Real time surgical simulation using a lattice-continuum approach

Implementation and validation

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SOFA

Some words about me

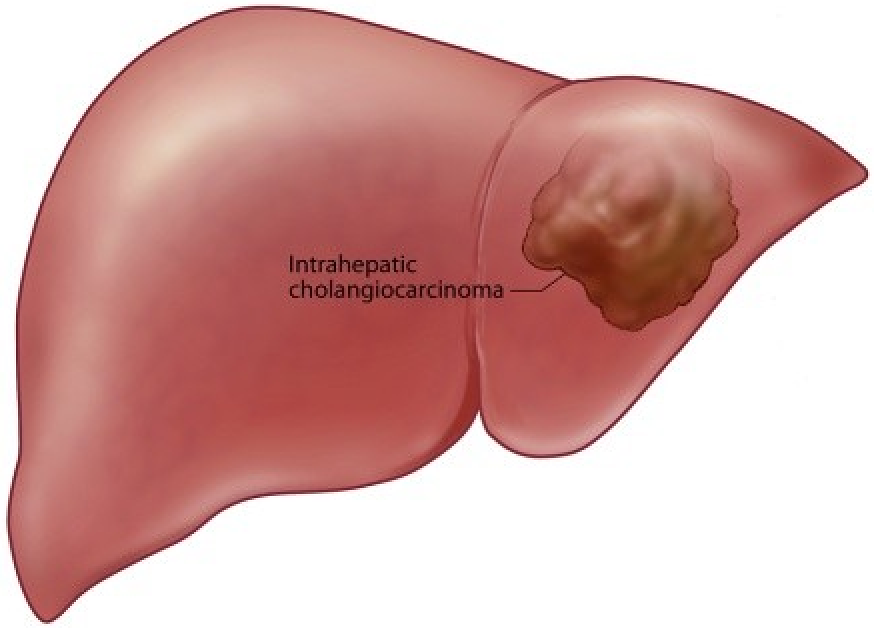
- PhD at University of Grenoble (November 2013)

  Multiscale approach of concrete structure failure

- Postdoc at 3SR laboratory (2014)

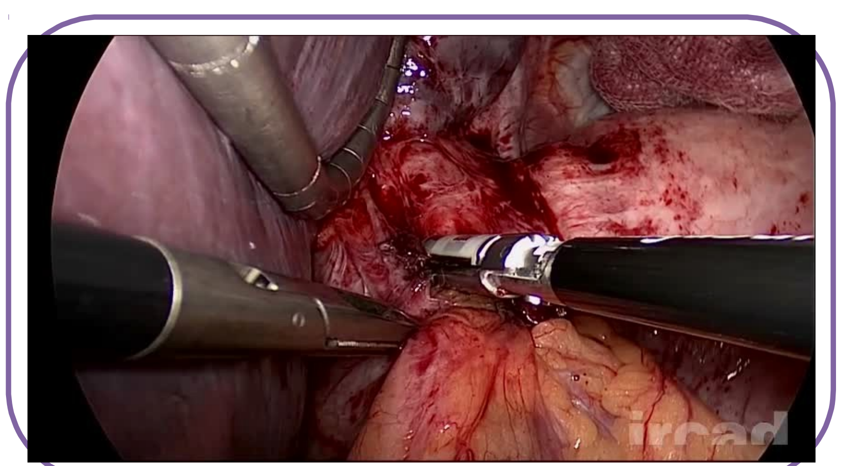
  Segmentation of cracks in concrete structure

- Arrived in Strasbourg (September 2014)



Context

- Surgery: complex practice
  - Experiences of surgeons
  - A number of risks



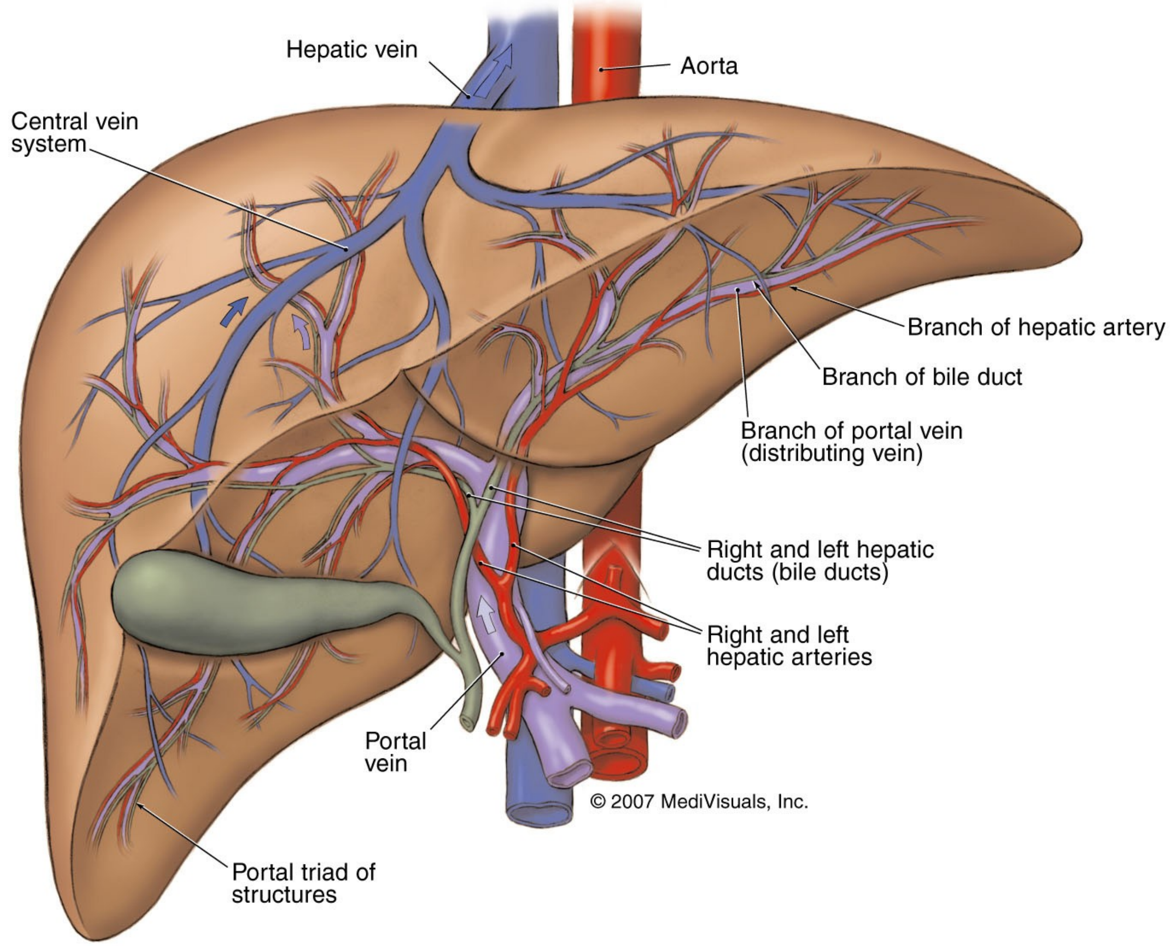
Context

Courtecuisse *et al*, 2013

- **Computer-based simulation**
  - Surgical training
  - Guidance
  - Surgical robotics

- **Challenges:** cutting, tearing, needle insertion, ...
  - Topological changes
  - Contacts
  - Microstructure of the tissue (discontinuities, holes,)

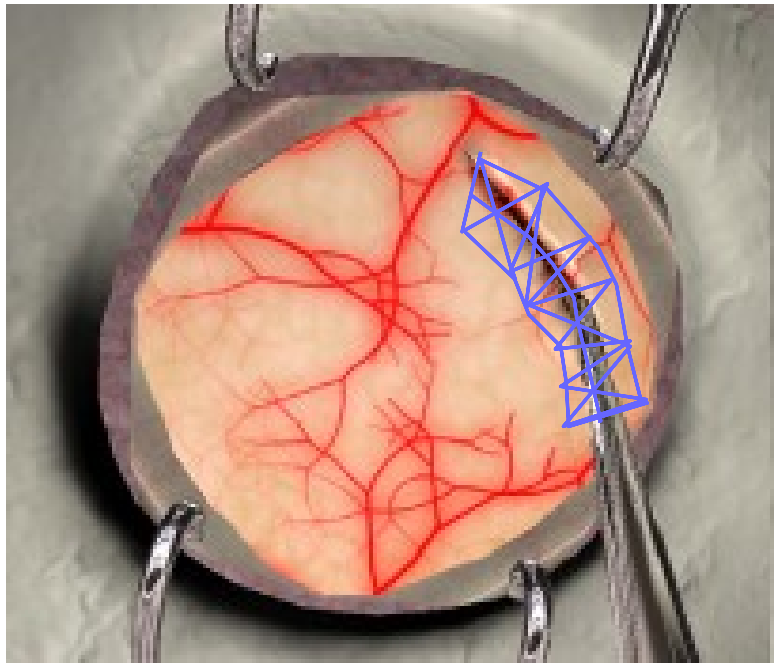
Internal Anatomy of Liver



Objectives

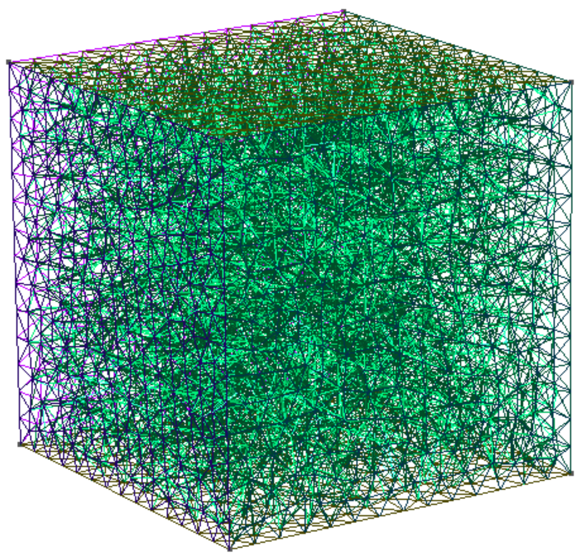
- Development of numerical tool
  - Real-time simulation
  - Multi-domain: continuum-lattice approach
  - Multiscale: macro, mesoscopic scale (material scale)

⇨
- Computational gains
- Increase the quality of the cut

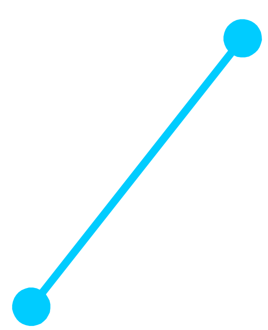


- The algorithm is implemented into SOFA framework

Lattice approach



Discretization by 1D elements



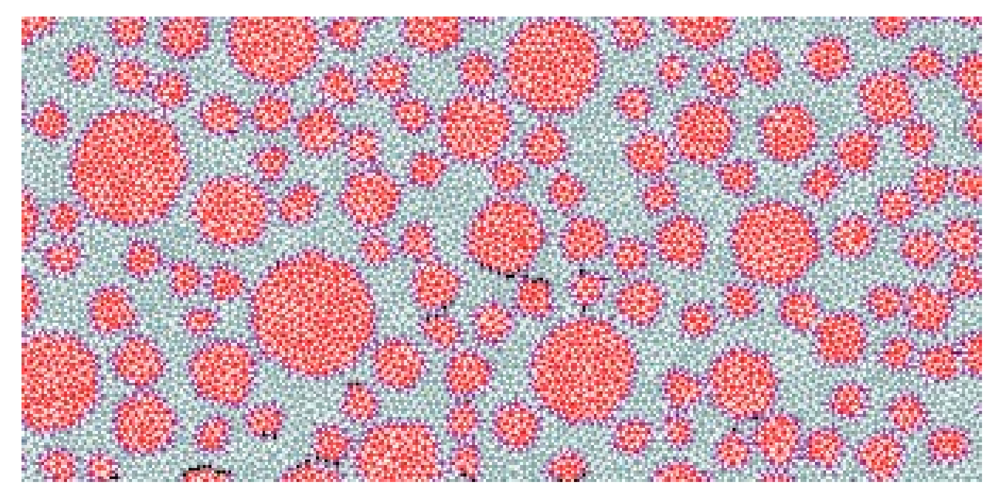
○ Beam element

○ Truss element

▲ Discrete model: suitable for discontinuity problems

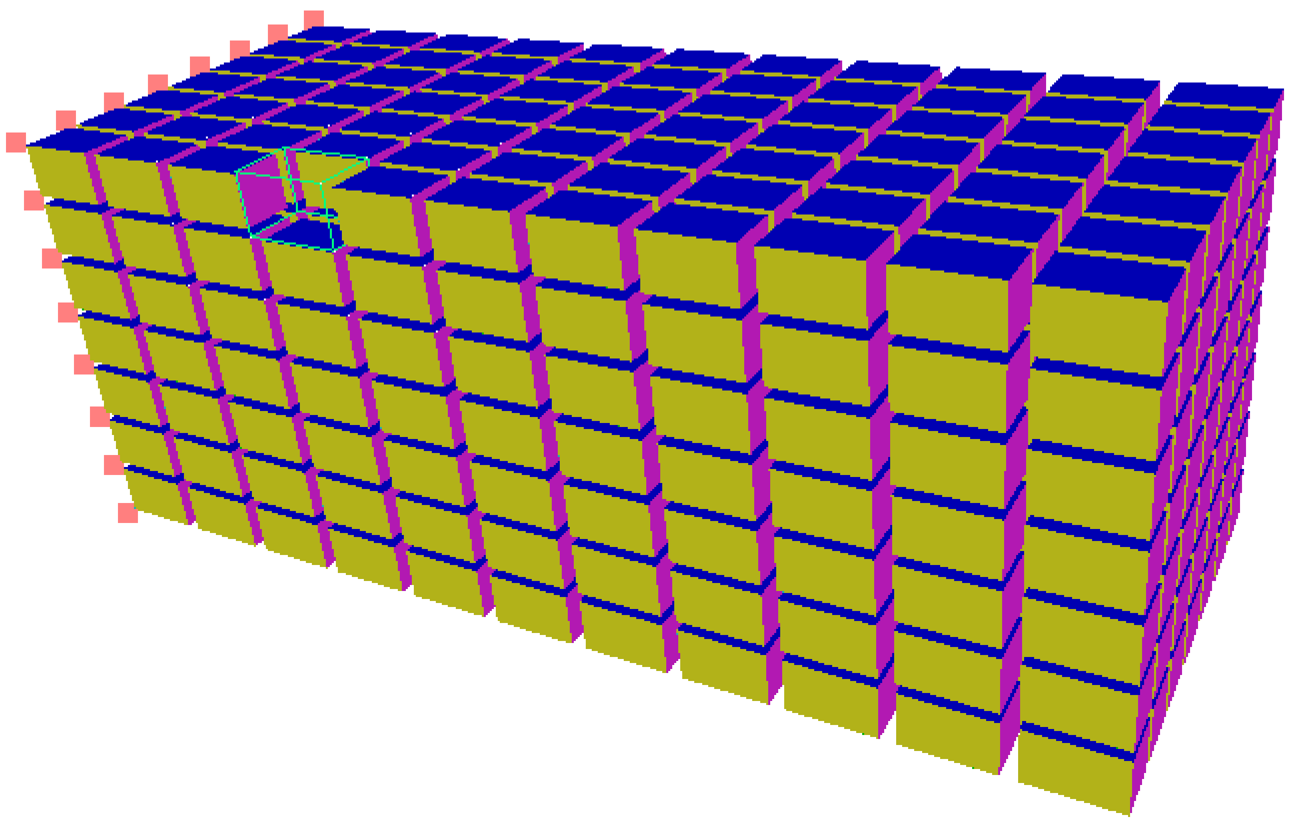
▲ Simplicity to incorporate fracture, cutting

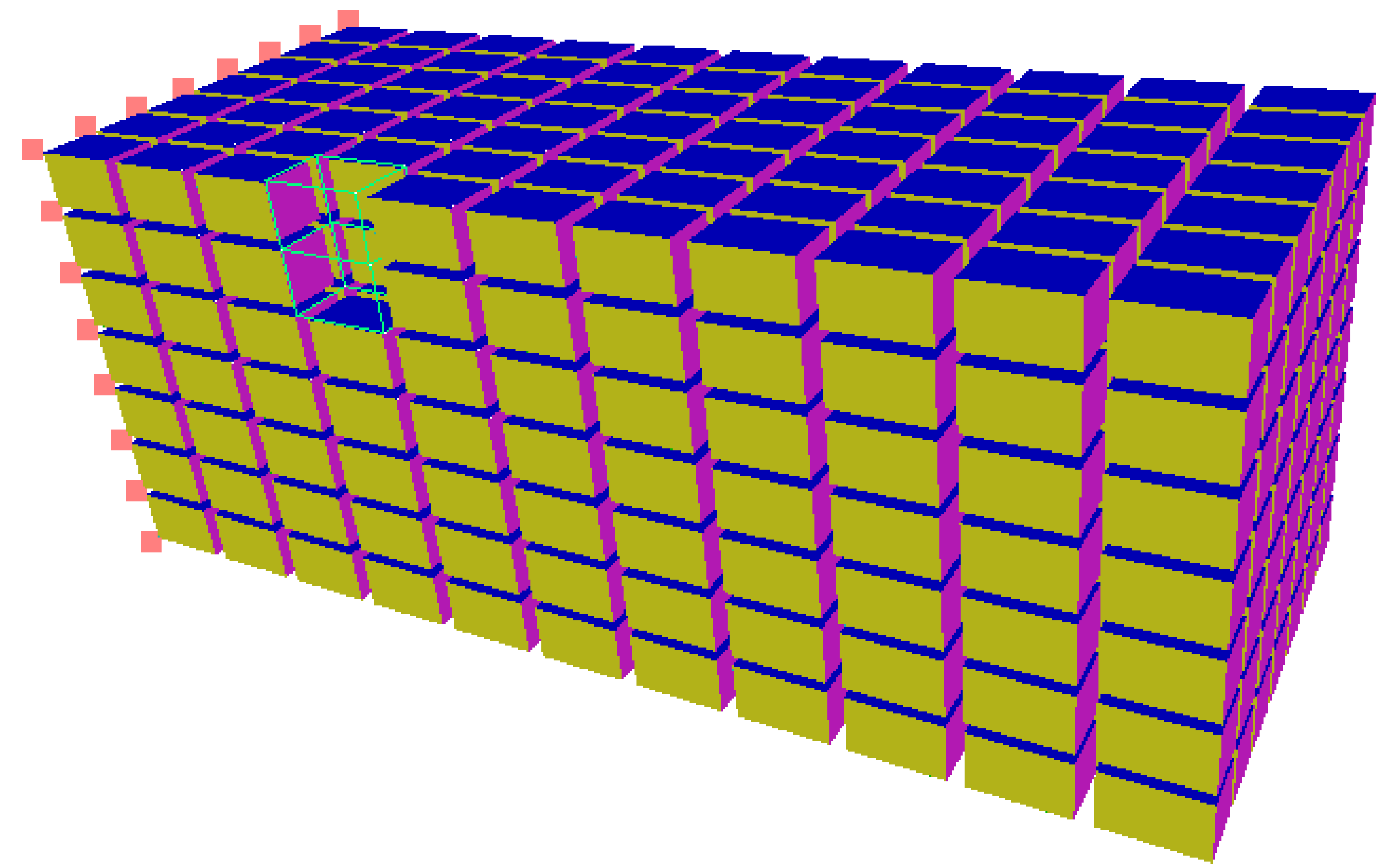
▲ Modeling of material heterogeneity



▼ Computational cost

Continuum-lattice approach





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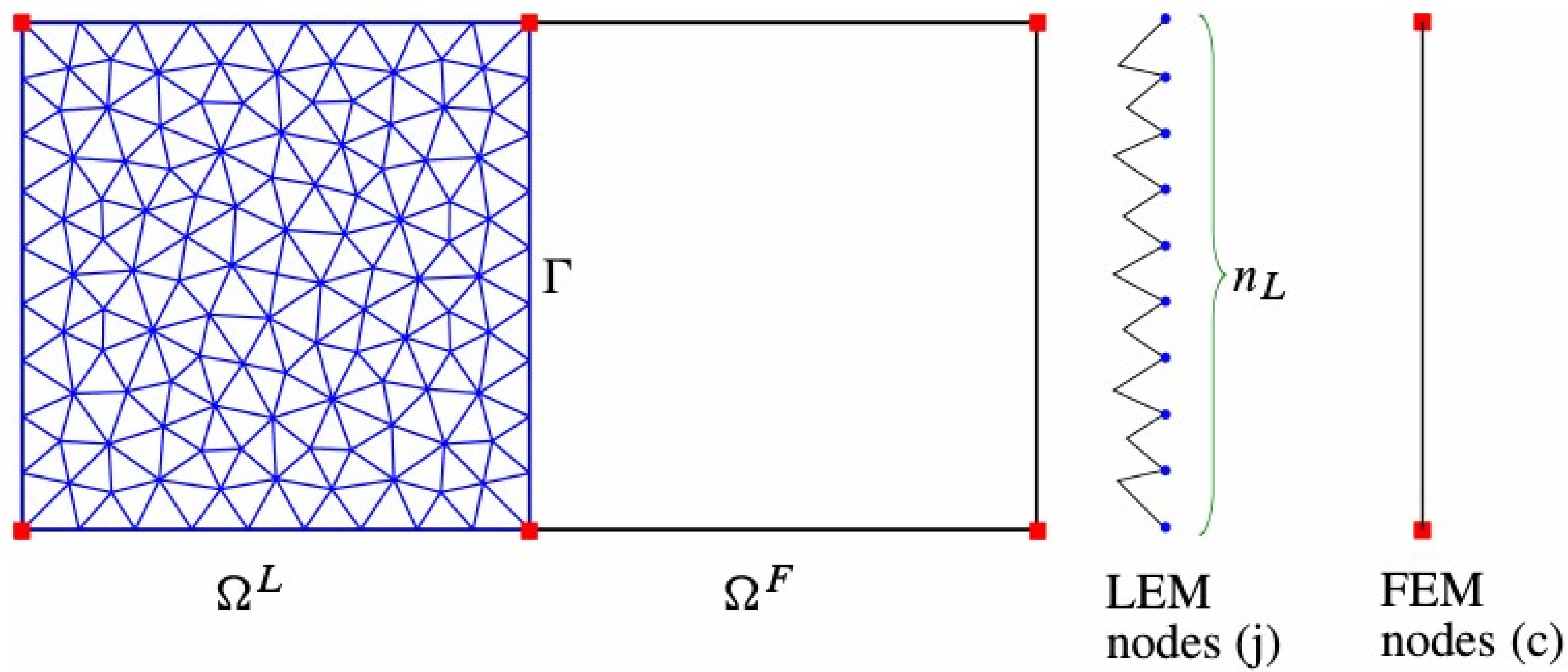
Continuum-lattice approach

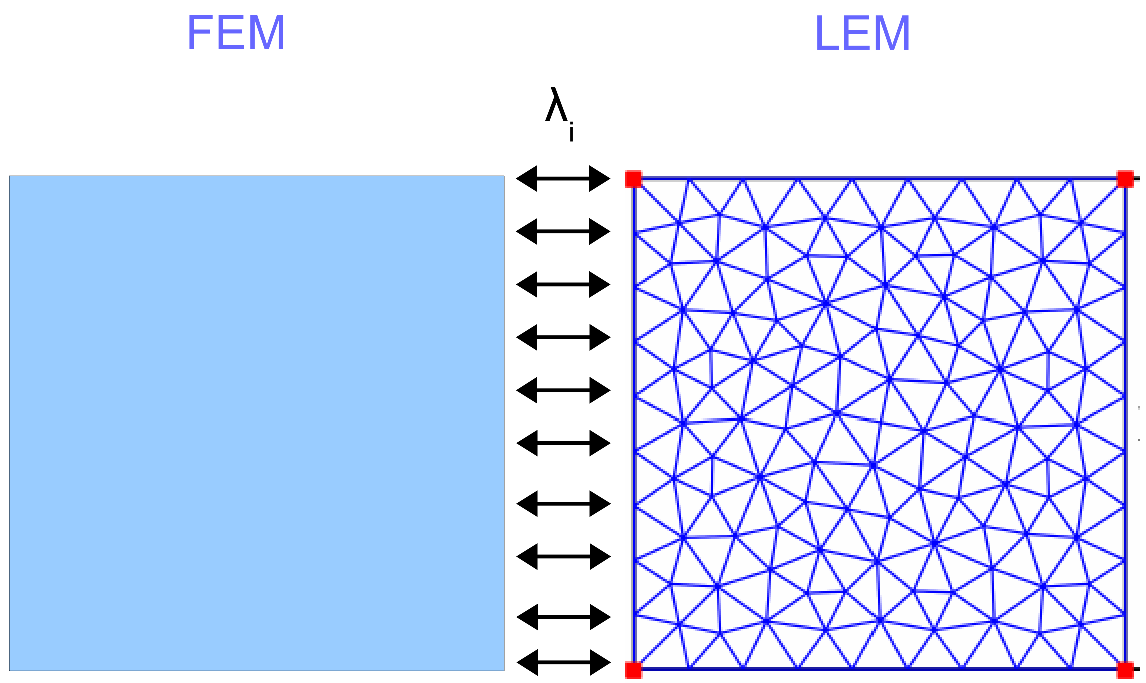


$$\mathbf{u}_j^L = \mathbf{N} \cdot \mathbf{u}_c^F = N_c(\mathbf{x}_j) \cdot u_c, \forall j = \{1, 2, \ldots, n_L\}$$

Continuum-lattice approach

Constraint-based solution

Courtecuisse *et al*, 2013
Duriez *et al*, 2006



FEM $$\mathbf{A}_1\mathbf{x}_1 = \mathbf{b}_1 + h\,\mathbf{H}_1^T\lambda$$

LEM $$\mathbf{A}_2\mathbf{x}_2 = \mathbf{b}_2 + h\,\mathbf{H}_2^T\lambda$$

Interface With Lagrange multiplier **λ** such that $\mathbf{u}_j^L = \mathbf{N}\cdot\mathbf{u}_c^F$

Step 1: Free motions $\mathbf{x}_1^{free}$, $\mathbf{x}_2^{free}$ — $\mathbf{A\,x = b}$ with $\boldsymbol{\lambda} = 0$

Step 2: Corrective motions $\mathbf{x}_1^{cor}$, $\mathbf{x}_2^{cor}$ — $\mathbf{A\,x = hH}\boldsymbol{\lambda}$ with b = 0

Asynchronous **preconditioner** using sparse **LDL**^{T} factorization

Step 3: Apply correction — $\mathbf{x} = \mathbf{x}^{free} + \mathbf{x}^{cor}$

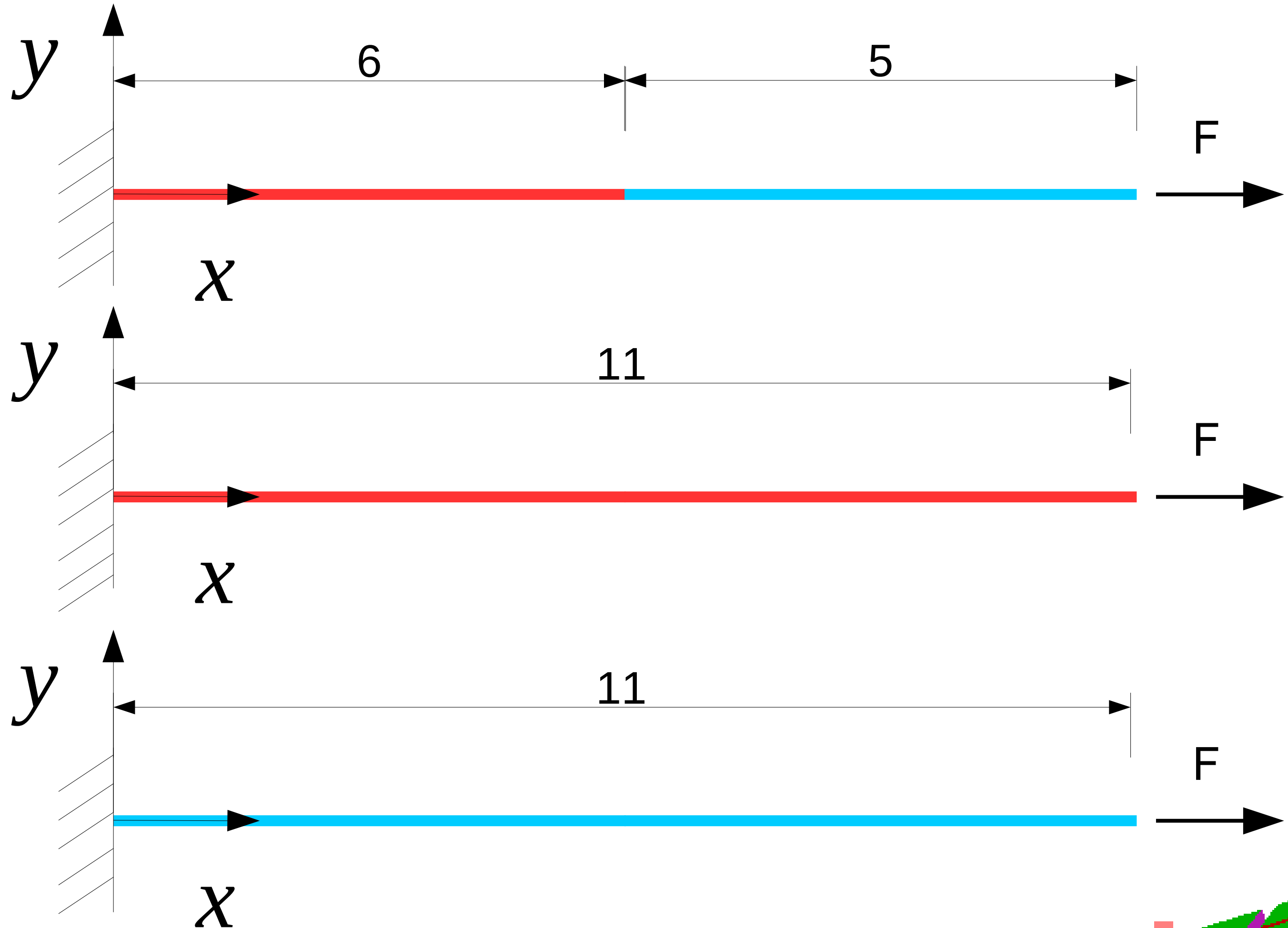
Validation tests

Validation tests: 3D tensile test

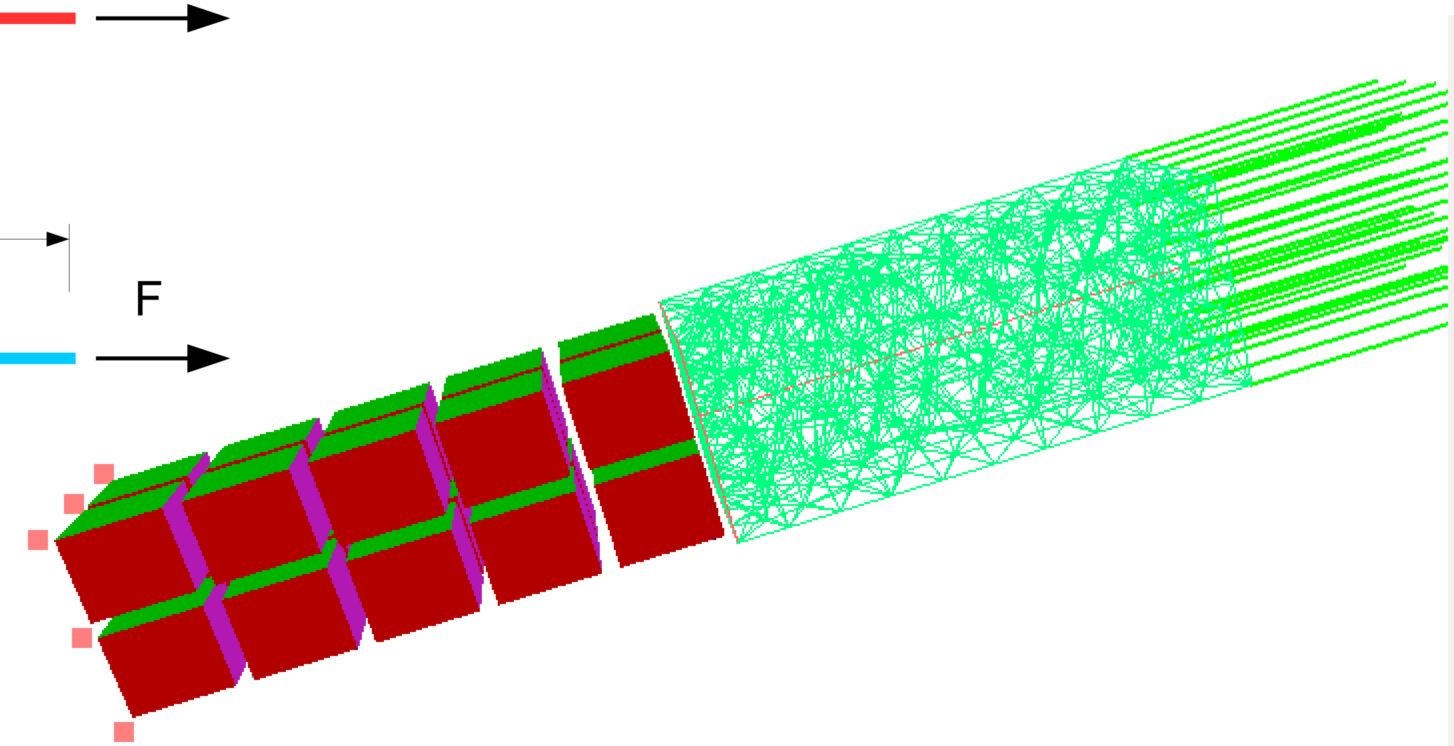
Coupling

FEM

LEM



E = 19.5 GPa
ν = 0.1
bxh = 2x2 mm
F = 100 N



Analytical solution

$$u(x) = \int \frac{F}{EA} \mathrm{d}x = \frac{F}{EA} x$$

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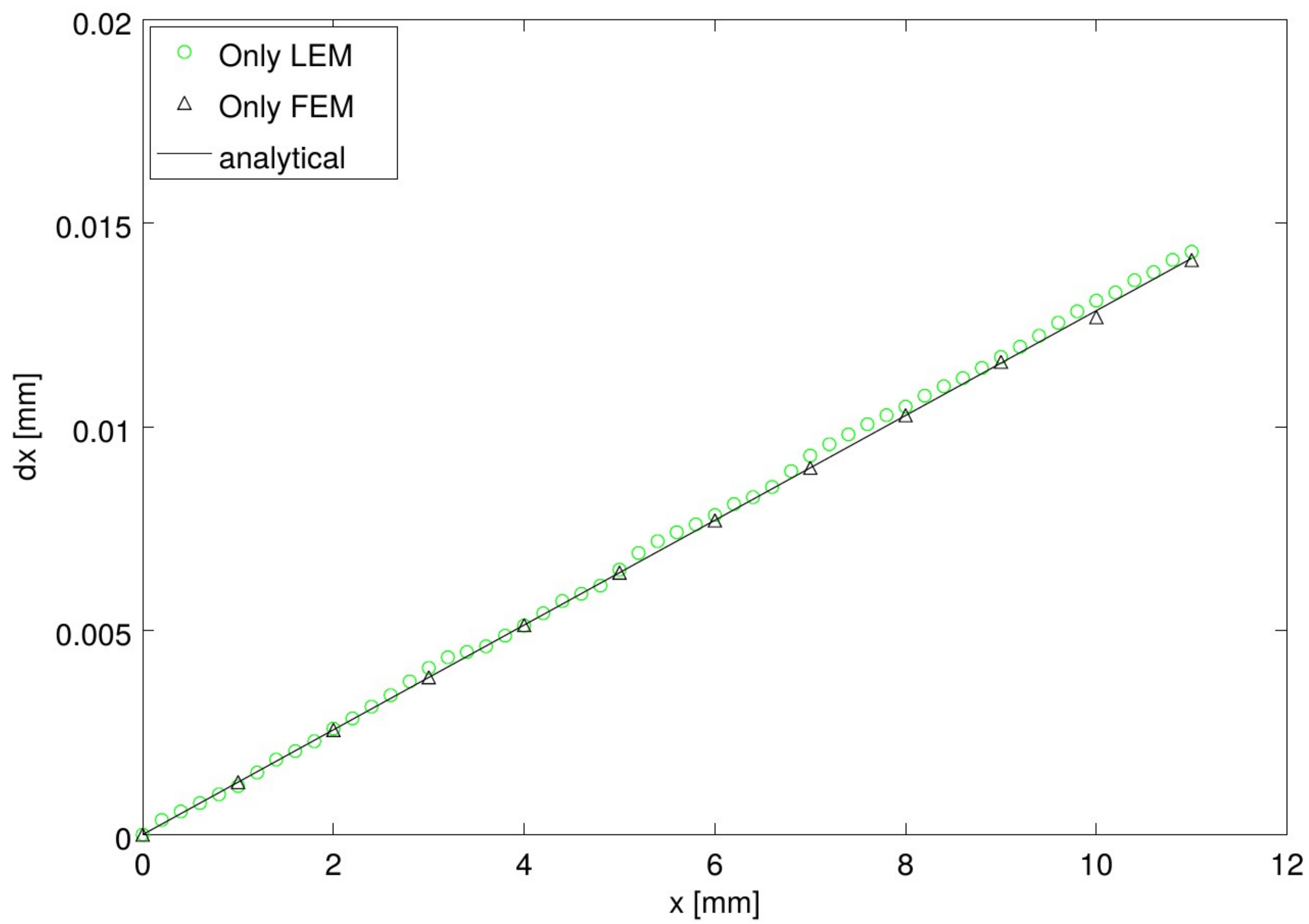
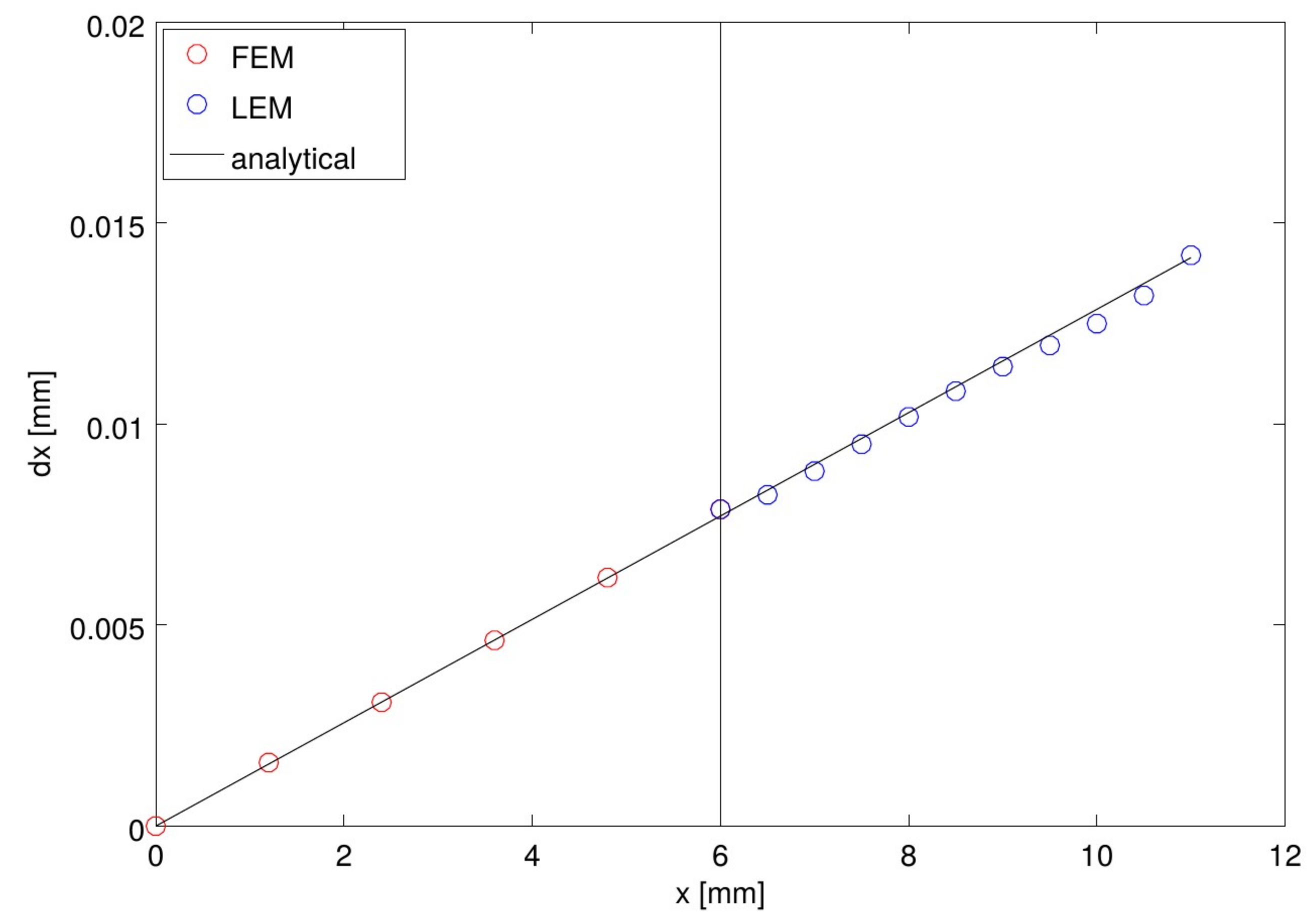
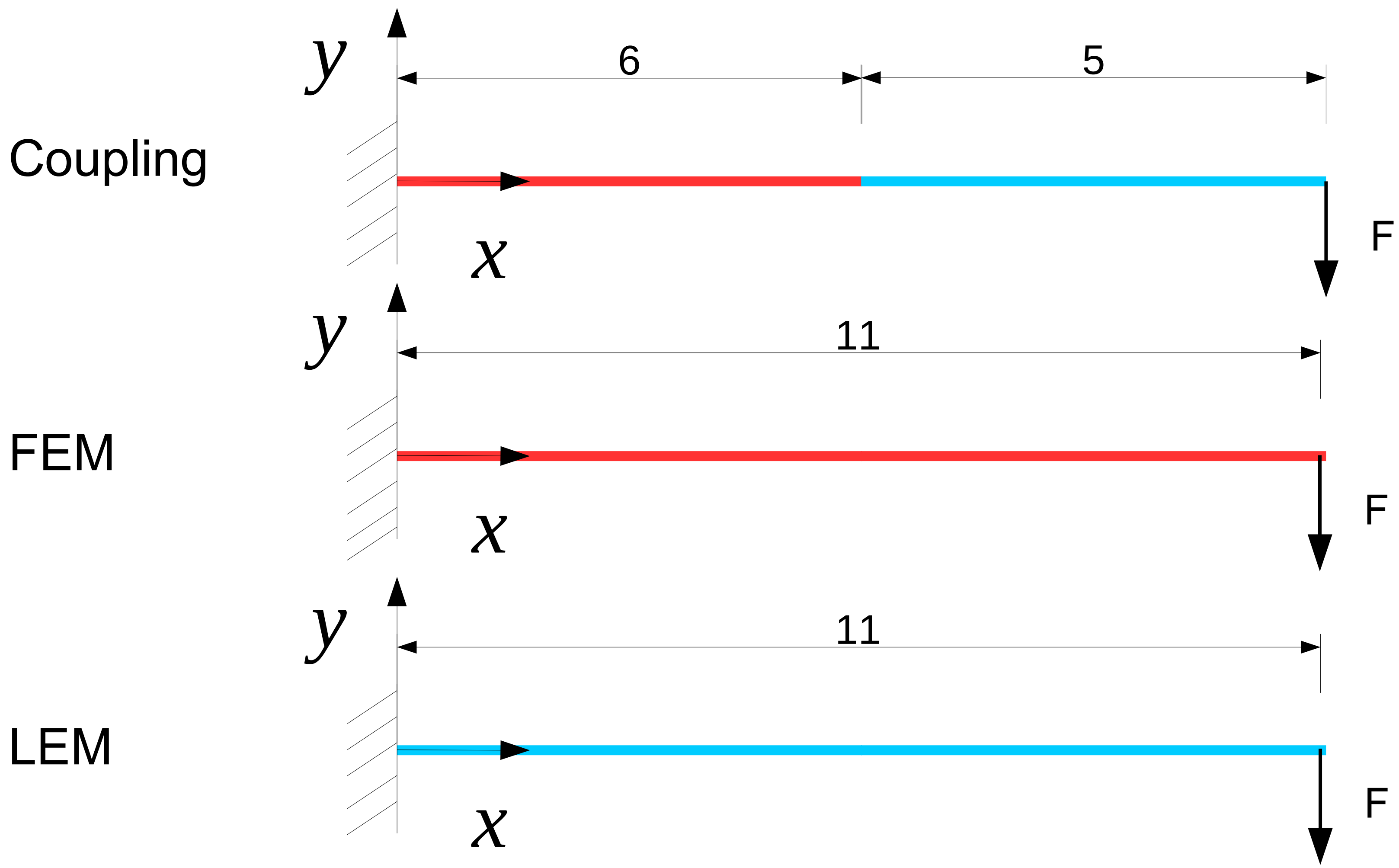
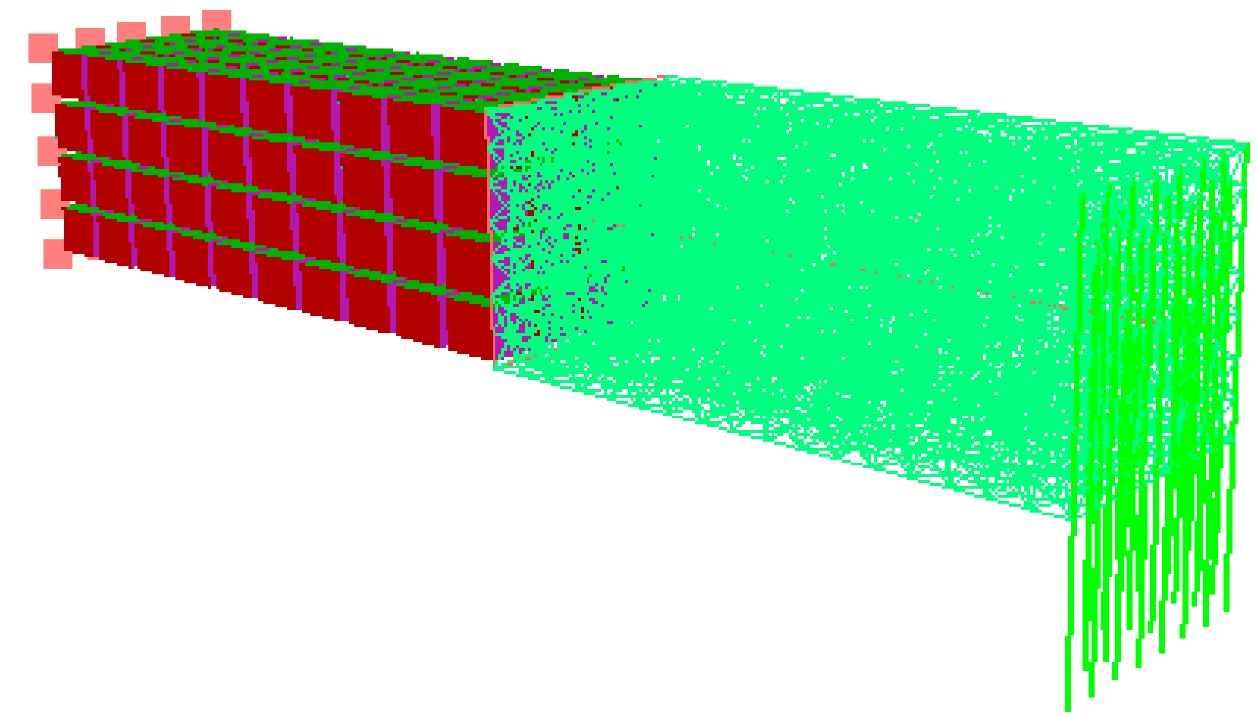
Validation tests: 3D tensile test





Validation tests: 3D bending test





Analytical solution $$v(x) = \frac{-Fx^2}{6EI}(3L - x)$$

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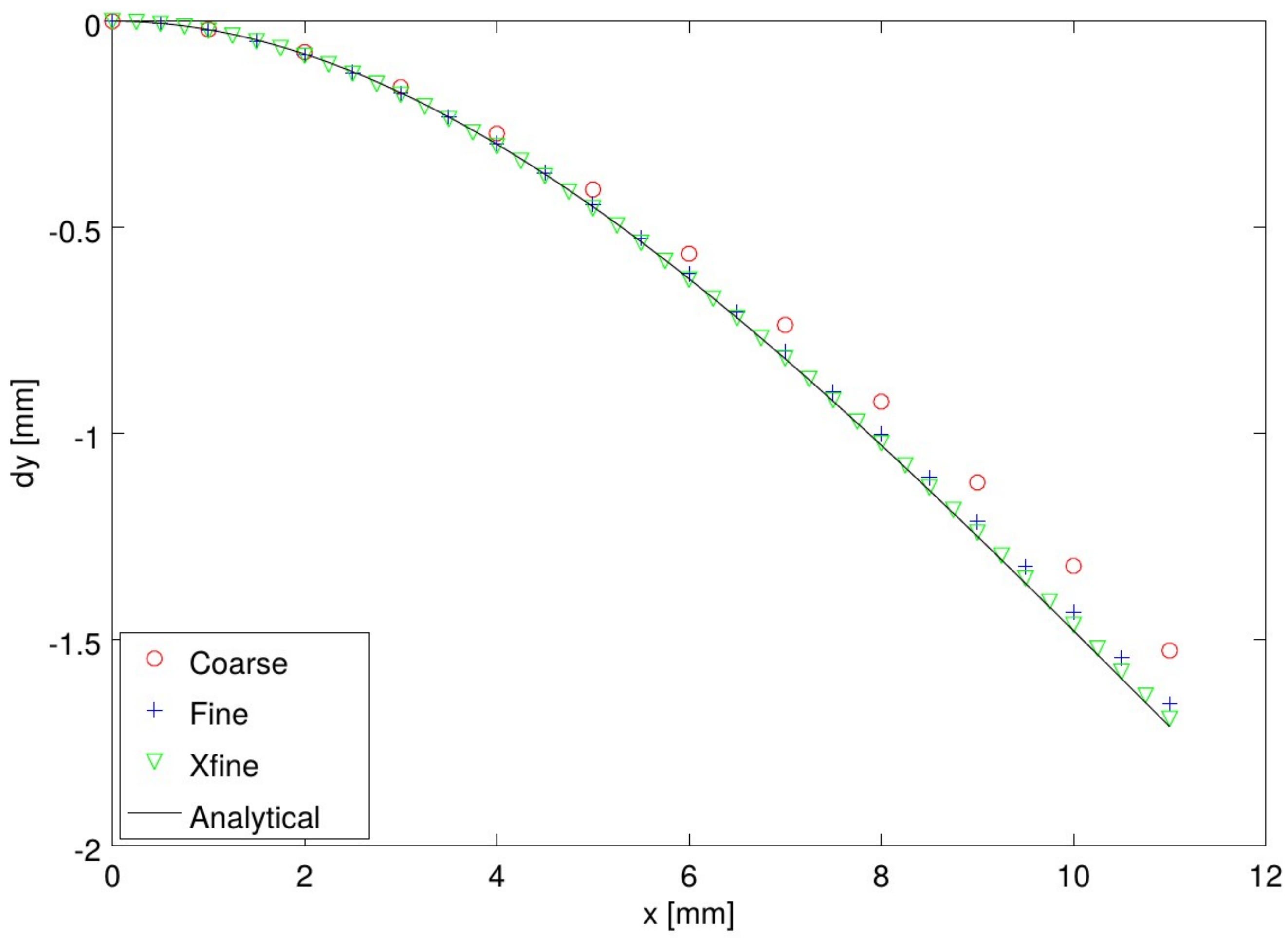
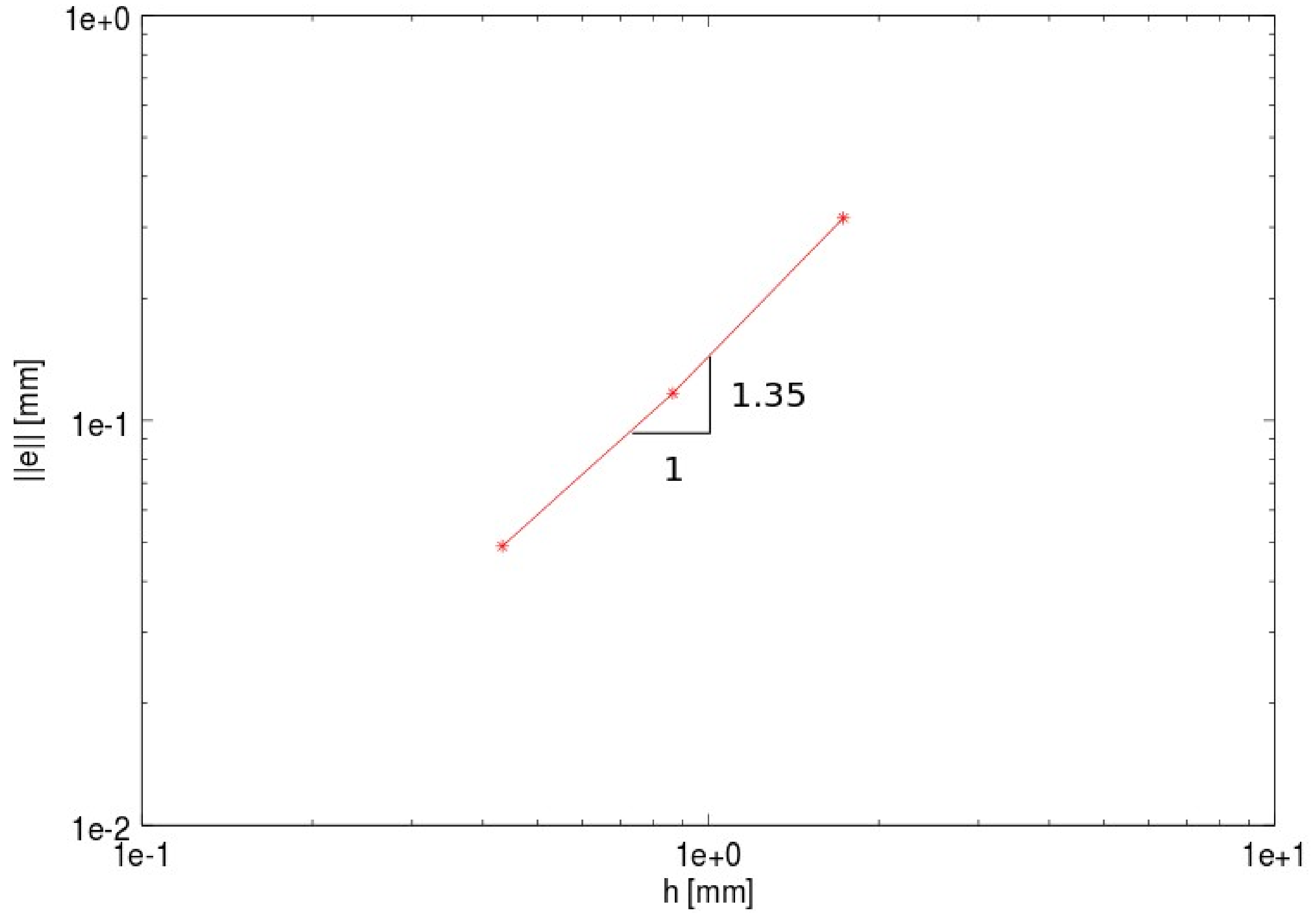
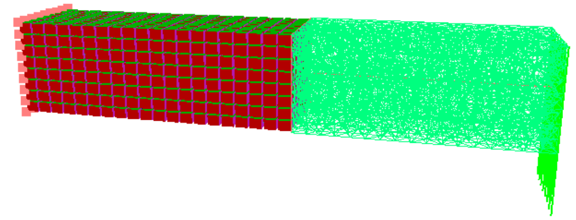
Bending test: FEM approach

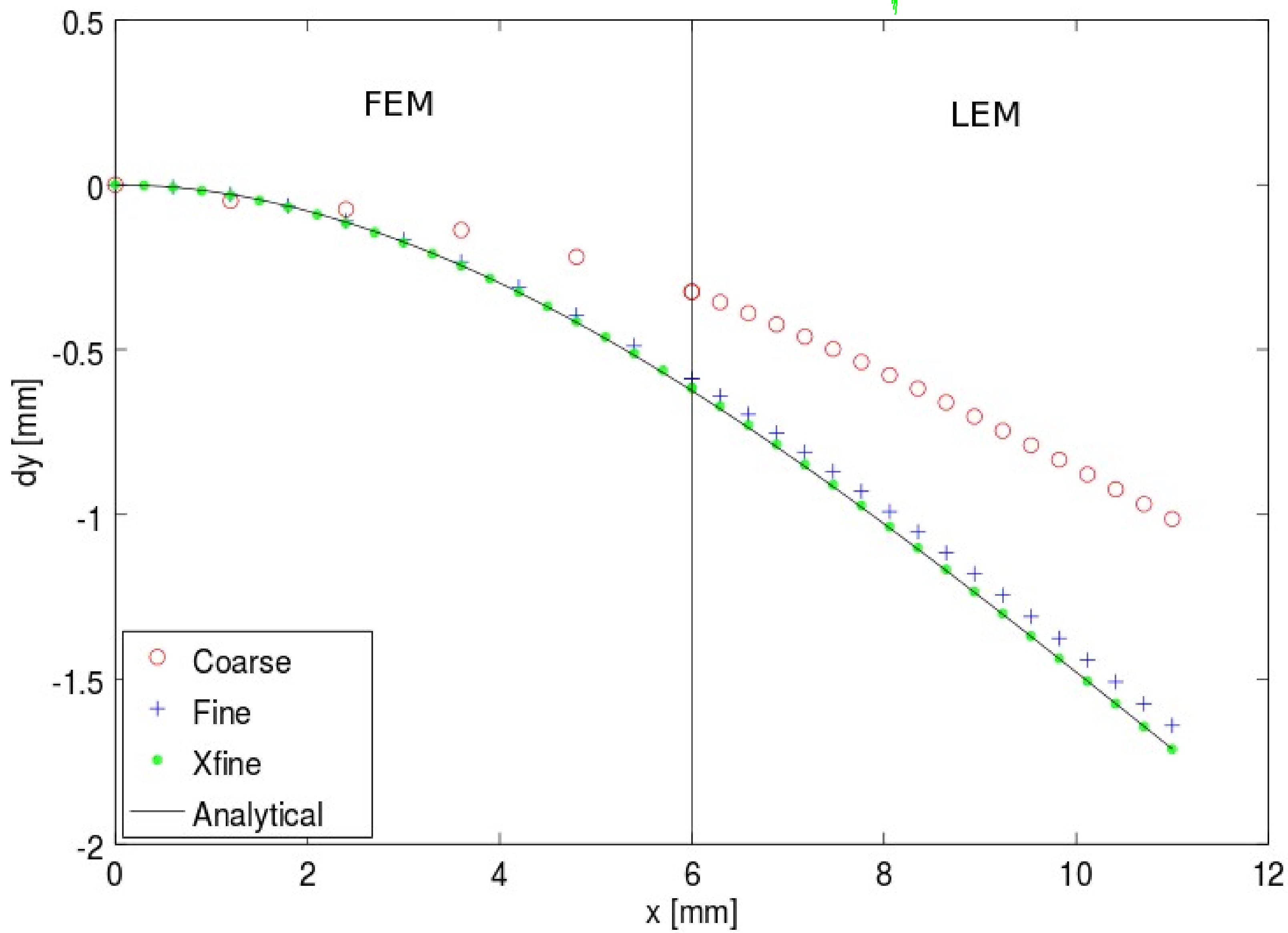
$$\|e\|_{L2} < C h^{(p+1)}$$





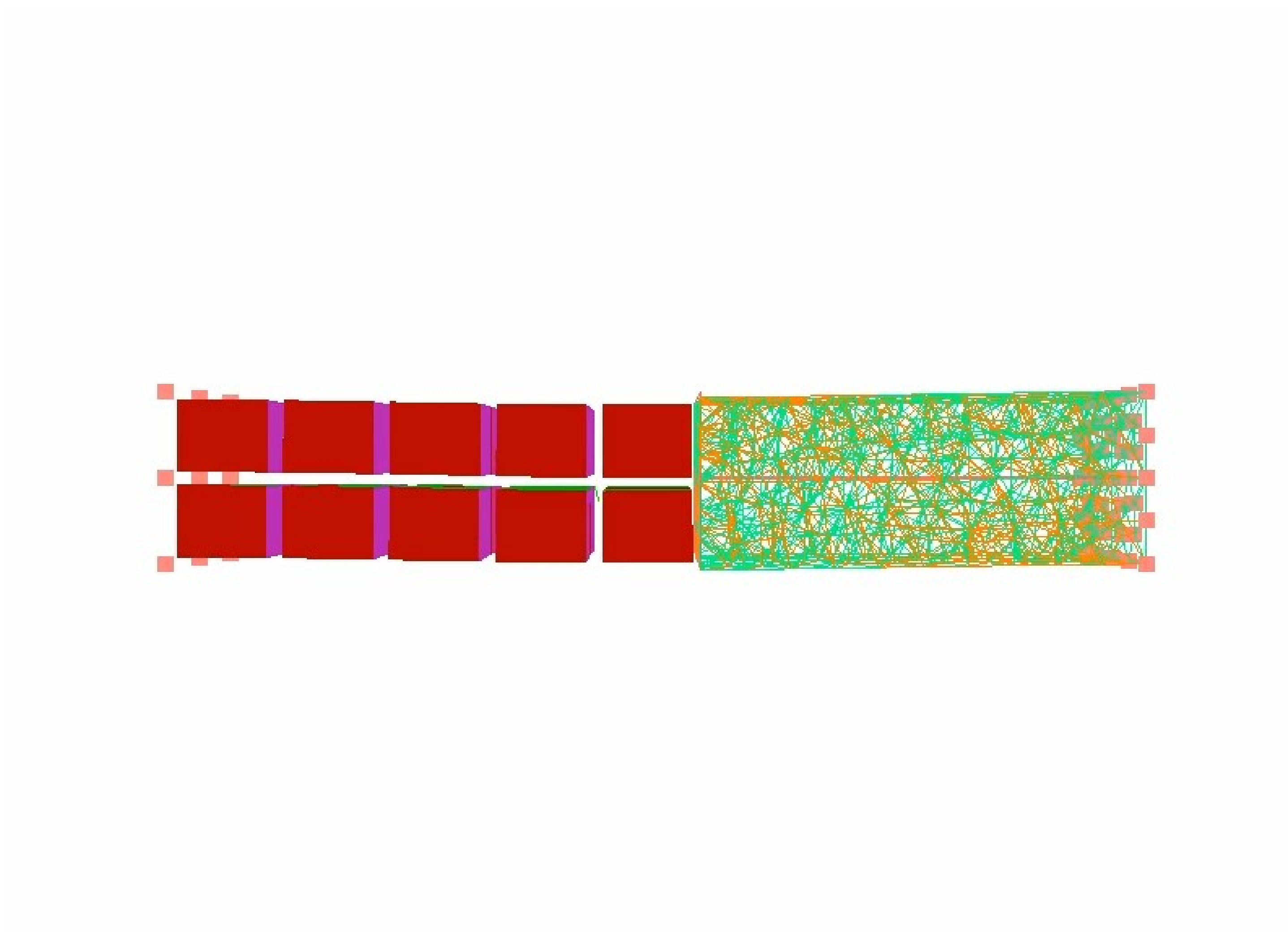
Bending test: FEM-LEM approach

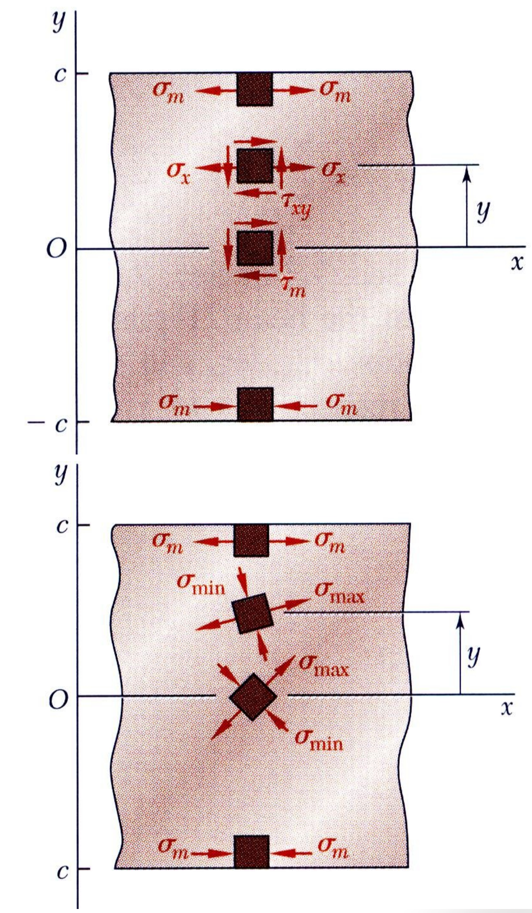




Fracture application

Failure due to tearing





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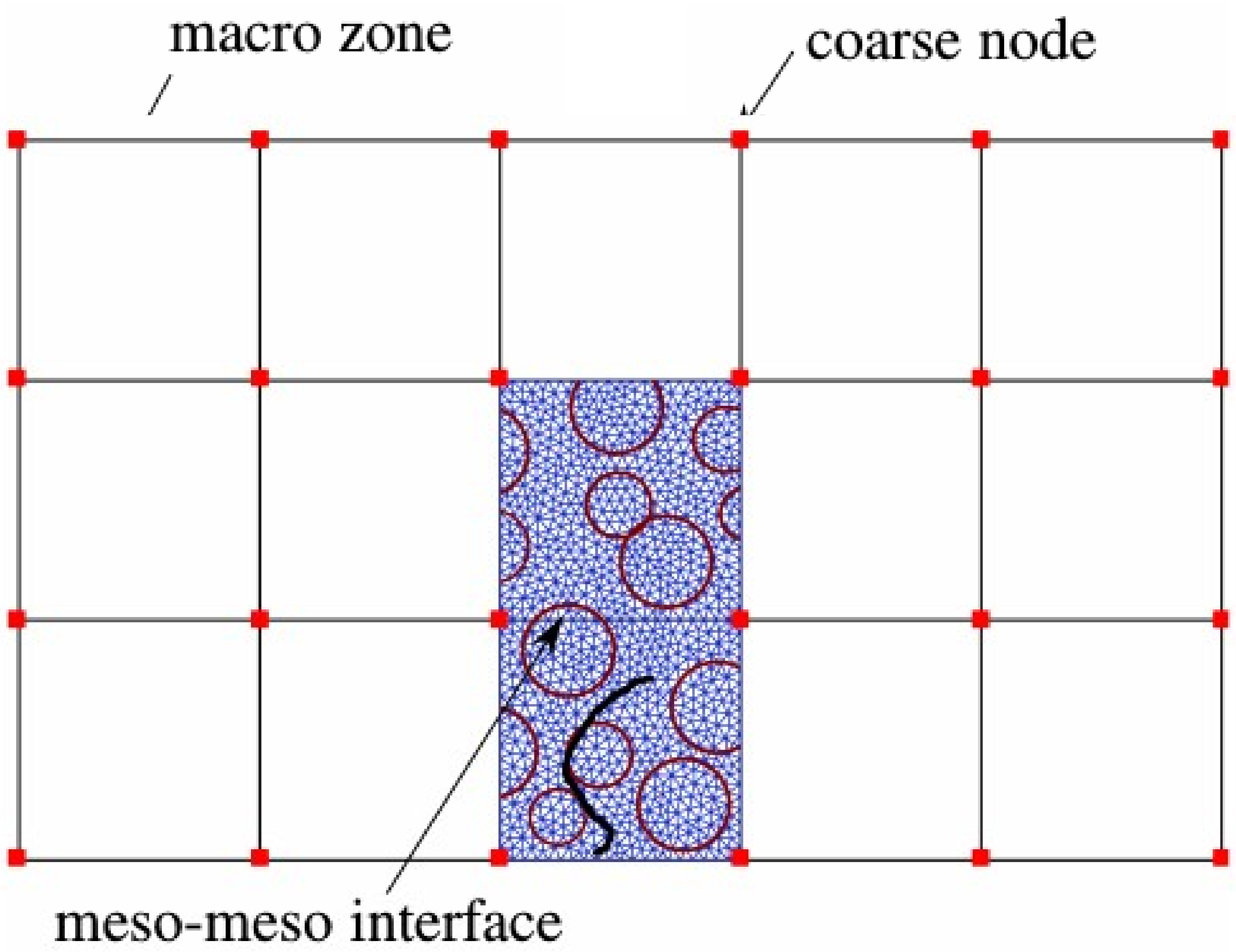
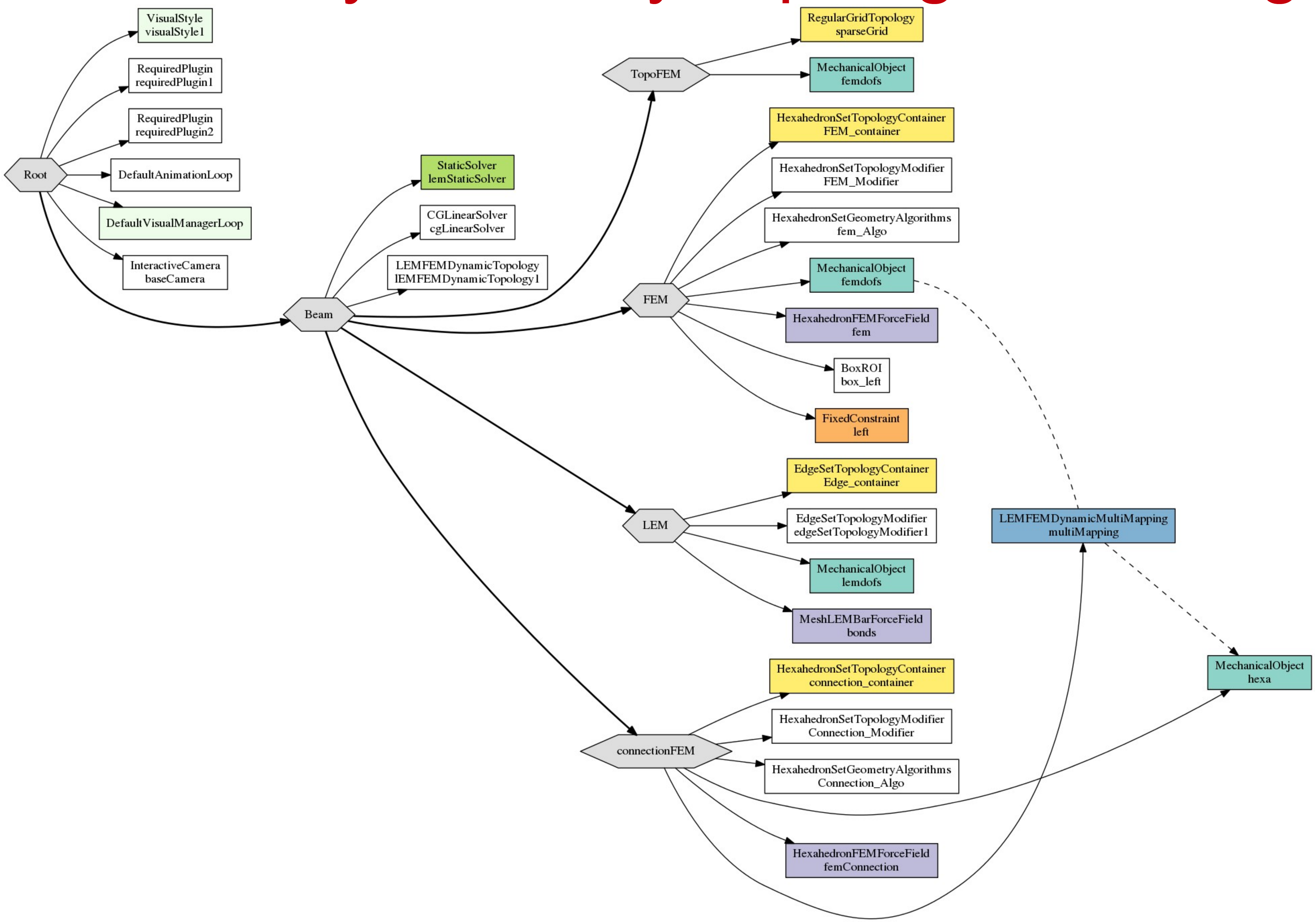
Dynamically Topological Changes



Dynamically Topological Changes



Conclusions & Perspectives

Conclusions

☺ Continuum-lattice coupling is valid

☺ Fracture simulation

Perspectives

☻ Dynamic topological changes

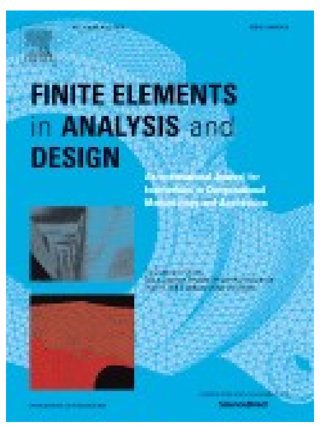
☻ Cutting of soft tissue

☻ Implementation on GPUs

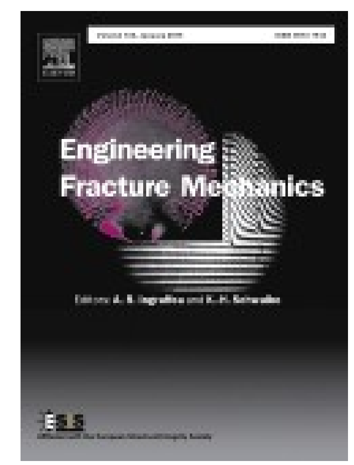
Conclusion & Perspectives

Outlook

- A paper on SOFA implementation with validation tests



- A paper on fracture results



- A paper on real-time cutting

Thank you very much for your kind attention