Istituto Universitario di Studi Superiori di Pavia
PhD program in Computational Mechanics and Advanced Materials

Advanced modeling of stents: from constitutive modeling to biomedical (isogeometric) analysis.

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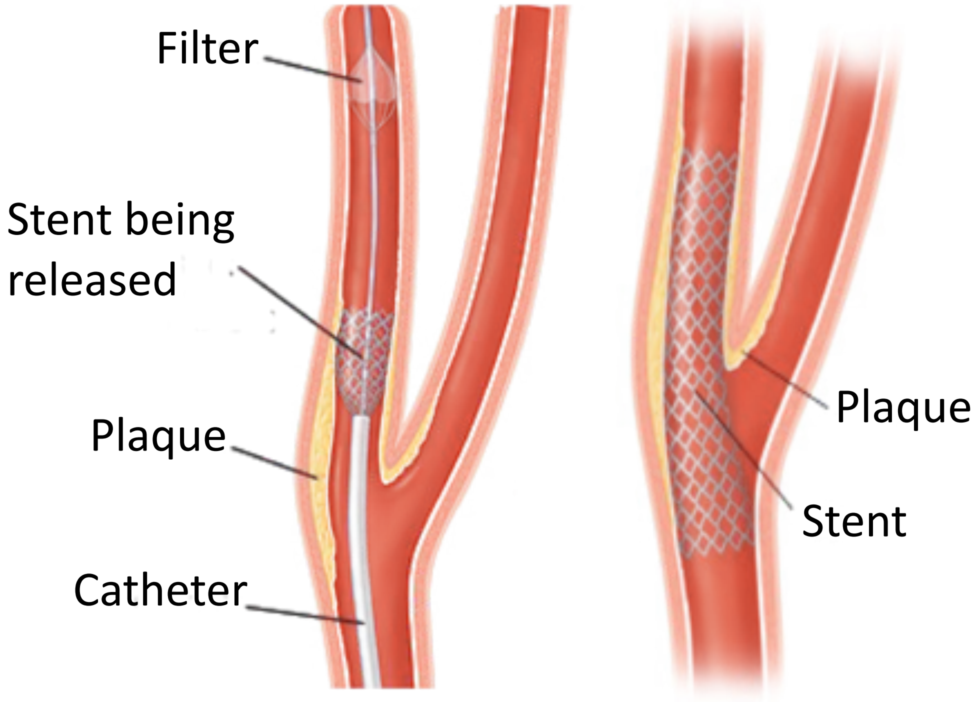
Supervisor: Prof. Alessandro Reali
Coadvisors: Prof. Ferdinando Auricchio
Dr. Simone Morganti

XXVII Ciclo

Carotid Artery Stenting (CAS)



Benefits

- Minimally-invasive approach
- Reduced hospitalization costs

Issues

- Prediction of long-term performance
- Influence of stent design

The importance of stent design

- Closed cell stent

Lower free cell area

Less flexible

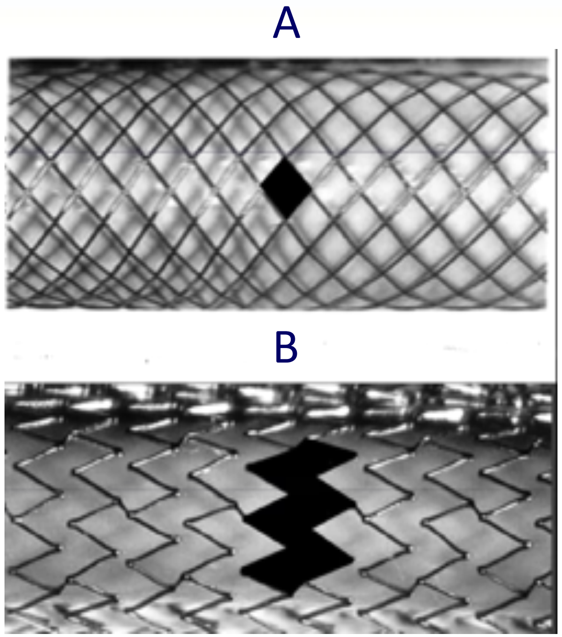
High radial strength

- Open cell

Higher free cell area

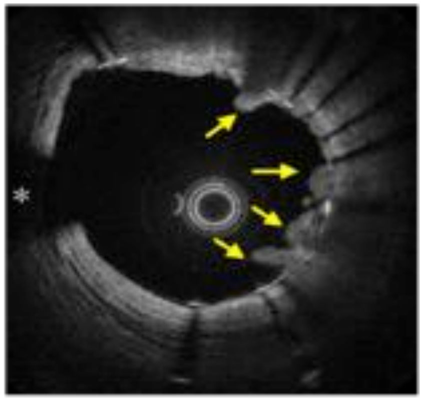
More flexible

Low radial strength



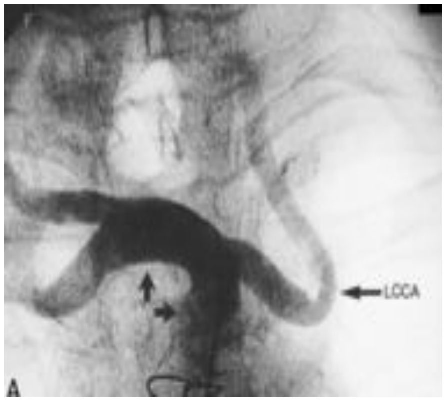
A: closed-cell; B: open-cell [Eskandari, 2010, JEVT]

Minimize the plaque prolapse (**Vessel scaffolding**)



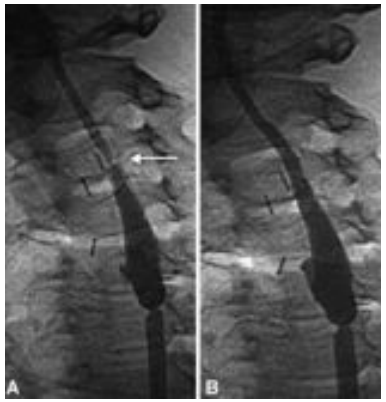
Prolapse imaging[Tearney 2012]

Guarantee sufficient **flexibility** for a safe deployment



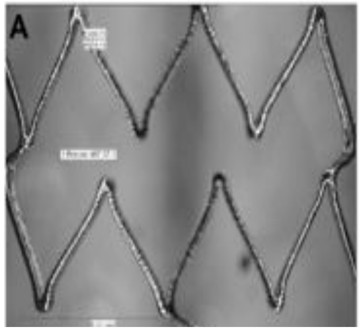
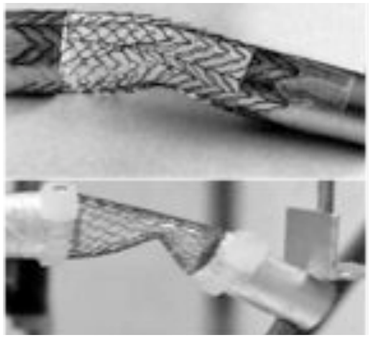
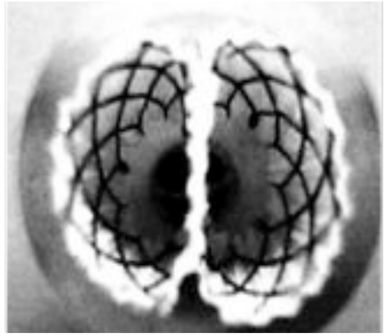
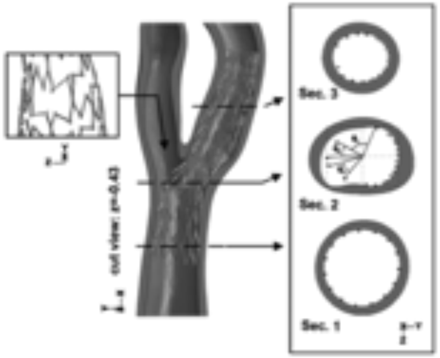
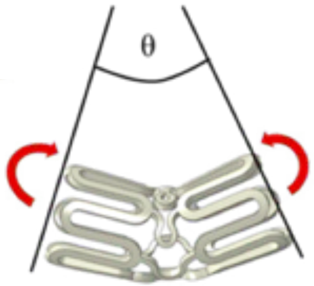
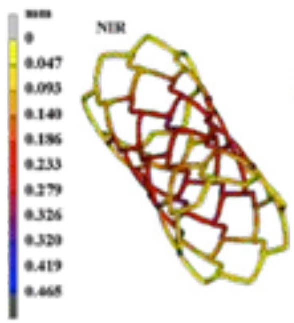
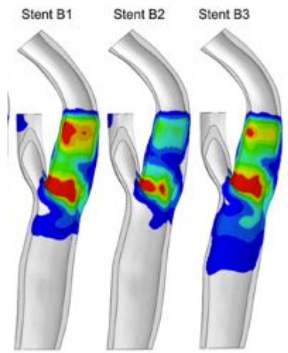
Tortuous vessel in elder patient

Provide sufficient **radial strength** to minimize the elastic recoil



in-stent restenosis [Chakhtoura 2001]

Experimental vs. Numerical approach

	VESSEL SCAFFOLDING	FLEXIBILITY	RADIAL STRENGTH	PREDICTIVE MEDICINE
EXPERIMENTAL	 Müller-Hülsbeck [2009]	 Müller-Hülsbeck [2009]	 Duerig [2002]	
NUMERICAL	 Conti [2010]	 Grogan [2012]	 Lally [2006]	 Conti [2011]

Modern computational methods (tipically based on FEA) make possible to test different combinations of materials, geometries and working conditions prior to prototype manufacturing or when the traditional experimental approach is too expensive or difficult to implement

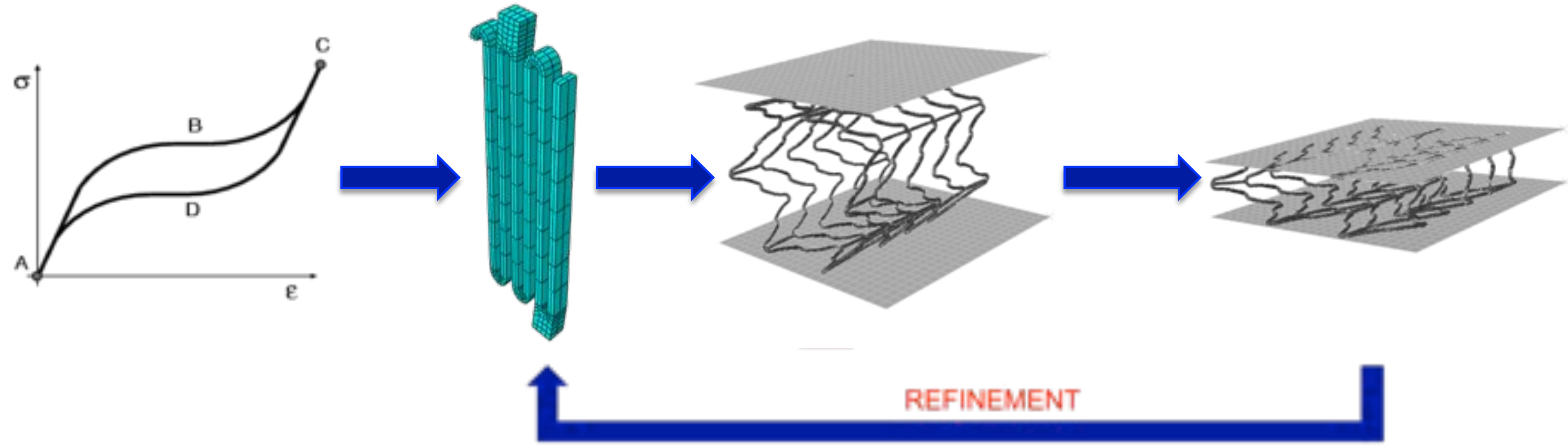
Carotid artery stent FEA simulations

SHAPE MEMORY ALLOY (SMA) CONSTITUTIVE MODELING

STENT MESH GENERATION

BCS AND MODEL NON LINEARITIES MODELING

FEA SIMULATION



Carotid artery stent FEA simulations

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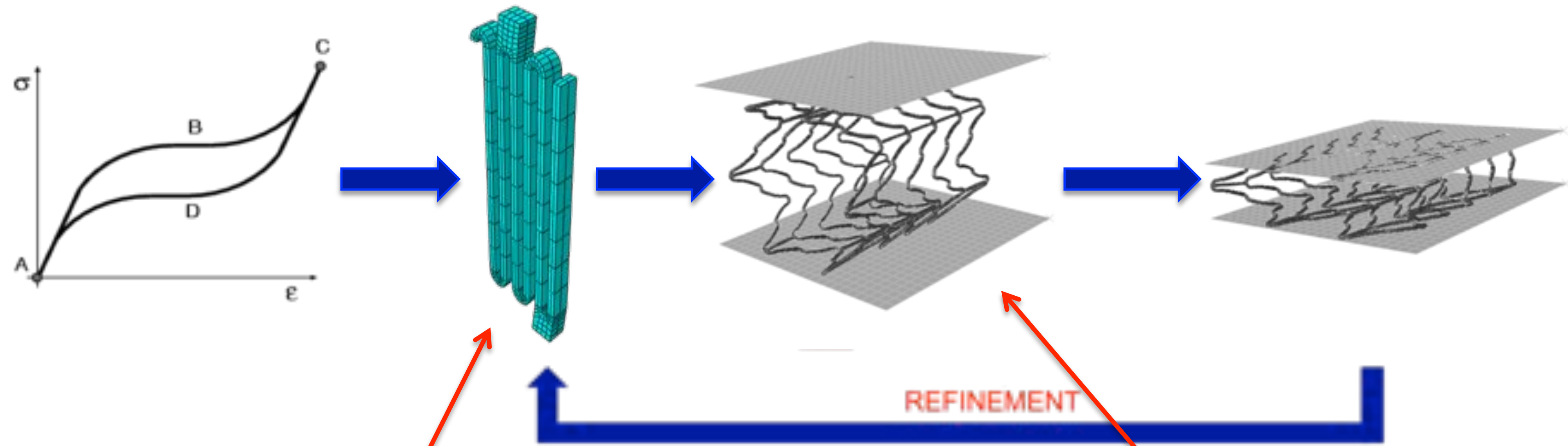


- Meshing process can be expensive
- Geometric representation is not exact
- Refinement needs new meshing process

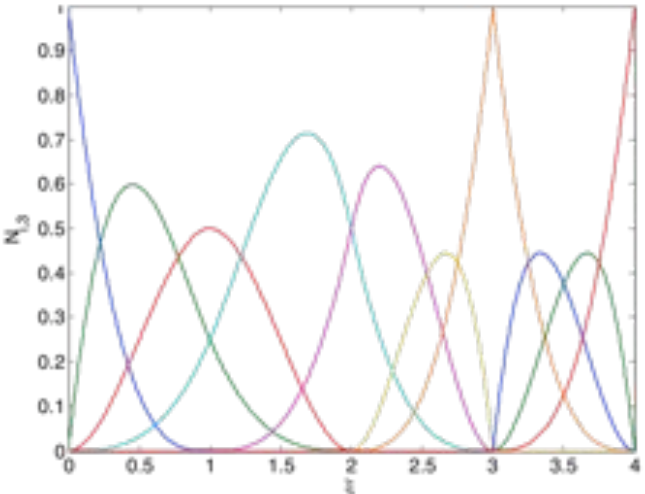
- Low-order, low-continuity elements can have problems in dealing with model non linearities, e.g., contact or buckling.

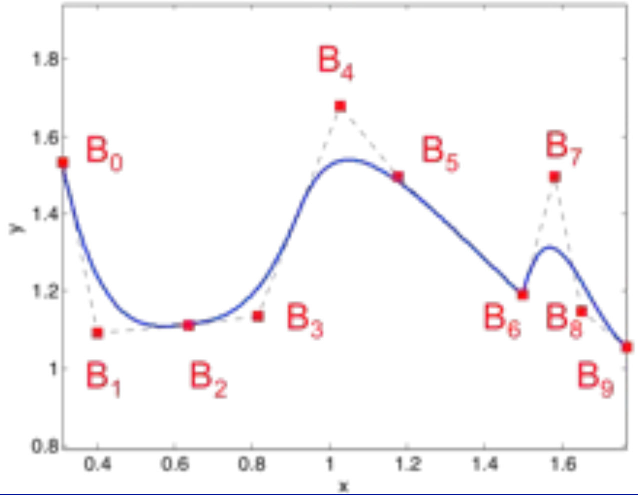
Is there still room for improvements?

Idea (Hughes et al. 2005)

Extract geometry file from commercial CAD modeling software and use it **directly** in commercial FEA software (**TO AVOID MESHING PROCESS**)

Non uniform rational B-splines (NURBS) basis functions





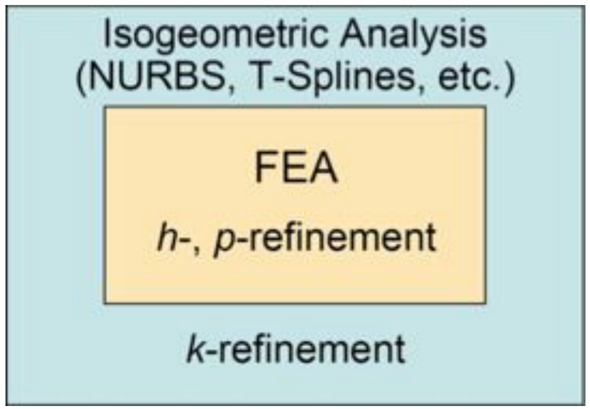
Properties

- Non-negativity
- Partition of unity
- C^{p-m} continuity

Isogeometric Analysis (IgA)

Cost-effective alternative to standard FE analysis (based, e.g., on NURBS), *including FEA as a special case,* but offering other possibilities:

- *precise and efficient* geometric modeling;
- *superior* approximation properties;
- *simplified* mesh refinement;



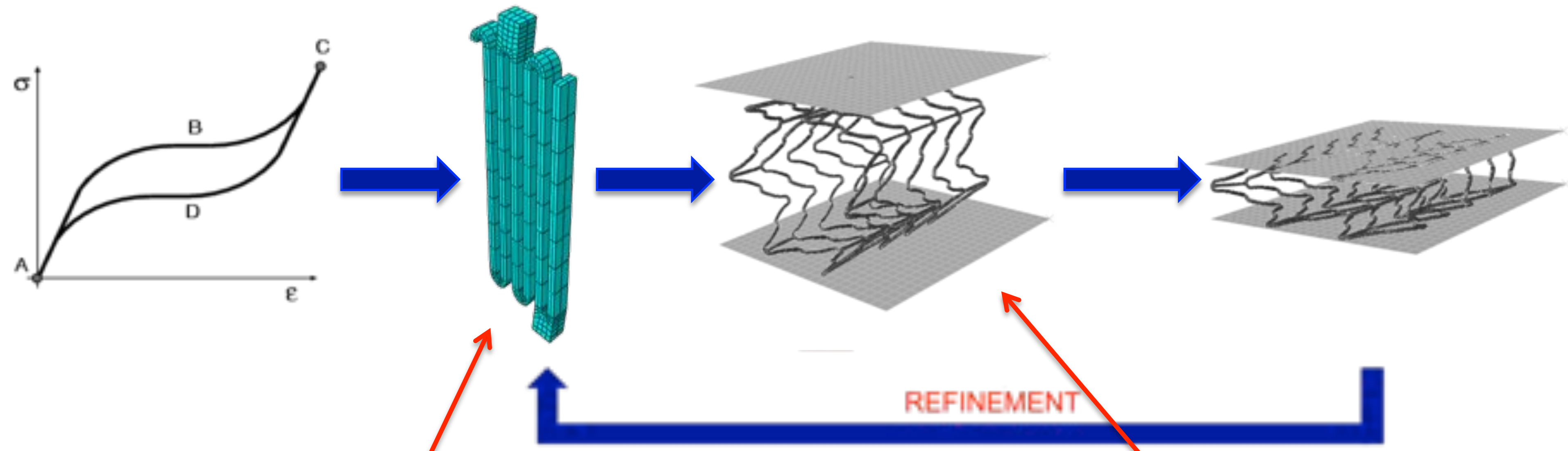
Carotid artery stent IGA simulations

SHAPE MEMORY ALLOY (SMA) CONSTITUTIVE MODELING

STENT MESH GENERATION

BCS AND MODEL NON LINEARITIES MODELING

IGA SIMULATION



- No meshing process is necessary
- Geometric representation is exact
- Efficient refinement preserving geometry

- High-order, high continuity elements can improve the reproduction of non linear phenomena

YES, THERE IS STILL ROOM FOR IMPROVEMENT!

Aim of the doctoral research

Ultimate goal: provide a set of **IgA** based numerical tools to efficiently evaluate the principal features of different SMA self-expanding carotid artery stents.

Study 0: development and testing of a set of reliable constitute models to predict the non linear, inelastic shape memory alloys behavior

Study 1: **FEA** simulations for the evaluation of carotid stent scaffolding

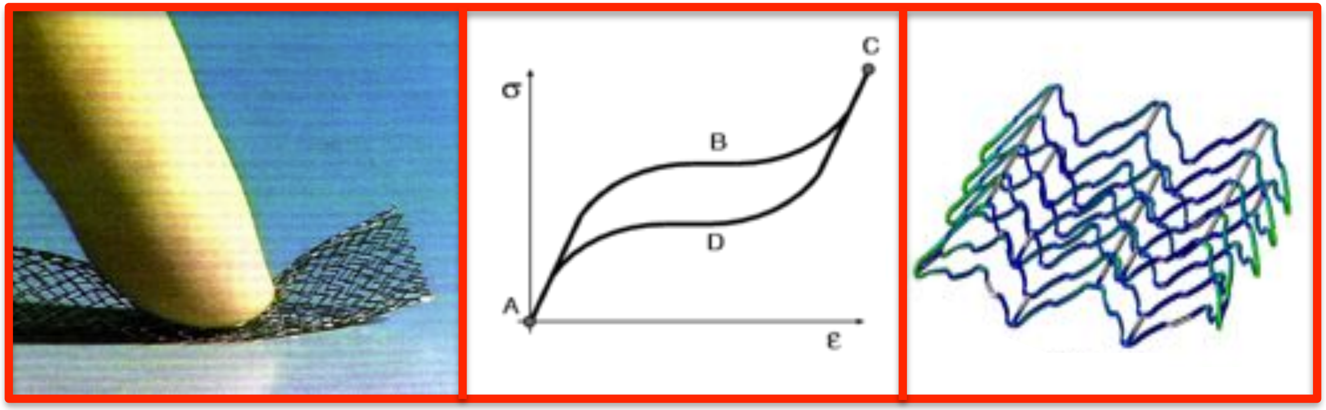
Study 2: set up of a novel framework based on **IgA** to investigate the carotid stent flexibility and to compare the numerical performance with respect to **FEA**

Study 3: extension of the proposed **IgA** framework to include frictionless contact modeling

Study 0

Shape memory alloys constitutive modeling

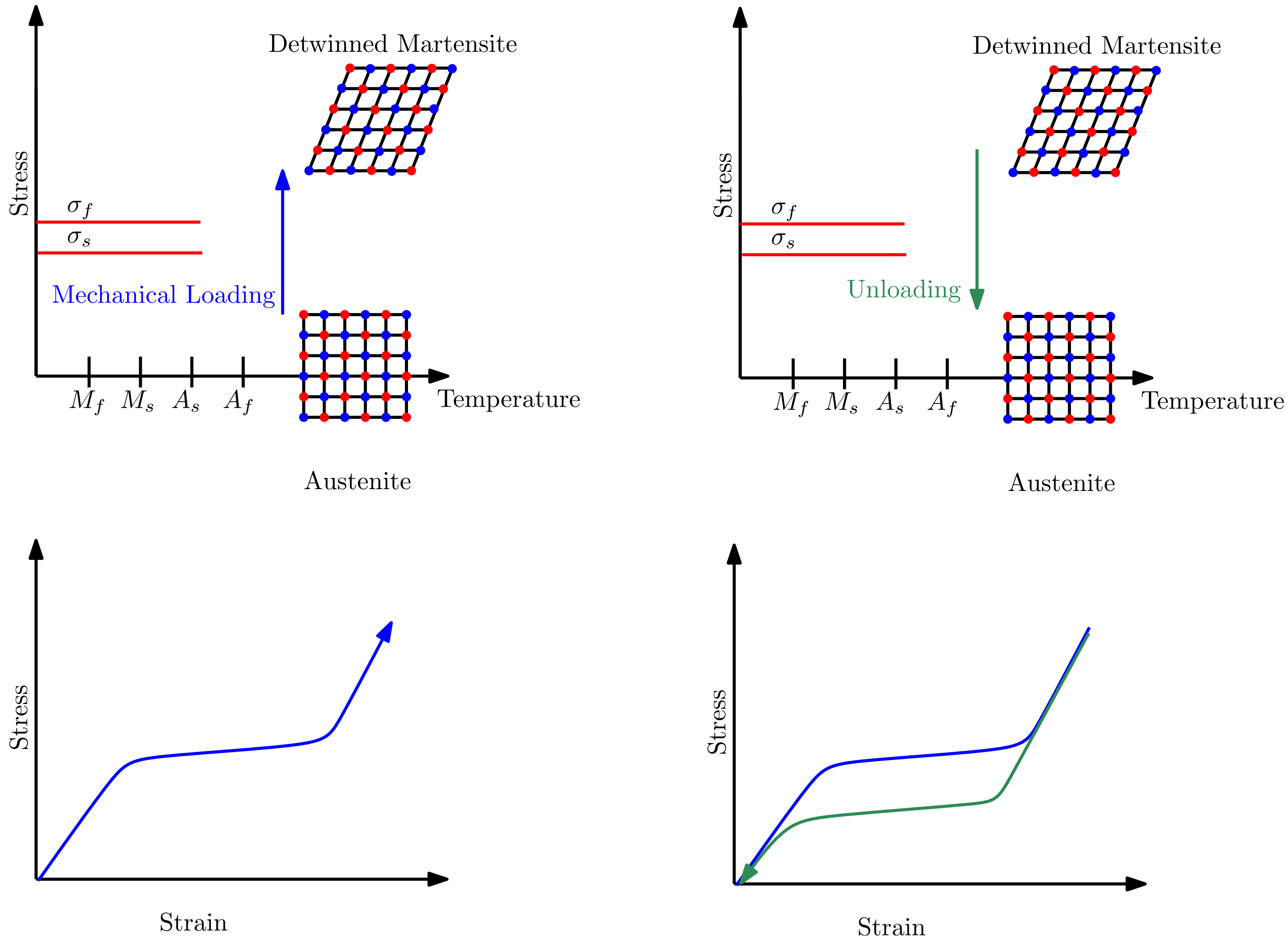
Work derived from a collaboration with FEOPS (Gent University, Belgium)



Shape memory alloys: pseudoelastic effect

The majority of carotid artery stents are made of NiTiNOL, the most employed shape memory alloy (SMA) for engineering applications.

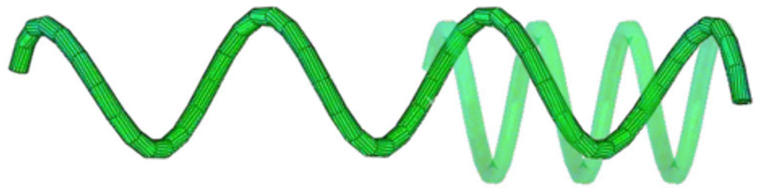
Mechanical recovery (pseudoelasticity)

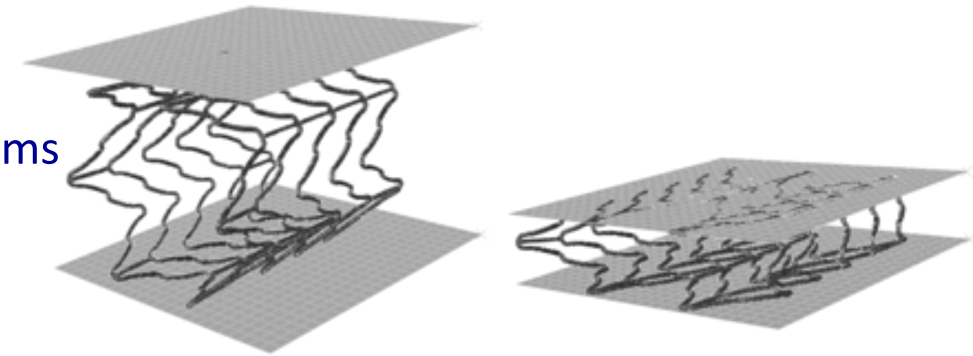


Shape memory alloys constitutive modeling

Motivation

In the last years SMA have been deeply investigated from the point of view of **modeling**, **analysis**, and **computation**





Issues:

- Complex material behavior
- Numerical treatment of non-smooth problems

Objective

- Present the structure of two SMA constitutive models investigated during the doctoral research
- Calibrate the models starting from experimental data
- Investigate the behavior of both models with simple benchmarks and real life **FEA** test

Shape memory alloys constitutive modeling

Souza model [Souza et al. 1998, Auricchio and Petrini, 2004] STUDY 2 STUDY 3

Control variables: strain **ε**, temperature T

Internal variables: transformation strain $\mathbf{e}^{tr}$

Thermodynamic potential: additive decomposition + Helmhotz free energy

Large deformation – Small strain regime

Implementation: ABAQUS UMAT – FEAP UMAT

Auricchio-Taylor model [Auricchio and Taylor 1997, Lubliner and Auricchio, 1996] STUDY 1

Developed within the generalized plasticity framework

Control variables: strain **ε**, temperature T

Internal variables: transformation strain $\boldsymbol{\varepsilon}^{tr}$, single variant martensite volume fraction ξ_S

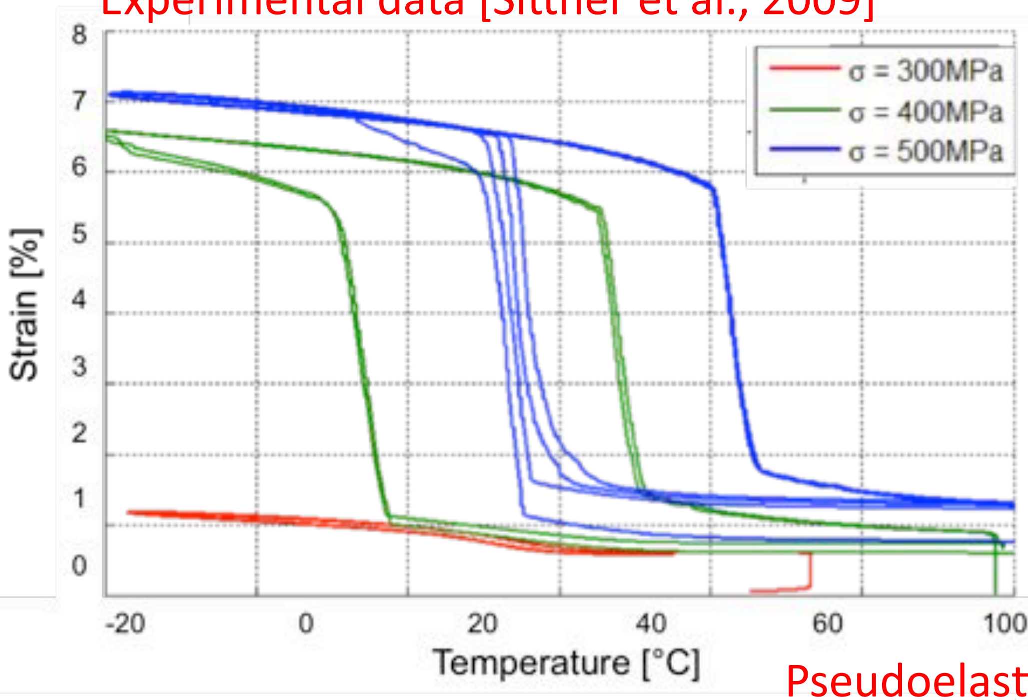
Thermodynamic potential: multiplicative decomposition + quadratic elastic free energy function

Large deformation – Large strain regime

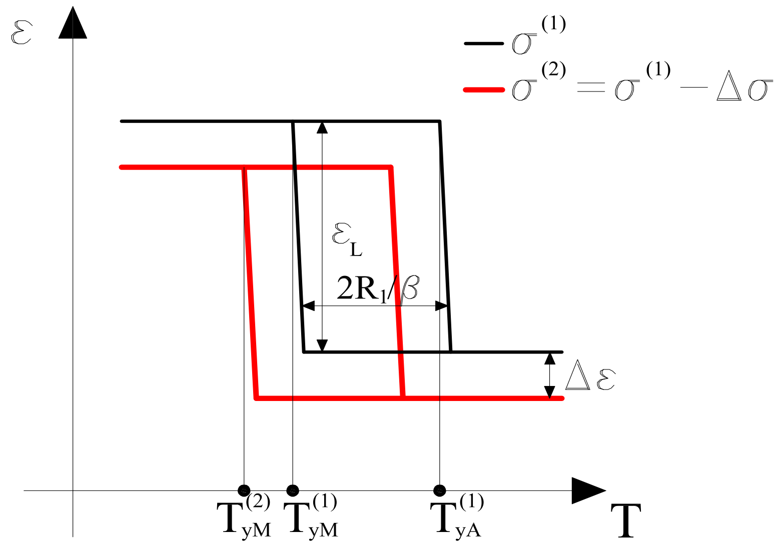
Implementation: ABAQUS BUILT-IN MATERIAL

Model calibration

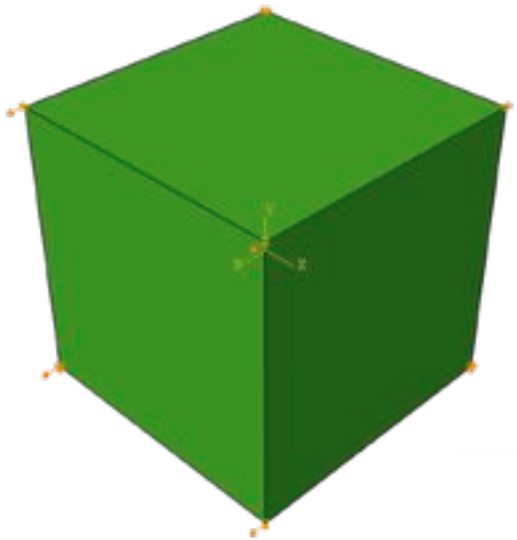
Experimental data [Sittner et al., 2009]

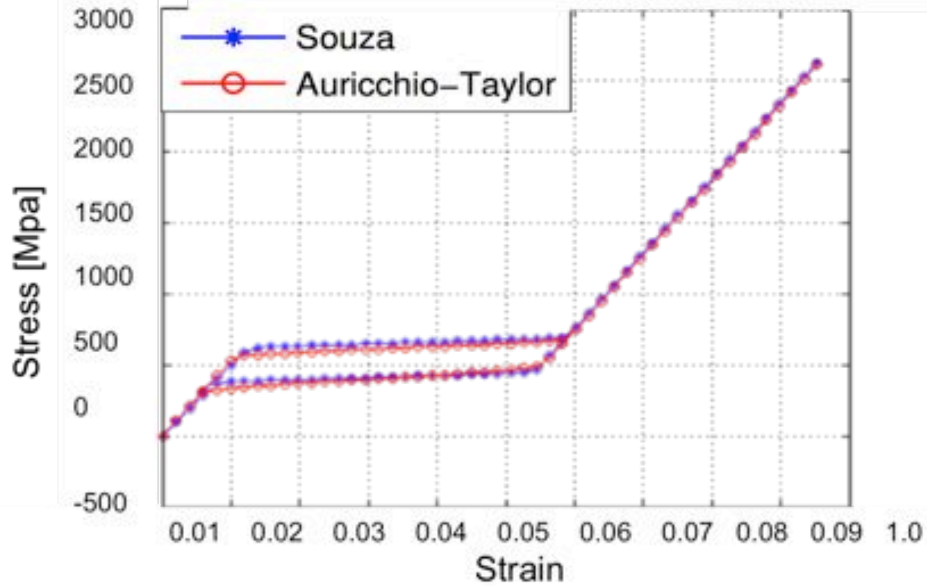


Calibration approach [Auricchio et al., 2009]



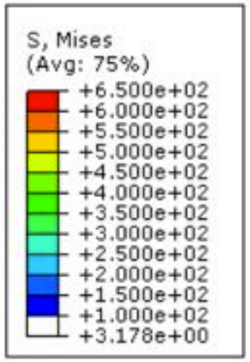
Pseudoelastic test





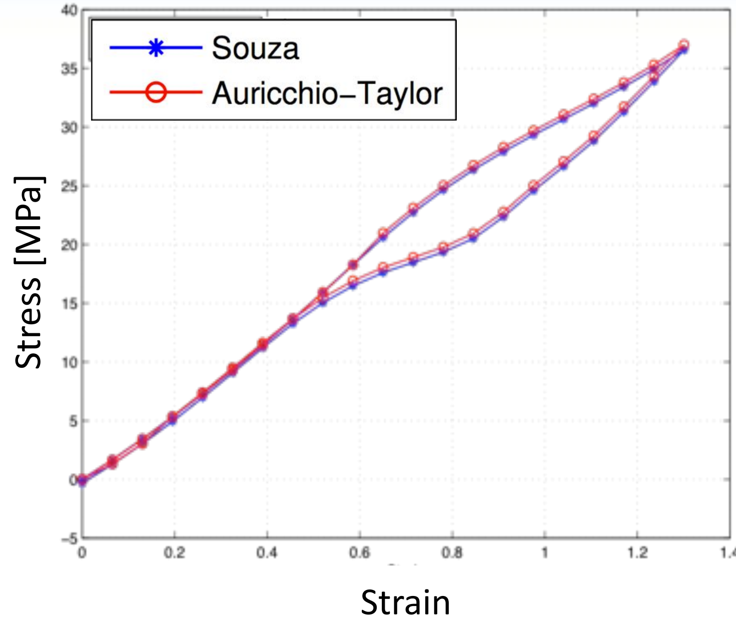
Numerical examples

Pseudoelastic spring

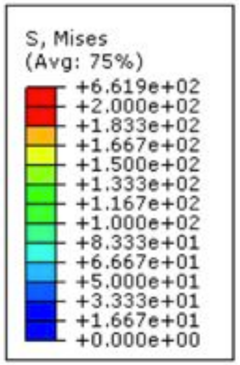


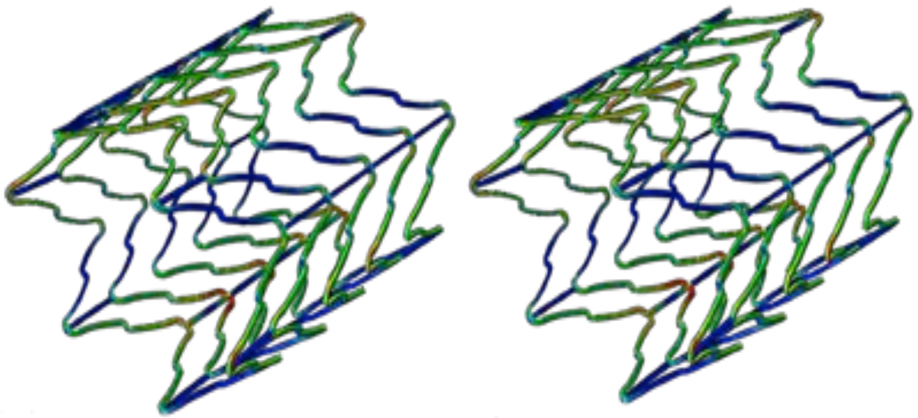
Souza model

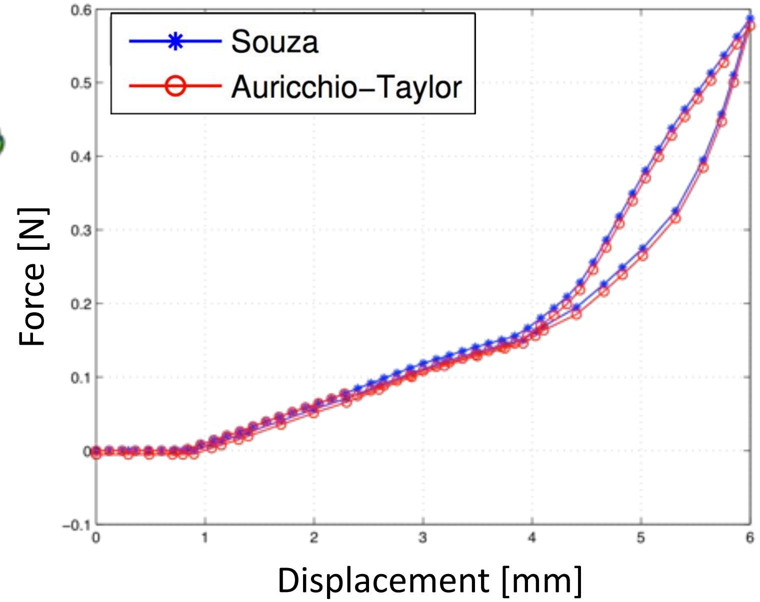
Auricchio model



Stent crush





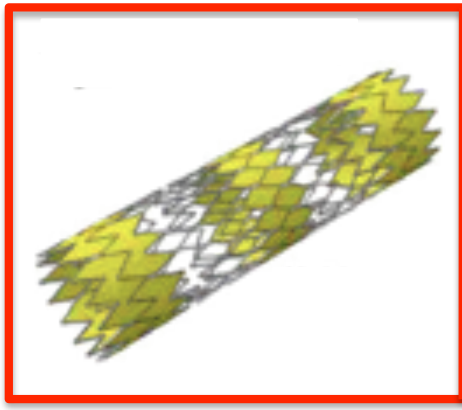


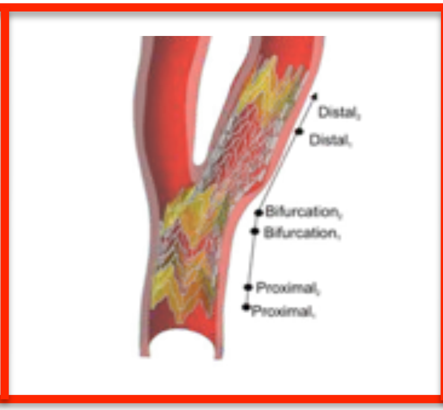
- Both models are efficient and robusts to reproduce real life SMA simulations

Study 1

Vessel scaffolding evaluation for carotid artery stents: a FEA-based approach

Evaluation of carotid stent scaffolding through patient-specific finite element analysis *International journal for numerical methods in biomedical engineering* 28(10), 2012





Stent scaffolding evaluation: a FEA-based approach

Motivation

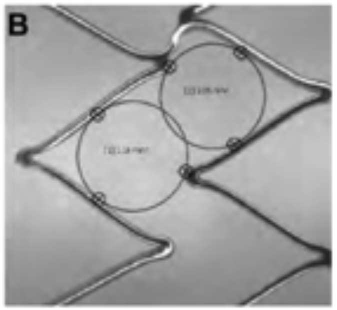
Scaffolding: stent capability to support the vessel wall after stenting

ISSUES

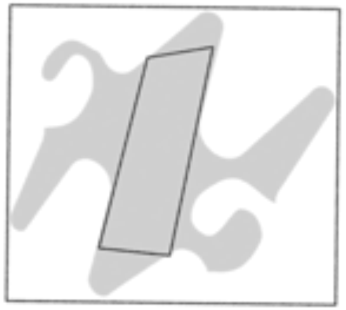
Free expanded configuration only
Planar projection

Evaluation techniques:

- Largest fitted-in circle
- Cell area measure
- Prolapse index



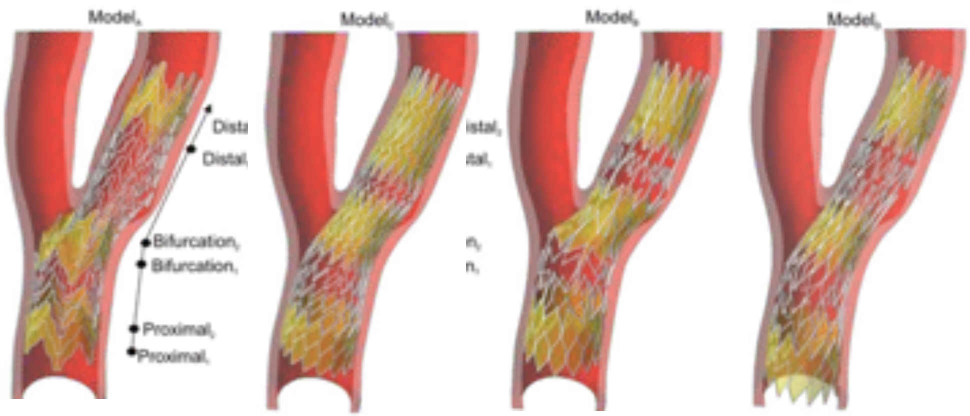
Müller-Hülsbeck [2009]


Capelli [2009]

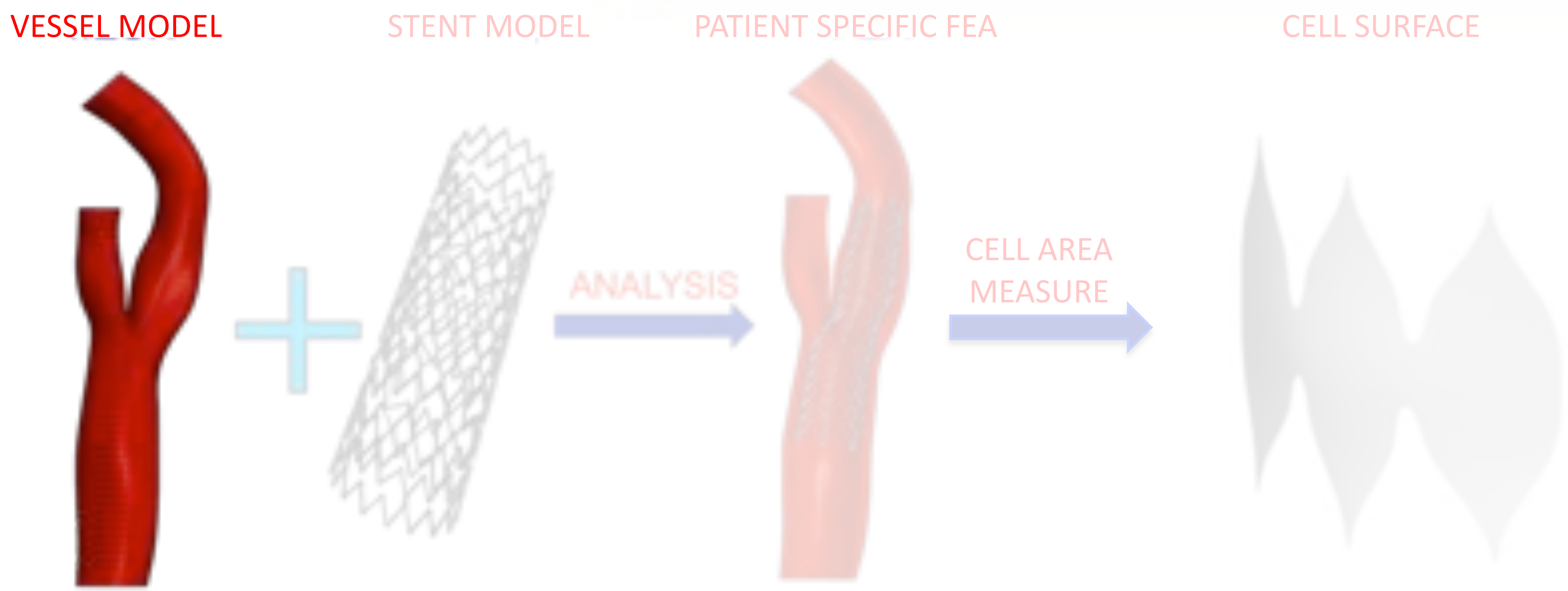
Objective

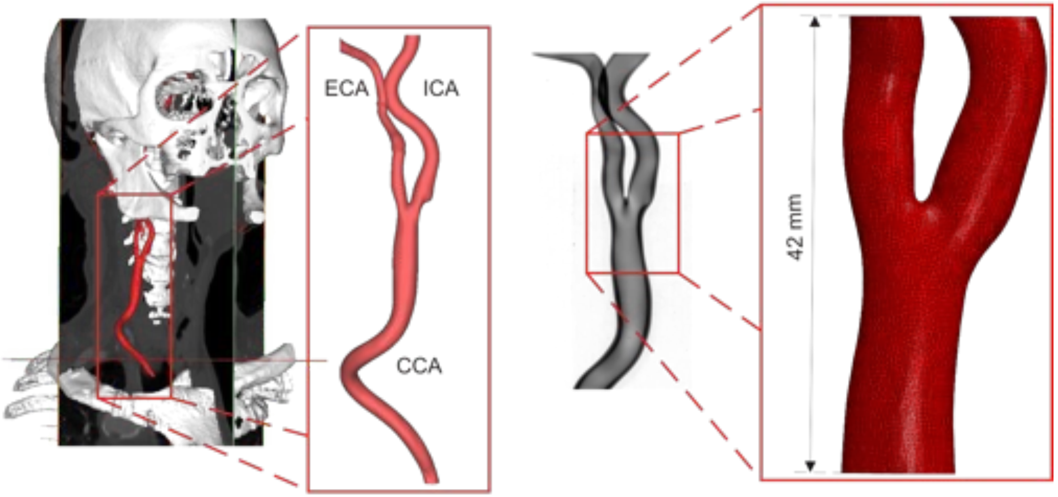
Patient-Specific **FEA** of stent deployment and semi-automatic cell area measure

Model A: Open cell
Model B: Closed cell
Model C: Open cell
Model D: Hybrid design



Computational framework

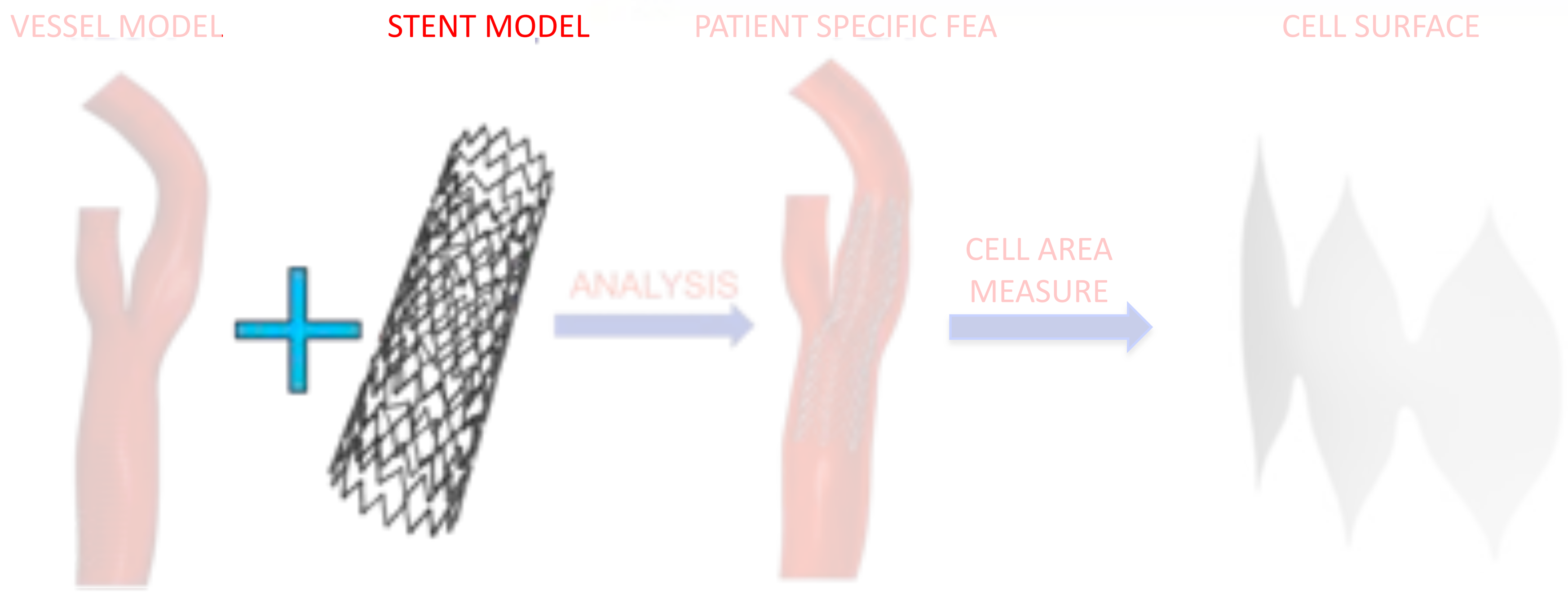


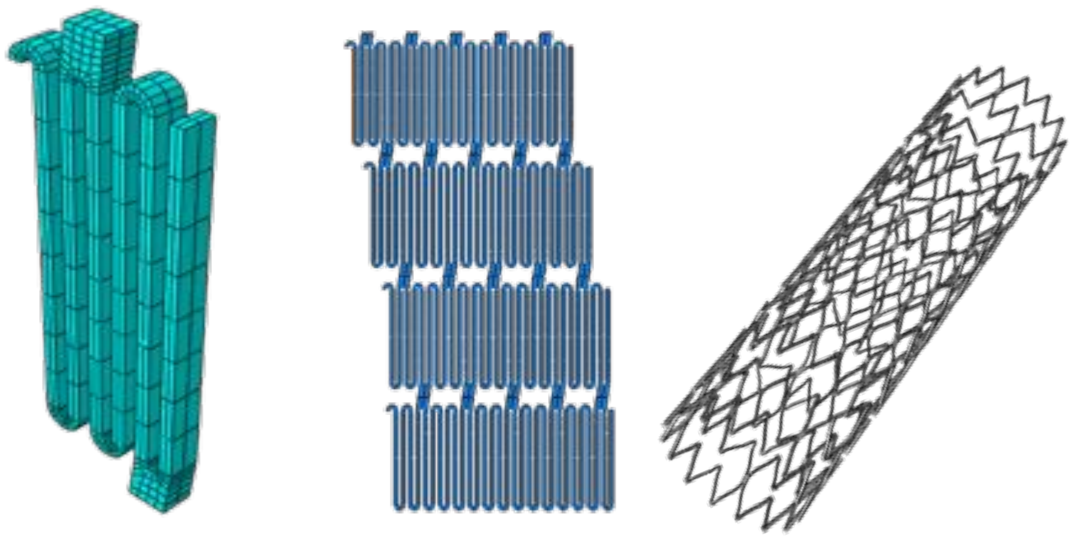


Element: C3D10M

Material: Hyperelastic

Computational framework

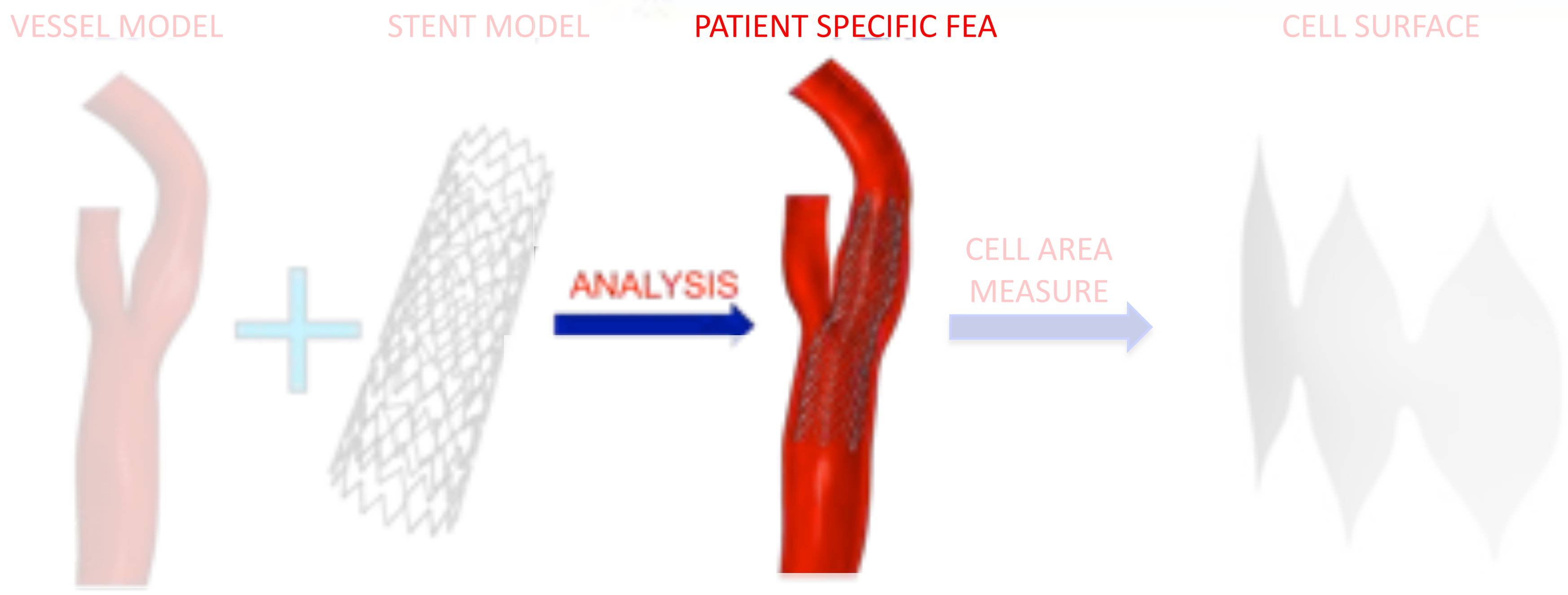


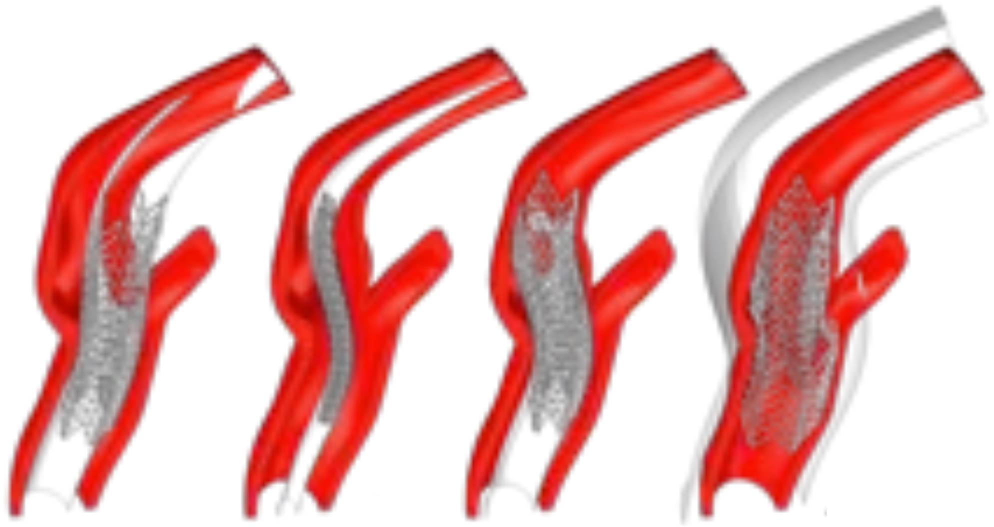


Element: C3D8R

Material: Auricchio model

Computational framework



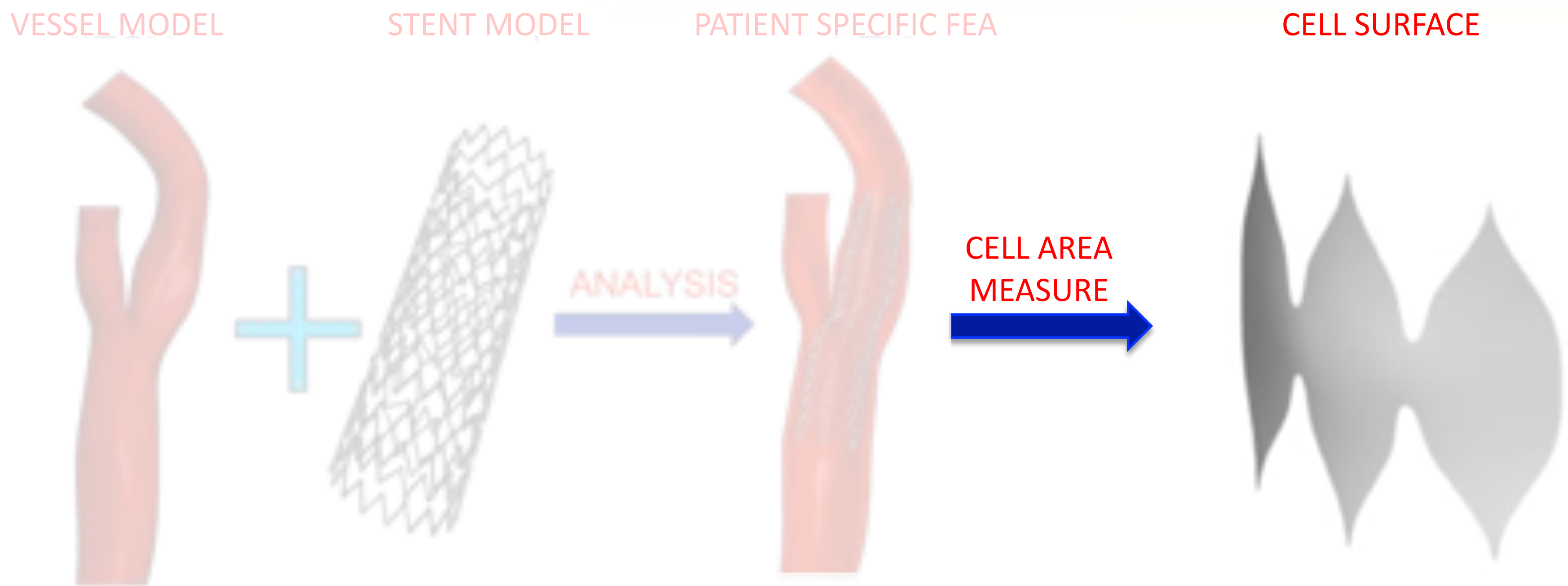


- Quasi-static analysis (Abaqus/ Explicit)
- Large deformations and contact

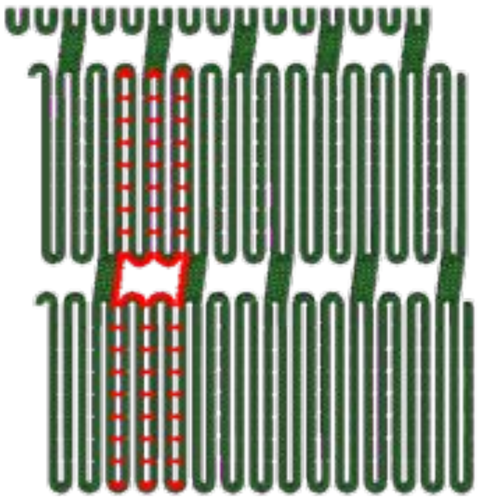
Two steps simulation:

- crimping
- releasing

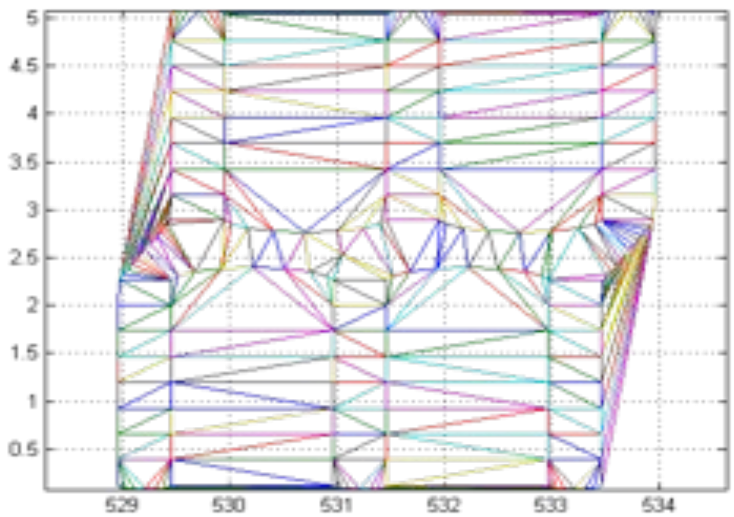
Computational framework



Cell area identification



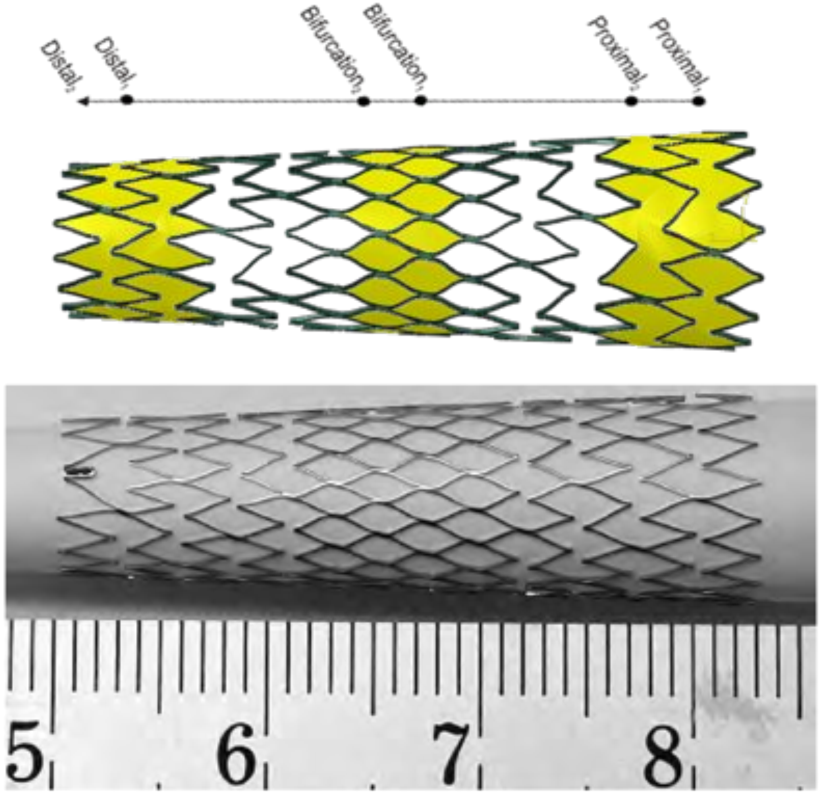
Delaunay triangulation



Target surface creation

Validation step (Model D)

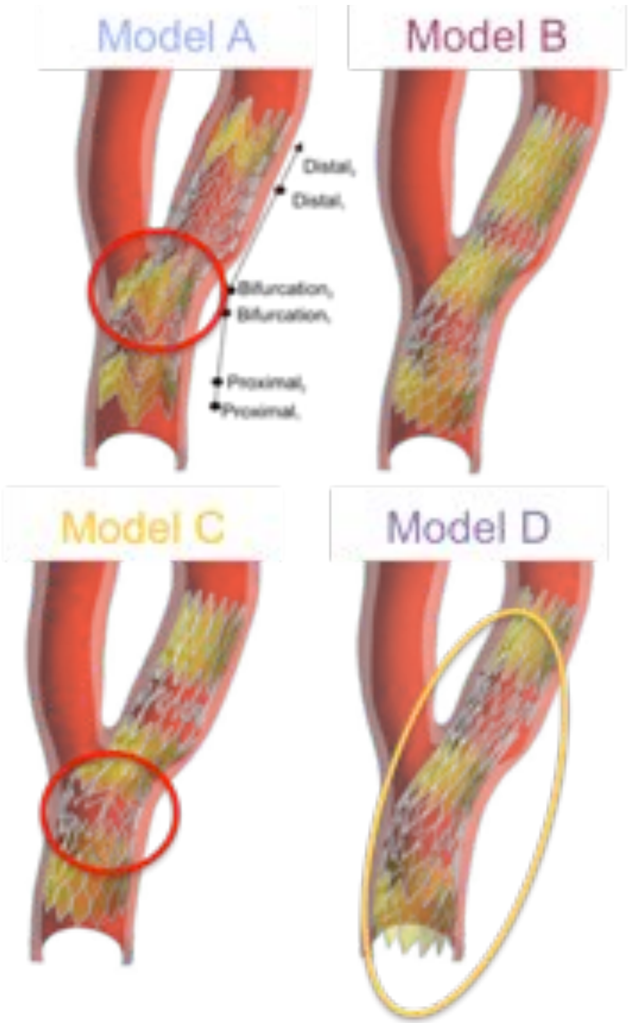
- Experimental data coming from the work of Müller-Hülsbeck

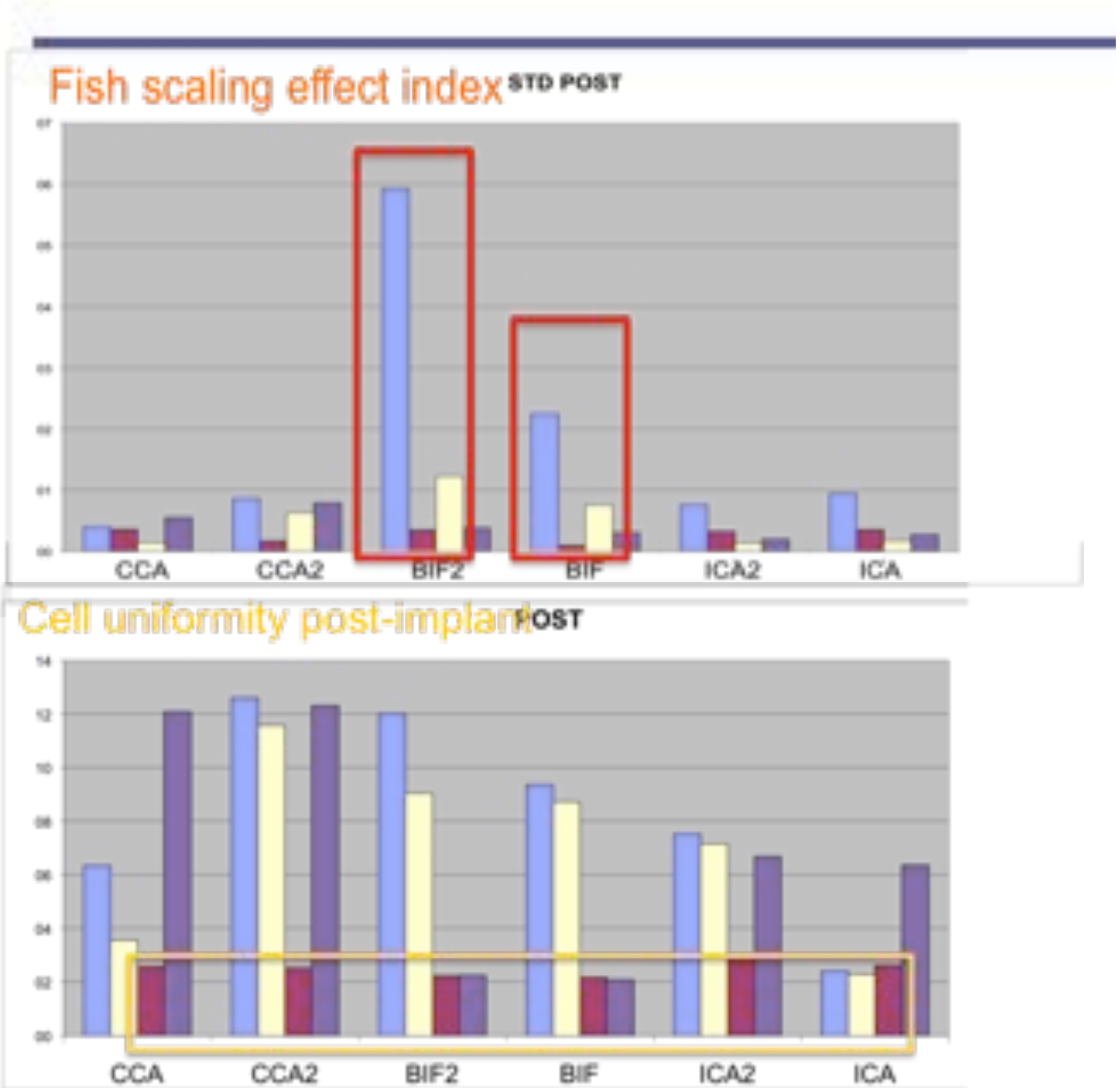


Stent segment	Model [mm^2]	Müller-Hülsbeck et al., 2009
$Proximal_1$	15.8 ± 0.1	13.5
$Proximal_2$	16.3 ± 0.24	
$Bifurcation_1$	3.4 ± 0.12	3.3
$Bifurcation_2$	3.3 ± 0.1	
$Distal_1$	11.7 ± 0.1	12.4
$Distal_2$	11.0 ± 0.1	

Numerical and experimental results are in good agreement

Results





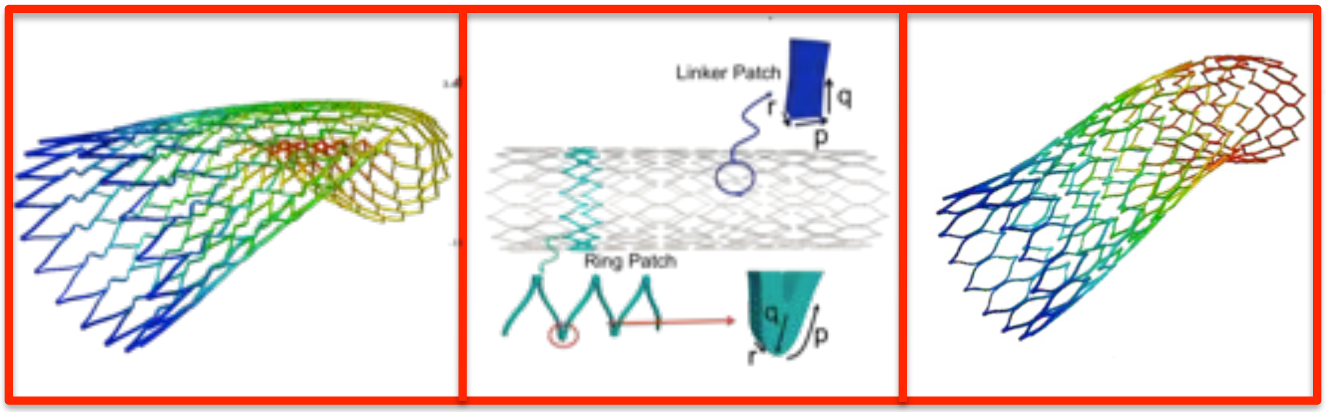
-TRADITIONAL TECHNIQUES ARE VALUABLE TOOL TO EVALUATE SCAFFOLDING
- PATIENT-SPECIFIC FEA CAN HELP TO PROVIDE ADDITIONAL INFORMATION TO CLINICIANS AND MANUFACTURERS

Study 2

Stent bending modeling:
a comparison between FEA and IgA

Collaboration with Prof. Robert L. Taylor, University of California Berkeley

Innovative and efficient stent flexibility simulations based on isogeometric analysis,
Submitted to Computer Methods in Applied Mechanics and Engineering

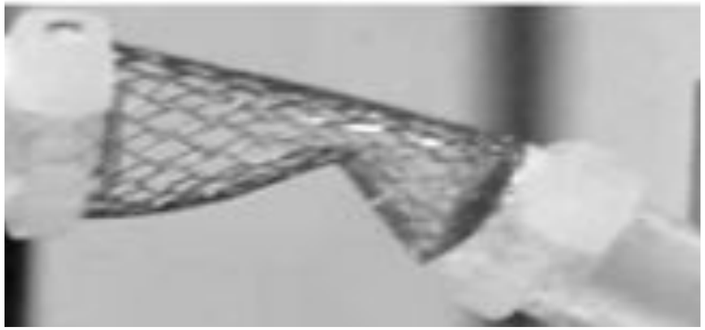


Stent bending: a comparison between FEA and IgA

Objective

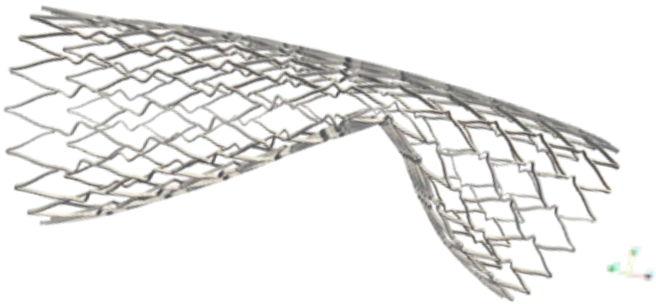
- Establish a **novel**, **fast** and **accurate** computational framework, based on IgA, to evaluate the flexibility performance of endovascular stents

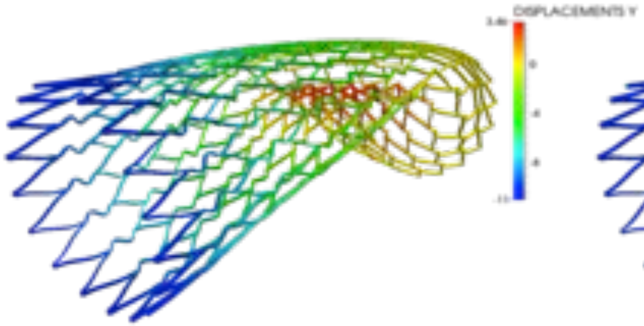
- Compare FEA and IgA performance on stent bending analysis

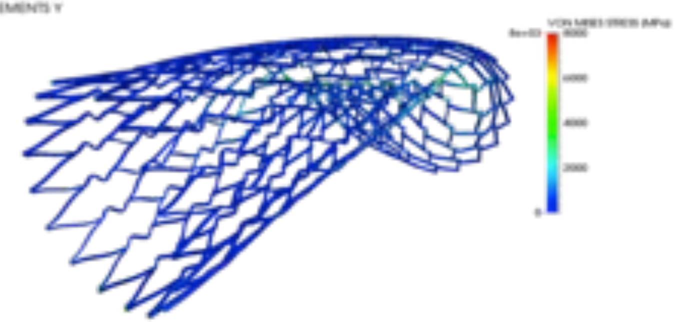


Experimental benchmark:

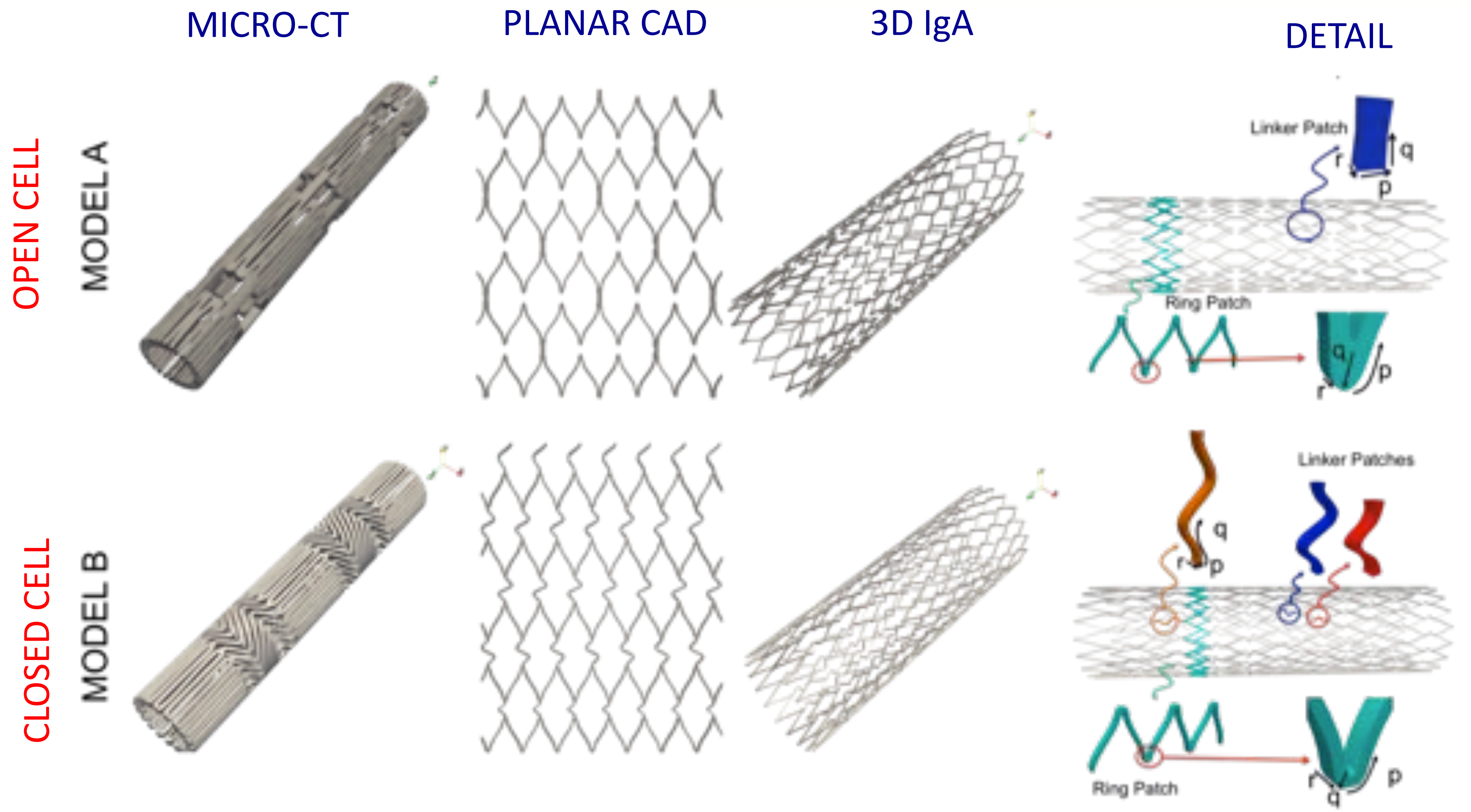
Cantilever beam test (Müller-Hülsbeck et al., 2009).







Stent geometric modeling

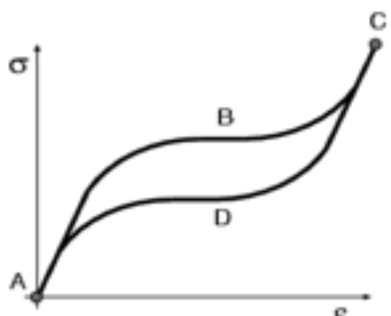


Note: for closed-cell stent bending, buckling is expected to be an important issue

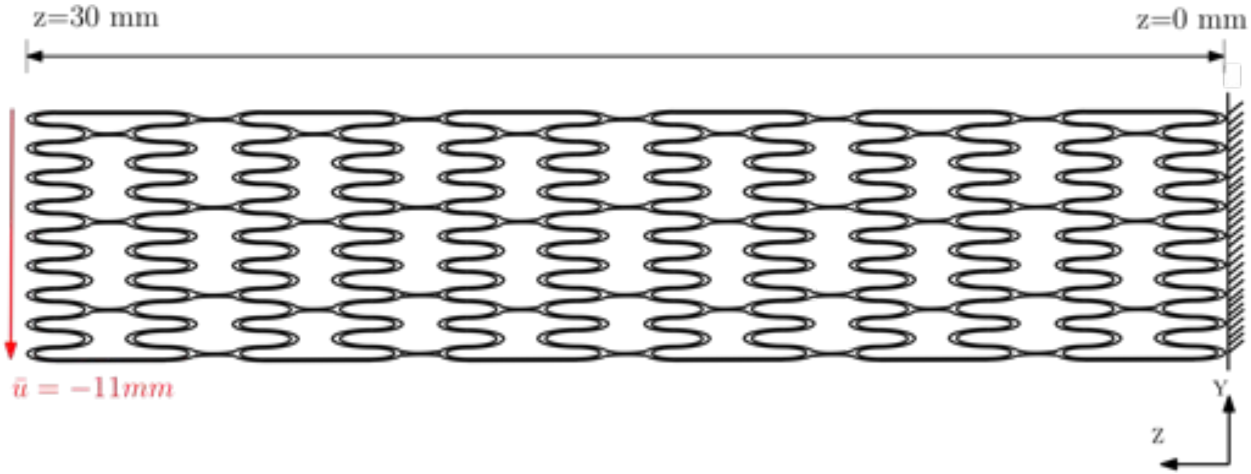
Analysis setup

- FEAP: Finite Element Analysis Program
  - Primarily for research & educational
  - Based on the Finite Element Method

- FEAP Isogeometric package for NURBS blocks or T-splines
  - Geometric linear and non-linear problems
  - Static and transient analysis
  - Solid (displacement based and mixed) + shell (Kiendl et al. 2009)
  - Linear and non-linear constitutive models (Souza model UMAT).
  - 8 *h-refined* FEA meshes and 4 *k-refined* IgA meshes



Souza et al., 1998.

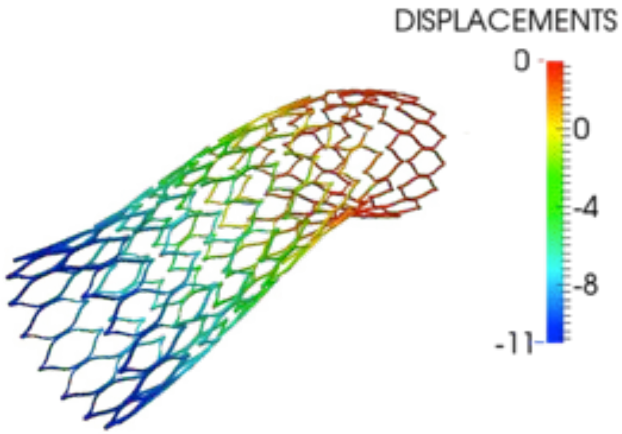


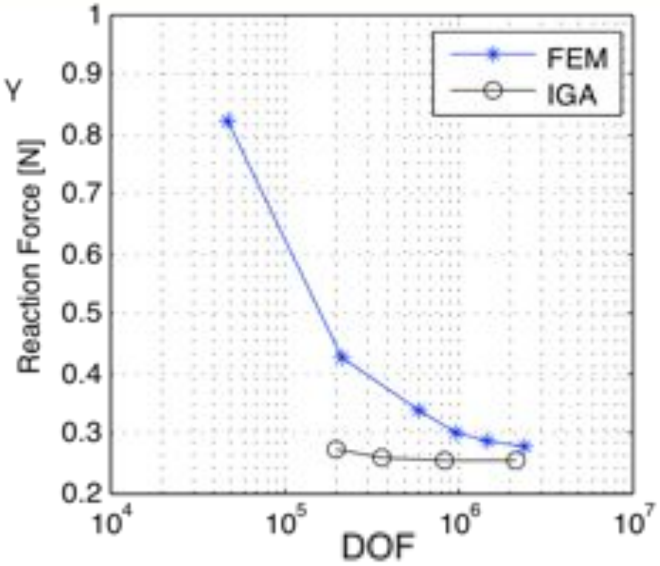
Results: Model A

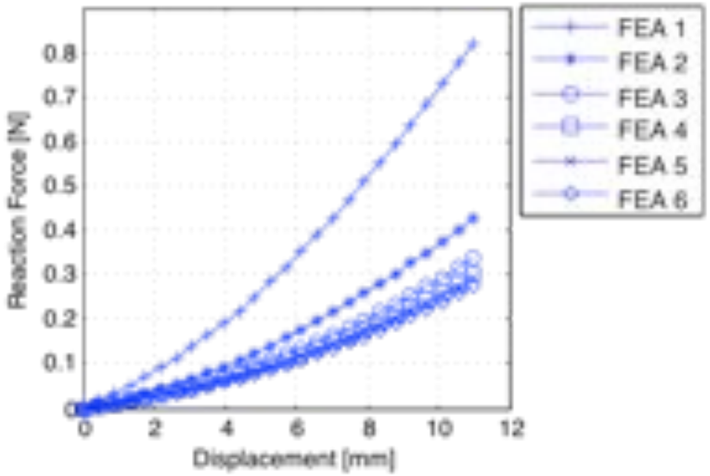
Design: open cell

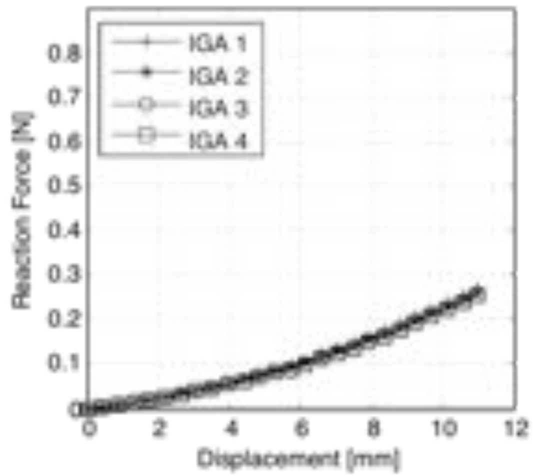
Deformation pattern: smooth

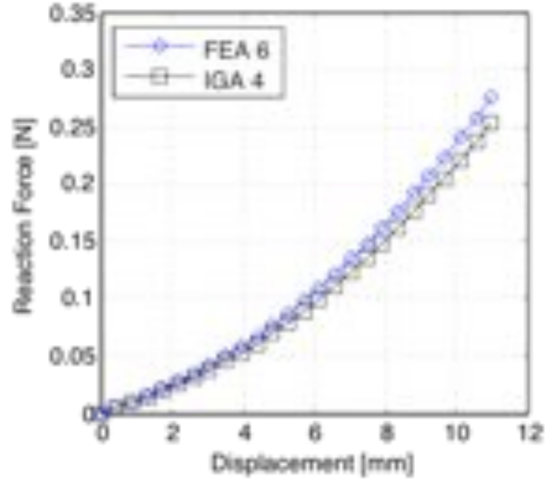
Material: SMA











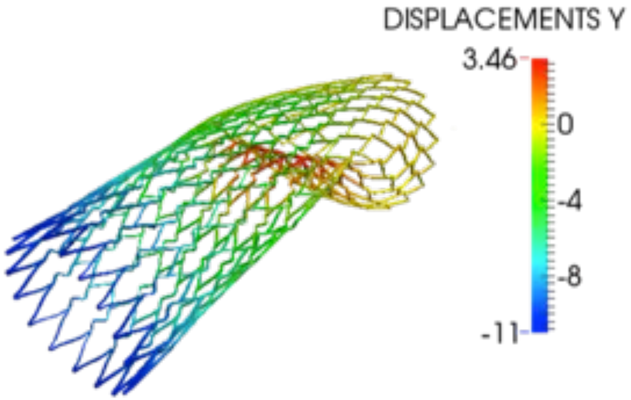
- IgA presents an average gain of **over one order of magnitude** in DOF number with respect to FEA
- The coarsest IgA mesh (directly from CAD, no refinement) has better behavior than finest FEA

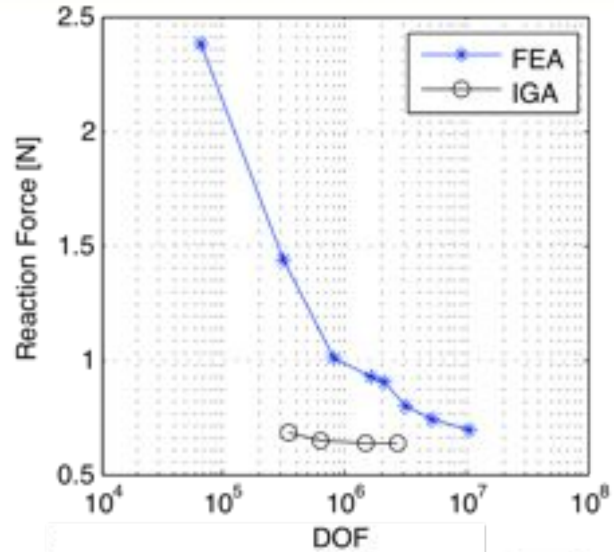
Results: Model B

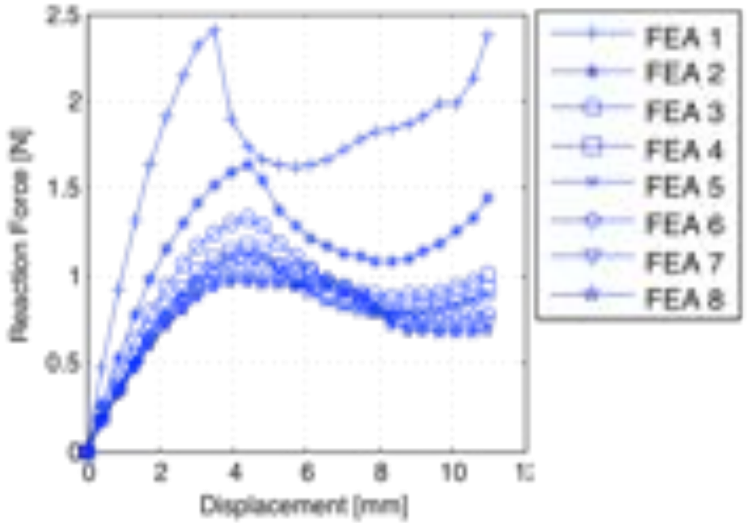
Design: closed cell

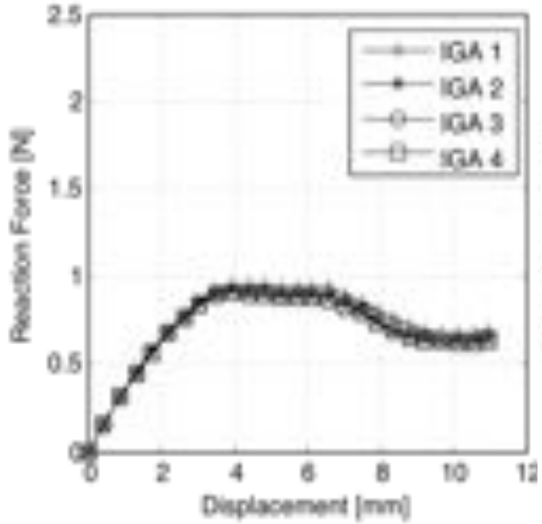
Deformation pattern: buckling

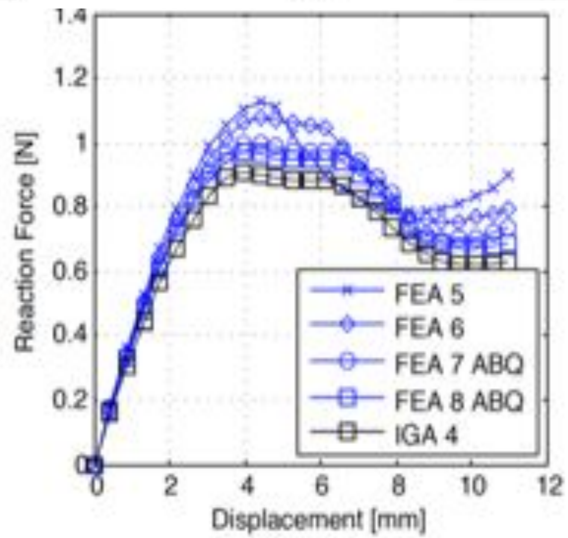
Material: SMA





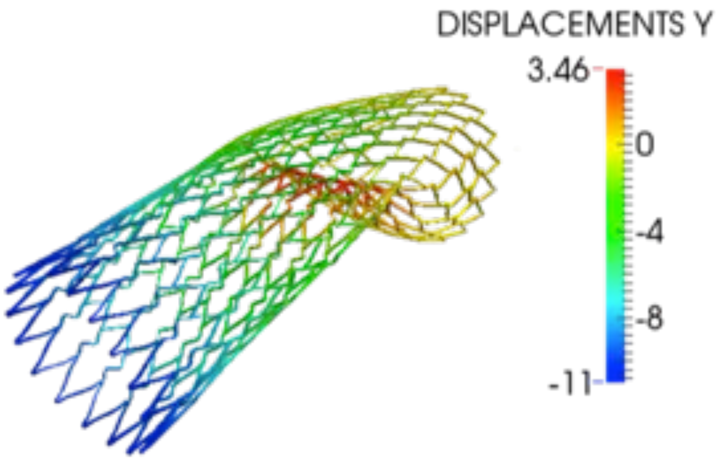


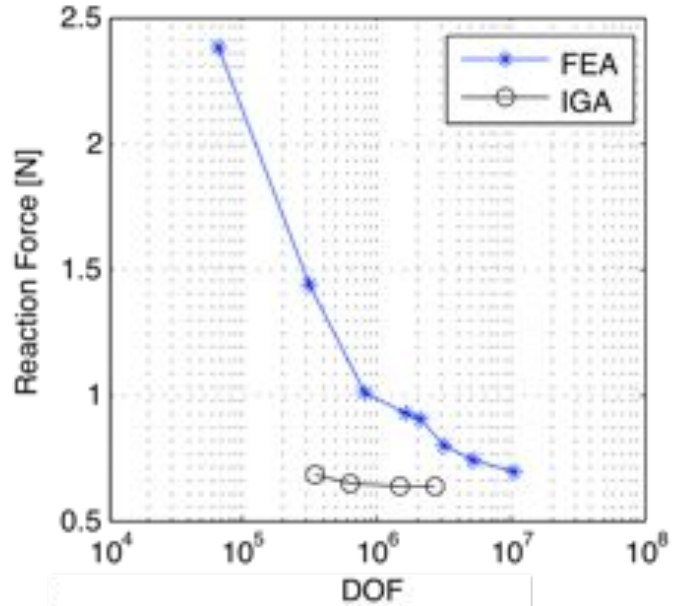


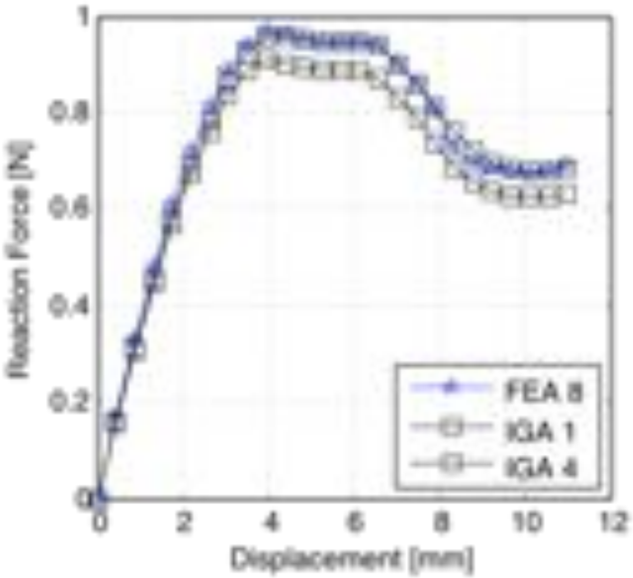


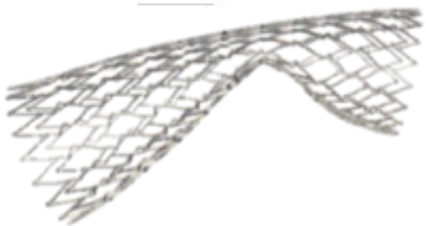
- IgA presents the **same deformation pattern** for all considered refinements
- FEA up to F-5 presents only one stage of local buckling, F-6 recovers the Iga deformation pattern

FEA does not catch the correct physical behavior unless *very fine meshes are used!*

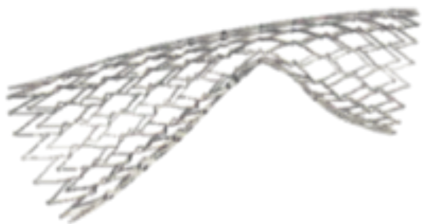






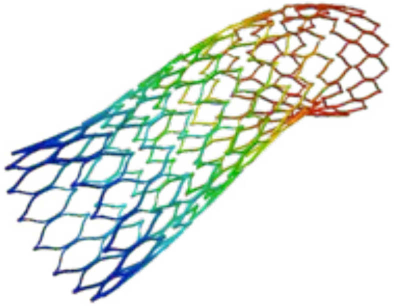


FEA-8 [10 M DOFs]



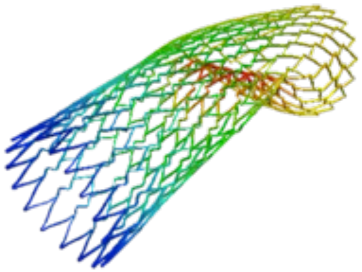
IGA-1 [325 K DOFs]

Results: Computational times



	Mesh label	DOF	# CPU	Solver	Total analysis time
Model A	IgA-1	204,525	1	FEAP	**47 min**
	FEA-6	2,473,875	1	FEAP	**6 h 55 min**

9 times slower!



	Mesh label	DOF	# CPU	Solver	Total analysis time
Model B	IgA-1	346,413	1	FEAP	**6 h 41 min**
	FEA-8	10,622,016	8	Abaqus/Standard	**26 h 23 min**

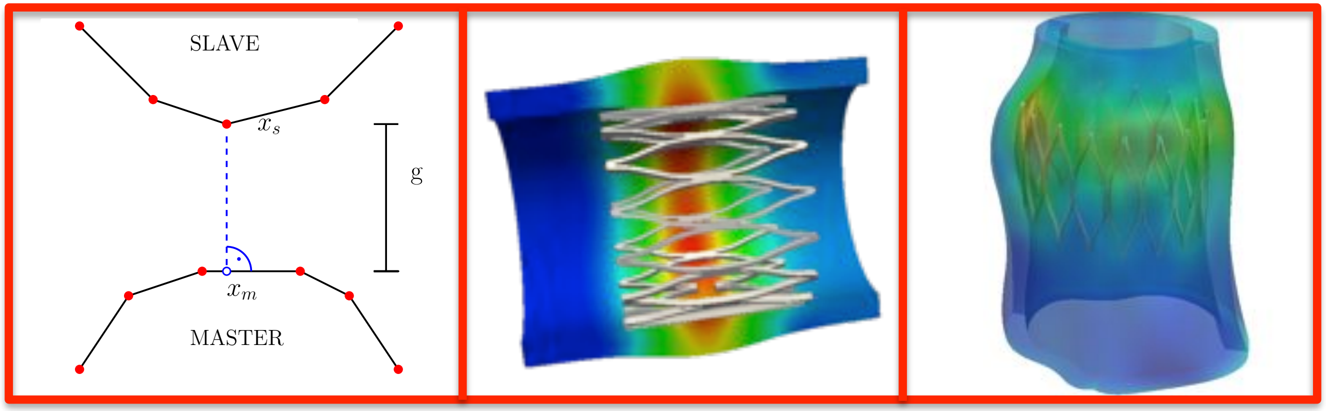
4 times slower despite 8 processors versus 1!

-IgA IS FASTER, MORE ACCURATE AND MORE EFFICIENT THAN LINEAR FEA
-TO REPRODUCE COMPLEX STENT BENDING BEHAVIOR

Study 3

IgA-based contact mechanics: from basics to real life applications

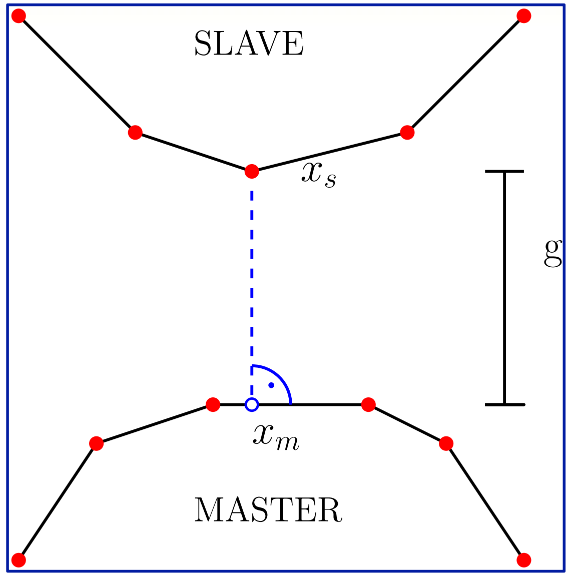
Collaboration with Prof. Robert L. Taylor, University of California Berkeley
and Prof. Laura de Lorenzis, Braunschweig University



From Node-to-segment to Knot-to-segment (KTS)

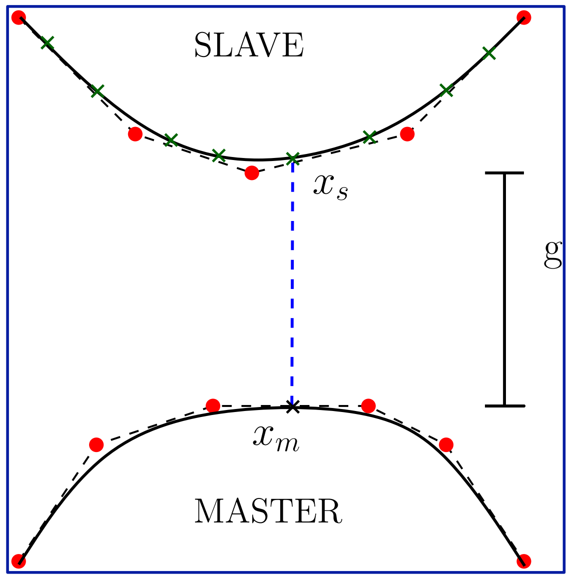
FEA: Node-to-segment approach

- Non-exact surface description
- Non-smooth basis functions
- Collocation of the contact constraint at nodal points



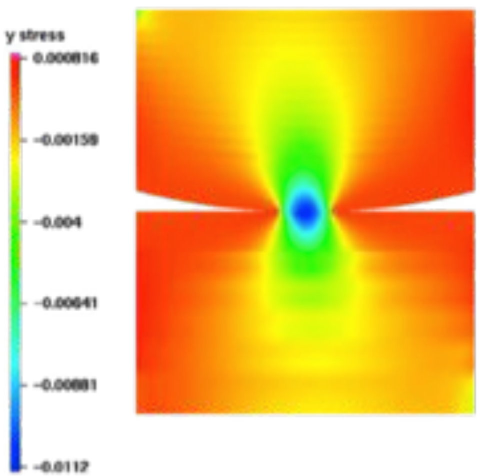
IgA: Knot-to-segment approach

- **Exact surface** description
- **Smooth** basis functions
- Collocation of the contact constraint not at nodal points, i.e. gauss points on contact facets

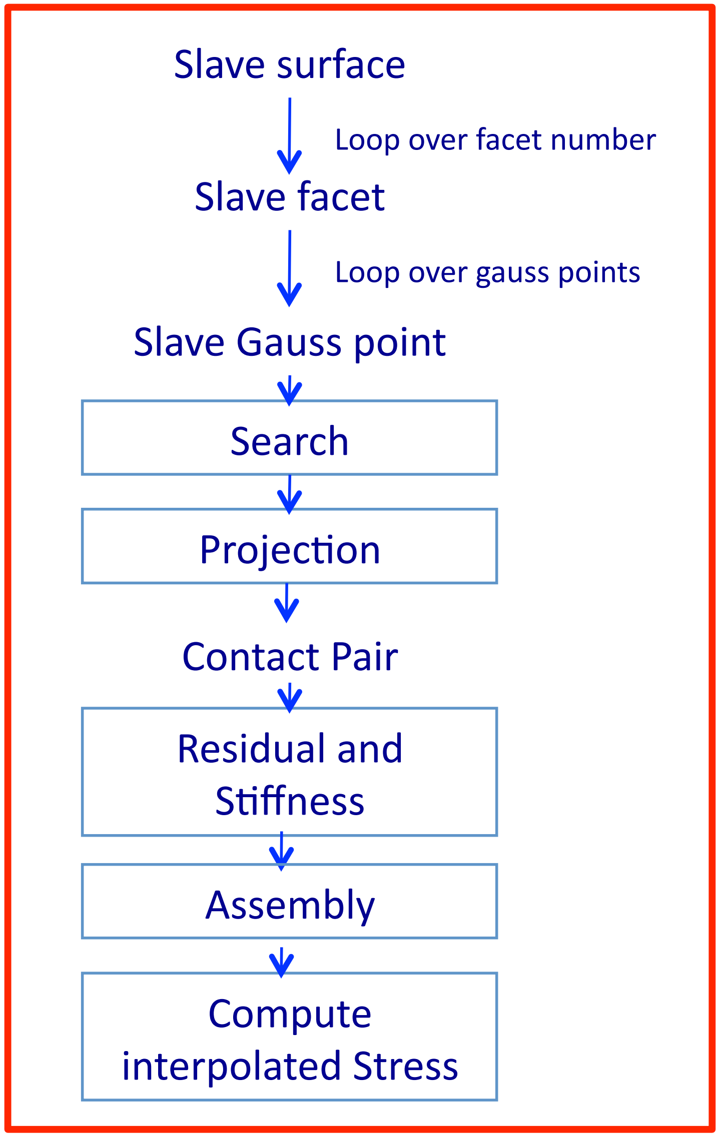


Contact element 06 (De Lorenzis et al. 2011)

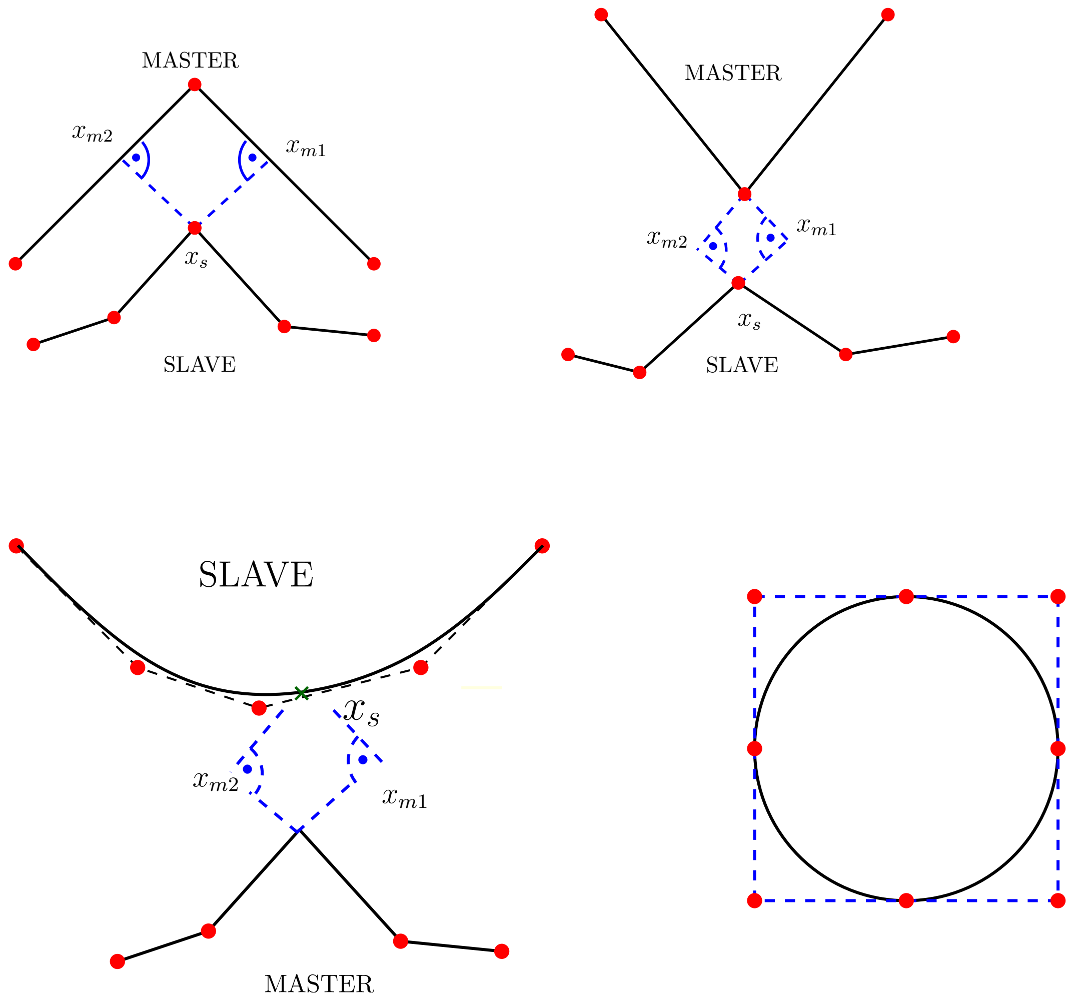
- 3D KTS NURBS driver
- Gauss Point (slave) to segment (Master) contact
- Frictionless
- Constraint imposition: Penalty method

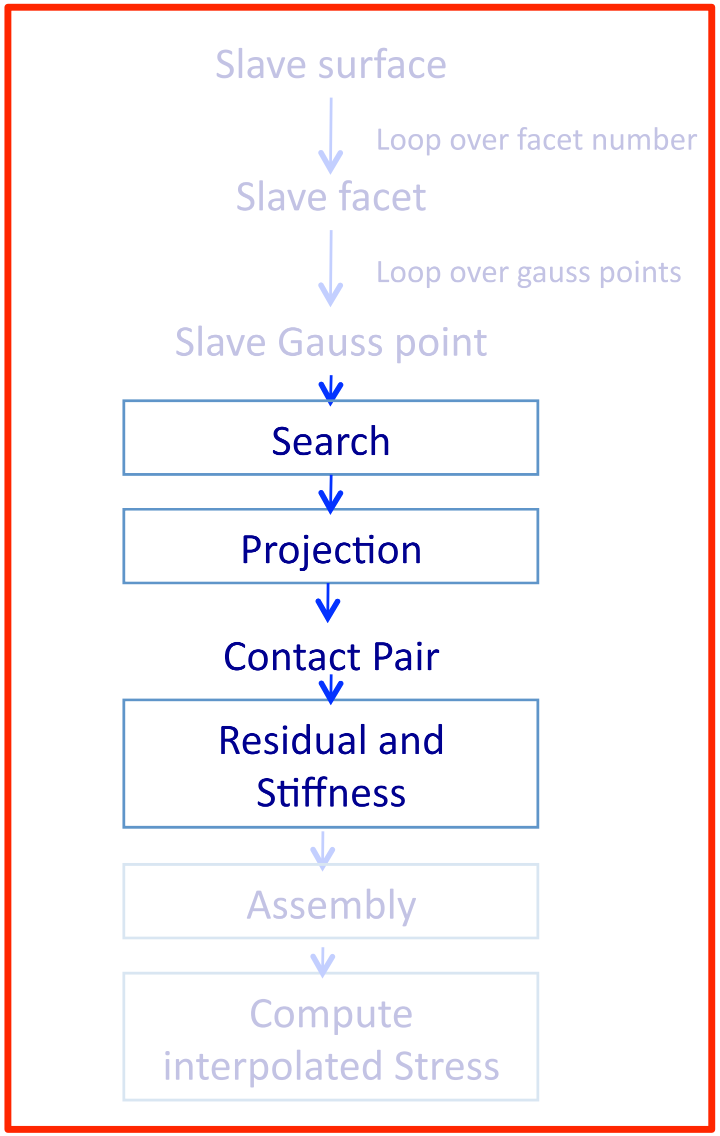


σy distribution on hertzian contact
[De Lorenzis 2011]



Knot-to-edge exception (Pimienta et al., 2009)





Add-ons

Uszawa algorithm

From penalty

$$C_c^P = \int_{\Gamma_c} k\cdot g\cdot\delta g\, dA$$

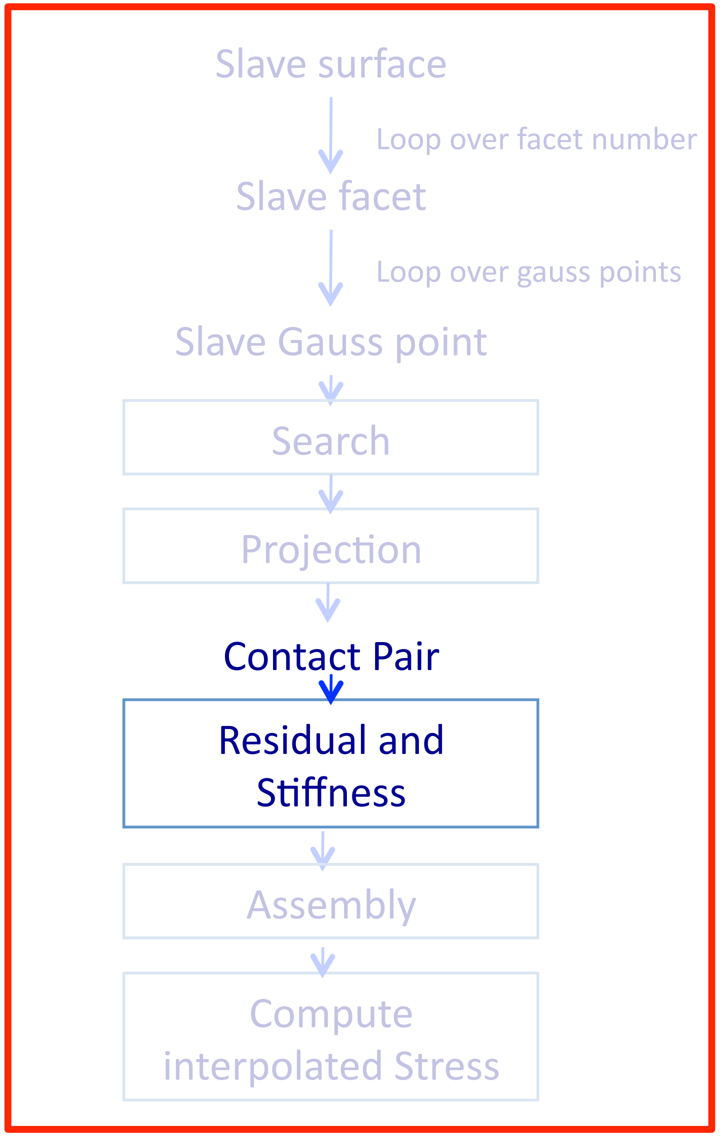
To Uszawa algorithm

$$C_c^P = \begin{cases} \int_{\Gamma_c} (\bar{\lambda} + k\cdot g)\delta g\, dA \\ \bar{\lambda}_{NEW} = \bar{\lambda}_{OLD} + k\cdot g_{NEW} \end{cases}$$

K= Penalty parameter

g= gap

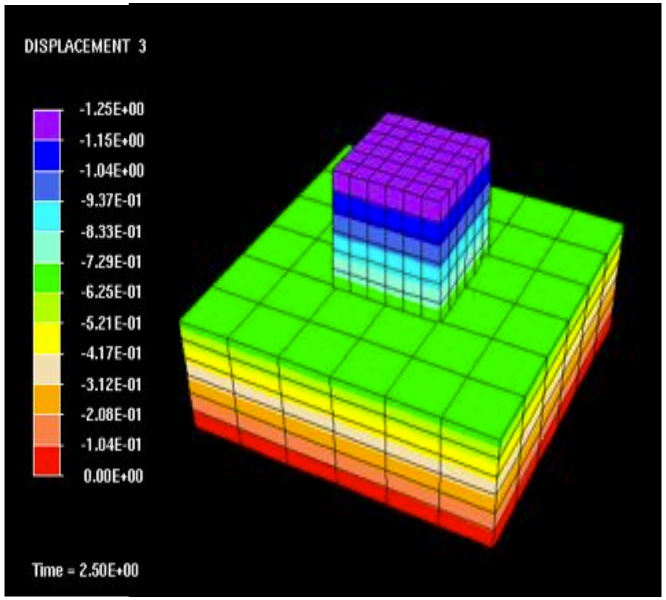
λ= Lagrange multiplier



Numerical examples

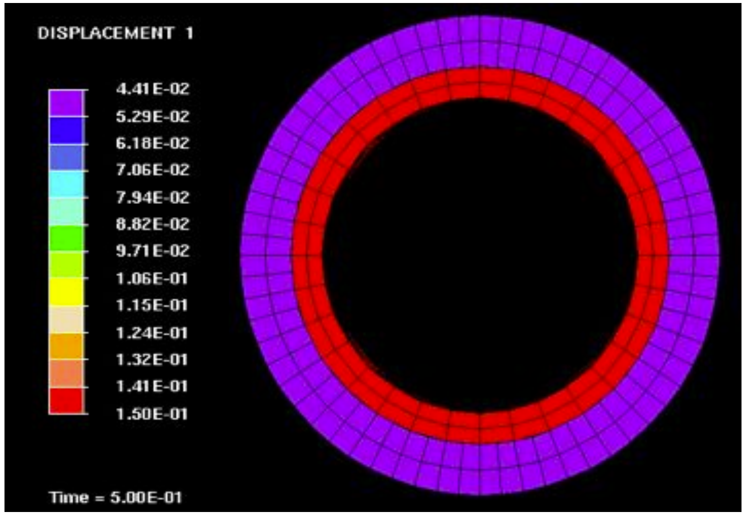
- Cube-Cube NURBS contact test
- Displacement controlled
- Benchmark test proposed by the developers

Model	IgA	FEA
Avg iteration number/step	2	2
Gap magnitude [mm]	10^{-5}	10^{-5}
CPU time [s]	0.56	0.34



- Cylinder-Cylinder NURBS contact test
- Displacement controlled

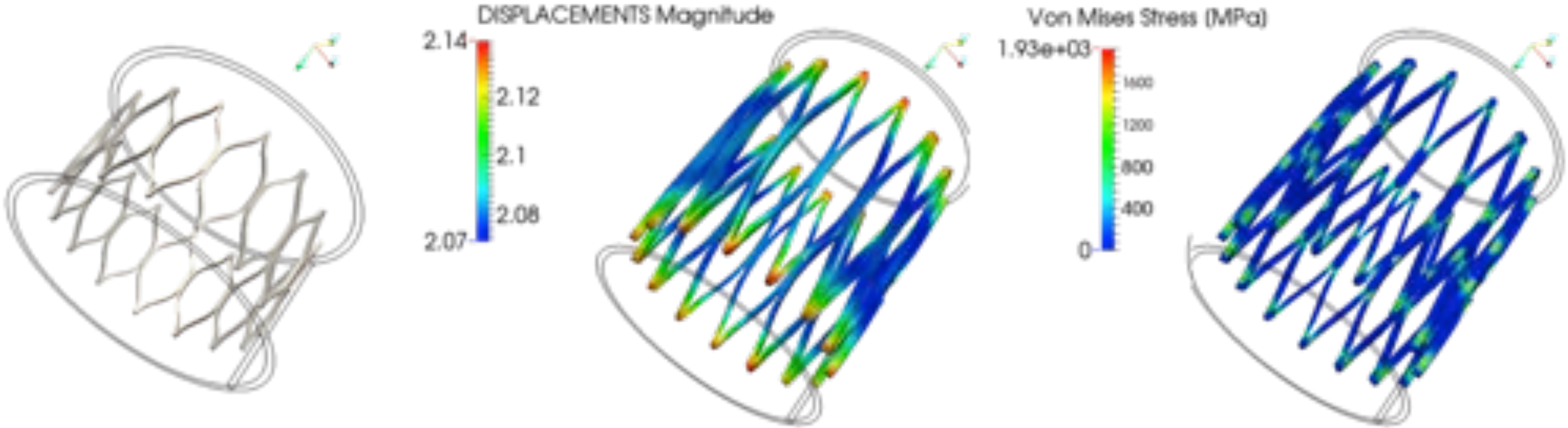
Model	Penalty	Uszawa
Avg iteration number/step	3	7
Gap magnitude [mm]	10^{-5}	10^{-9}
CPU time [s]	33.16	73.64



Toward real life applications

Stent crimping

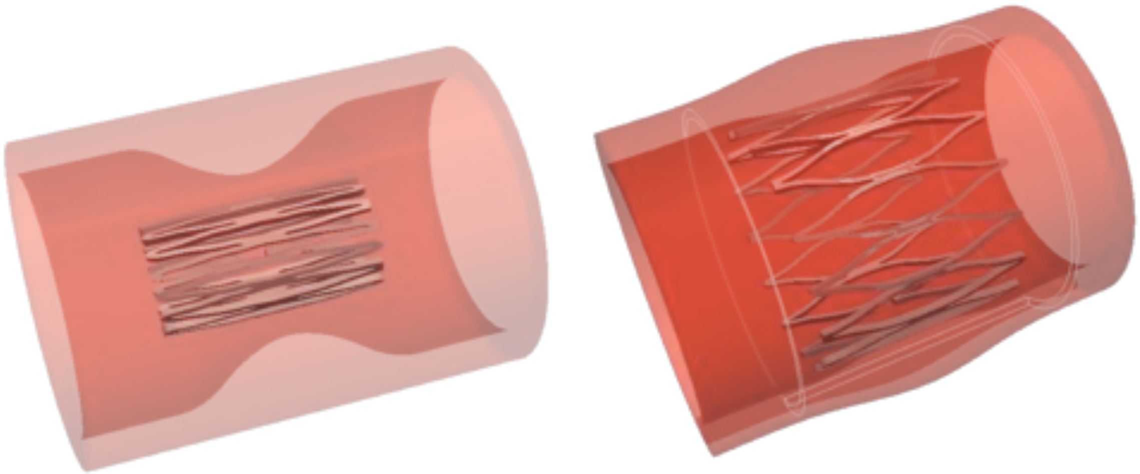
CPU TIME < 2 min !



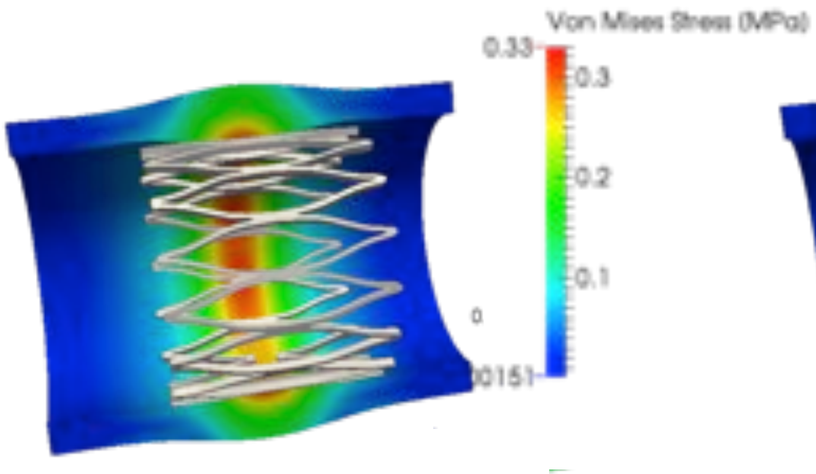
Stent ring implant (simplified vessel)

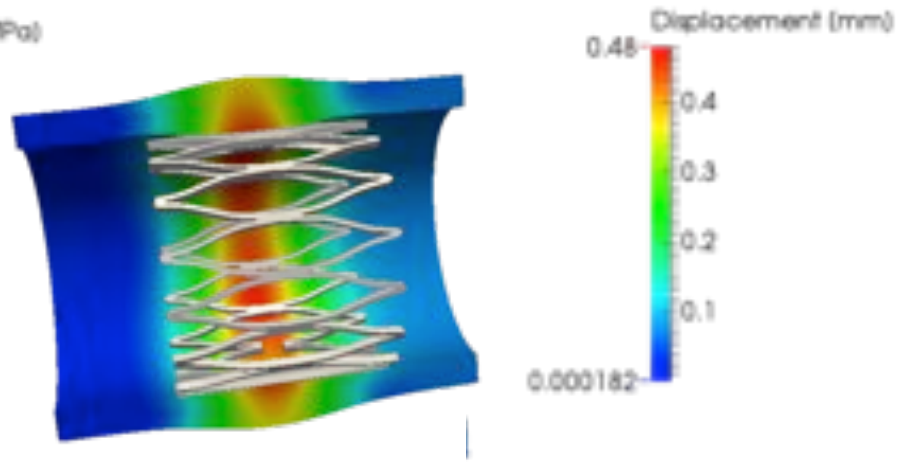
Details

- Stenosis degree: 20 %
- Vessel model: Neohookean
- Stent model: Souza model

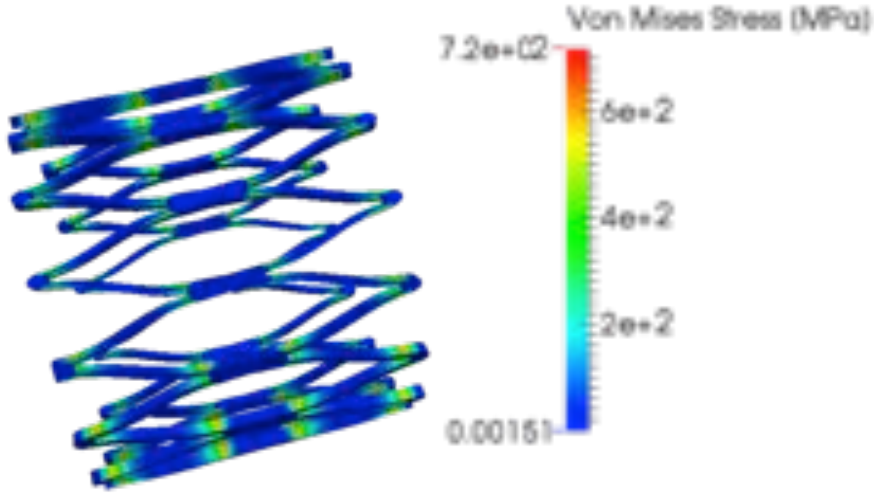


Stent ring implant (simplified vessel)

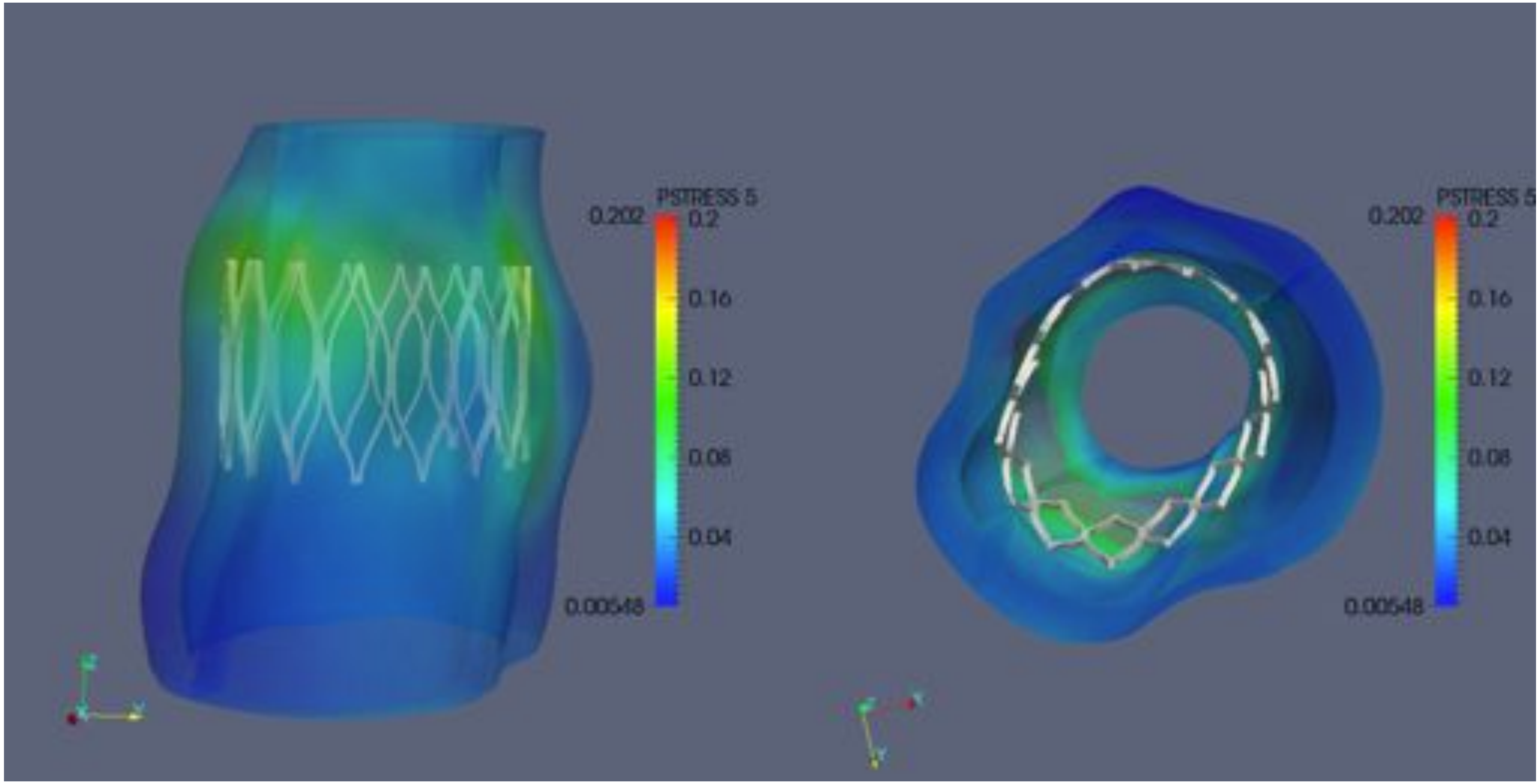




The obtained results confirm the results obtained by Auricchio et al. CMES, 2010



- Stent ring implant (patient specific model)



Final remarks

- The present doctoral research demostrated the capability of *in-silico* models to predict different complex behaviors of endovascular stents, that can have clinical relevance into determining the outcomes of the CAS procedure

- Study 1: the results confirmed the capability of dedicated **FEA** simulations to provide useful information about complex stent features.

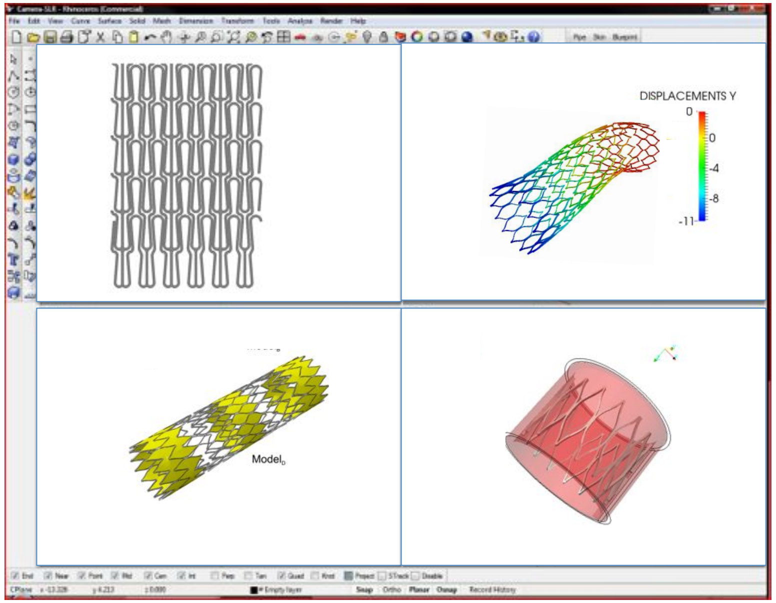
- Study 2: this work demonstrated that novel **IgA** allows to get better approximation of the solution with a widely reduced number of DOF with respect to traditional **FEA**

- Study 3: the results coming from the **IgA**-based contact simulations represent a promising basis for further investigations and clinical-relevant simulations.

Final remarks

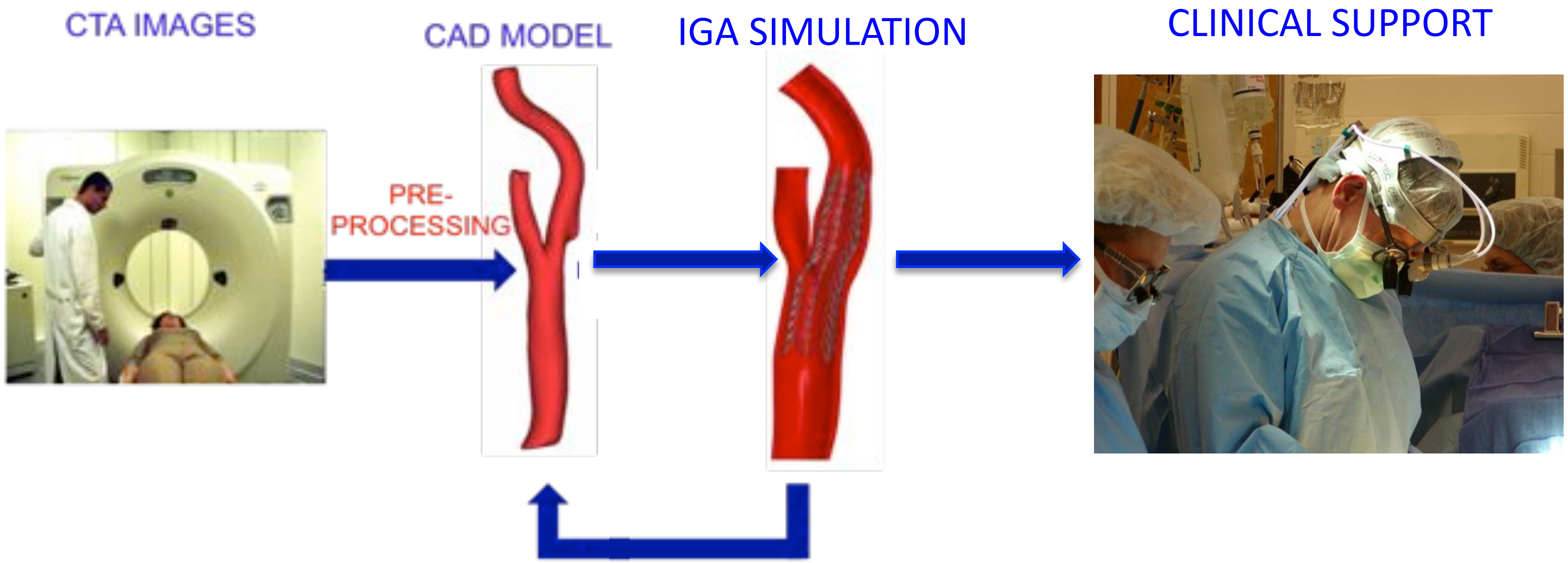
Future developments

- IgA computational efficiency:
  - IgA FEAP parallel implementation;
  - Ad-hoc numerical quadrature, solvers etc.



- Advanced NURBS mesh generation:
  - Trimmed NURBS management;
  - T-splines, LR B-splines, Hierarchical B-splines

- From research to industrial design/ clinical reality



Thank you
for your kind attention!