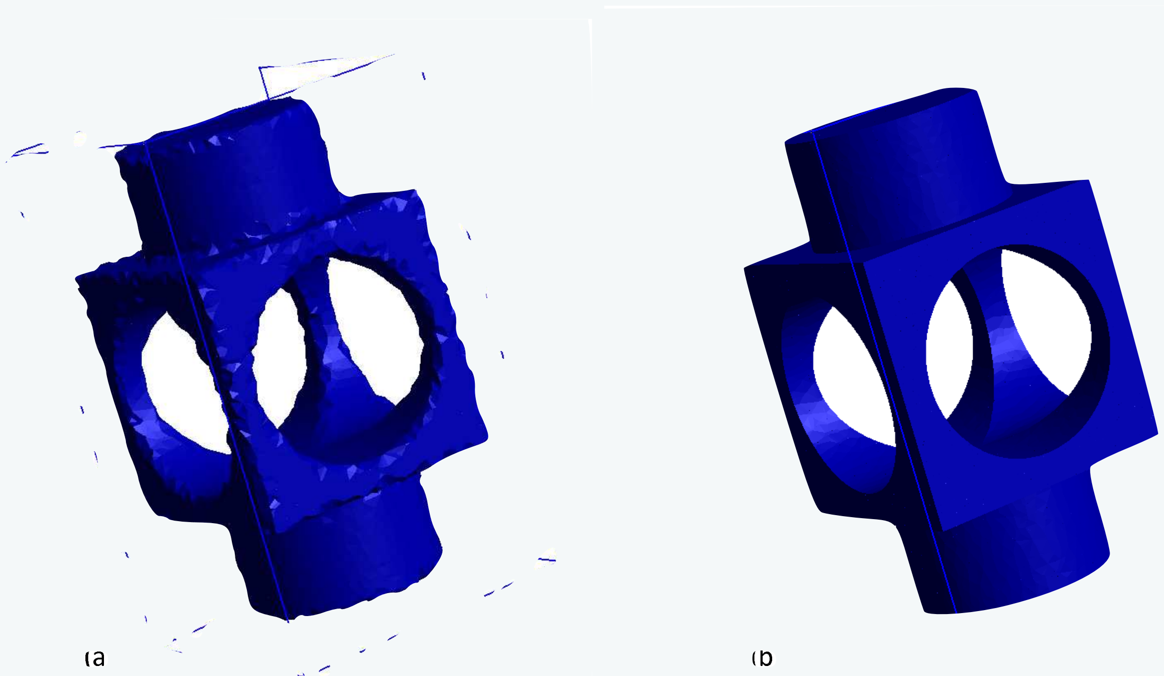


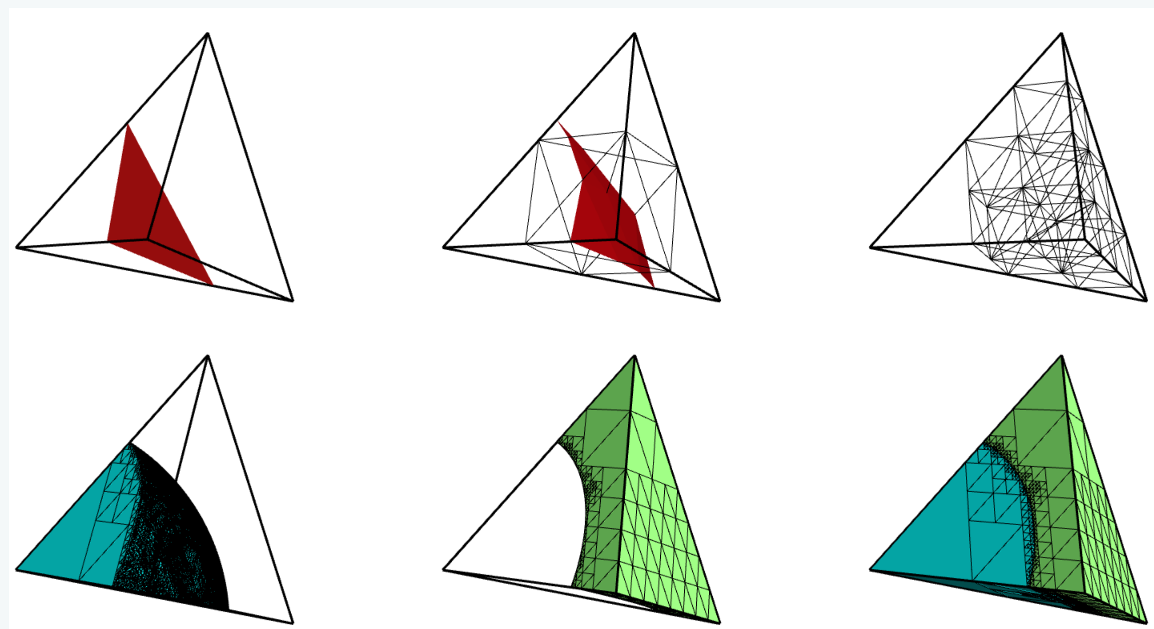
Examples

- multiple level sets

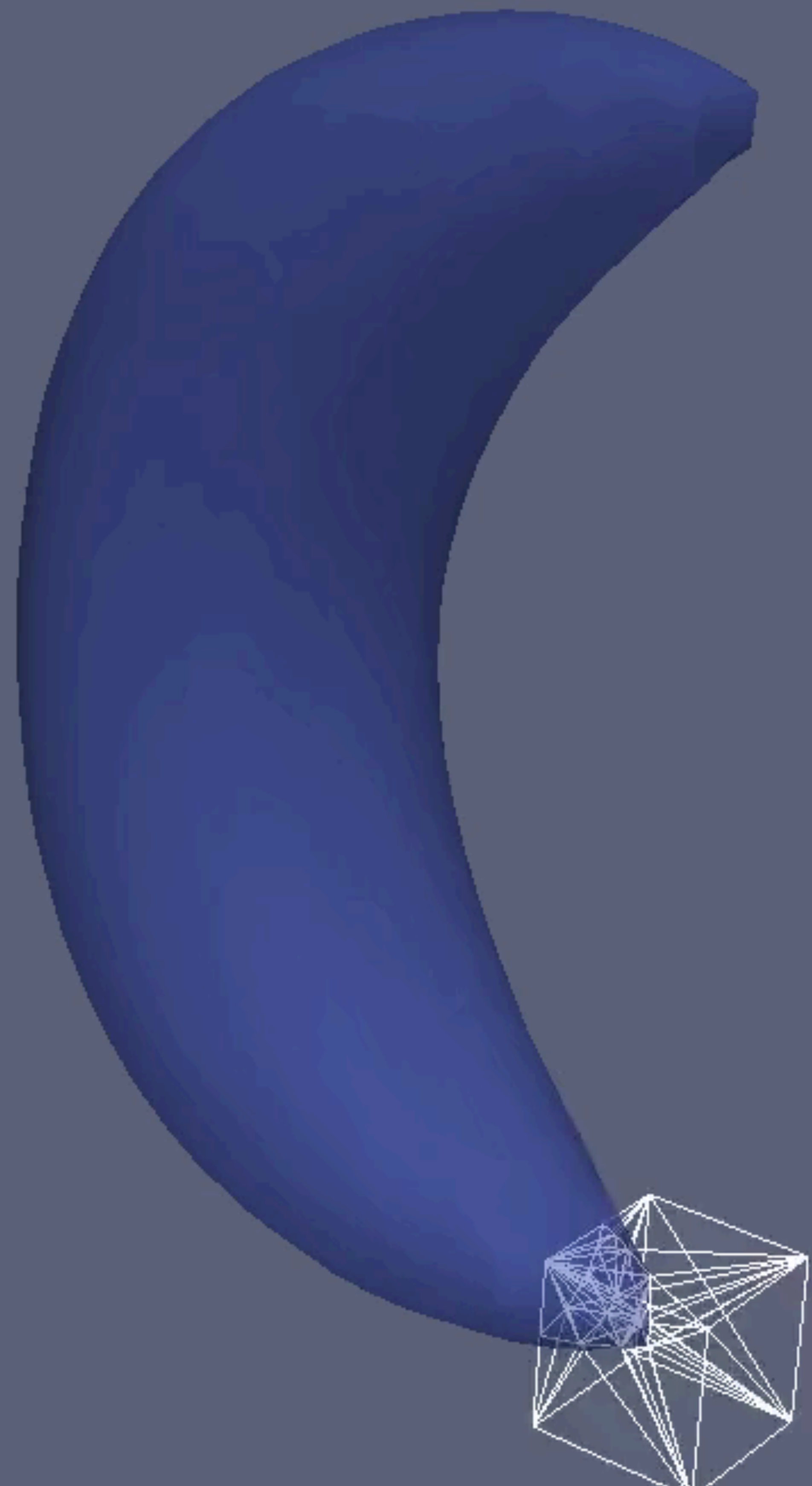


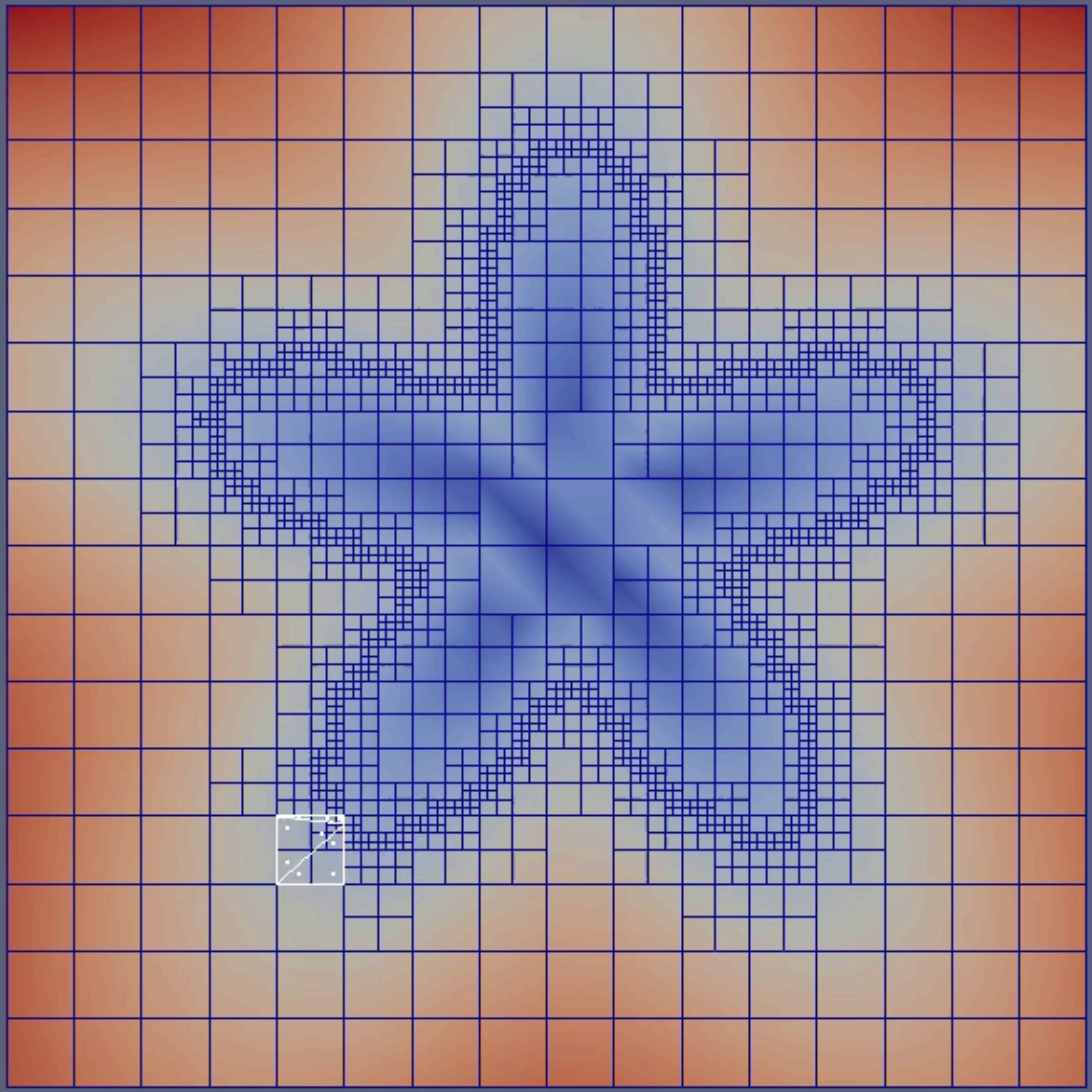
- single (left) versus multiple (right)





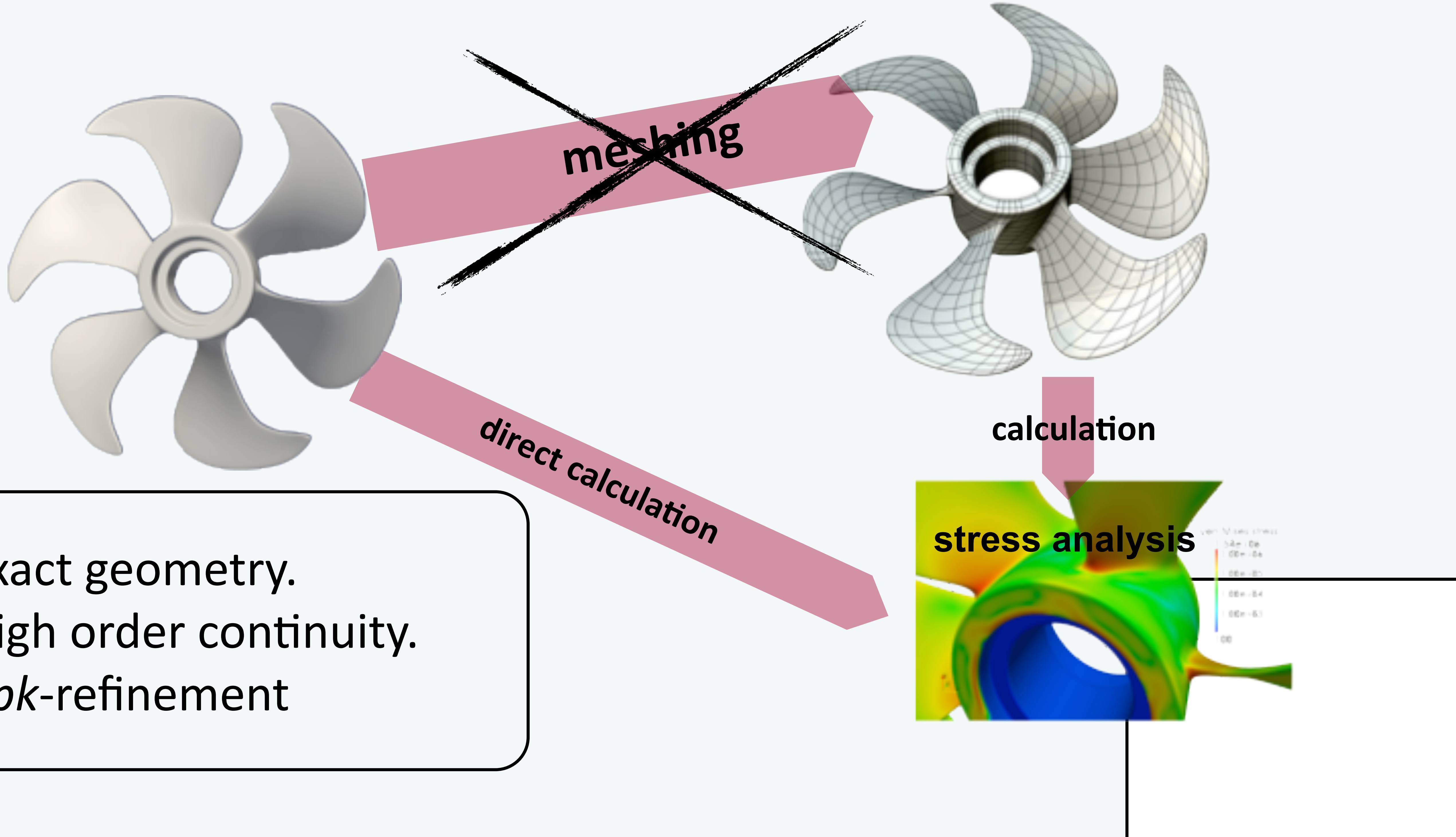
http://legato-team.eu/project/mesh-burden/quadtree-and-octree-implicit-boundary-methods/





Coupling CAD and Analysis.

Approximate the unknown fields with the same basis functions (NURBS, T-splines ...) as that used to generate the CAD model



- Exact geometry.
- High order continuity.
- *hpk*-refinement