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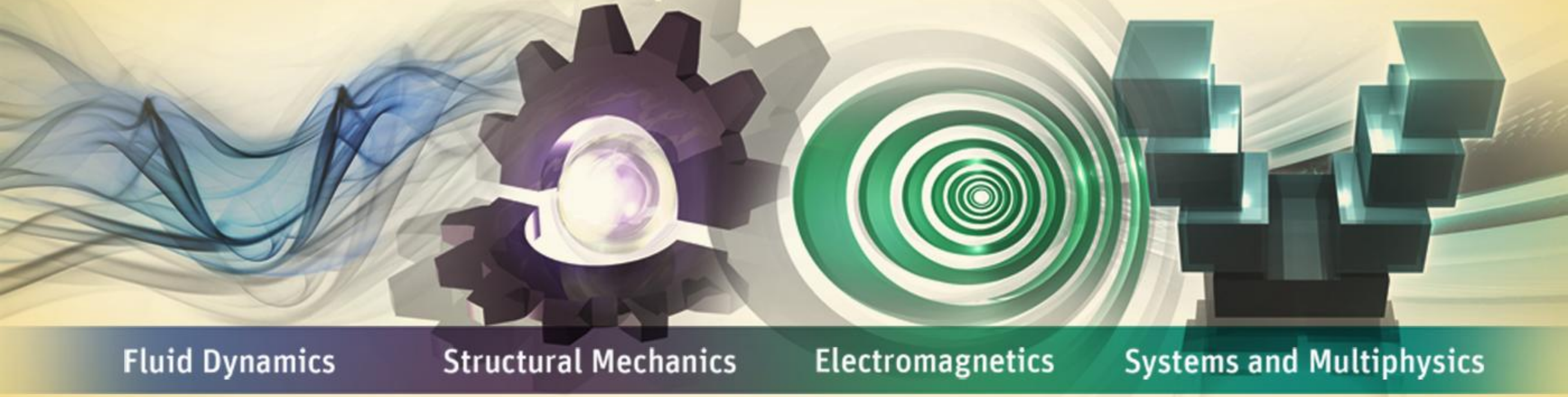
Reduced Oder Modeling techniques to predict the risk of fatigue fracture of peripheral stents



Michel Rochette

ANSYS

RT3S: Real Time Simulation for Safer vascular Stenting

The University Of Sheffield.

University of Bedfordshire

Medtronic INVATEC

ANSYS

POLITECNICO DI MILANO

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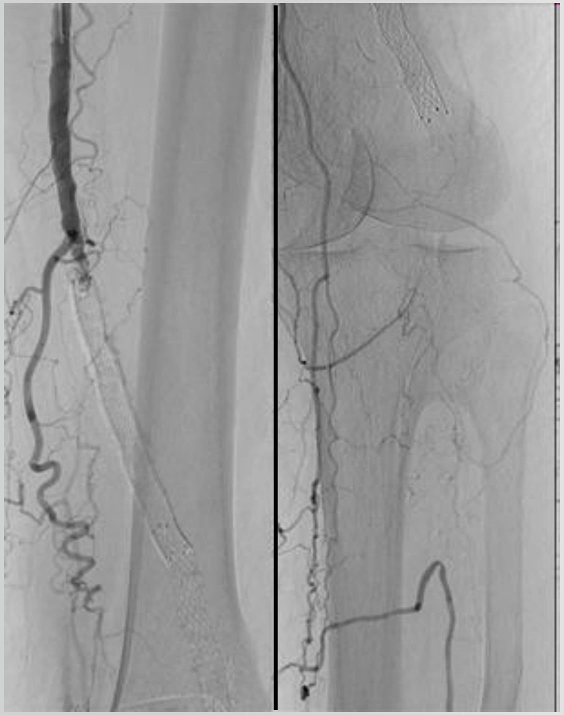
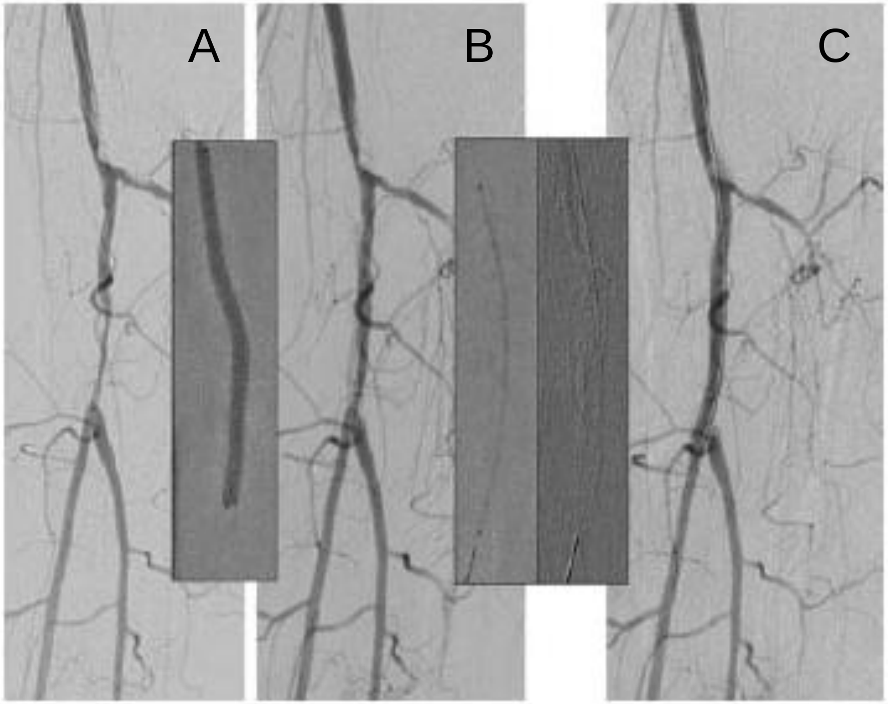
  July 30, 2014

The vascular disease in peripheral arteries and its treatment

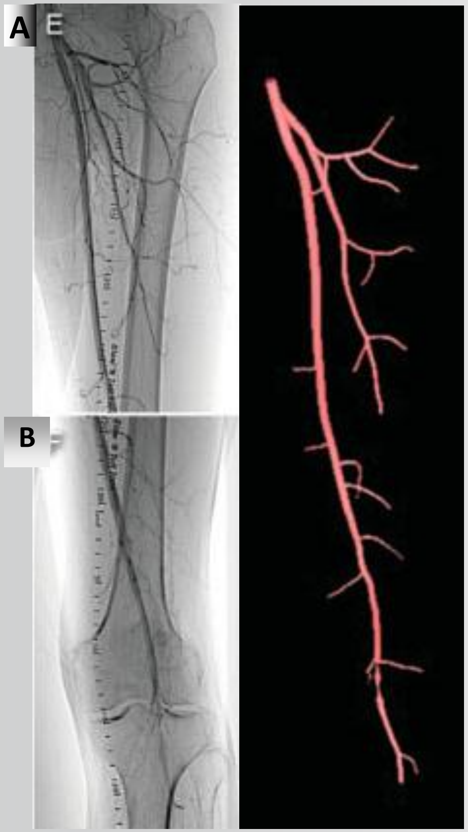




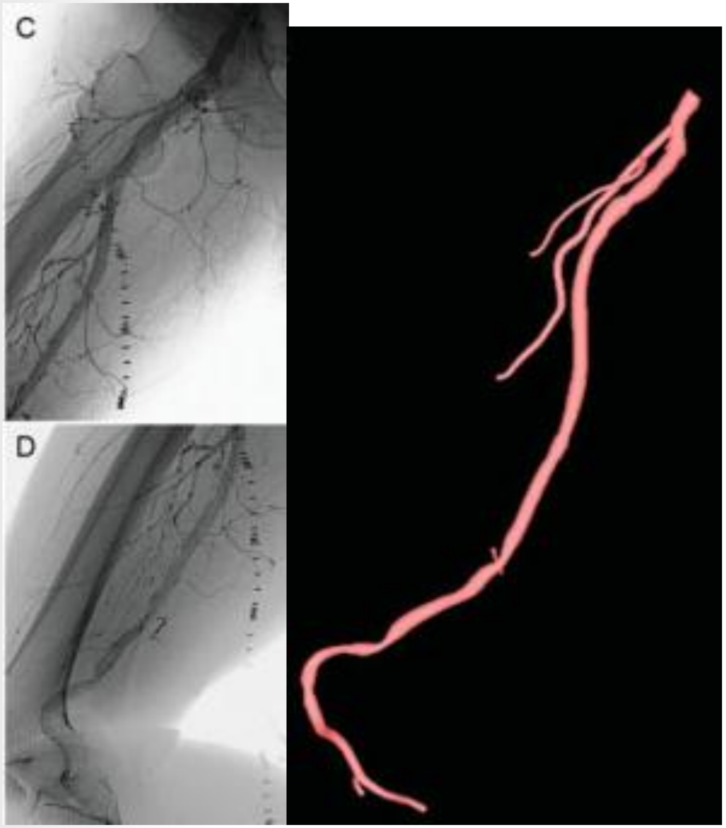
Left: angiographic findings of superficial femoral artery (SFA) stent
Right: popliteal Artery (PA) occlusion in an elderly gentleman with ischaemic rest pain in the foot and dusky discolouration of the toes.

A) Preoperative angiographic imaging showing lesion at the level of tibiofibular trunck;
B) Suboptimal treatment with percutaneous transluminal angioplasty and
C) successful stenting with Chromis Deep stent (Invatec, Roncadelle, Italy).

Conformational change in the femoropopliteal artery with leg movement



Straight leg

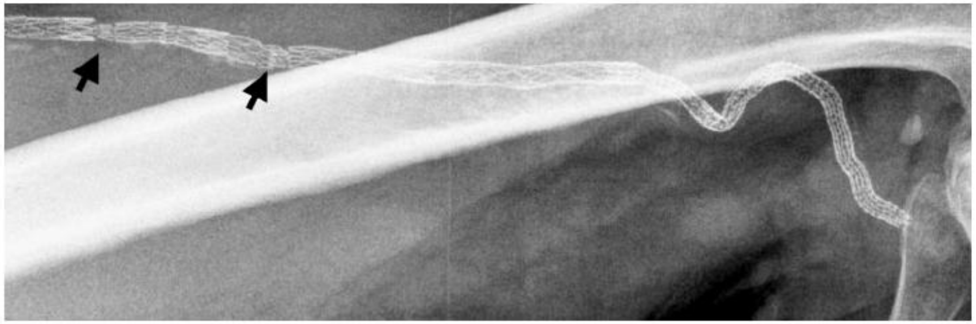


Crossed leg

Klein et al. Catheter Cardiovasc Intervent 2009;74:787–798

In vivo peripheral stent deformation with leg movement

Two stent-grafts in a recanalized femoropopliteal segment.

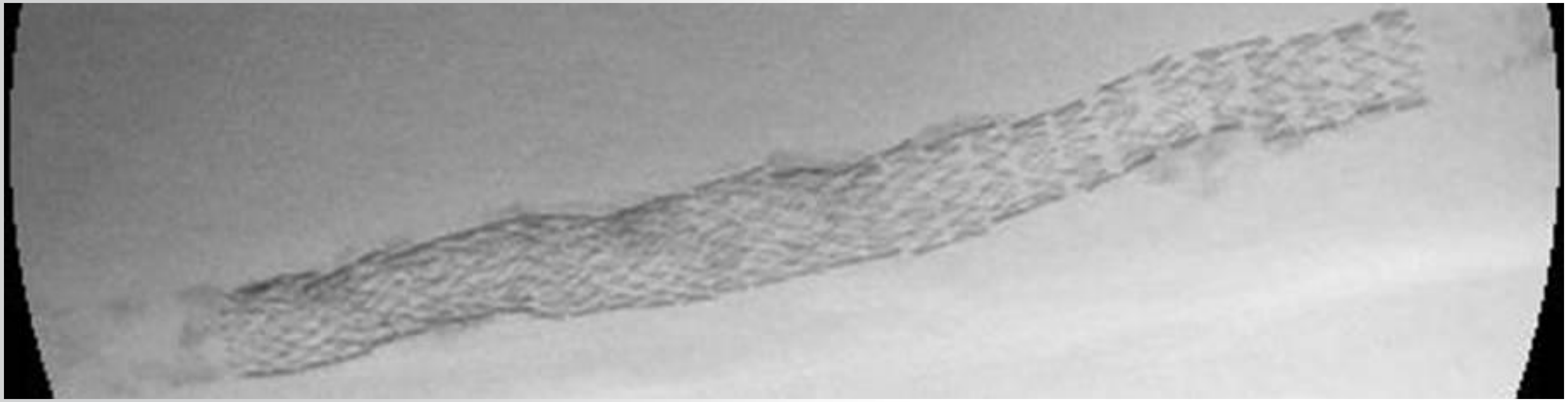


Ten stents placed to recanalize a long SFA occlusion

Kroger et al.
J Endovasc Ther
2004;11:686–694

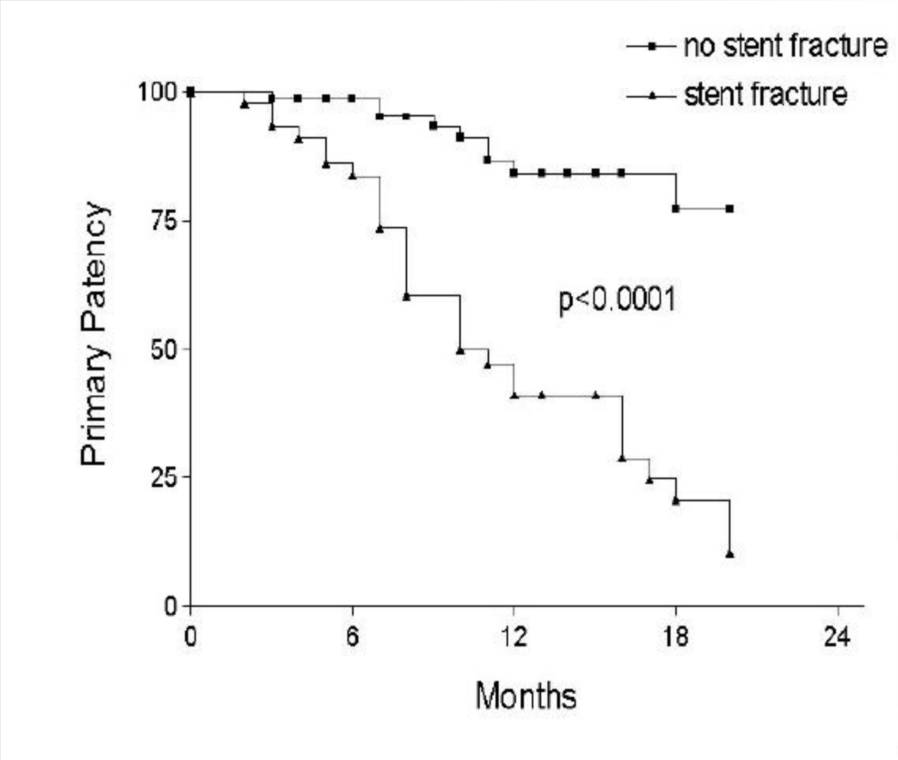
The problem: stent fatigue fracture in peripheral arteries

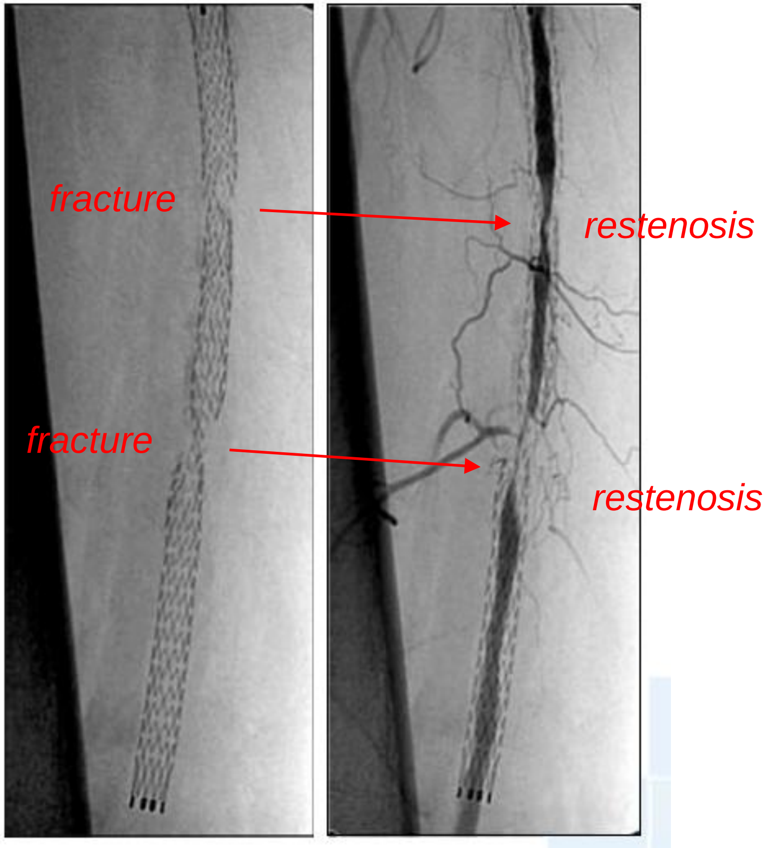
‘If we could compute the risk of stent fatigue fracture while the surgeon is planning or performing the intervention, the computer could give a warning when the combination of patient-specific and surgery-specific factors create risk for the patient, and drastically reduce the incidence of this important complication.’



The problem: stent fatigue fracture in peripheral arteries

Stent fracture leads to in-stent restenosis

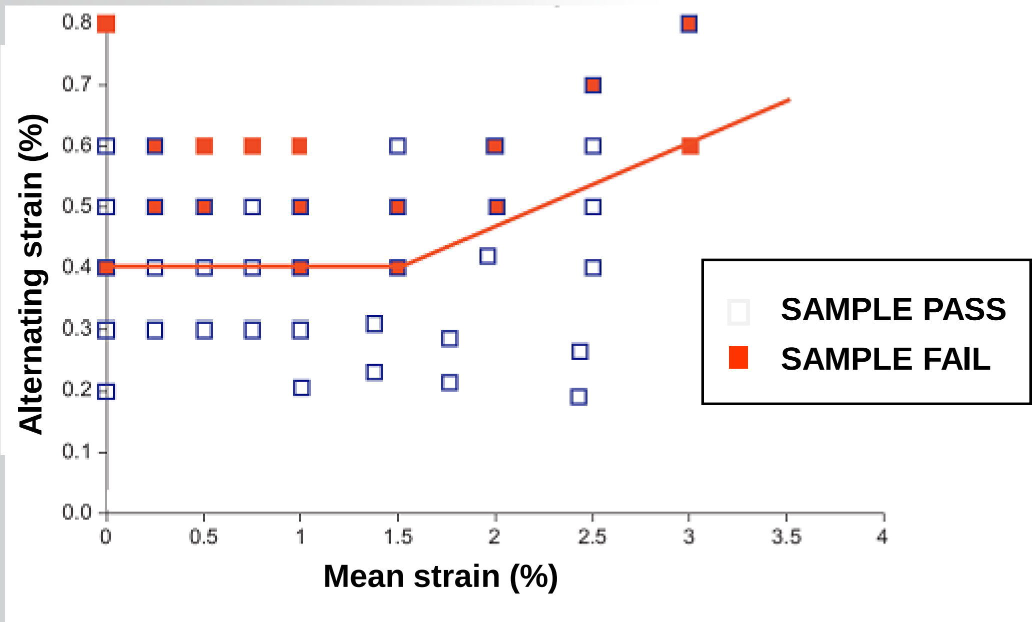




Scheninert et al. JACC 2005

The problem: stent fatigue fracture in peripheral arteries

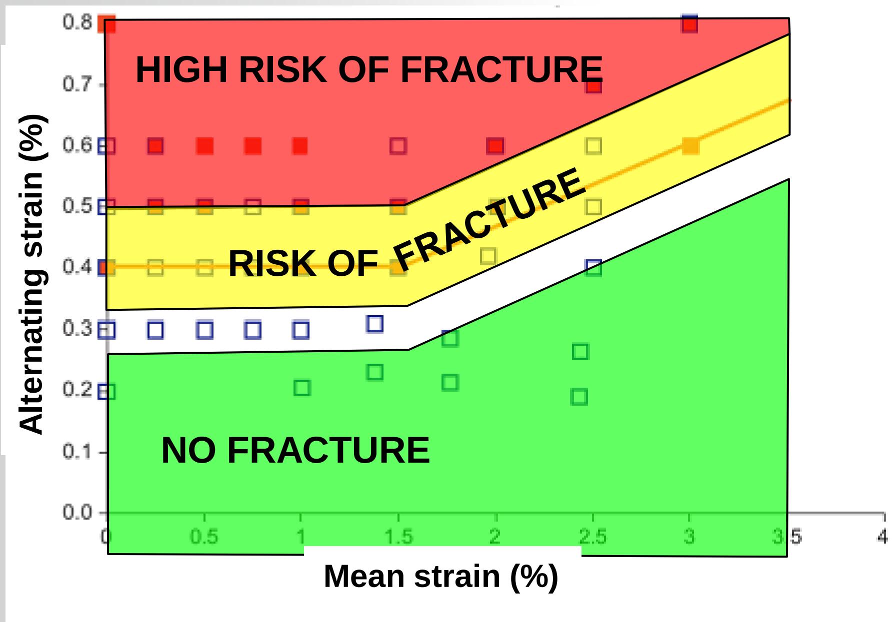
Safe or unsafe conditions ?



Goodman diagram at a fixed fatigue life
(**experimental data** for Nitinol)

The problem: stent fatigue fracture in peripheral arteries

Safe or unsafe conditions ?



Goodman diagram at a fixed fatigue life
(**experimental data** for Nitinol)

“RT3S will transform the planning of endovascular procedures to treat peripheral arterial disease”

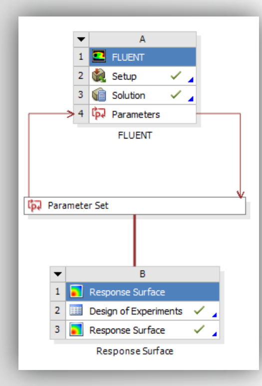
http://www.rt3s.eu/

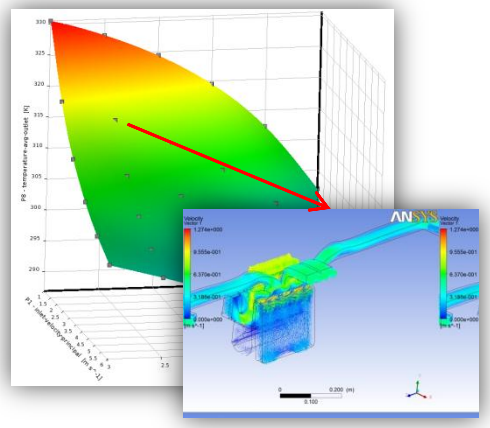
RT3S project is partially funded by the European Commission under the 7th Framework Programme, GA FP7-2009-ICT-4-248801

Comprehensive Robust Design Optimization & Design for Six σ Becomes a 4 Stages Process

Identify Parameters → Compute Solution → Create ROM → Navigate Parameterized Solution

	ID	Parameter Name	Value	Unit
2	Input Parameters			
3	FLUENT (A1)			
4	P1	inlet-velocity-principal	3.1	m s^-1
5	P2	inlet-temperature-principal	5	C
6	P3	inlet-velocity-secondary	1.1	m s^-1
7	P4	inlet-temperature-secondary	60	C
9	Output Parameters			
10	FLUENT (A1)			
11	P5	pressure-drop-principal	3778.5278	Pa
12	P6	pressure-drop-secondary	4790.7544	Pa
13	P7	temperature-max-outlet	320.61569	K
14	P8	temperature-avg-outlet	288.22202	K
15	P9	temperature-point-outlet	320.4126	K





Predefine some input scalar parameter value ranges

Compute a DOE, say e.g. 50 Design Points (DP)

Generate a ROM from 10 DP + Validate the ROM with e.g. 40 DP

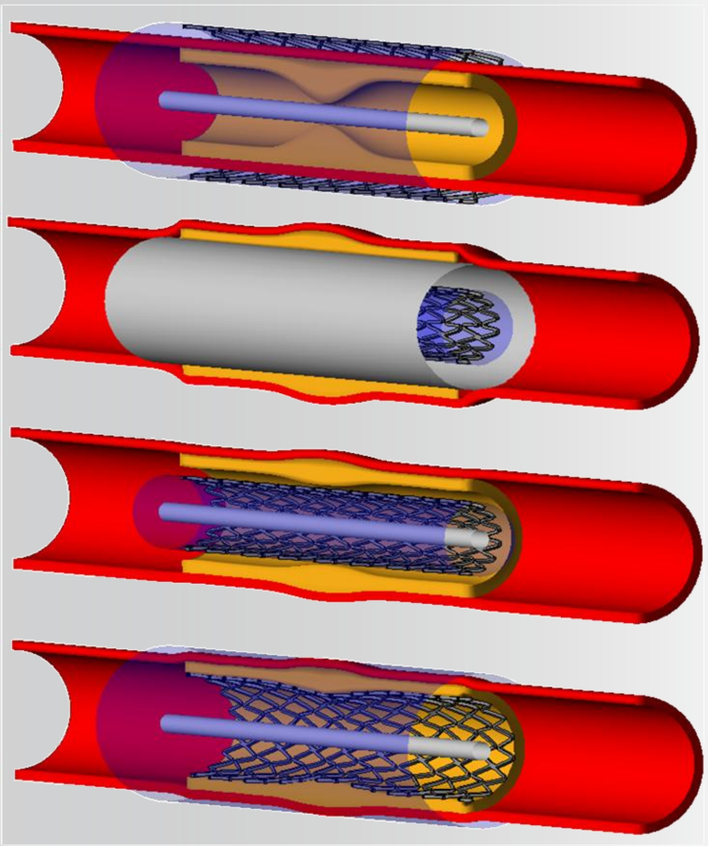
Use the ROM

Any param value
Any point in space
Any time-step

3 out of these 4 stages are standard tools already available through DesignXplorer

stent simulations in a vessel with atherosclerotic plaque

→ **<u>Simulation of a stenting procedure in a vessel with atherosclerotic plaque</u>**



Stent *crimping* with a cyindrical rigid body

Angioplasty with a cylindrical rigid body as a balloon

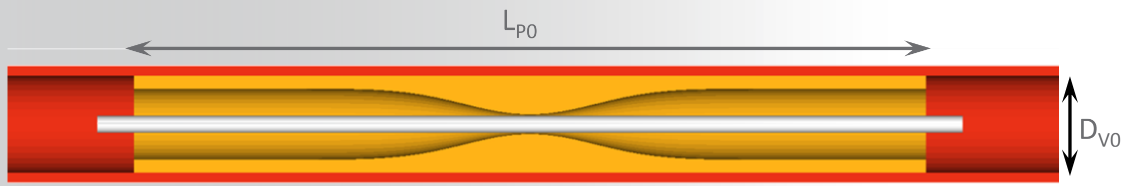
Deflation of the balloon for angioplasty

Deployement of the stent into the vessel

Response Surface of angioplasty procedure

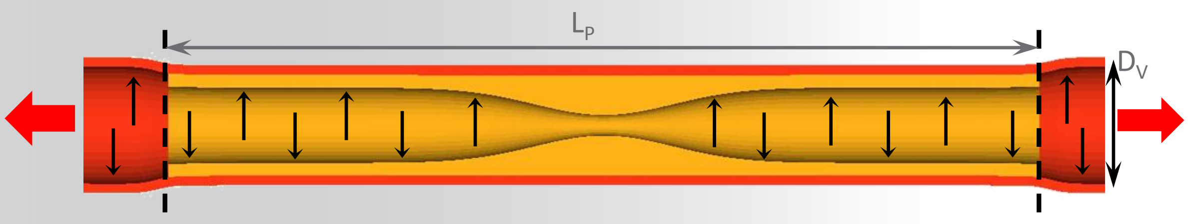
Load Steps of the angioplasty simulation

1)



Undeformed configuration

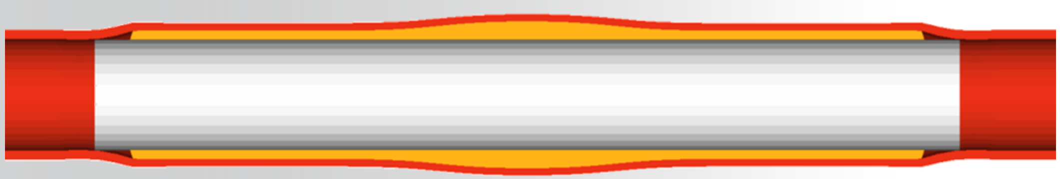
2)



Pressure

Axial prestretch (6%)

3)

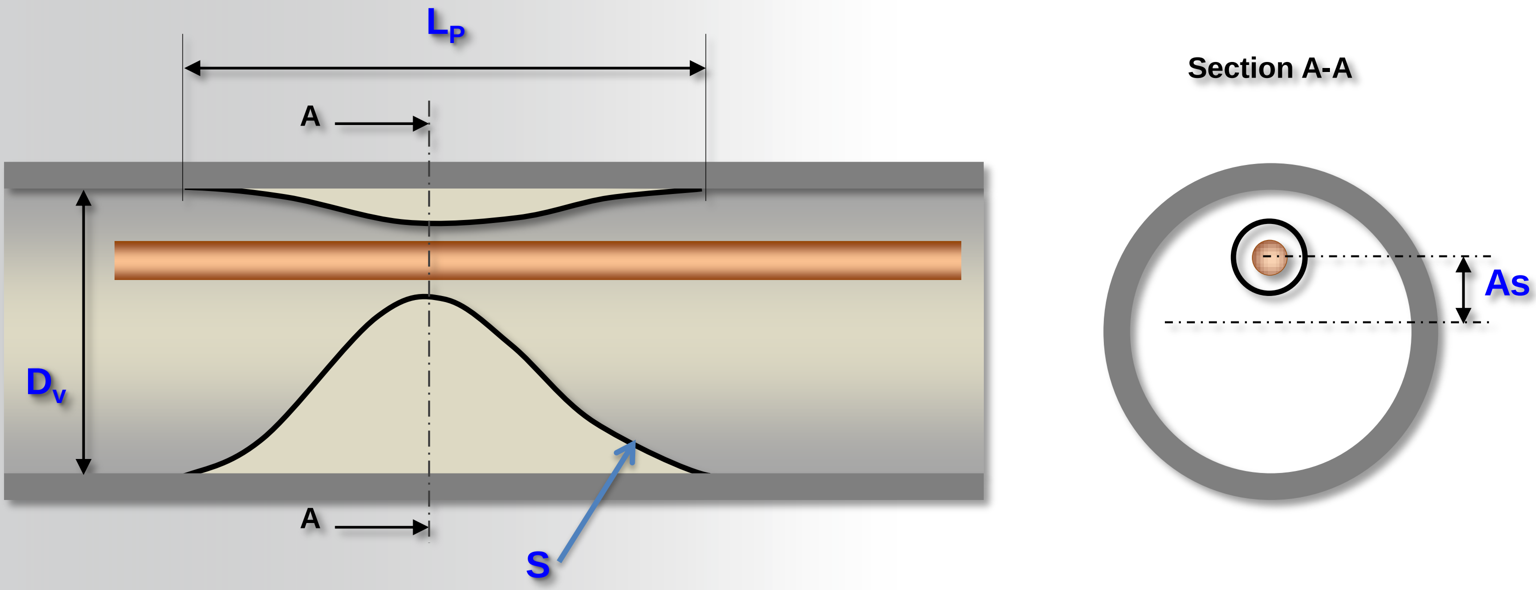


Balloon expansion → Positive ***radial displacement*** applied on balloon nodes

4)

Balloon deflation

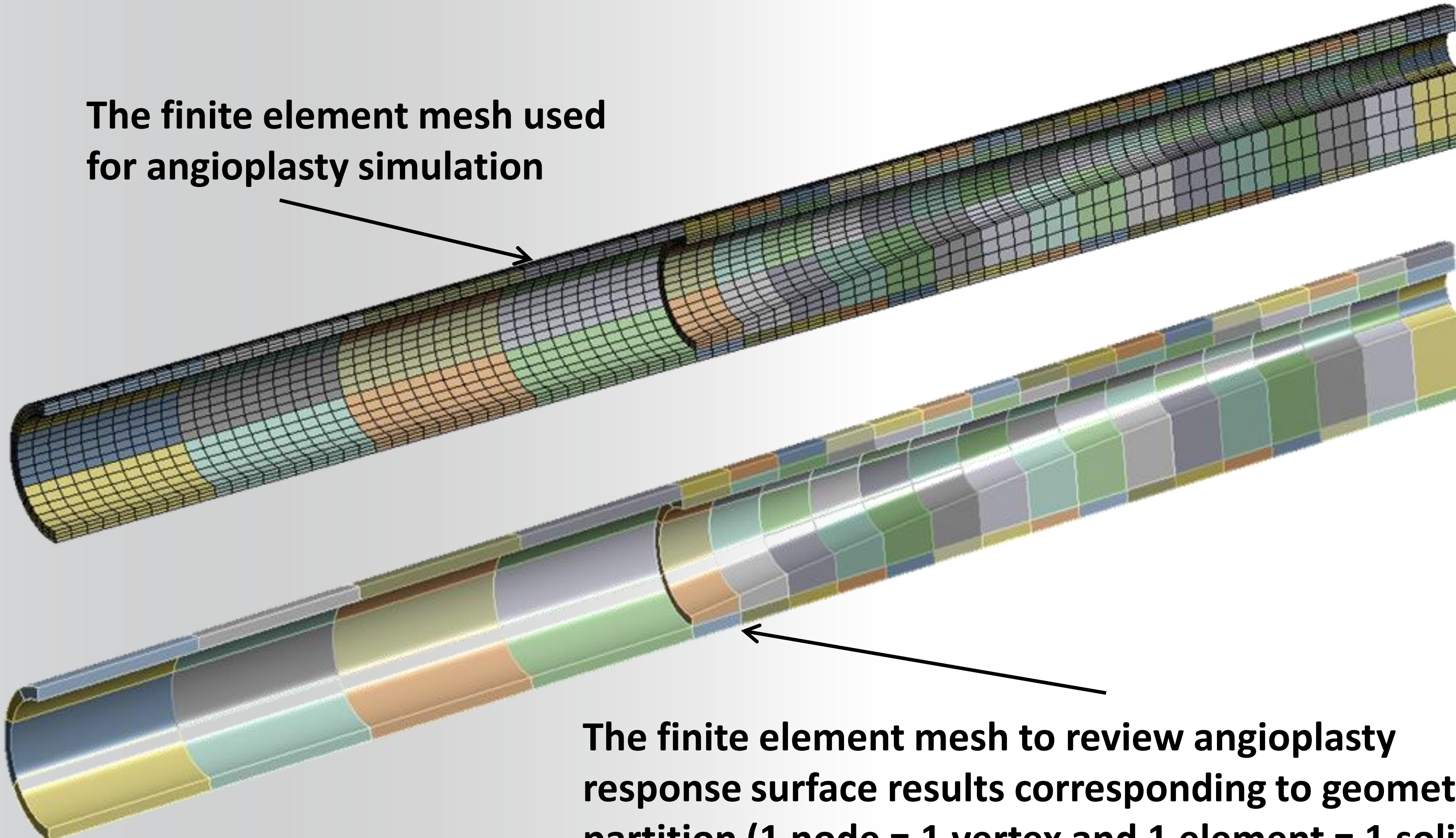
Input Parameters



Input Parameters	Description	Variation range
D_V	Inner diameter (mm)	3.464 - 6.062
L_P	Plaque length (mm)	40 - 190
RL	Residual lumen	0.65 - 0.95
As	Asymmetry coefficient	0 - 1
S	Sharpness	0.1 - 1
%ID	Percentage inner diameter	0.85 - 1.15
%Stretch	Percentage initial stretching	0. – 0.20

Geometry Partition

The finite element mesh used for angioplasty simulation



The finite element mesh to review angioplasty response surface results corresponding to geometry partition (1 node = 1 vertex and 1 element = 1 solid)

Angioplasty Response Surface

Around 450 Angioplasty solves launched in parallel on the CINECA PLX Cluster: Intel Xeon E5645 @2.4Ghz

- Average computation time for converged simulations (4 CPU used per run): 78 min

2 sets of design points

- Learning set to build the response surface
- Validation set to compare interpolated results and reference results

Parameterization of solution fields based on

- Singular Value Decomposition of the list of vectors
- Scalar output parameters computed from solution fields

Variation of the number of learning points

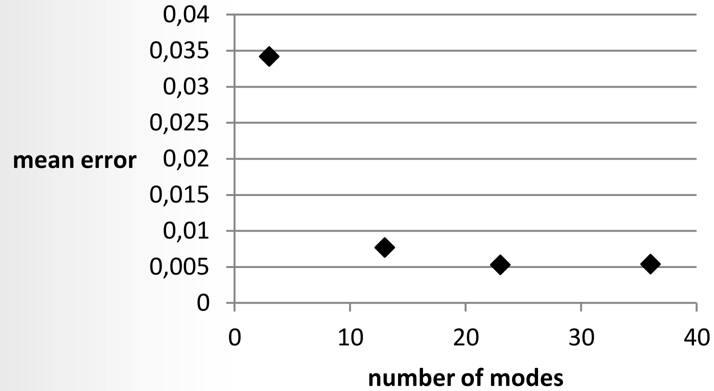
Variation of the number of modes

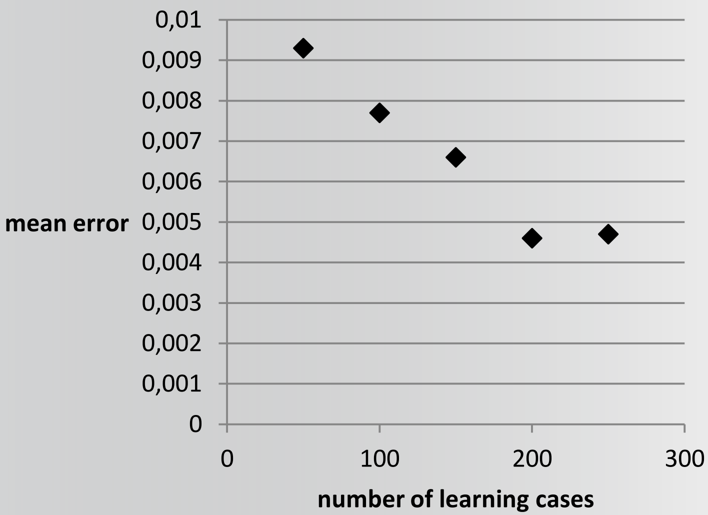
Validation using scalar output parameters accuracy

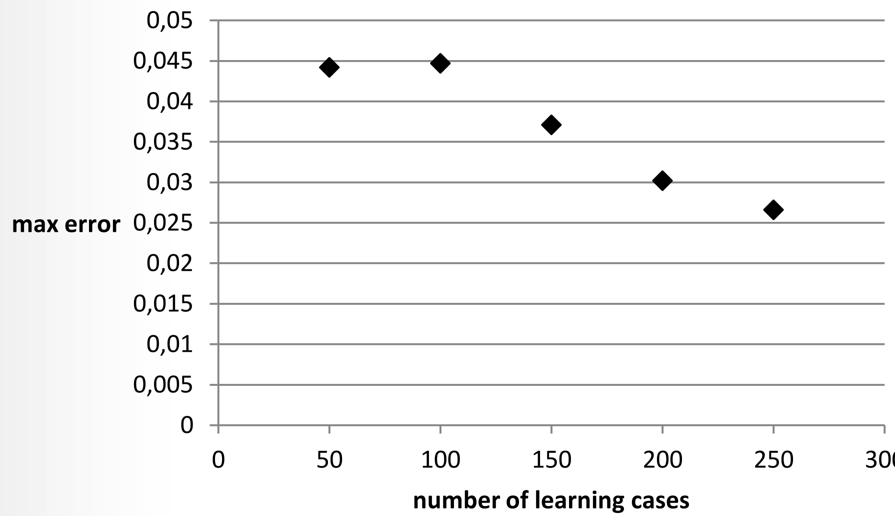
Response Surface Validation

Results on Residual Stenosis

Variation from 0.13 to 0.83
Mean Value = 0.42





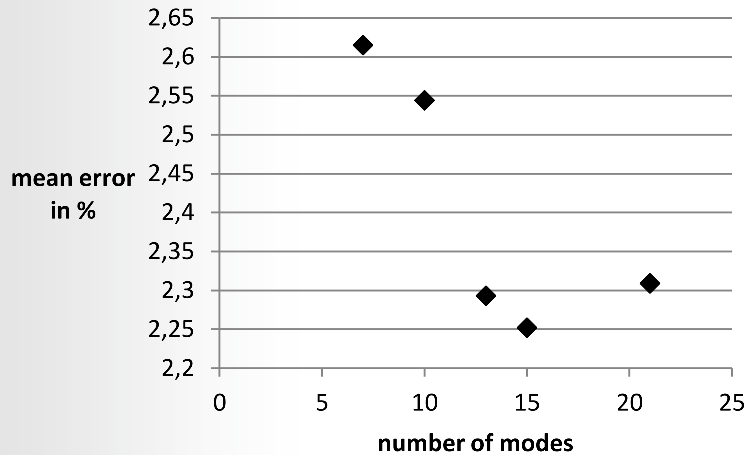


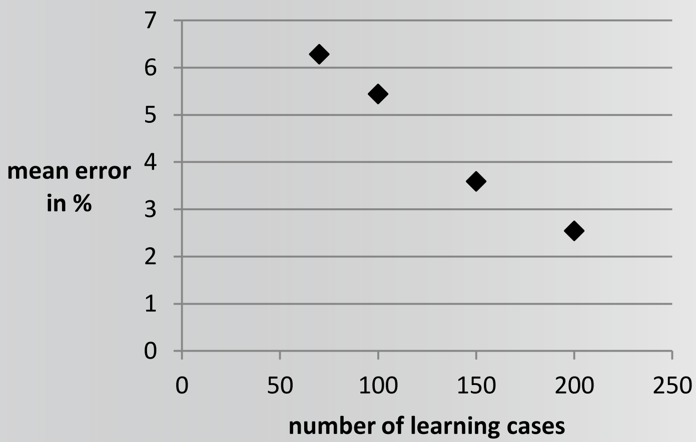
Validation using the full set of points (around 450)

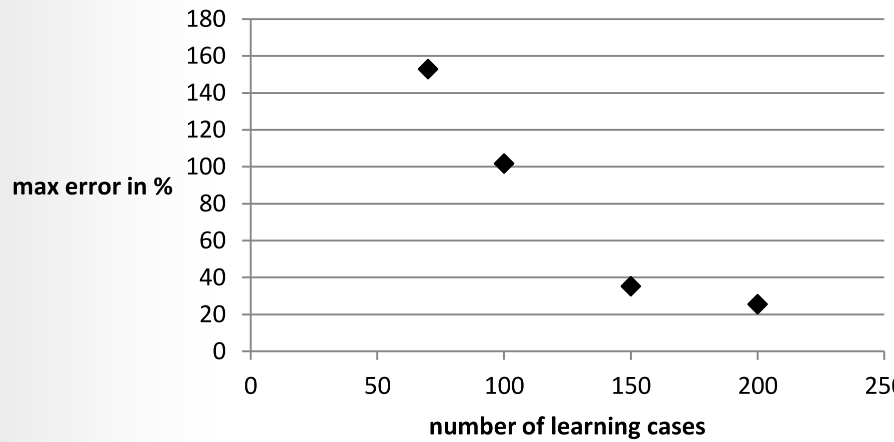
Response Surface Validation

Results on Maximum
Von Mises Stress

Variation from 0.16 to 2.29
Mean Value = 0.94
From -83% To +144%

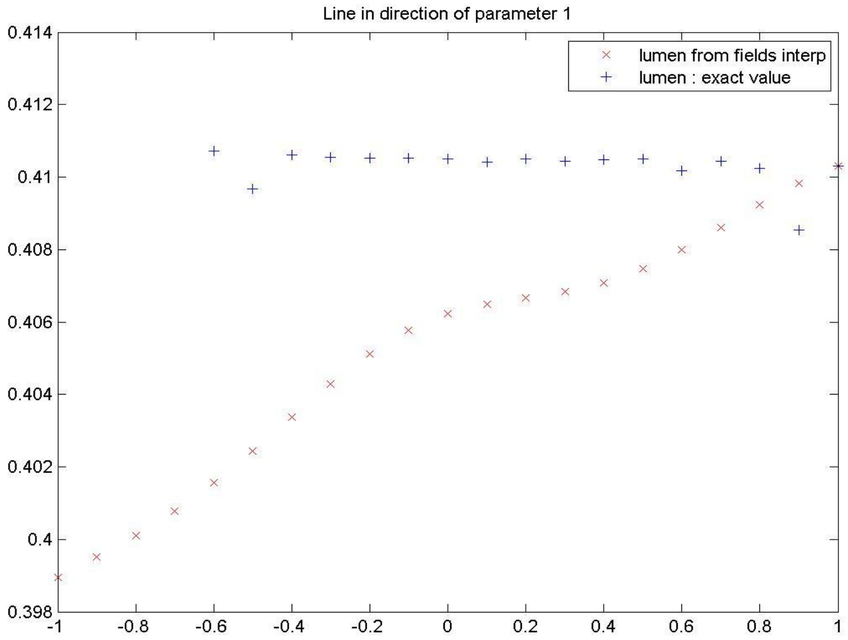


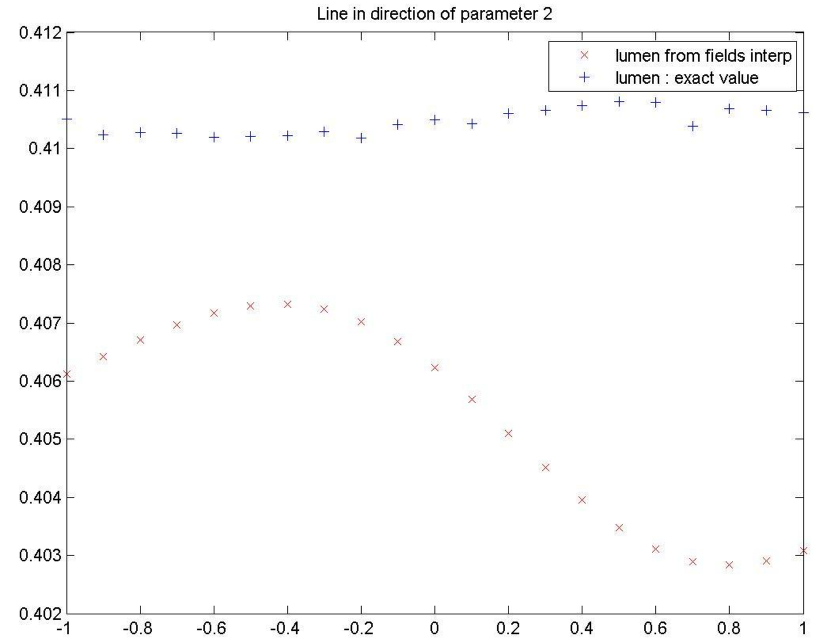




Validation using the full set of points (around 450)

Response Surface Validation

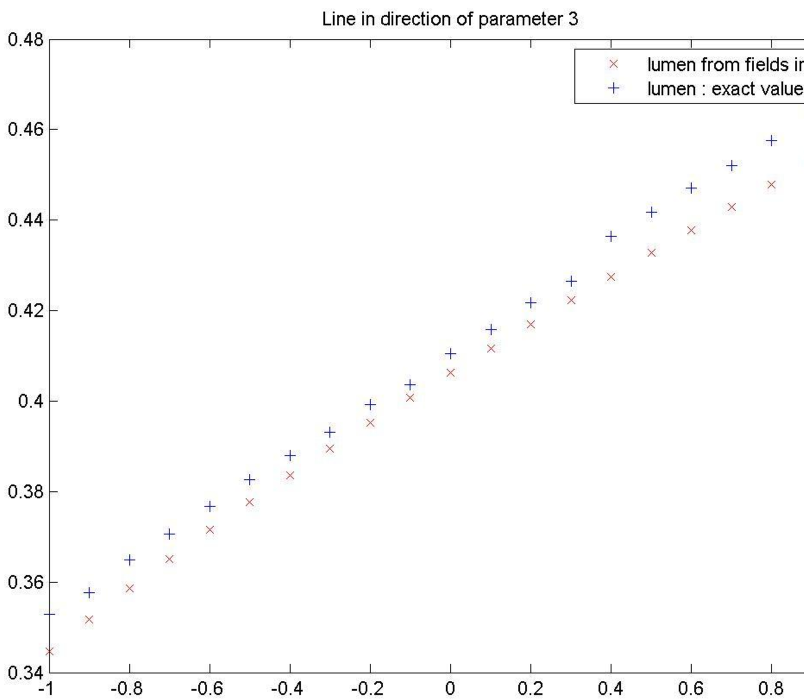


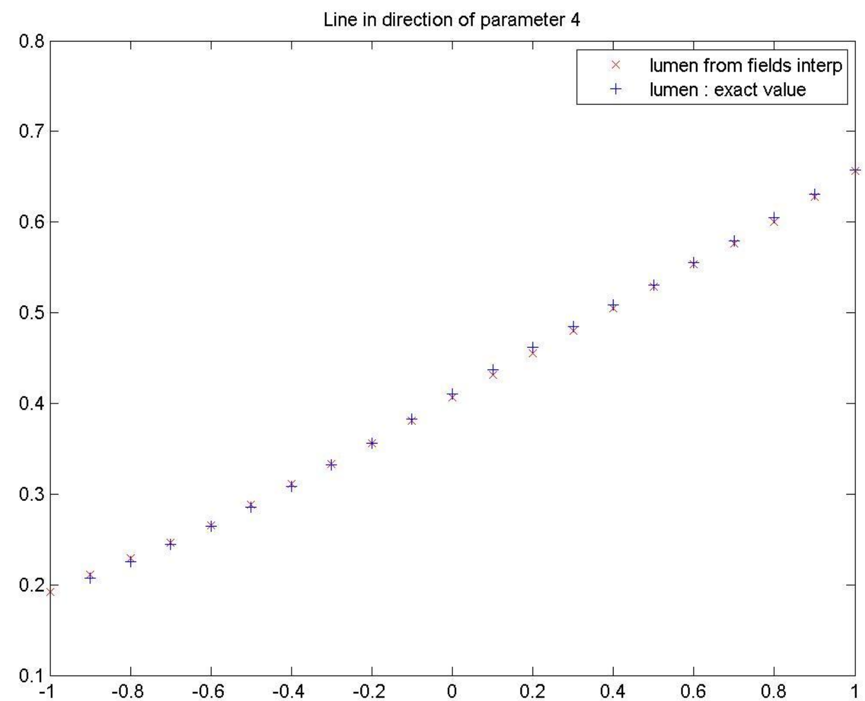


Residual Stenosis wrt Inner Diameter

Residual Stenosis wrt Plaque Length

Response Surface Validation

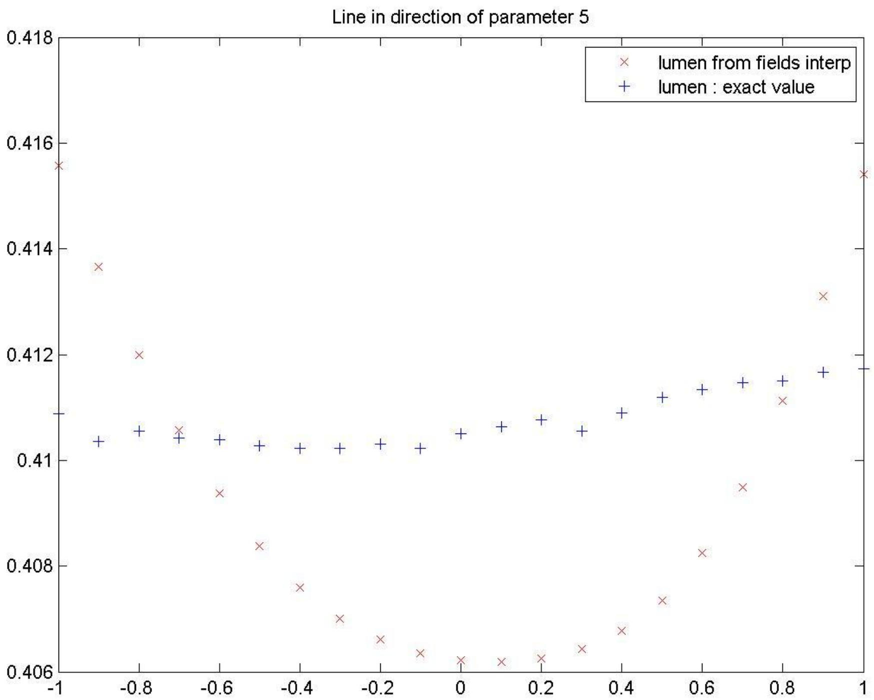


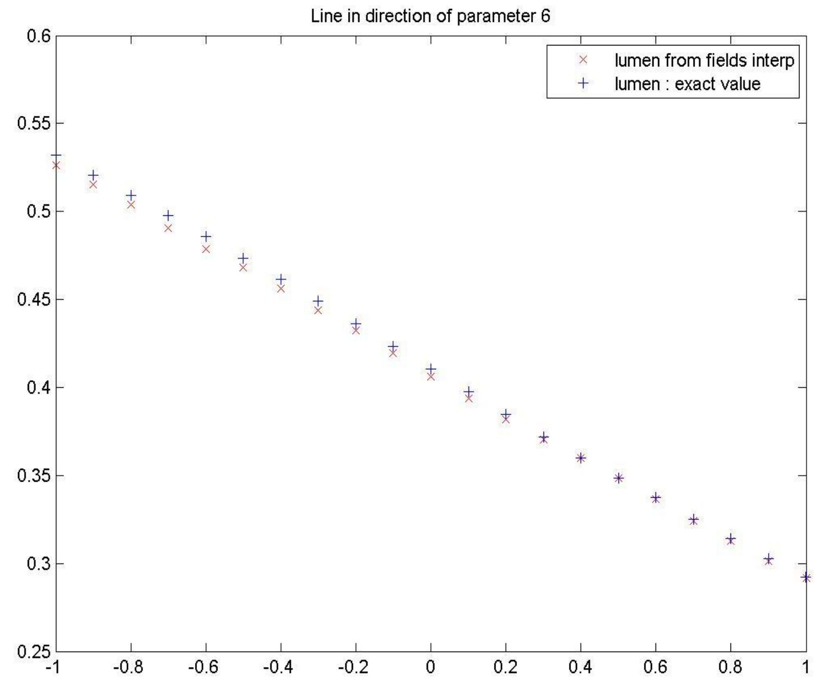


Residual Stenosis wrt Residual Lumen

Residual Stenosis wrt Plaque Assymmetry Coefficient

Response Surface Validation

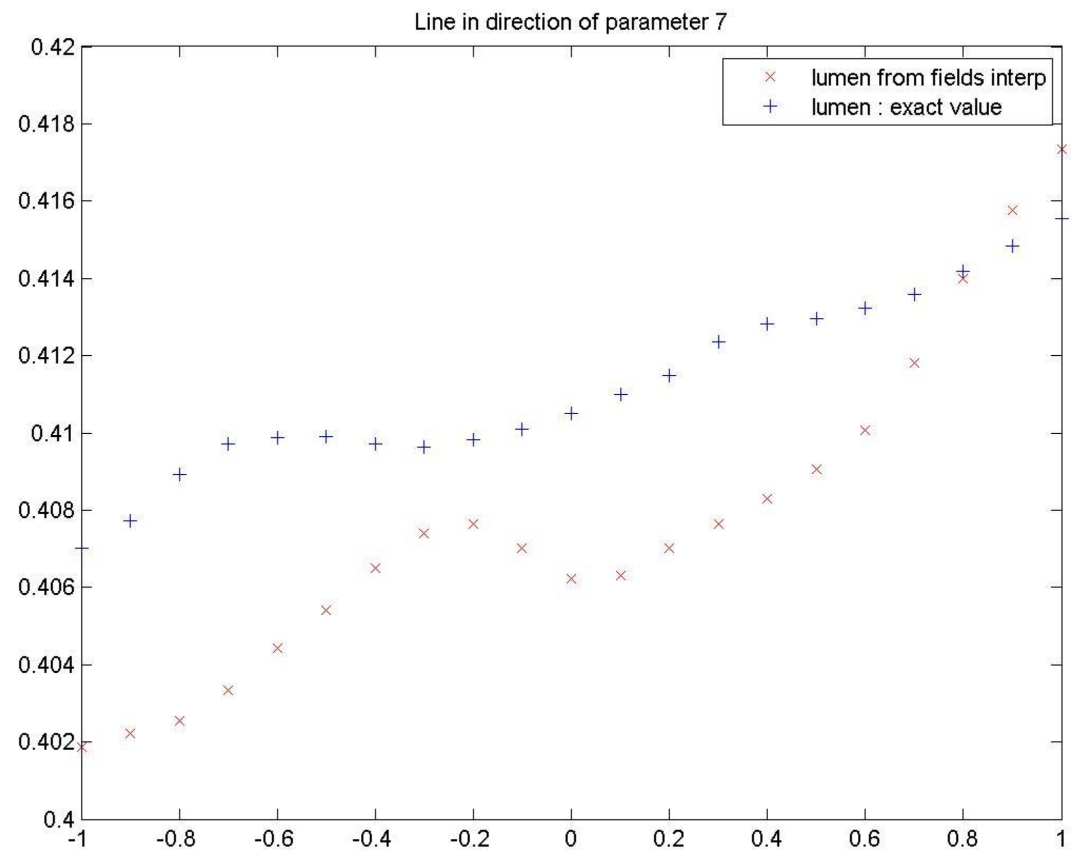




Residual Stenosis wrt Sharpness

Residual Stenosis wrt Percentage Inner Diameter

Response Surface Validation



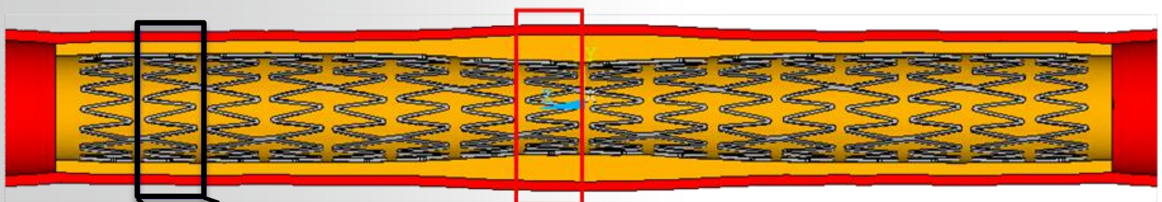
Residual Stenosis wrt Percentage
Initial Stretching

Simplified Model for stenting and fatigue risk

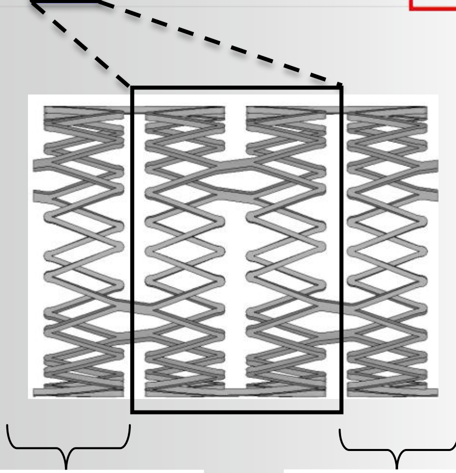
Building a simplified model: why and how?

- **High computational costs of the "full 3D fatigue simulations": from 5 to 10 days using 8 cores for a single fatigue analysis**
- **Focus on a small portion (e.g. a single or few rings) of a specific stent design and evaluate its risk of fatigue fracture as a function of a few important factors related to the main local features of the stenotic vessel where the stent is implanted**

Whole 3D model



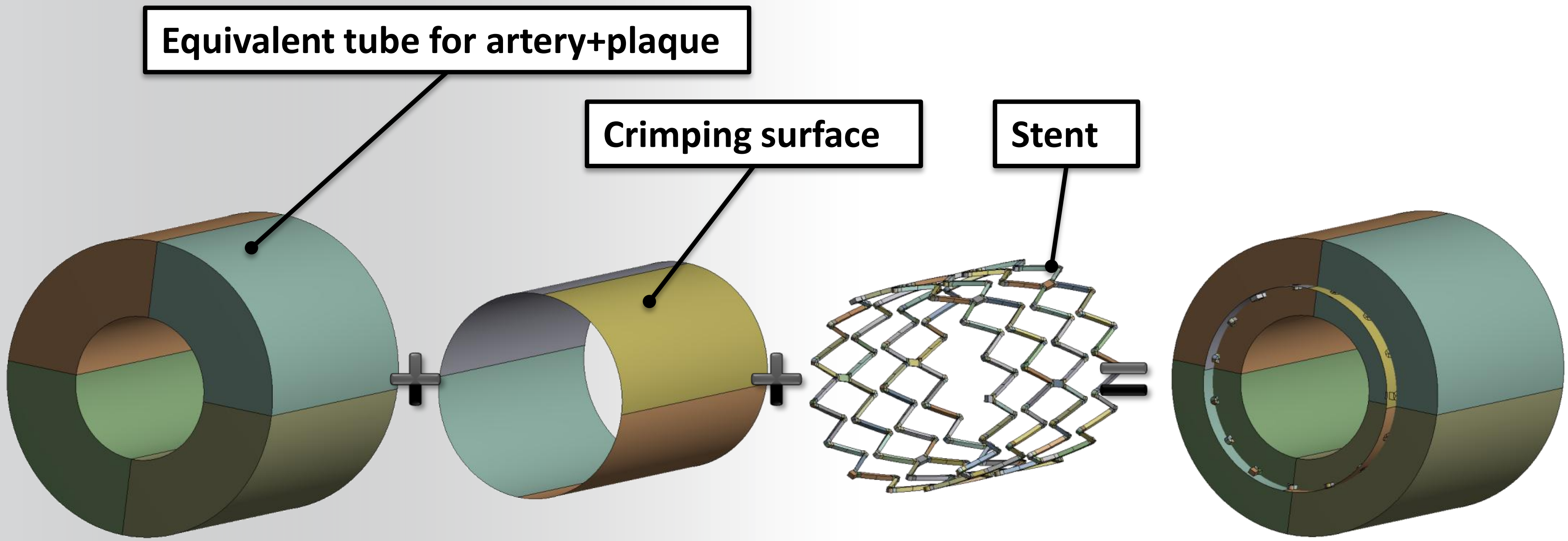
Stent simplified model



- It consists of the investigated ring with a few additional rings at its sides
- The lateral rings are necessary to avoid that end effects modify the behavior of the ring under study
- Only the central portion is taken into account for fatigue analysis because representative of the real behavior

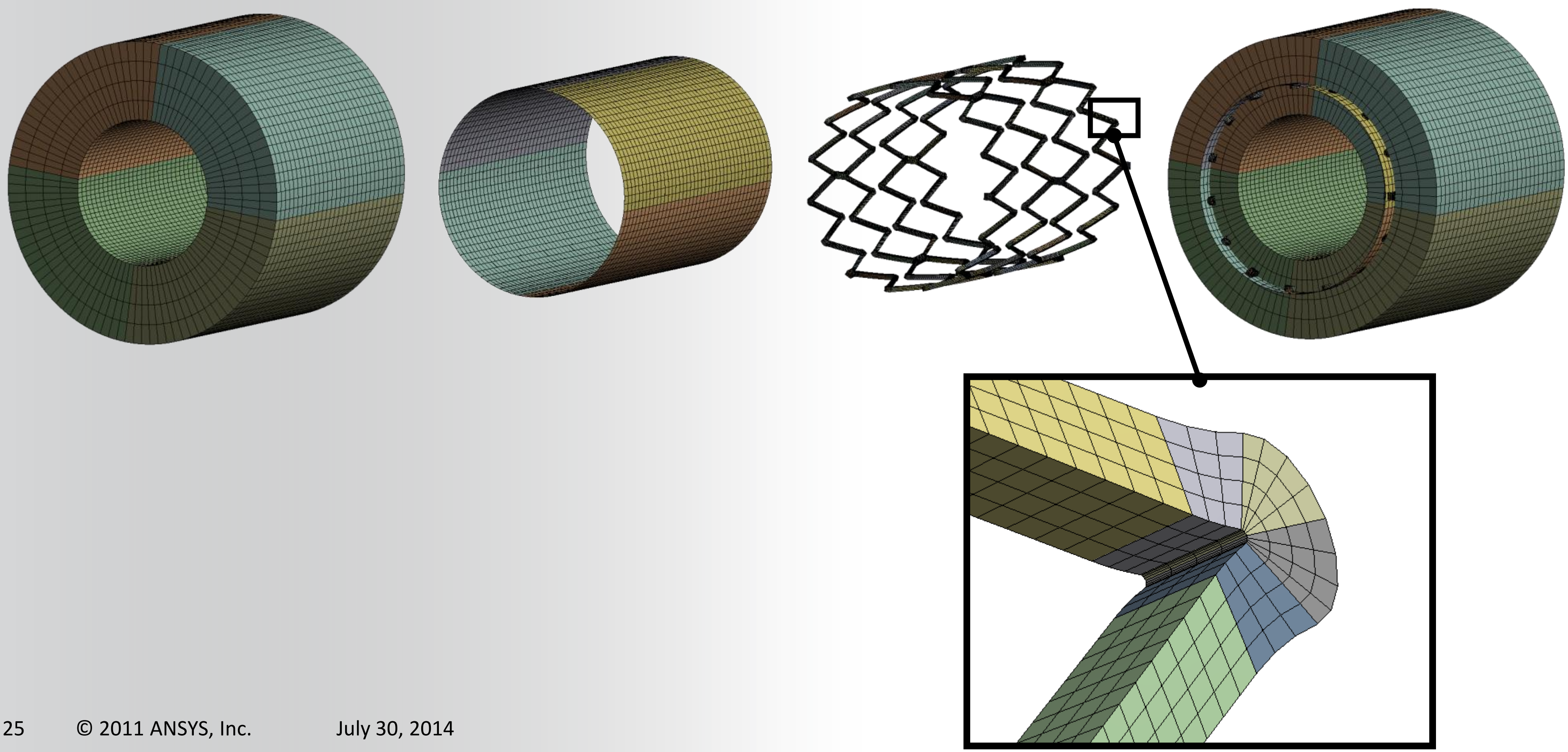
Axial Fatigue model

- 3 parts



Axial Fatigue model

- Artery+plaque mesh : 58 000 nodes, 12 000 elements
- Crimping surface : 3 500 nodes, 3 400 elements
- Stent mesh : 125 200 nodes, 80 850 elements



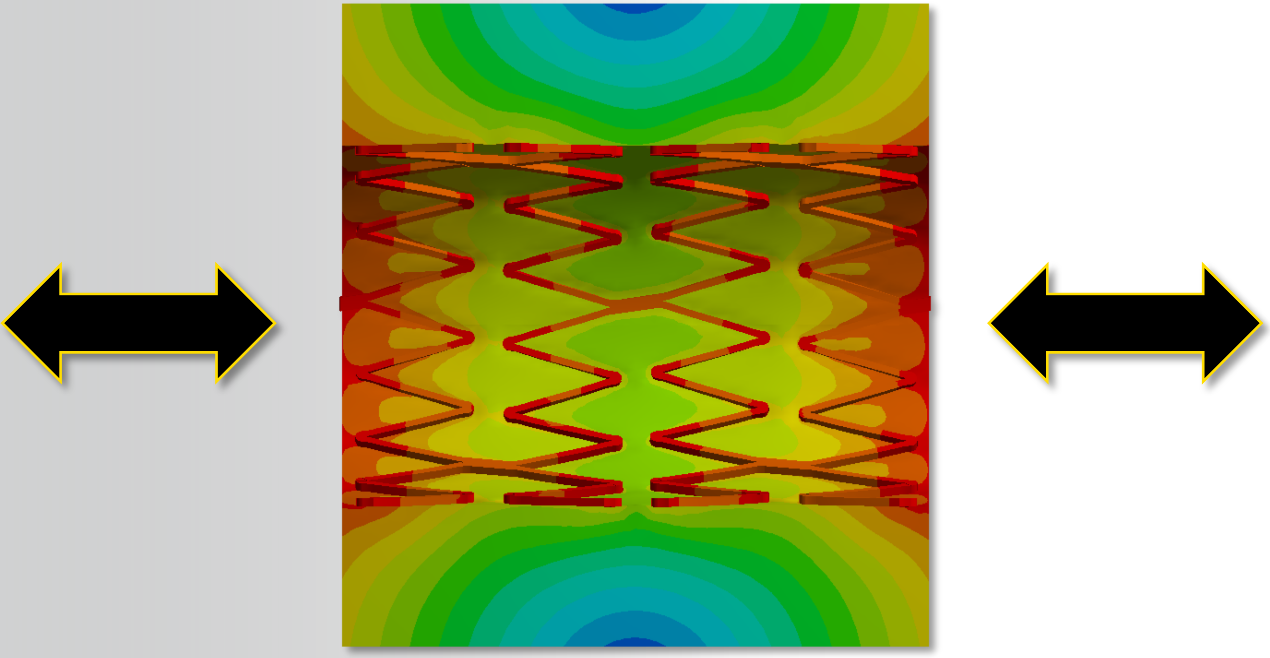
Axial Fatigue simulation

→8 steps for the full simulation :

→Step 1 : The vessel (representing artery+plaque) is axially stretched ; at the same time, the stent is crimped and introduced into the vessel

→Step 2 : The stent is deployed in the vessel

→Steps 3/4, 5/6, 7/8 : 3 fatigue cycles are applied on the vessel by successive tensile and compressive displacements



Axial Fatigue response surface

- **4 parameters can vary:**
  - Inner Diameter of the tube : [4.2 mm ; 7 mm]
  - Young Modulus of the tube : [0.15 MPa ; 1.5 MPa]
  - Initial stretching of the tube (Is) : [3% ; 20%]
  - Cyclic axial stretching : [20% x Is ; 100% x Is]

- **A 4-parameters Design Of Experiment of 200 points is launched on CINECA cluster**
- **4 additionnal 1-parameter DOE are launched for verifications (4*16 points)**
- **For each run, the following results are stored for the 2 central rings of the stent:**
  - Displacements for each step on each node
  - First Principal Strains for the last fatigue cycle (steps 7 and 8) on each element: Str_{LS7} and Str_{LS8}

Axial Fatigue response surface

- **Using CINECA PLX Cluster: Intel Xeon E5645 @2.4Ghz**
- **Metrics on the 200 points DOE :**
  - Number of calculation completed : 158
    (42 runs aborted due to I/O errors on the cluster)
  - 8 CPU per run used
  - Average computation time (for 1 run) : 19 hours
  - Minimum computation time : 7 hours
  - Maximum computation time : 70 hours
- **Metrics on the 4*16 (64) points DOEs :**
  - Number of calculation completed : 60
    (3 runs aborted due to I/O errors on the cluster, 1 diverged)
  - 8 CPU per run used
  - Average computation time (for 1 run) : 16 hours
  - Minimum computation time : 7 hours
  - Maximum computation time : 42 hours

Reduced Order Model Building

- **158 point in the DOE:**
  - 107 used as learning points
  - 51 used as verification points

- **ROM of the result X = (DefLS7 + DefLS8) /2**
  - Built with 107 learning points
  - 7 modes

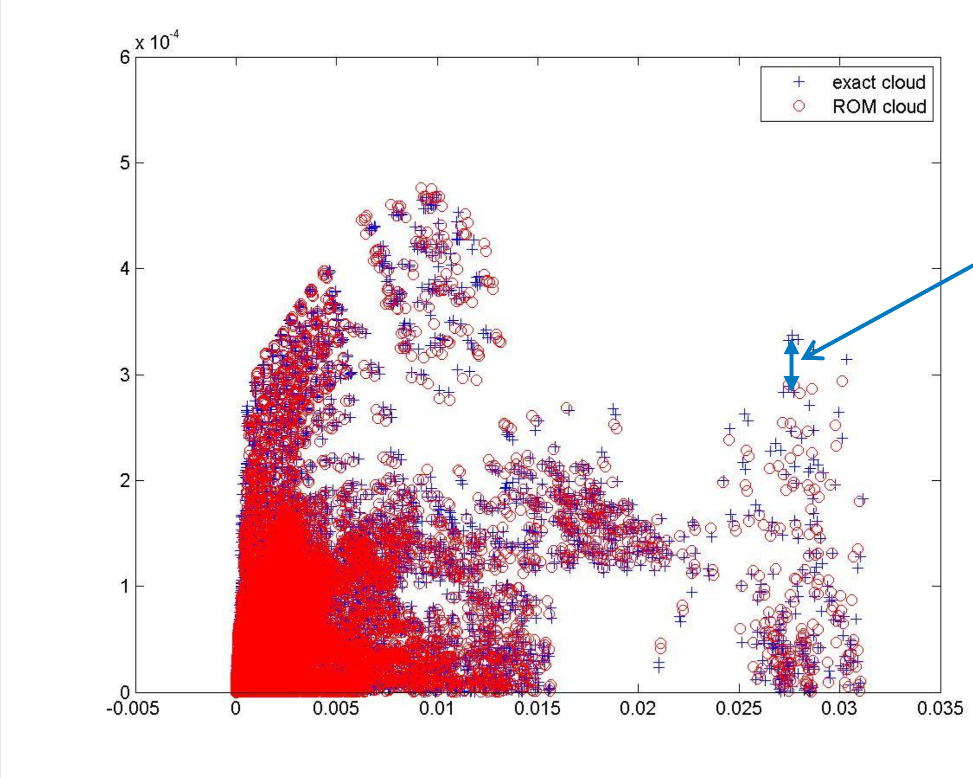
- **ROM of the result Y = (DefLS7 - DefLS8) /2**
  - Built with 107 learning points
  - 16 modes

- **Exploitation of the 2 ROM to build the fatigue cloud for each point in the parameter space**

Validation of the ROM : Step 1 (1)
Building the fatigue cloud for the 158 points of the initial DOE

→ **Error criteria : for a point of the DOE the error criteria is the max difference in Y value between the exact points and the points obtained by using ROM**

Y = abs(DefLS7 - DefLS8) /2

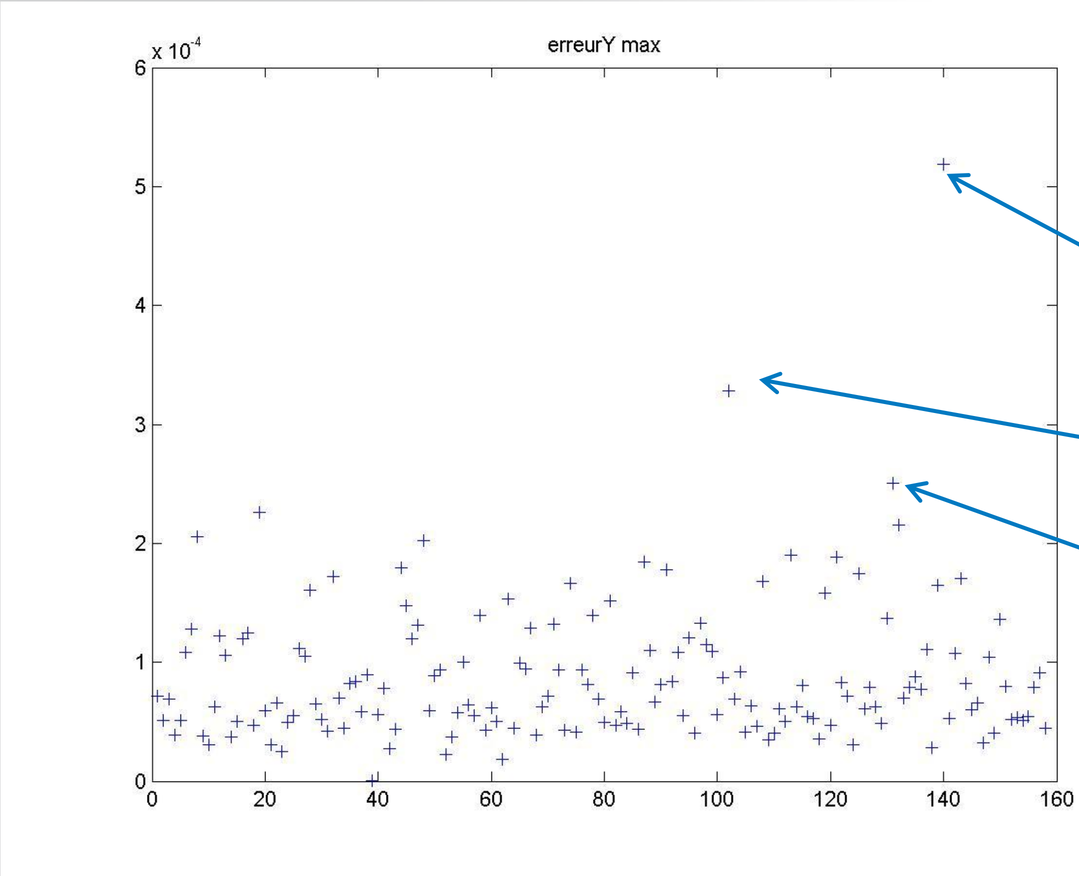


Error criteria = max (delta Y)

X = (DefLS7 + DefLS8) /2

Validation of the ROM : Step 1 (2)

→ **Error criteria for the 158 points of the initial DOE**



→ **For all the points of the DOE and all the points of the cloud: Error < 5.2 10-4**

→ **Worst points:**

→ Point 140

Err = 5.2 10-4

→ Point 102

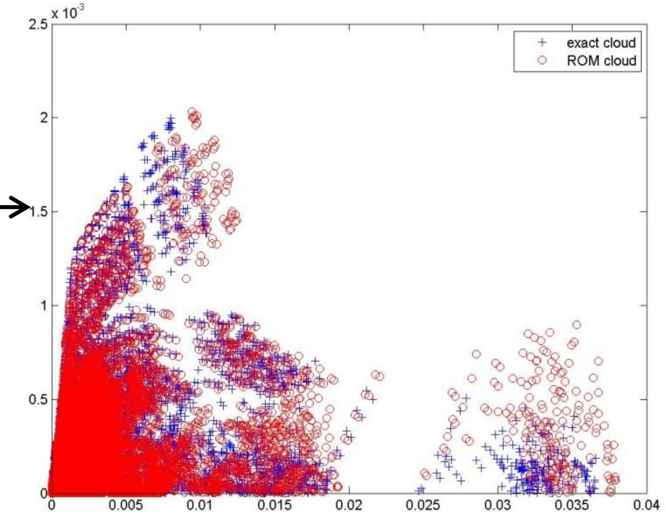
Err = 3.3 10-4

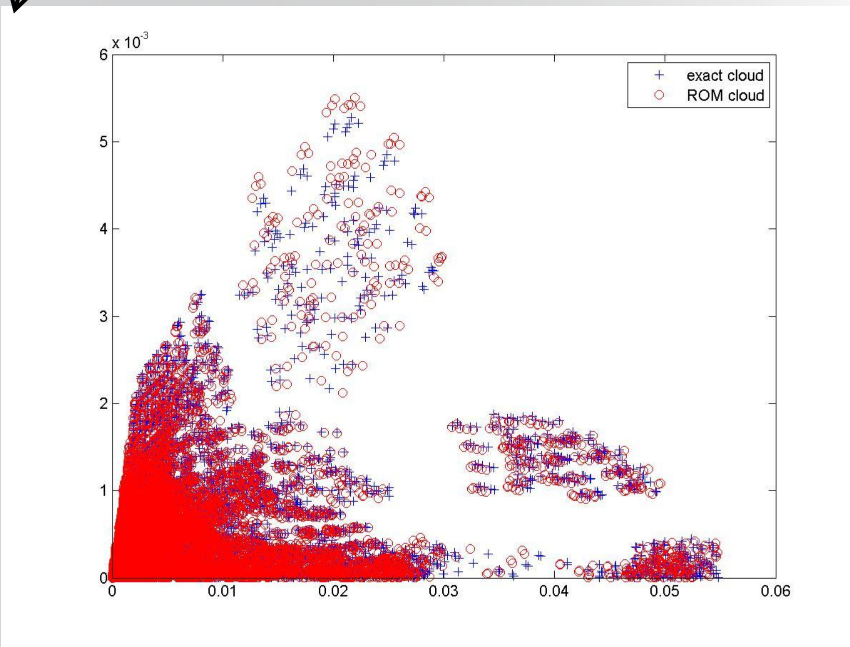
→ Point 131

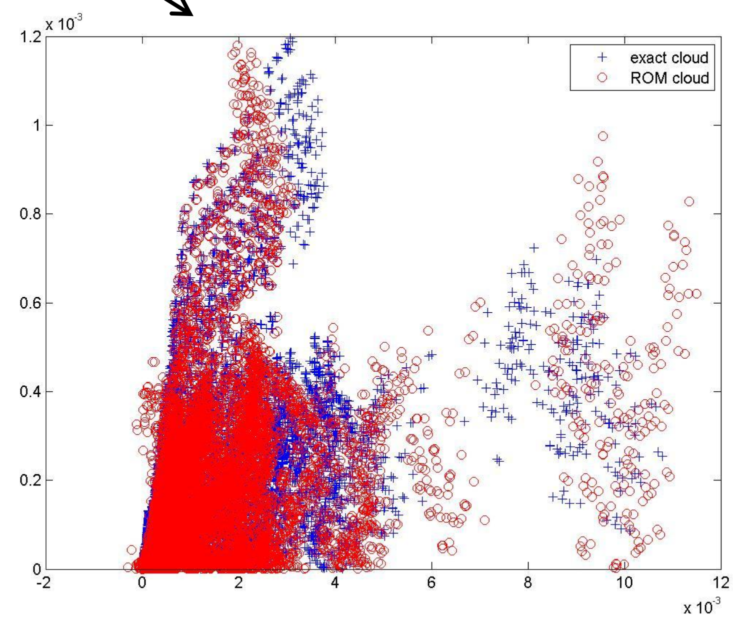
Err = 2.5 10-4

Validation of the ROM : Step 1   (3)

- **The 3 worst points of the DOE**
  - Point 140, Err = 5.2 10-4
  - Point 102, Err = 3.3 10-4
  - Point 131, Err = 2.5 10-4



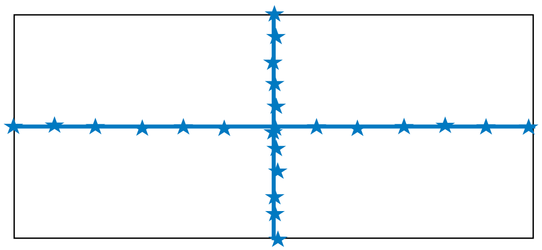




Validation of the ROM : Step 2

- **Exploitation of the 2 ROM to build the fatigue cloud for several points of lines in the parameter space**

- **from the central point of the parameter space:**
  - Inner Diameter = 5.6 mm
  - Young Modulus =0.825 Mpa
  - Initial Stretching =11.5%
  - Cyclic Axial Stretching = 60%



- **Line 1: We vary the first parameter (Inner Diameter) from the min value to the max value: exact run for 15 points on this line**

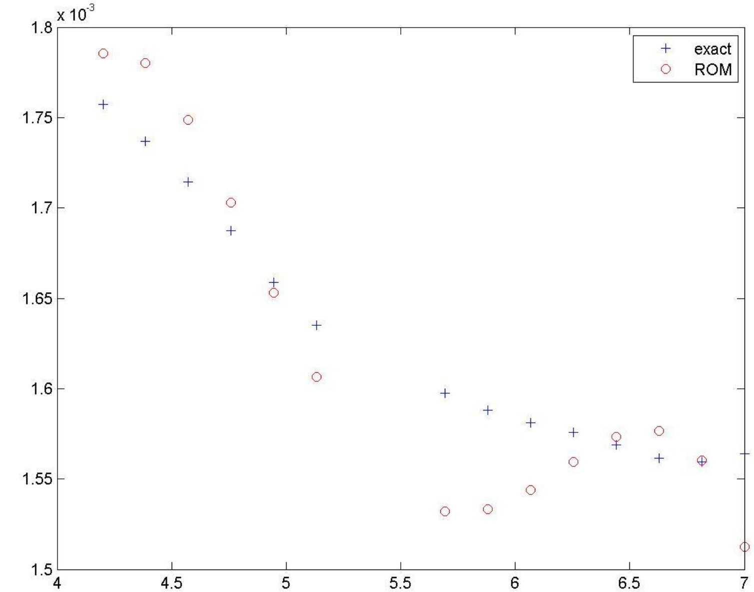
- **Line 2 : variation of the 2nd parameter (Young Modulus)**

- **Line 3 : variation of the 3rd parameter (Initial Stretching)**

- **Line 4 : variation of the 4th parameter (Cyclic Axial Stretching)**

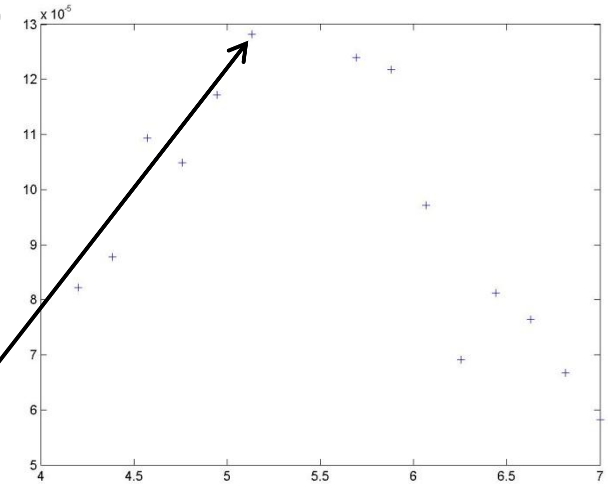
Validation of the ROM : Step 2 Line 1

Ymax

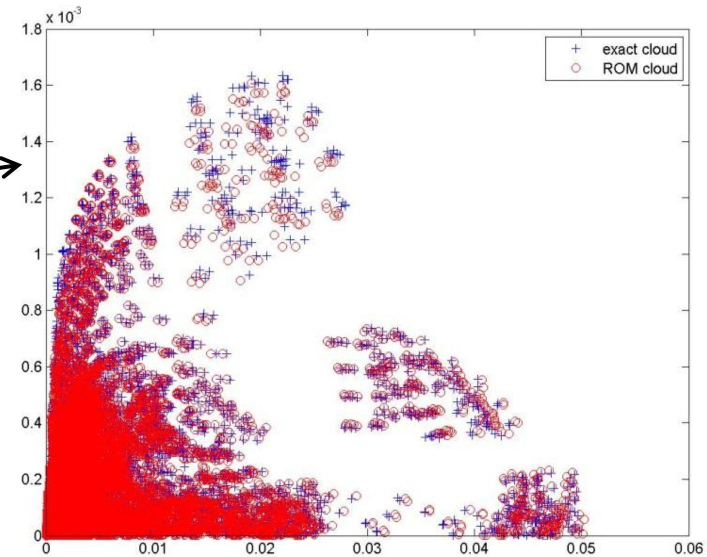


Parameter : Inner Diameter

Max(errY)

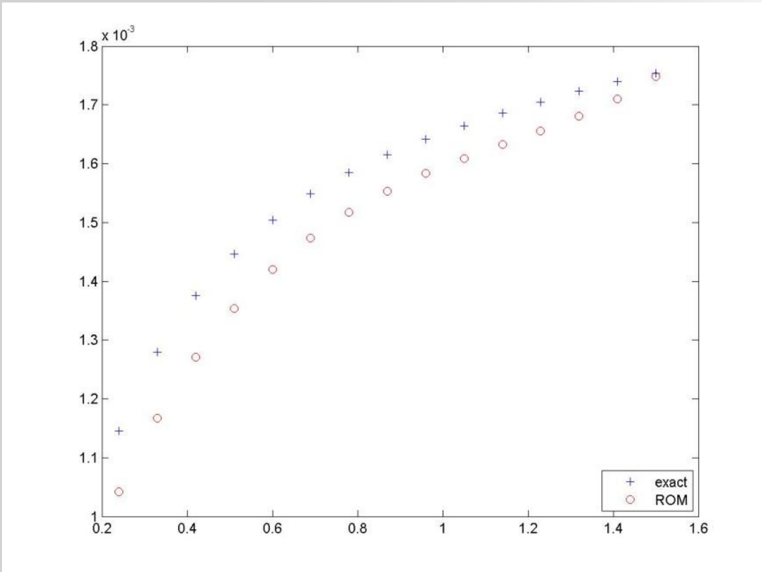


Worst point
err = 1.28 10^{-4}
and its cloud



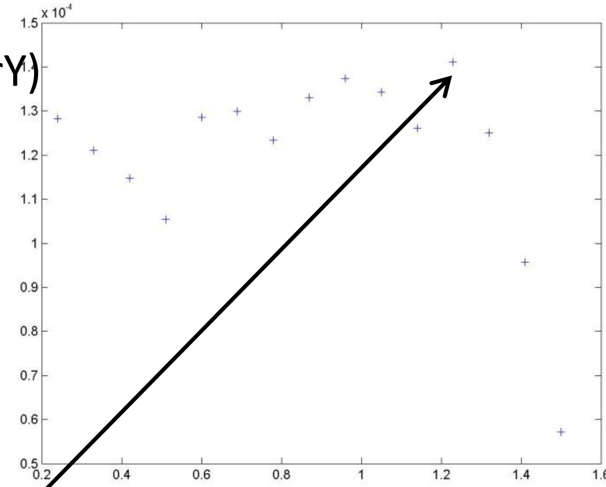
Validation of the ROM : Step 2 Line 2

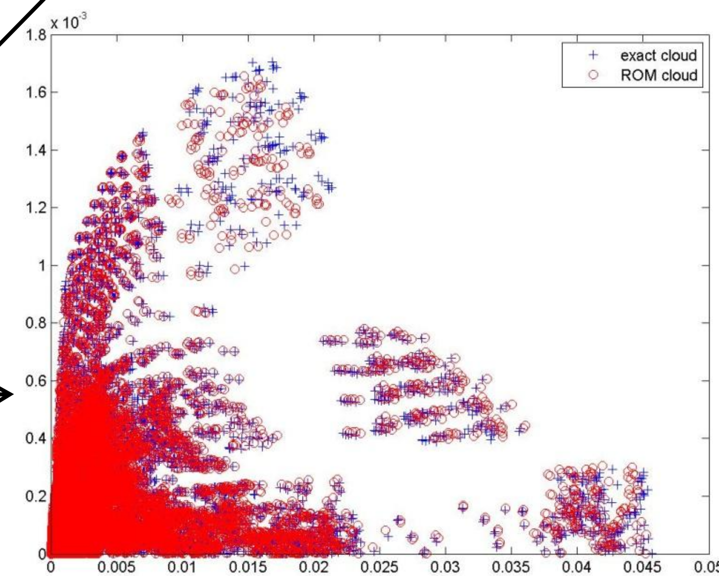
Ymax



Parameter : Young Modulus

Max(errY)

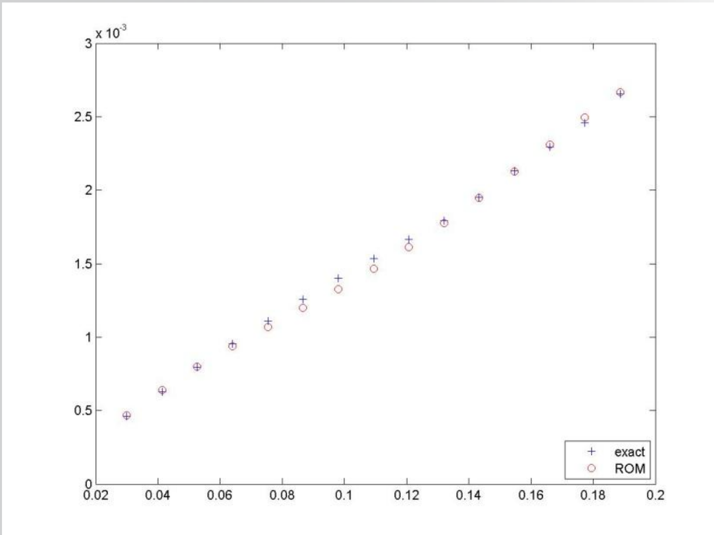




Worst point
Err = 1.4 10^{-4}
and its cloud

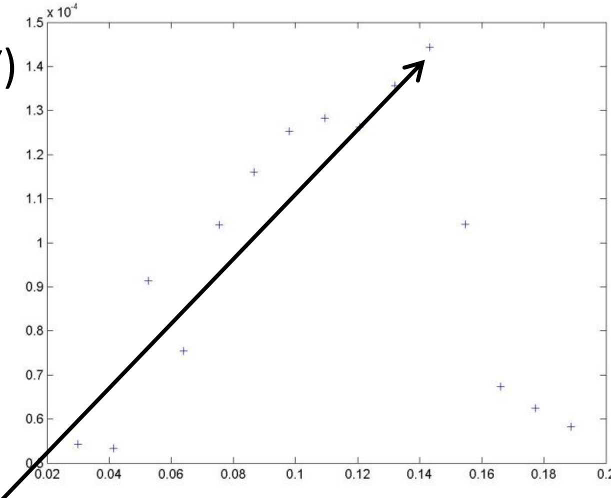
Validation of the ROM : Step 2 Line 3

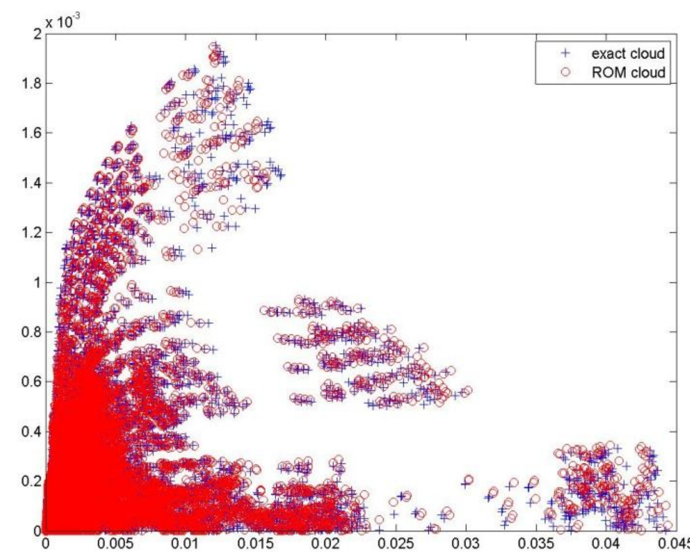
Ymax



Parameter : Initial Stretching

Max(errY)

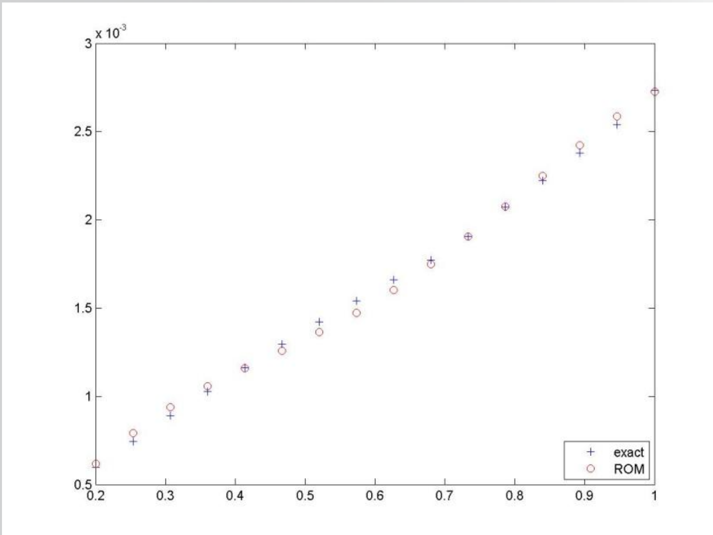




Worst point
Err = 1.4 10^{-4}
and its cloud

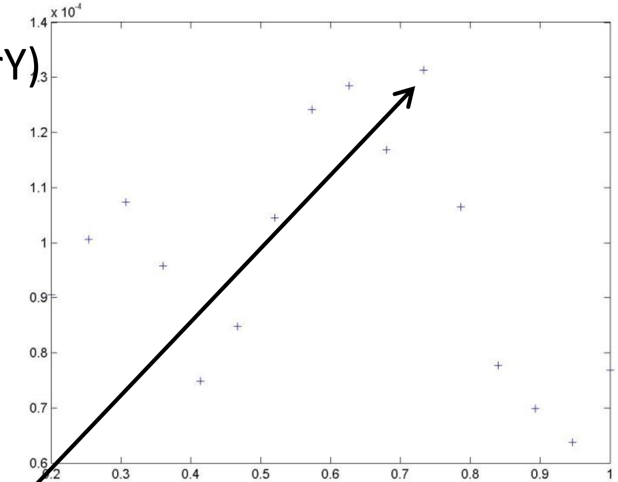
Validation of the ROM : Step 2 Line 4

Ymax

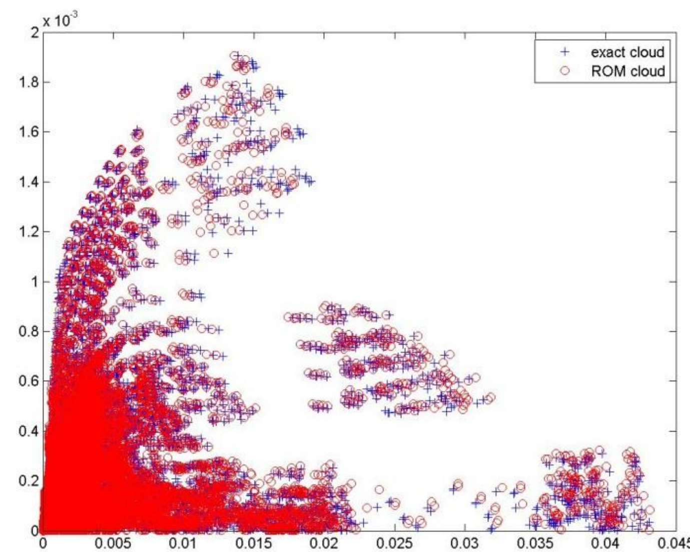


Parameter : Cyclic Axial Stretching

Max(errY)



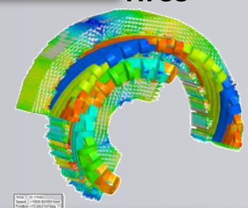
Worst point
Err = 1.3 10^{-4}
and its cloud

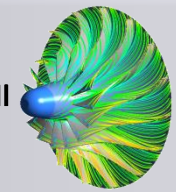


ROM are an Essential Component for Efficient Full System Modeling

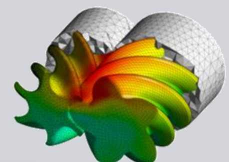
Detailed 3D Multiphysics

ANSYS Maxwell HFSS





ANSYS CFD



ANSYS Mechanical

Full 3D models are very accurate and reliable but too slow to be part of a instantaneously reacting system.

ROM

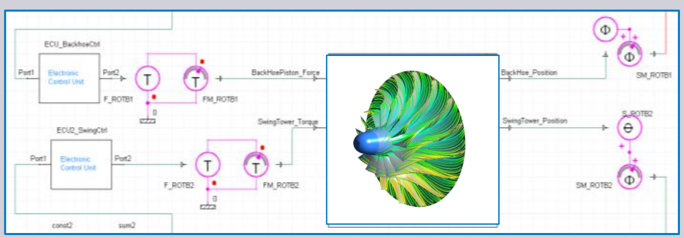
Software Engineering

SCADE SUITE

SCADE DISPLAY

Software engineering will be increasingly coupled with hardware modeling. It needs quick and reliable prediction of the system reaction to software.

System Simulation



ANSYS Simplorer

System modeling are essential for full system modeling and efficient Robust Design Optimization but cannot rely on oversimplified models.

