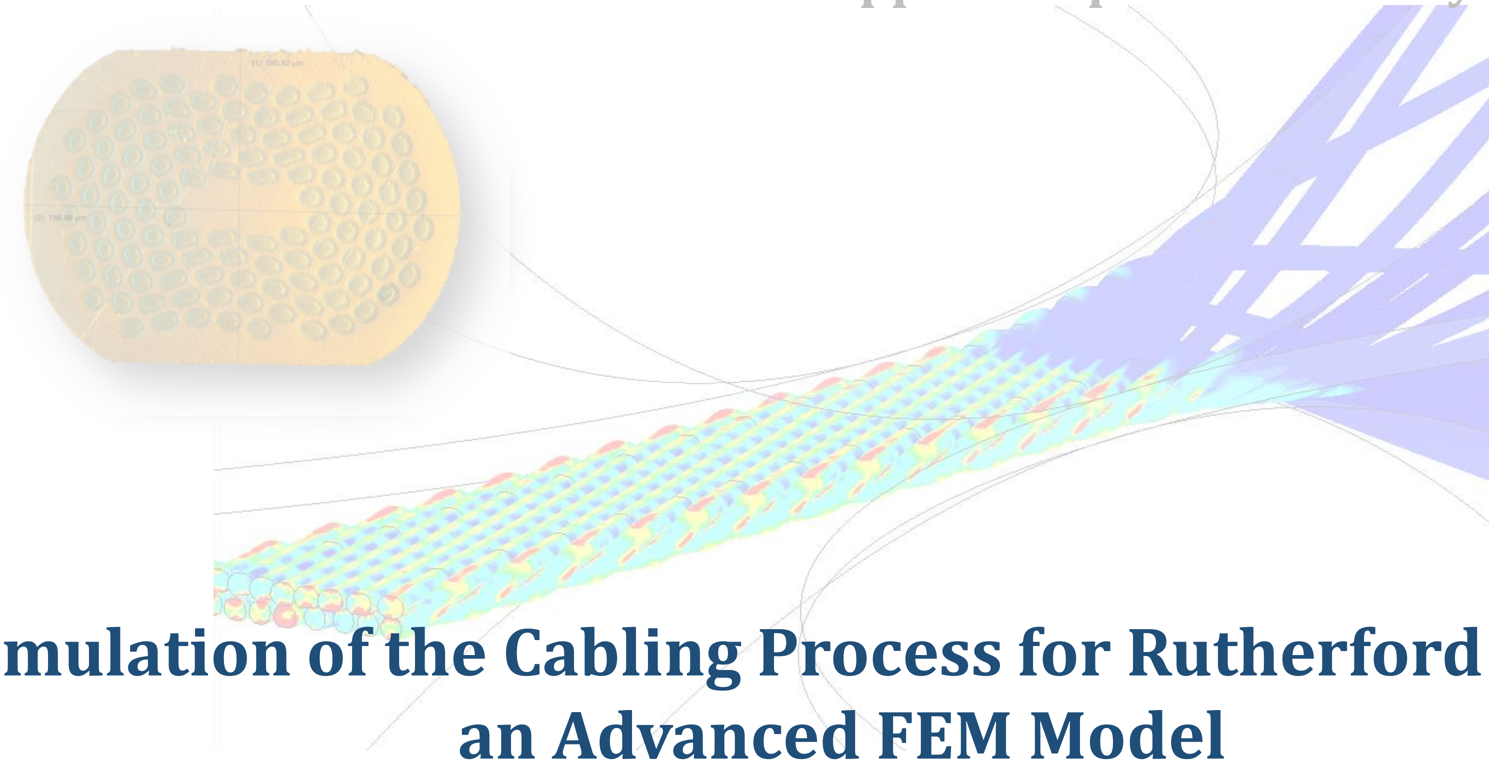

Simulation of the Cabling Process for Rutherford Cables: an Advanced FEM Model

J. Cabanes, M. Garlaschè, B. Bordini, A. Dallocchio

Acknowledgements!

A. Ballarino (TE/MSC/SCD)
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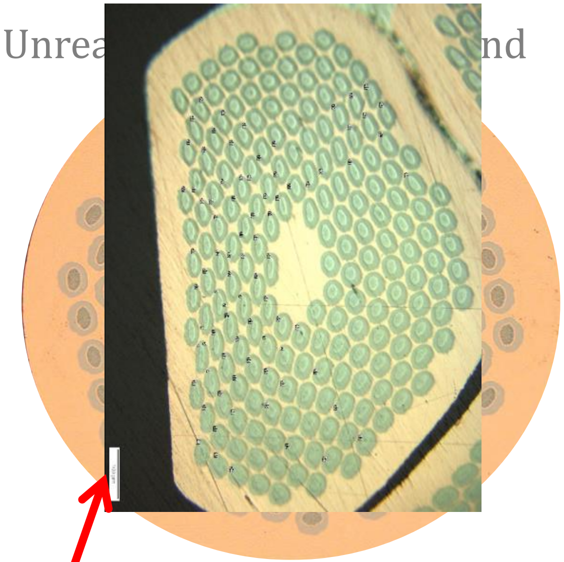
Aim of the Study - 1/2

Nb-Ti is **not suitable** for magnets with peak fields larger than **10 T**

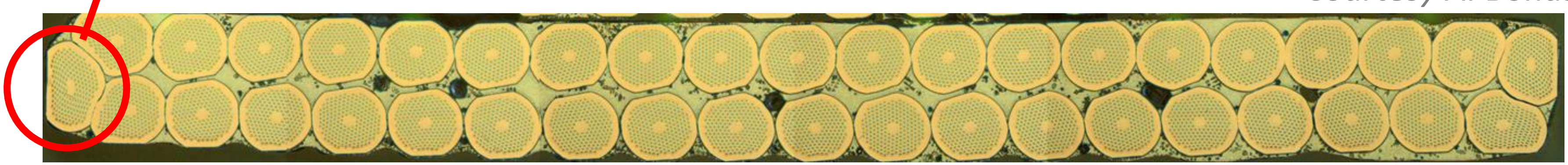
CERN main future magnets (HiLumi-LHC & FCC) will be made of **Nb_3Sn strands**



Main differences between Nb_3Sn and Nb-Ti:

1. Nb_3Sn is extremely **brittle** → the cabling process occurs before the Nb_3Sn phase is formed
2. The **filaments** (or better the sub-elements) of Nb_3Sn wires are significantly **larger** than the filaments of the LHC Nb-Ti wires

Courtesy A. Bonasia

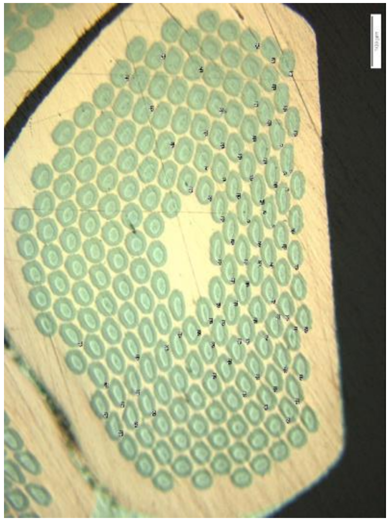


During **cabling**, the sub-elements undergo **large plastic deformations** that significantly modify their shape

Aim of the Study - 2/2

Applied Superconductivity

Courtesy A. Bonasia



Large plastic deformations of the sub-elements affect the **electric performance** of the strands**:**

During the reaction heat treatment, part of the tin source can diffuse into the copper stabilizer matrix thus reducing

- the Nb_3Sn formation or quality → lower critical current
- The electrical and thermal conductivity of the Copper

At pr

The current study aims at creating a **reliable** & **powerful** simulation tool in order to

a) Get **insight** of the main **parameters** of the cabling process

b) Provide **support** for the cable process **optimization**

Content

- Overview of Cabling Process
- Analytical Model
- Approach to Numerical Model
- Numerical Model
- Conclusions

The Cabling Process

Cabling Machine @ CERN Superconducting LAB

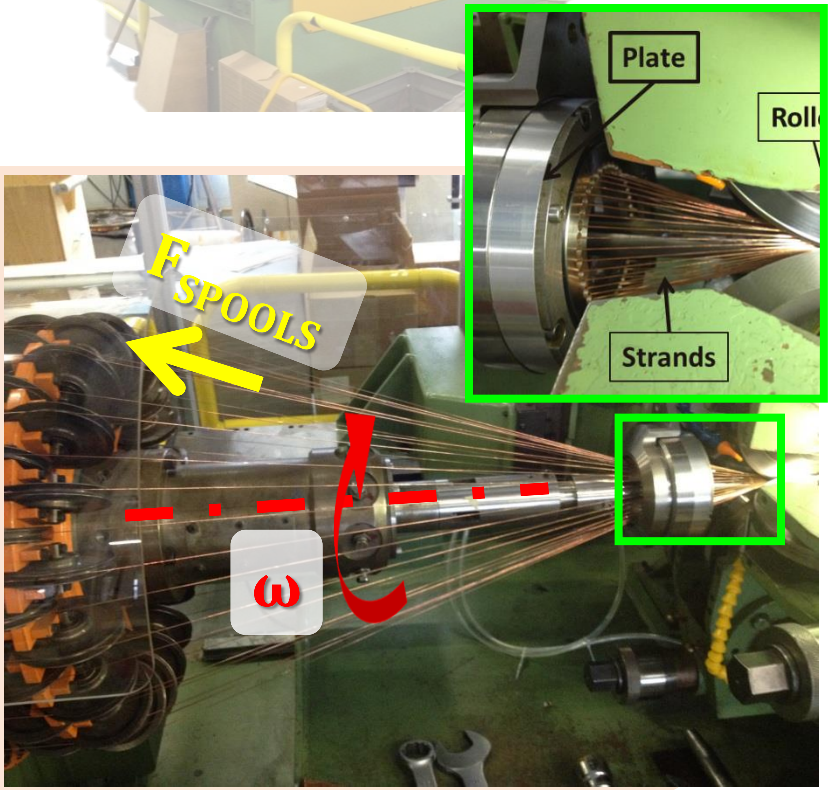
3 Main Subsystems for Modelling

Cabling Process: Subsystems

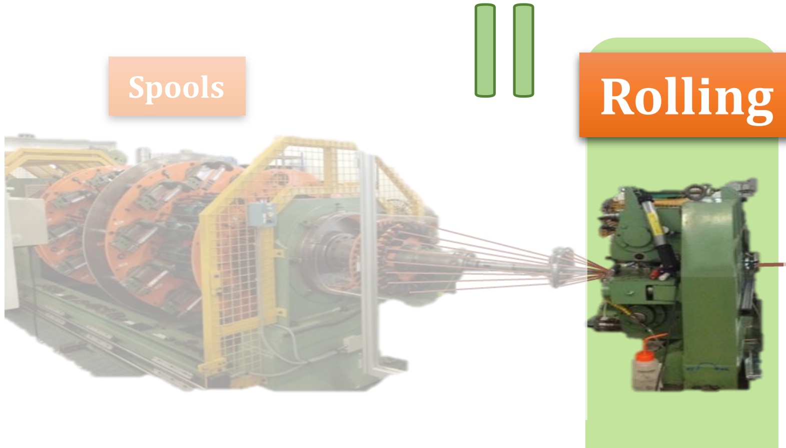
Accomodates strands **supply**

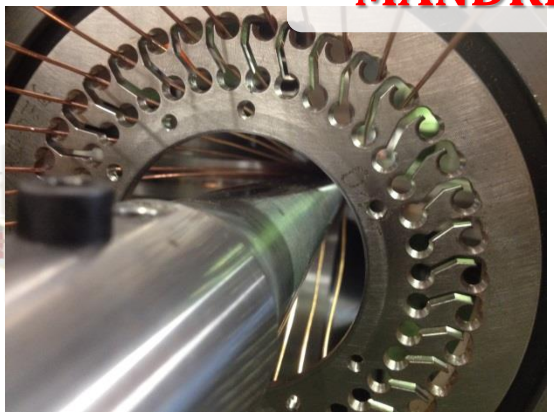
Process parameters:

- Strand backward-pulling Force
- Angular Velocity of strands
- Attack Angle of strands onto rollers



Cabling Process: Subsystems

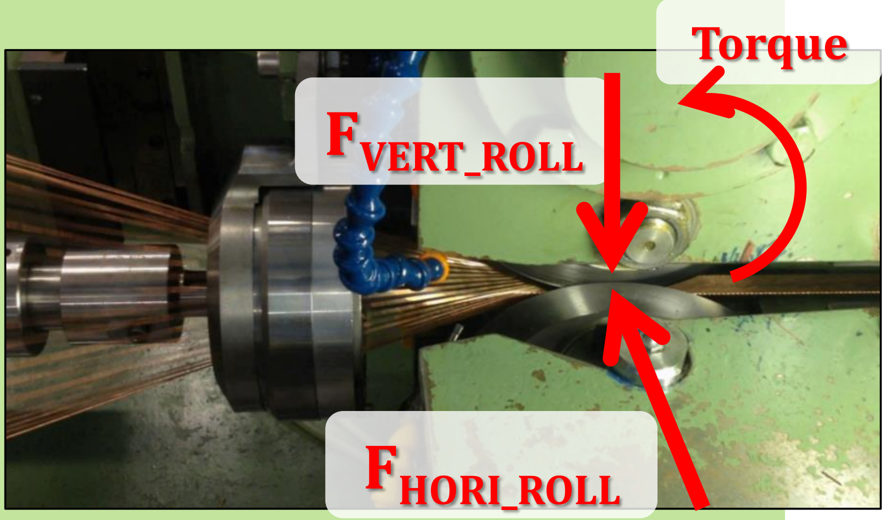




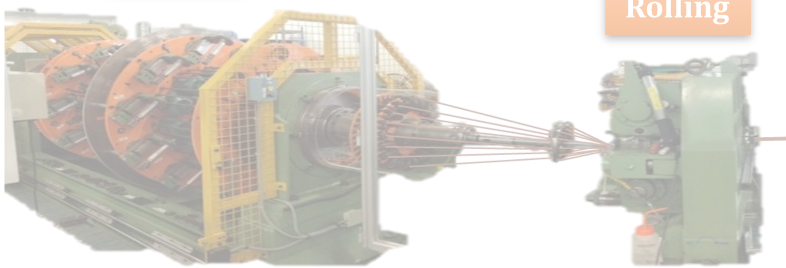
Deforms strands into **cable final shape**

Process parameters:

- **Rollers Forces**
- **Geometry** features (Rollers, Mandrel)



Cabling Process: Subsystems



Caterpillar

Provides

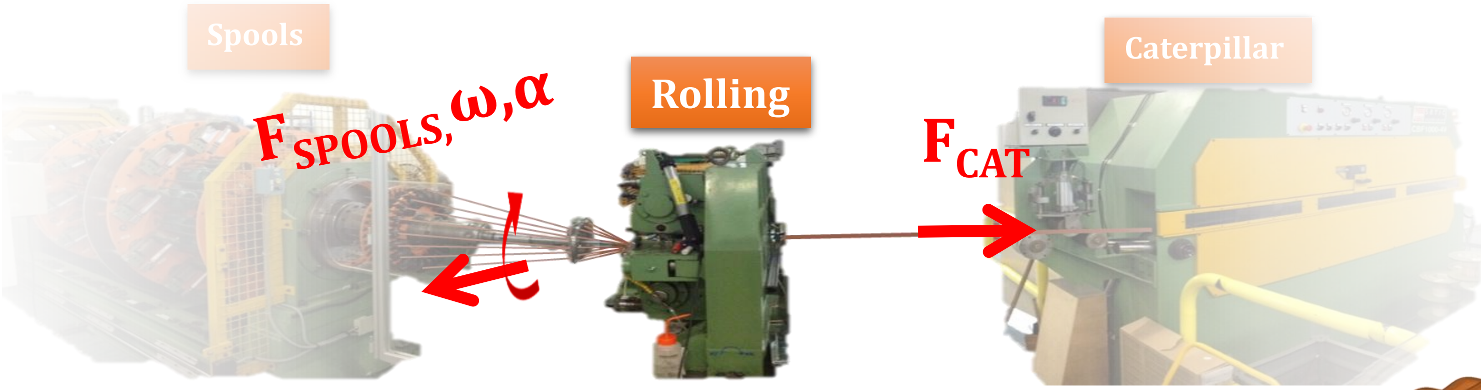
Forward-pulling Force

Measurement of F_{CAT}

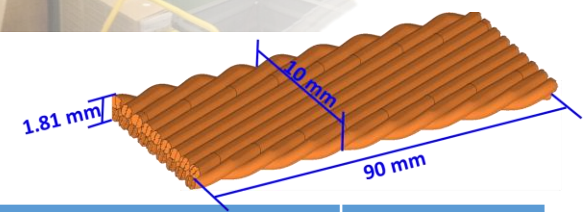
Meas. of cable height & pitch

Process Interpretation and Assumptions

Process synthesized to core Load and Geometry Parameters



Arbitrary assumption on cable type

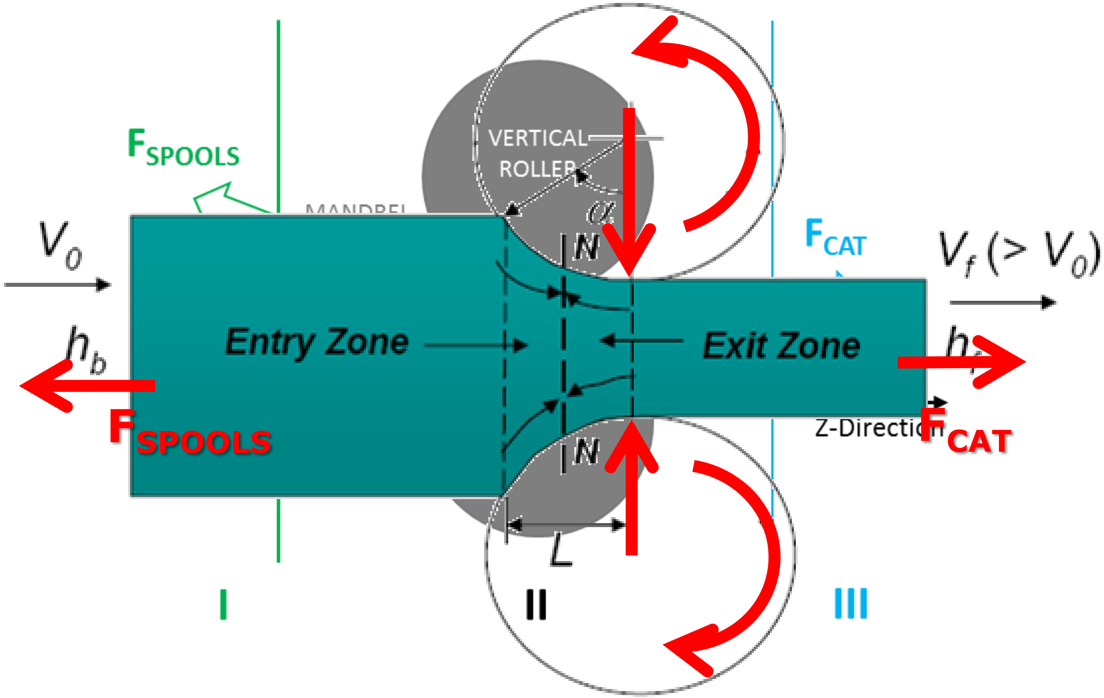


Cable Features	
Number of Strands **(N)**	18
Diameter (d)	1 mm
Material	Cu
Cable Height (h)	1.81 mm
Cable Width (w)	10 mm
Total Length (L)	90 mm
Pitch length (P_{length})	75.75 mm

Process Features	
Spool Force per Strand (F_{SPOOLS})	50 N
Caterpillar Force on Cable (F_{CAT})	900 N
Produced Cable Speed **(v_{CABLE})**	1 m/min
Strands Angular vel. (ω_{PLATE})	13 rpm

- Simplification of initial modelling
- Cable used for machine set-up
  →Readily available for benchmark

Theory of 2D sheet metal rolling implemented to cabling process



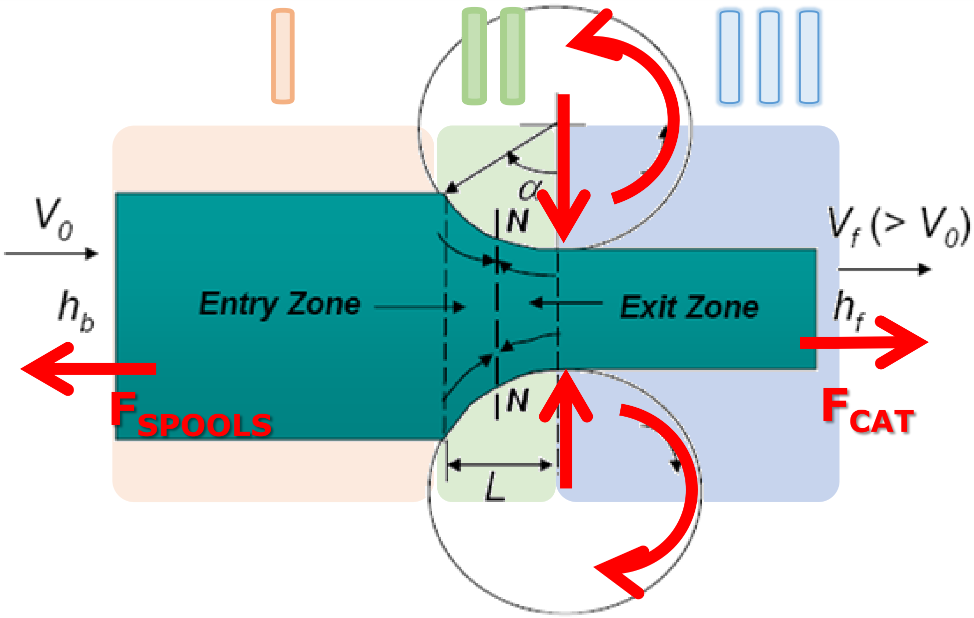
INPUT

- 2D: plain strain state
- Material & Geometry parameters (roller, sheet)
- Material failure criteria

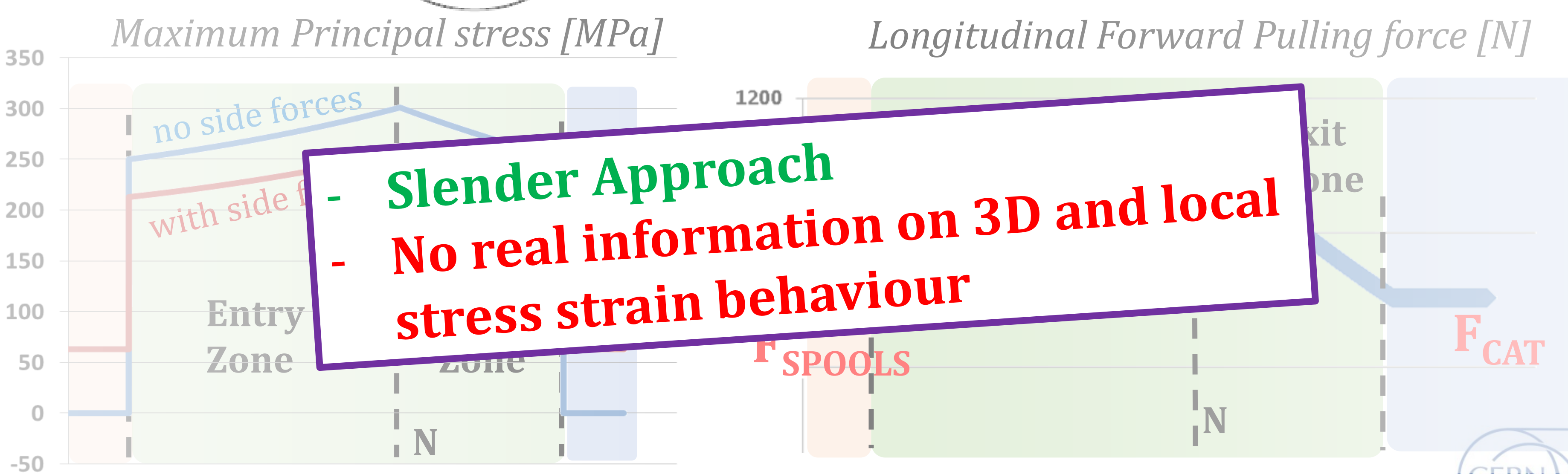
OUTPUT

σ_1(=pressure), σ_2, σ_3
Roller Forces
Torque

Analytical Model: Results

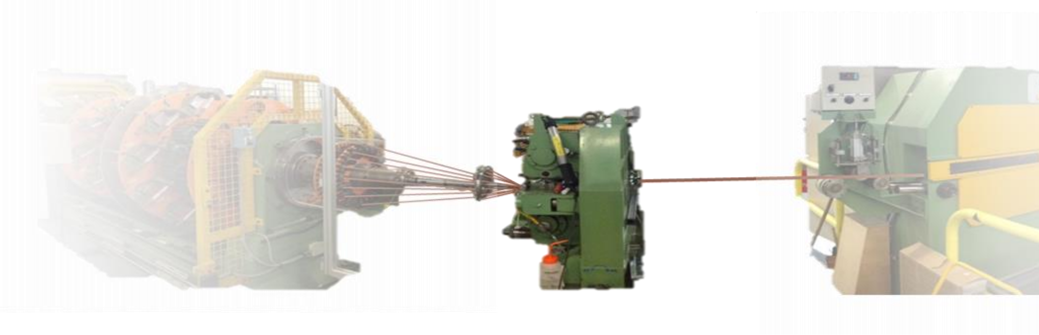


- Influence of main process parameters → better understanding of process: *Why do we push and pull?*
- Output of parameters for benchmarking of F.E. Models

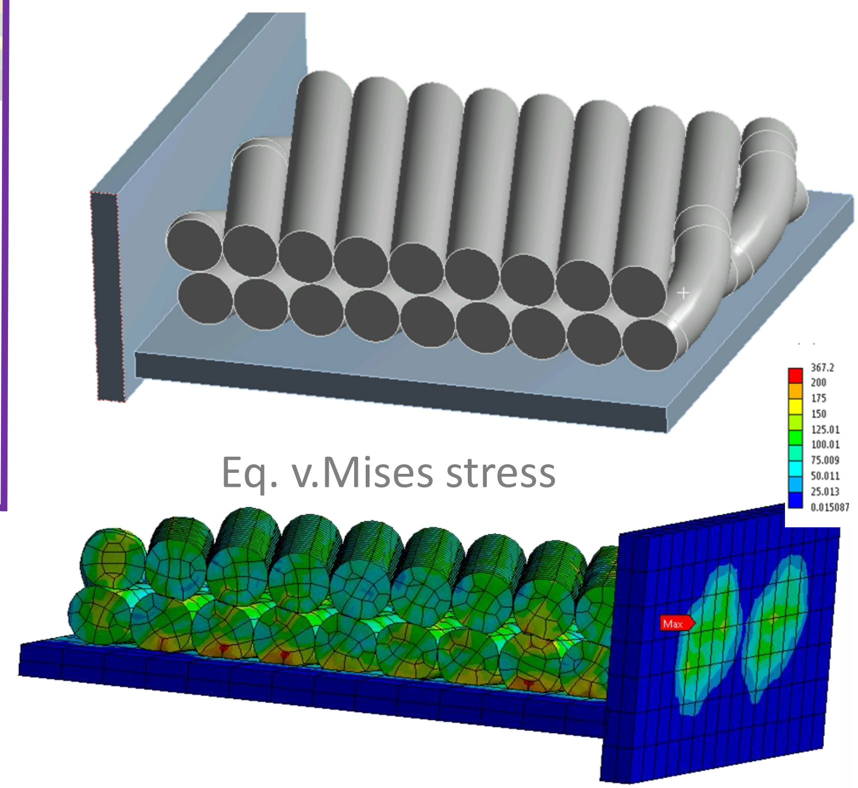


- **Slender Approach**
- **No real information on 3D and local stress strain behaviour**

Numerical Model: The Approach



Process entails
- Timescale: seconds, no high dynamic effects ✓
- Large displacements & deformations ✗
- Non trivial contacts ✗



Implicit F.E (ANSYS):
- **geometrically pre-cabled** strands
- **quasi-static** deformation

Results:
Not effective in terms of **computational time** and **boundary conditions**

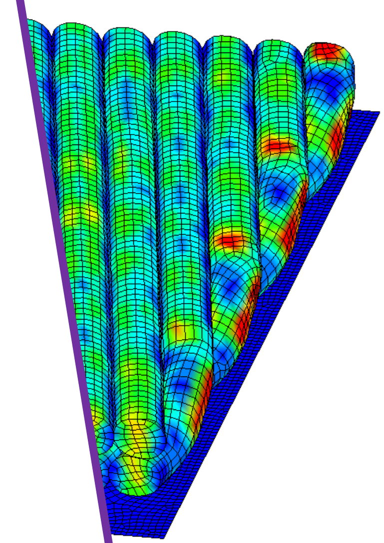
Numerical Model: The Approach

Process entails
- Timescal
  effects
- Large disp
- Non trivia

Explicit F.E (
- **geometri**

Process mod
Neglecting i
How are par ...ed?

eformation Gradient



...going for the **whole Rolling Subsystem**...

- Process speed: 1m/min
- 90mm of cable
- Time step: 1×10^{-8}s (mesh-dependant)
- 192x cores cluster

More than 1 year to complete

How to reduce computational time??

Mass scaling

Mesh size

Acceleration of the process

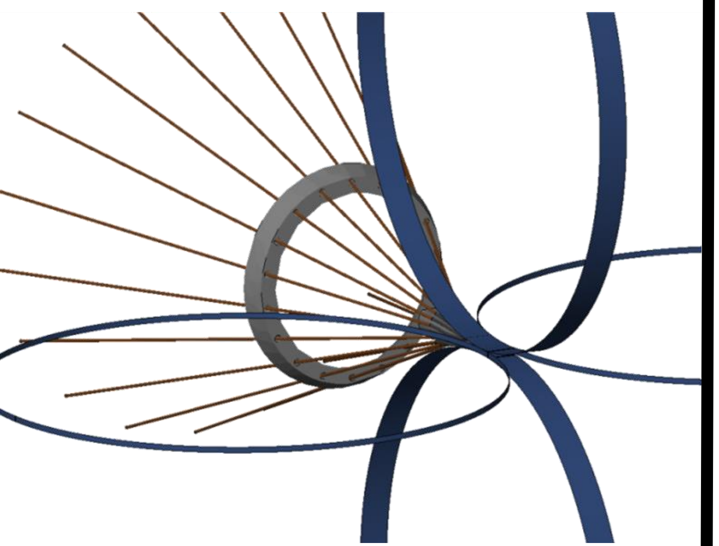
Content

- Description of the F.E. Model (Geometry, Boundary Conditions)
- Sensitivity Analysis
- Results & Benchmark
- Conclusion
- Future Work

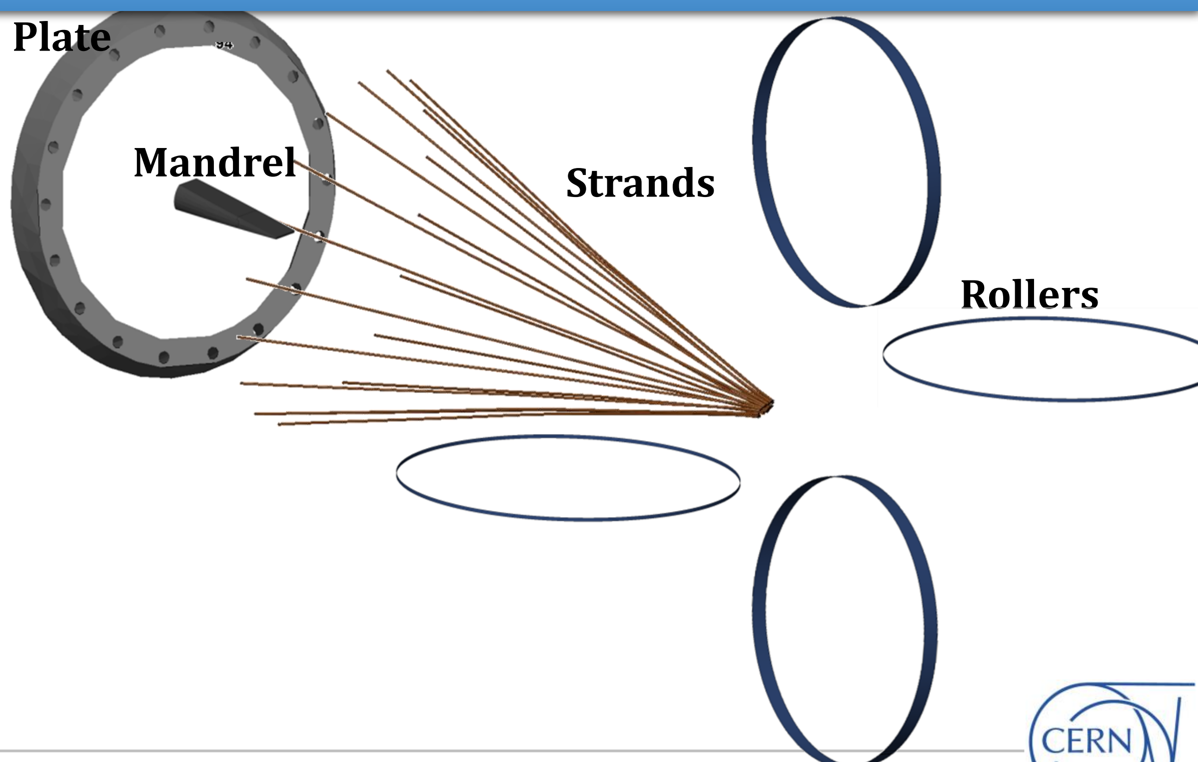
Description of the Model: Geometry Features

Machine elements
=
3D FEM model geometry parts

General view



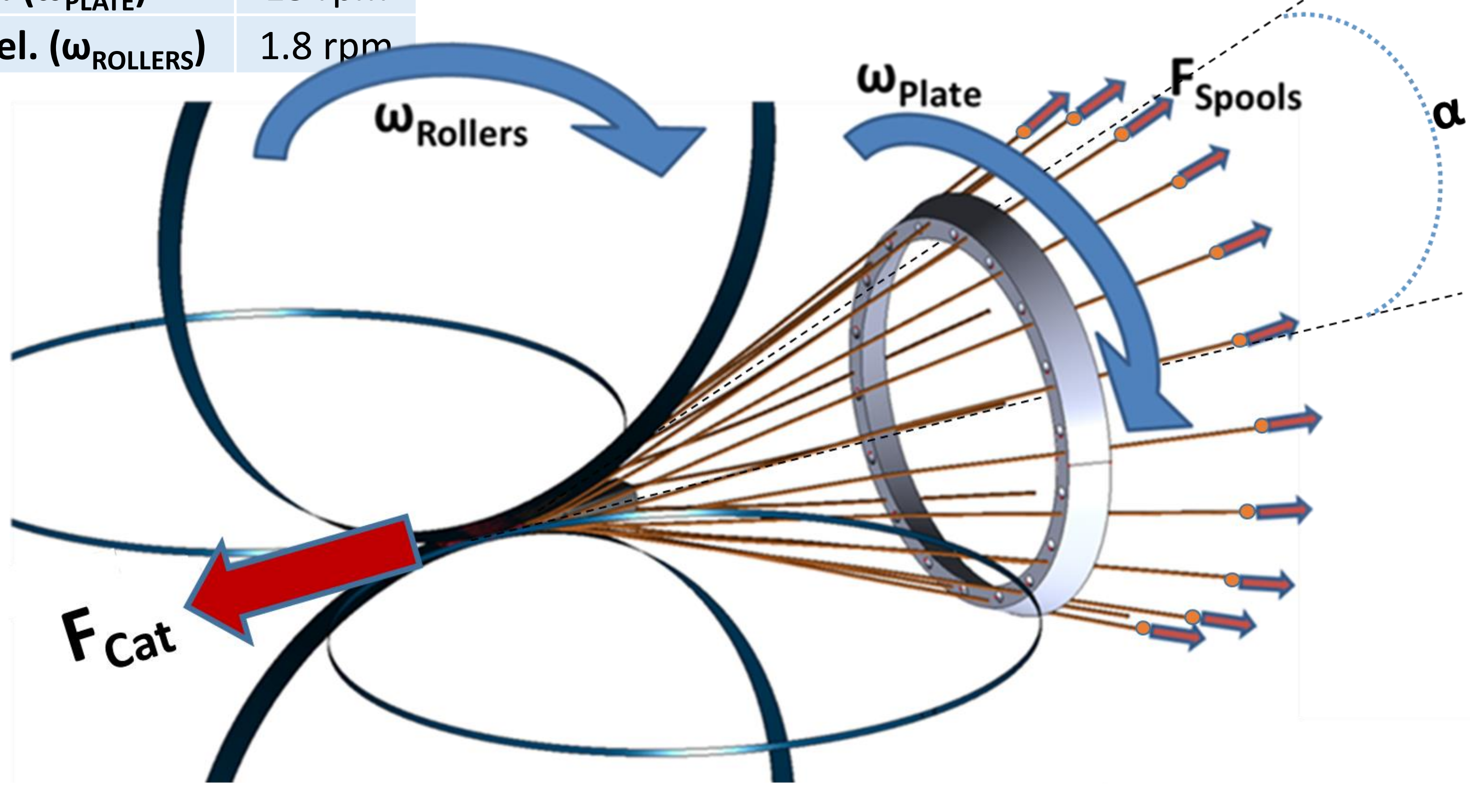
Exploded view



Description of the Model: Boundary Conditions

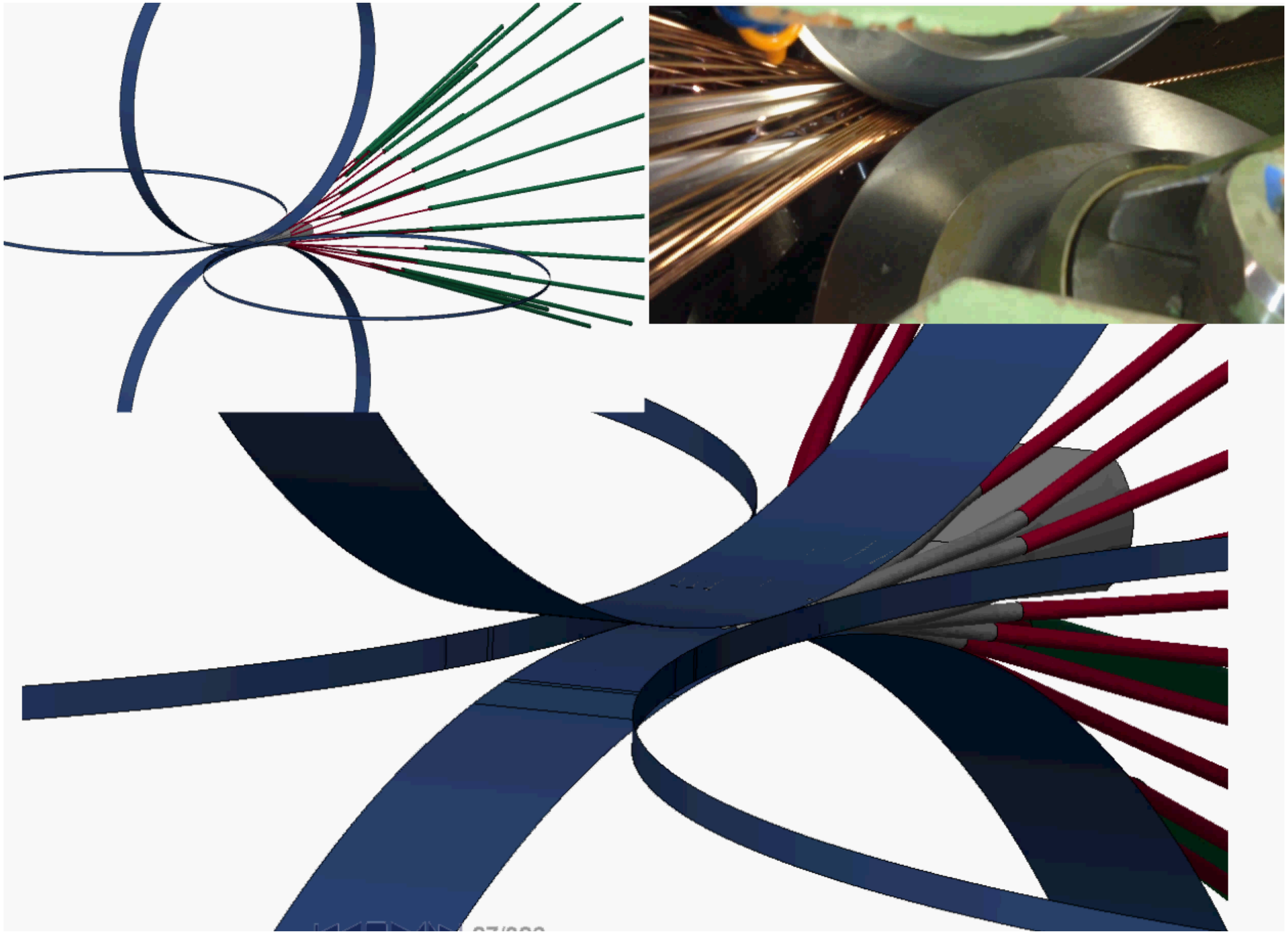
Process Features	
Spool Force per Wire (F_{SPOOLS})	50 N
Caterpillar Force on Cable (F_{CAT})	900 N
Produced Cable Speed (v_{CABLE})	1 m/min
Strands Angular vel. (ω_{PLATE})	13 rpm
Vert. Rollers Ang. Vel. ($\omega_{ROLLERS}$)	1.8 rpm

Process Parameters
=
Model Boundary conditions



Cabling Simulation

General view of the cabling simulation

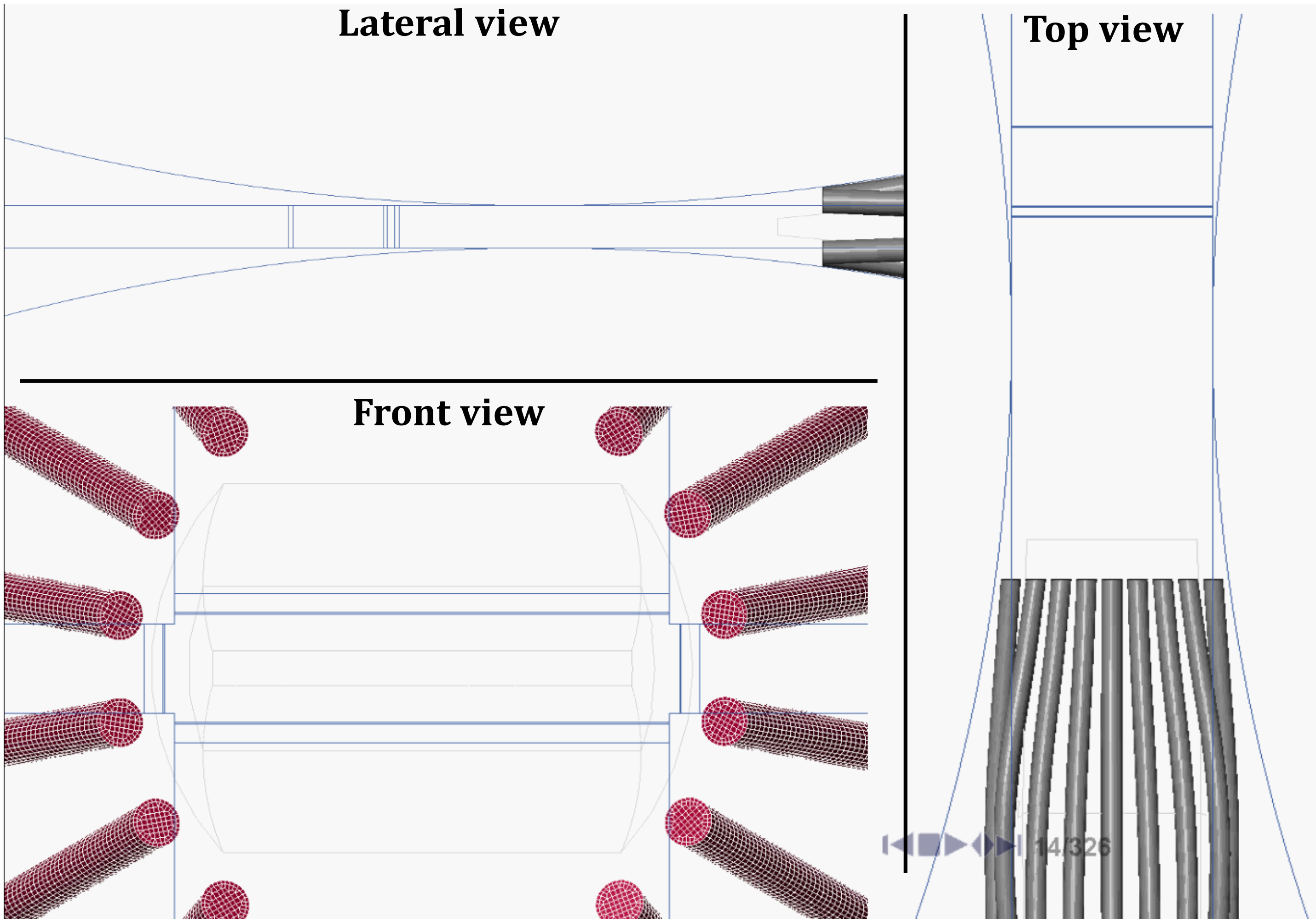


Transient:
accommodate strands
+
Initialize Boundary Conditions

Steady:
Geometric specifications meet

Cabling Simulation

Section views of the cabling simulation

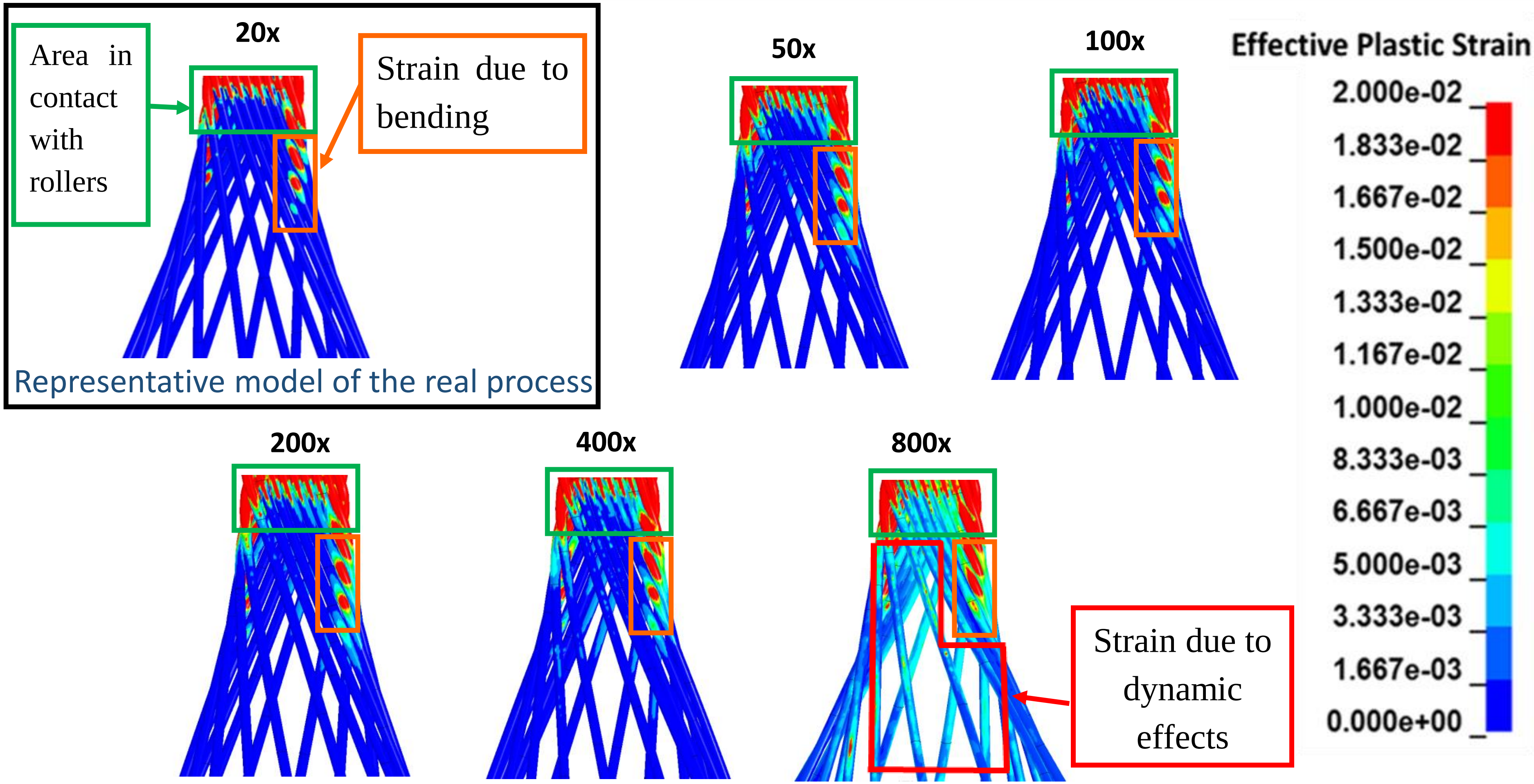


Many contacts
+
large displacement
+
large deformation
+
192 cores cluster
=
Very complex simulation

Content

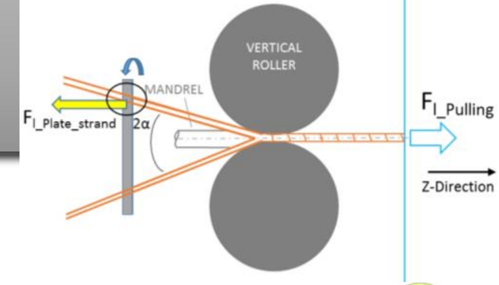
- Description of the F.E. Model (Geometry, Boundary Conditions)
- **Sensitivity Analysis** **(1 year to complete-Acceleration needed)**
  - ➢ Regarding Speed:
    20x, 50x, 100x, 200x, 400x, 800x:
    - Plastic strain analysis
    - Force analysis
  - ➢ Regarding Mesh:
    Fine vs. Coarse
- Results & Benchmark
- Conclusion & Future Work

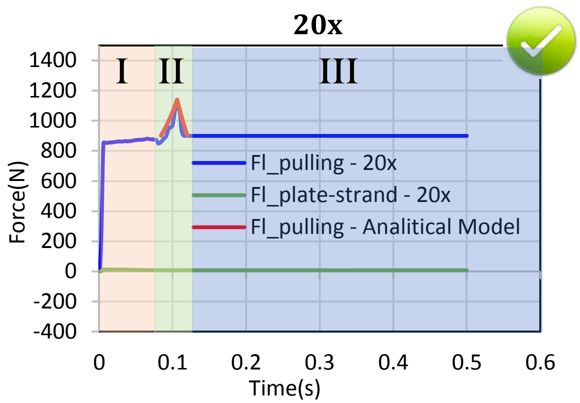
Speed Sensitivity Analysis: Plastic Strain

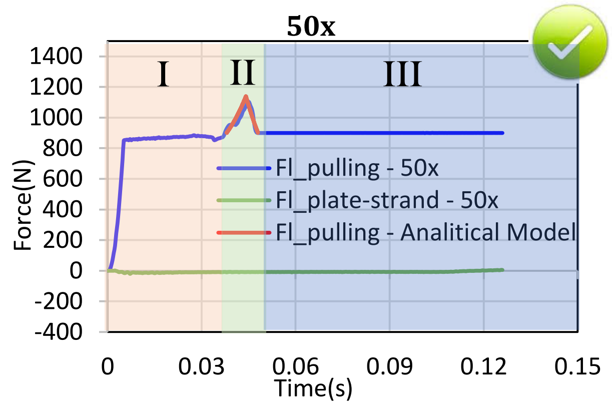


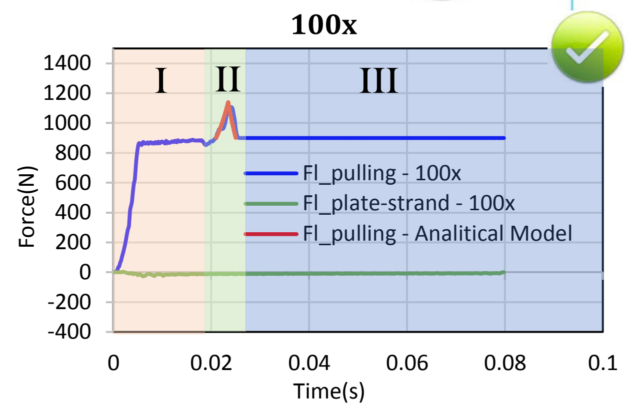
- **800x is not suitable**. Presents 2% plastic deformation before entering the rollers
- **Quantitative analysis is required** to determine the validity of 20x, 50x,100x, 200x and 400x

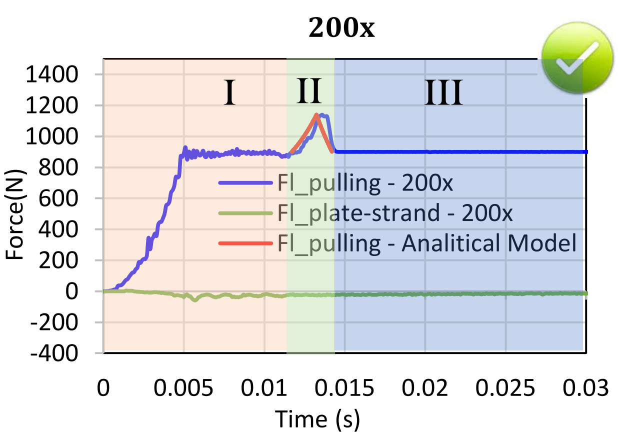
Speed Sensitivity Analysis: Force

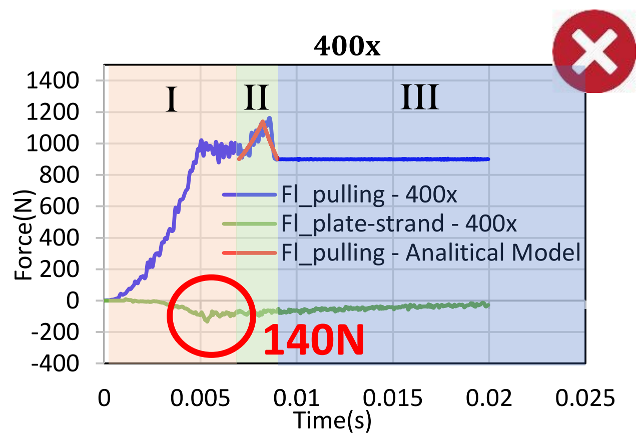


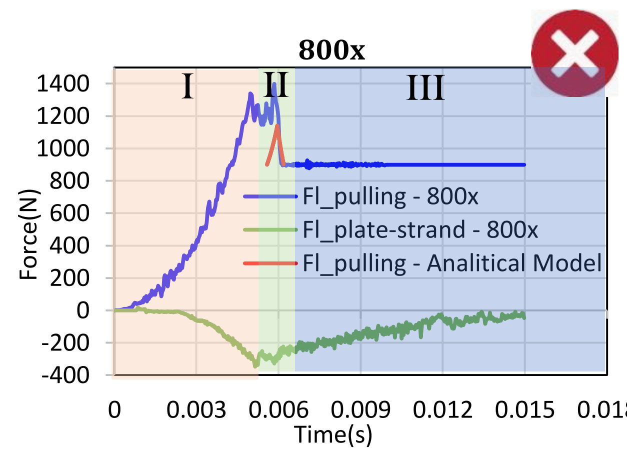












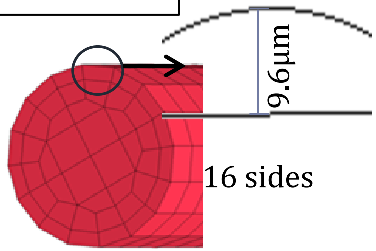
- **Excellent** agreement between the Analytical model and the 3D FEM model for **20x**, **50x, 100x** and **200x**
- Significant Plate **contact Force** introduced at **400x** and **800x.** E.g. Inertia and nodal compenetration

Mesh Sensitivity Analysis

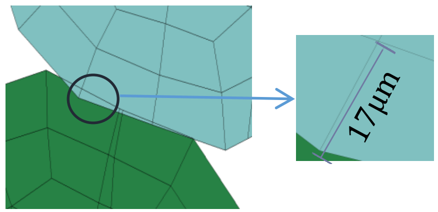
Coarse mesh	Fine mesh

Two Main sources of error:

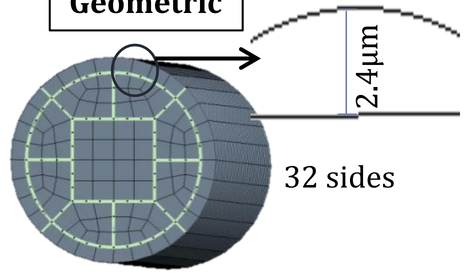
Geometric



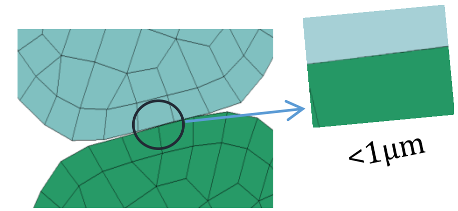
Contact penetration

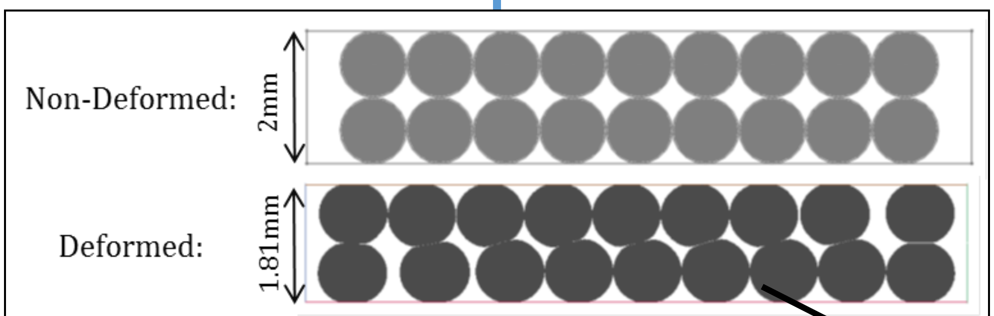


Geometric



Contact penetration





*Note: this was simulated at 200x

Coarse mesh

Expected deformation=NonDeformed - Deformed=190µm

Error=Geometric+Contact = 9.6µm x 2 sides x 2 strands+17µm=55.4µm

- **Total Error 30%**
- **Computational time: 2 days**

Fine mesh

Expected deformation=NonDeformed - Deformed=190µm

Error=Geometric+Contact = 2.4µm x 2 sides x2 strands+1µm=10.6µm

- **Total Error 5.5%**
- **Computational time: 7 days**

Sensitivity Analysis: Conclusions

- Speed sensitivity:
  - **800x** shows 2% of **plastic deformation** before getting in contact with rollers
  - **400x and 800x** present **significant** longitudinal **plate-strand contact force** – Not in the real process
  - **200x** and **20x**: analysis confirm that there are **not significant difference** between them
  - **200x** presents the **best** trade off between accuracy – computational time

- Mesh sensitivity:
  - **Fine mesh reduces** the geometrical **error** by a factor of 6 but **increases** the **computational time** by a factor of 3.5

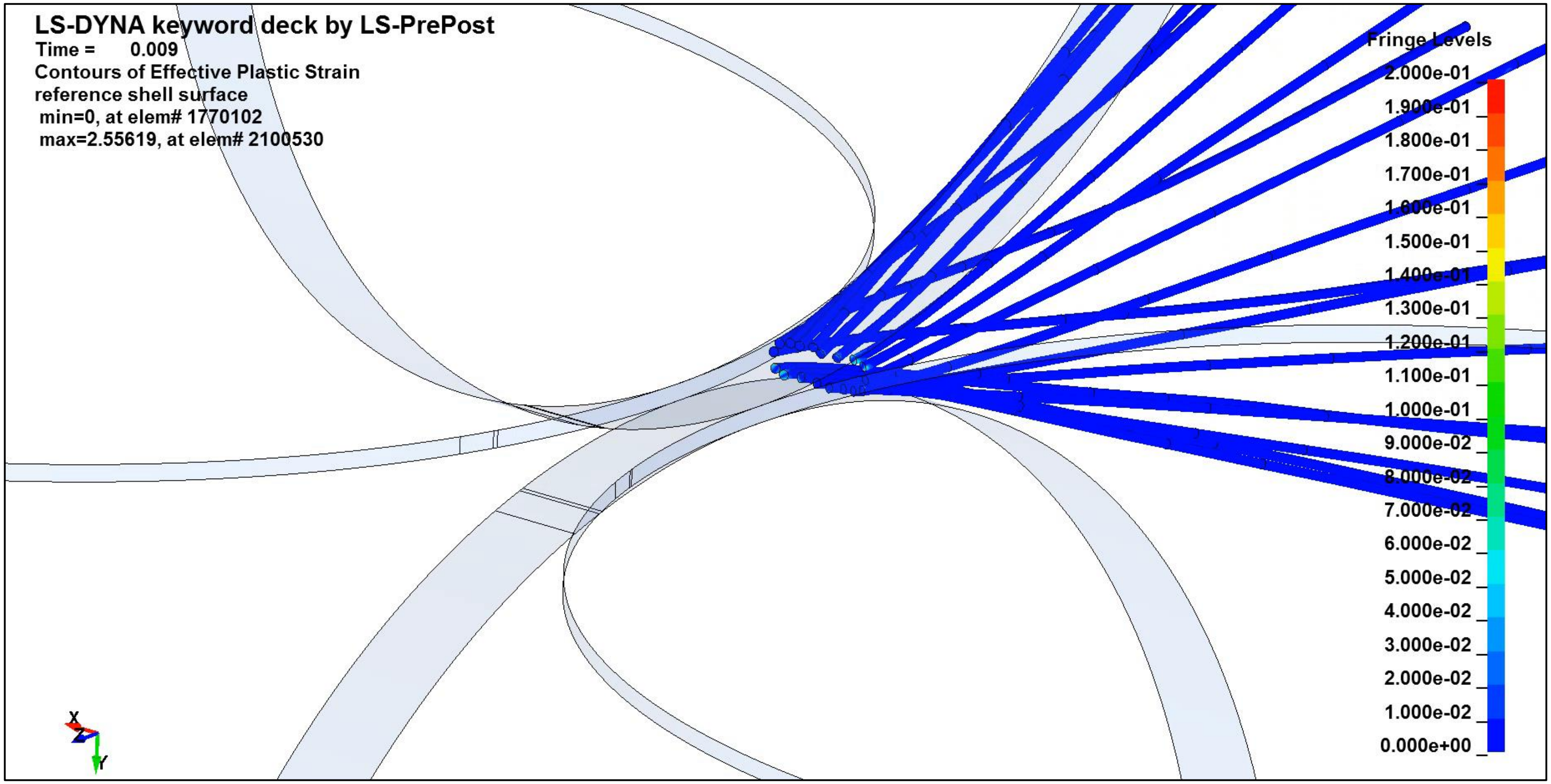
The simulation is carried out at 200x and fine mesh *7 days

Content

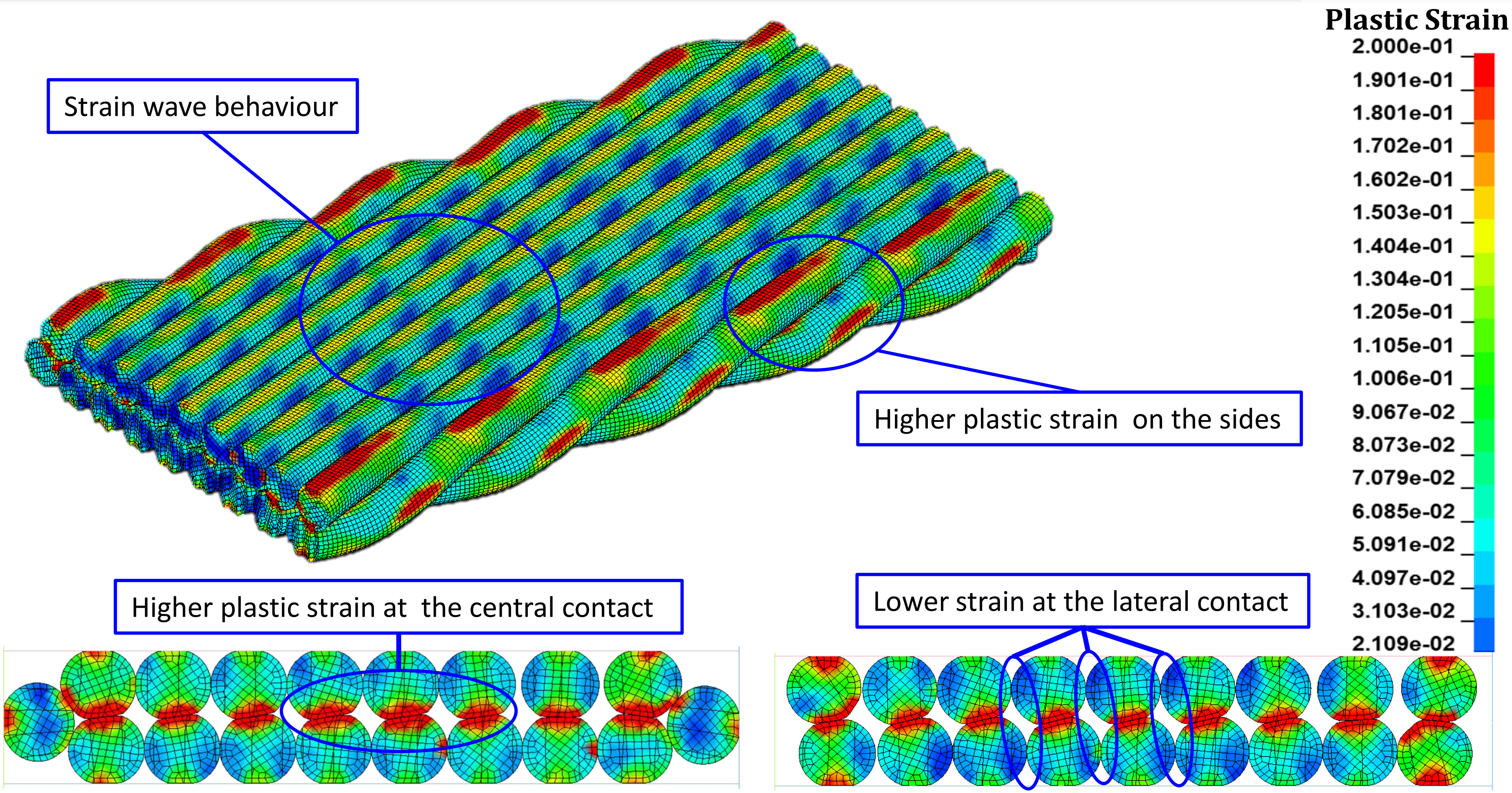
- Description of the F.E. Model (Geometry, Boundary Conditions)
- Sensitivity Analysis
- **Results & Benchmark**
- Conclusion
- Future Work

Results & Benchmarking

A cabling process at 200x and fine mesh is simulated – Post processing



Results 200x – Plastic Strain



Plastic strain distribution coherent with this specific cable

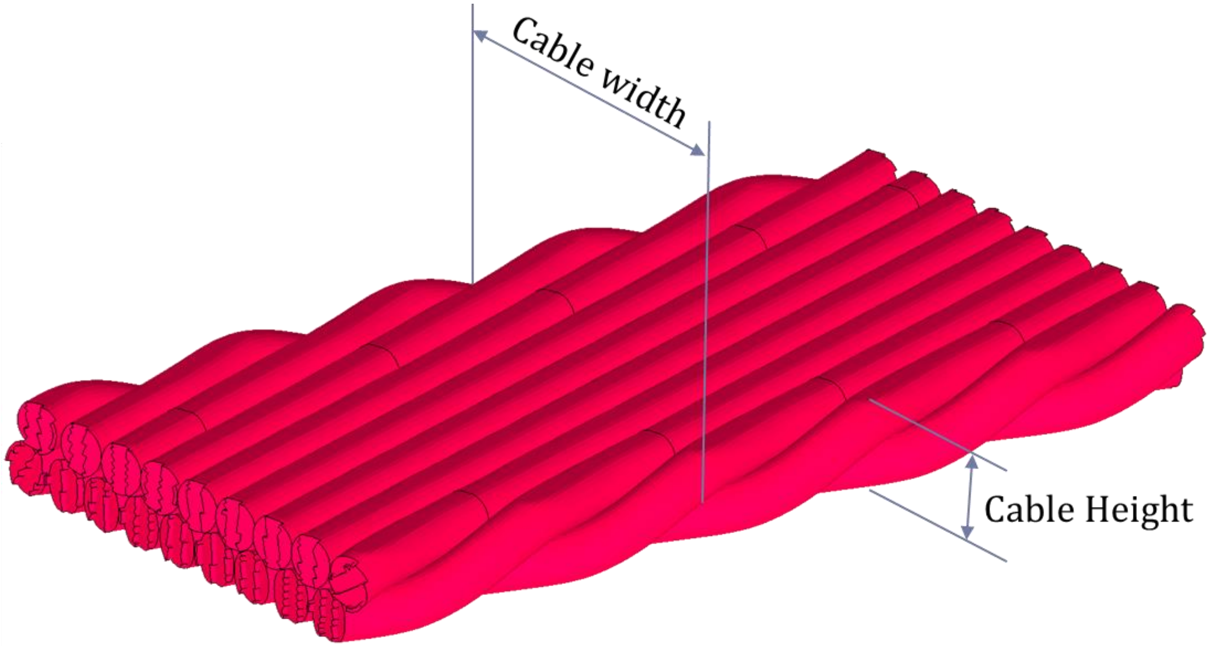
*Note: this was simulated at 200x

Applied Superconductivity

Are the results coherent with reality??

- Geometric benchmark
- Plastic Strain benchmark

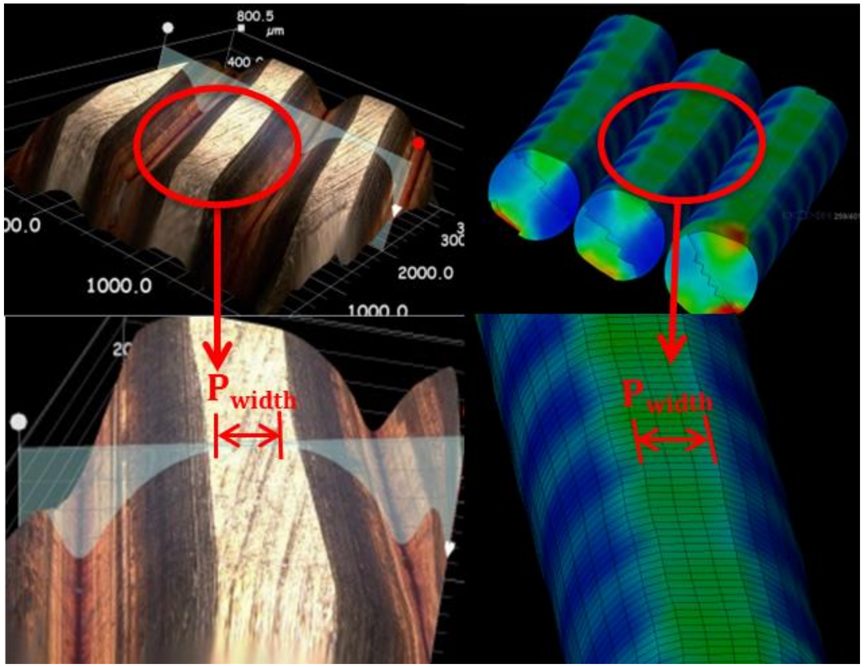
Geometric Benchmark



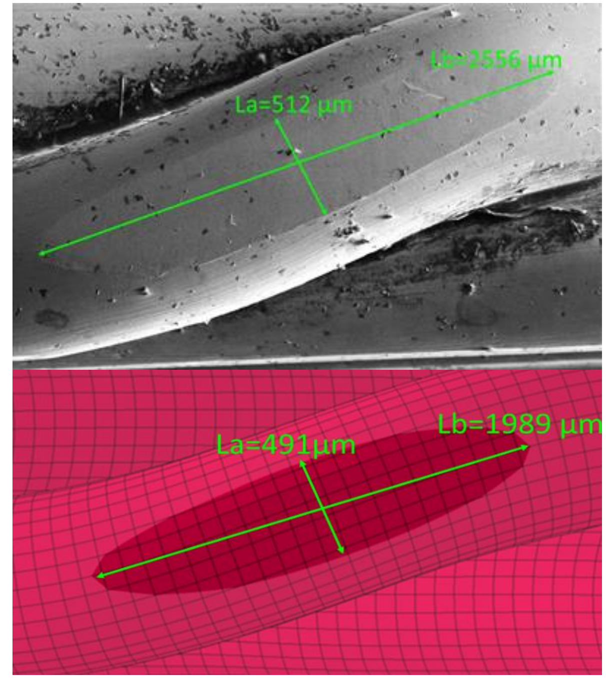
Parameter	Theoretical	Sample measured	3D Model
Cable height	1.81mm	1.81 ± 0.006 mm	1.808mm
Cable width	10mm	10 ±0.006 mm	9.998mm
Cable pitch length	75.75	74.3-75.0mm ±1mm	75.3-75.7 mm

Plastic Strain Benchmark - Quantitative

Top plastification



Lateral Plastification



Parameter		Sample measured	3D Model
Top Plastification	P_{width}	328μm	346 μm
Lateral Plastification	L_a	505 μm	491μm
	L_b	2530 μm	1989 μm

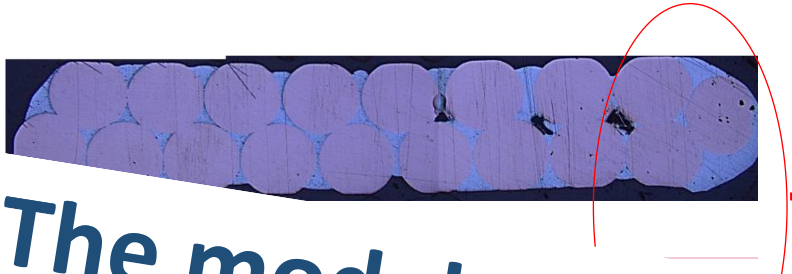
Excellent

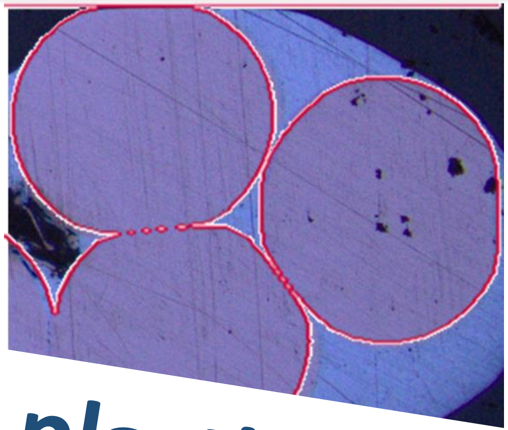
Good

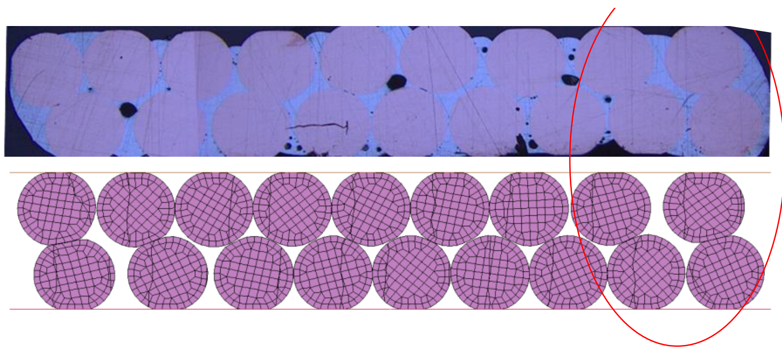
Plastic Strain Benchmark - Qualitative

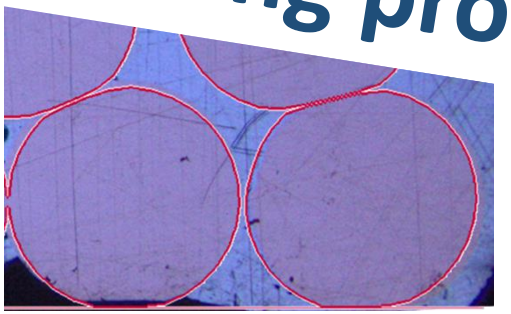
Cross section

Overlapping :sample and 3D FEM model









The model captures the plastification in the strands due to the cabling process!!!

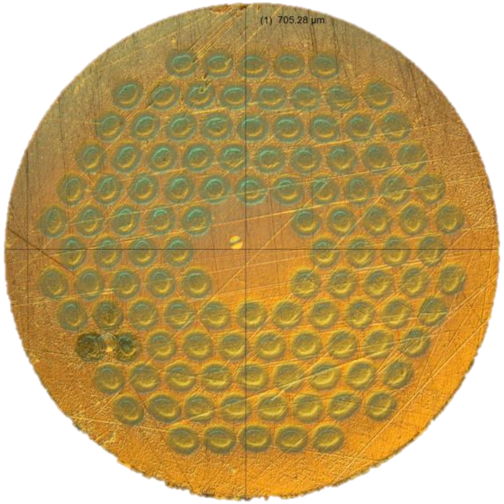
Conclusions

- **Analytical model** of the rolling theory **in good agreement with FEM**
- **Explicit FE code** proved to be the most **suitable** tool for simulating the **cabling process** (Rutherford cables)
- **3D full model** embedding **all the physics (Geometry and B.C.)** of the cabling process
- **Good agreement** between **experimental** and **simulated results**
- The **3D FEM** model **captures the deformation** that **Rutherford cables** experience during the cabling process
- **Powerful tool** that might contribute to the optimization of cabling process

Future Outlook

- **FEM model improvement:**
  - ✓ Reduce even further the computational time – refine the amount of cable needed
  - ✓ Increase Accuracy; Reduce the mesh down to 50µm
  - ✓ Parametric study to optimized the Cabling Process

- **From Cu to Nb_3Sn**
  - ✓ Final aim is to model Nb_3Sn cables



Thank you