Technical Division
Superconducting Materials Department

Mechanical Analyses of Nb3Sn Rutherford-type cables

Supervisor
Emanuela Barzi

Summer intern
Federico Bucciarelli

Contents

Background

Superconducting Nb_3Sn strands

- high performance superconducting cables
- composite structure
- high plastic deformation during manufacturing

Background

Superconducting Nb_3Sn strands

- high performance superconducting cables
- composite structure
- high plastic deformation during manufacturing

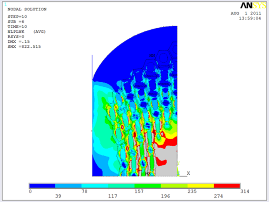
Previous work in the field

Elasto-plastic **FEM Analysis** based on the hypothesys of:

- 2-D geometry
- plane strain
- bi-linear isotropic material

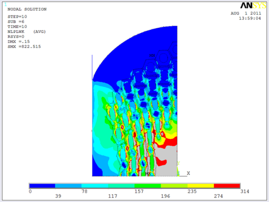
Detailed and approximated model

Detailed model

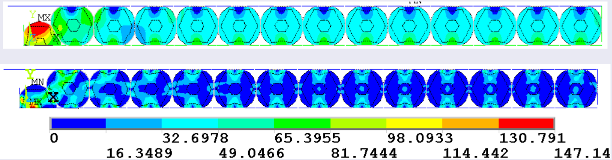


Detailed and approximated model

Detailed model



Macromodel



Previous analysis characteristics

For the detailed model:

- good description of the mechanical behaviour of a single strand
- higher number of elements
- higher computational cost

Previous analysis characteristics

For the detailed model:

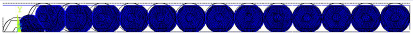
- good description of the mechanical behaviour of a single strand
- higher number of elements
- higher computational cost

For the macro-model:

- good description of the mechanical behaviour of the whole cable
- low number of elements
- lower computational cost

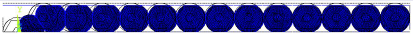
Strategy used in the previous analysis

Displacements of the first two strands taken from the the macromodel...



Strategy used in the previous analysis

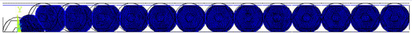
Displacements of the first two strands taken from the the macromodel...



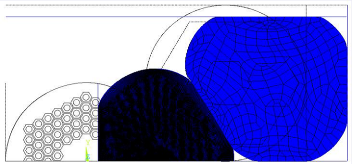
...and inserted as loads in the detailed first two strands model.

Strategy used in the previous analysis

Displacements of the first two strands taken from the the macromodel...

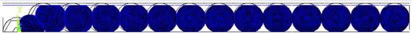


...and inserted as loads in the detailed first two strands model.

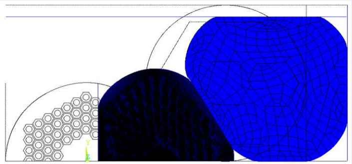


Strategy used in the previous analysis

Displacements of the first two strands taken from the the macromodel...



...and inserted as loads in the detailed first two strands model.



Objective

Sensitivity analysis of the plastic strain to the **width compaction** of the cable

New FEM model

Improvements

- mesh quality
- code reliability
- easier convergence

New FEM model

Improvements

- mesh quality
- code reliability
- easier convergence

More realistic loading

The vertical and horizontal loads are applied **together**.

New FEM model

Improvements

- mesh quality
- code reliability
- easier convergence

More realistic loading

The vertical and horizontal loads are applied **together**.

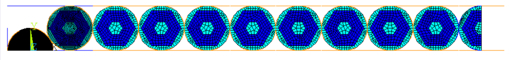
Parametric code

Only **one script** for different geometries

New FEM model

Improvements

- mesh quality
- code reliability
- easier convergence



More realistic loading

The vertical and horizontal loads are applied **together**.

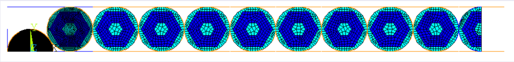
Parametric code

Only **one script** for different geometries

New FEM model

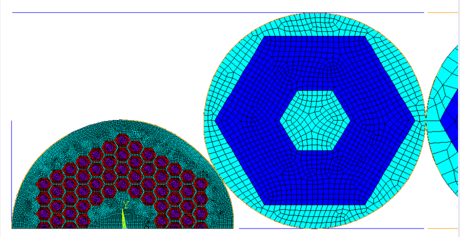
Improvements

- mesh quality
- code reliability
- easier convergence



More realistic loading

The vertical and horizontal loads are applied **together**.



Parametric code

Only **one script** for different geometries

Sensitivity analysis

Input parameters

- width compaction

$$w_c = \frac{l_f}{l_i} = \frac{l_i - \Delta l}{l_i}$$

- heigth compaction

$$h_c = \frac{h_f}{h_i} = \frac{h_i - \Delta h}{h_i}$$

Sensitivity analysis

Input parameters

- width compaction

$$w_c = \frac{l_f}{l_i} = \frac{l_i - \Delta l}{l_i}$$

- heigth compaction

$$h_c = \frac{h_f}{h_i} = \frac{h_i - \Delta h}{h_i}$$

Output parameters

- equivalent plastic strain
- plastic strain intensity

Sensitivity analysis

Input parameters

- width compaction

$$w_c = \frac{l_f}{l_i} = \frac{l_i - \Delta l}{l_i}$$

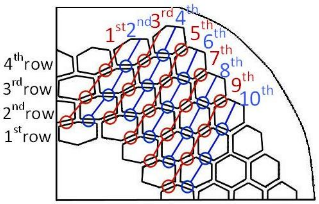
- heigth compaction

$$h_c = \frac{h_f}{h_i} = \frac{h_i - \Delta h}{h_i}$$

Output parameters

- equivalent plastic strain
- plastic strain intensity

Old strain map



Strain map

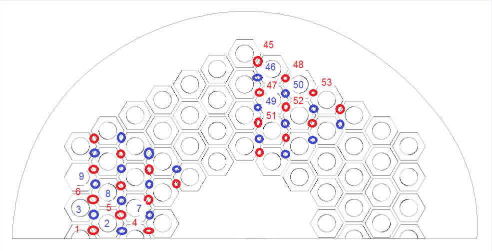
Characteristics

- equivalent plastic strain taken from diagonals
- ordered in **decreasing value** along diagonals
- only in points where there is **tensile stress**

Strain map

Characteristics

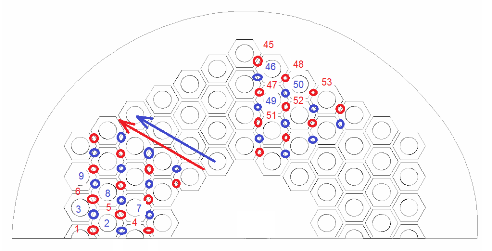
- equivalent plastic strain taken from diagonals
- ordered in **decreasing value** along diagonals
- only in points where there is **tensile stress**



Strain map

Characteristics

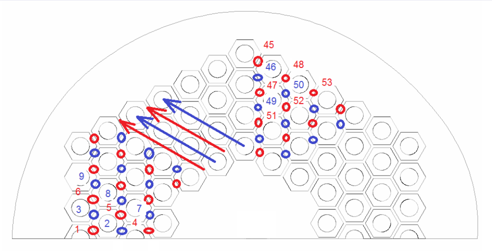
- equivalent plastic strain taken from diagonals
- ordered in **decreasing value** along diagonals
- only in points where there is **tensile stress**



Strain map

Characteristics

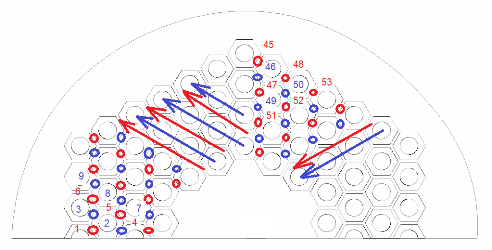
- equivalent plastic strain taken from diagonals
- ordered in **decreasing value** along diagonals
- only in points where there is **tensile stress**



Strain map

Characteristics

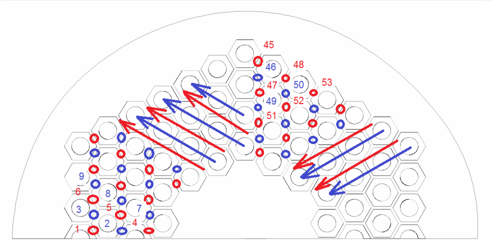
- equivalent plastic strain taken from diagonals
- ordered in **decreasing value** along diagonals
- only in points where there is **tensile stress**



Strain map

Characteristics

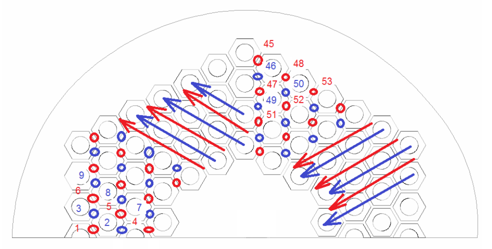
- equivalent plastic strain taken from diagonals
- ordered in **decreasing value** along diagonals
- only in points where there is **tensile stress**

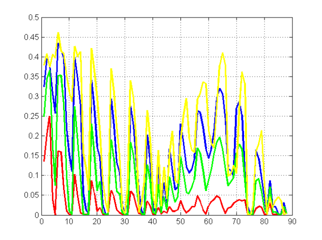


Strain map

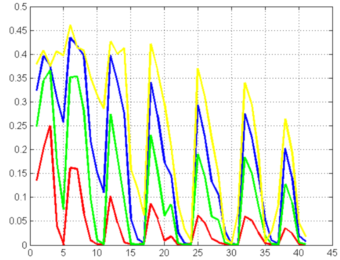
Characteristics

- equivalent plastic strain taken from diagonals
- ordered in **decreasing value** along diagonals
- only in points where there is **tensile stress**

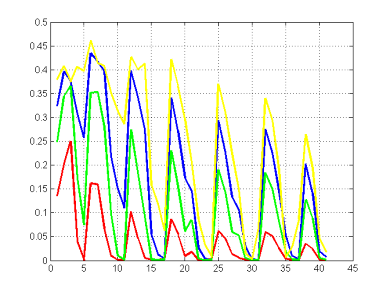


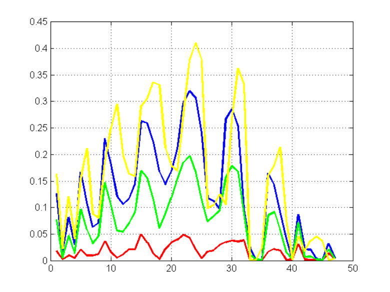


Results

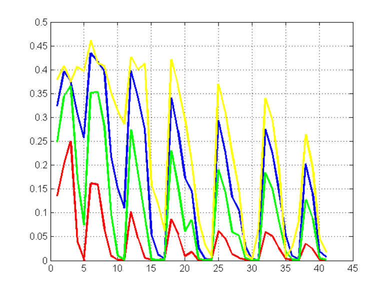


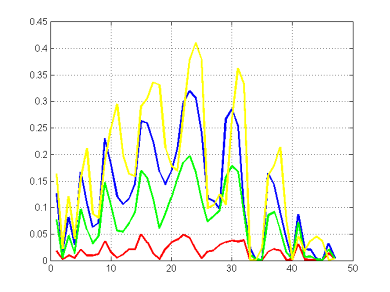
Results


0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0 5 10 15 20 25 30 35 40 45


0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0 10 20 30 40 50

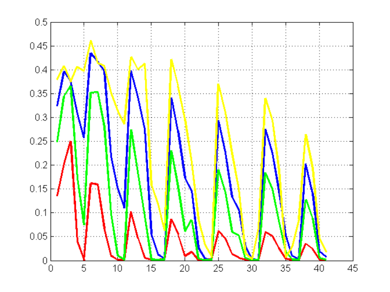
Results

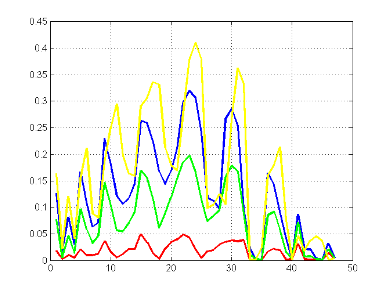




w_c between 0.99 and 0.95

Results





w_c between 0.99 and 0.95

For lower values of w_c the right part of the first strand can become as critic as the left one.

SS core technology

Further developments

Cables with a **stainless steel** core in order to decrease eddy currents

SS core technology

Further developments

Cables with a **stainless steel** core in order to decrease eddy currents

Objective

Studying the mechanical behaviour of the core and its influence on the strands deformation.

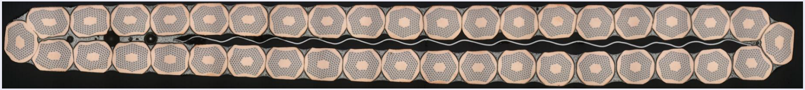
SS core technology

Further developments

Cables with a **stainless steel** core in order to decrease eddy currents

Objective

Studying the mechanical behaviour of the core and its influence on the strands deformation.



FEM modeling

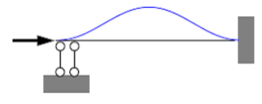
Experimental data observation

The core is affected by **buckling** before plastic deformation.

FEM modeling

Experimental data observation

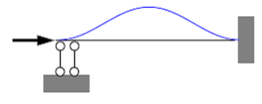
The core is affected by **buckling** before plastic deformation.



FEM modeling

Experimental data observation

The core is affected by **buckling** before plastic deformation.

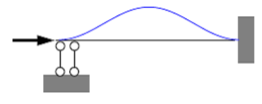


Friction with the strands represents the buckling load.

FEM modeling

Experimental data observation

The core is affected by **buckling** before plastic deformation.



Friction with the strands represents the buckling load.

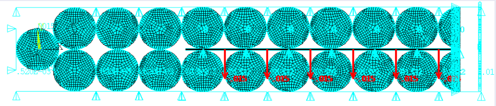
Issues

- After buckling the problem **loses a plane of symmetry**
- For non-linear buckling analysis it is necessary to insert a **defect** in the structure that is going to buckle.

FEM modeling

Strategy

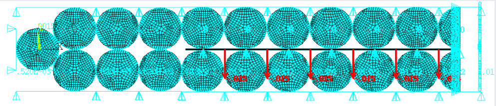
A **fictitious load** starts the buckling



FEM modeling

Strategy

A **fictitious load** starts the buckling

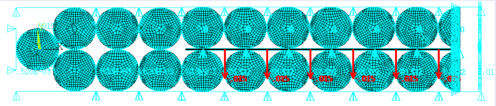


The fictitious load is then gently removed during regular steps

FEM modeling

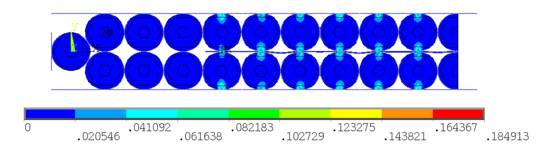
Strategy

A **fictitious load** starts the buckling

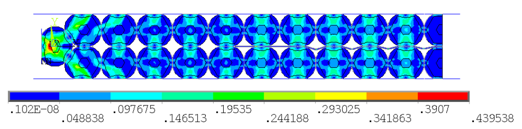


The fictitious load is then gently removed during regular steps

Plastic strain after fictitious load

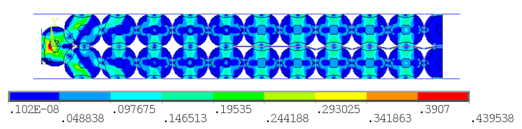


SS core simulation results

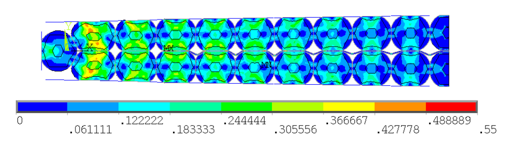


Plastic strain before keystoning

SS core simulation results

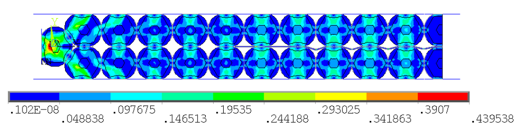


Plastic strain before keystoning

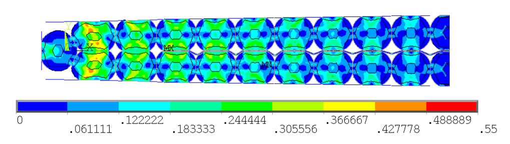


Plastic strain after keystoning

SS core simulation results



Plastic strain before keystoning



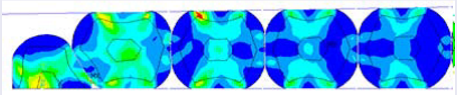
Plastic strain after keystoning

- The code permits to parametrize the core length and thickness
- A comparison with other cables is ongoing

Turk-head analysis

Previous work hypothesis

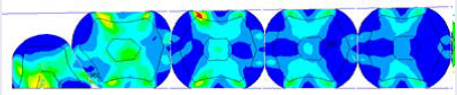
The most damaged strand location **can change** along the cable thanks to load ripartition effects.



Turk-head analysis

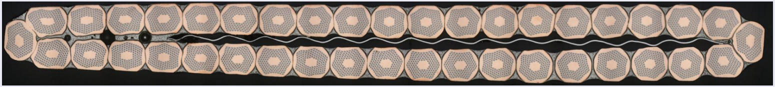
Previous work hypothesis

The most damaged strand location **can change** along the cable thanks to load ripartition effects.



New considerations

The **second strand** in cable is always the most loaded



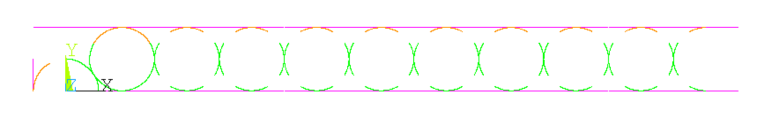
New analysis characteristics

- keystoning starts after a **spring-back** step
- not all the strands are loaded from the beginning

New analysis characteristics

- keystoning starts after a **spring-back** step
- not all the strands are loaded from the beginning

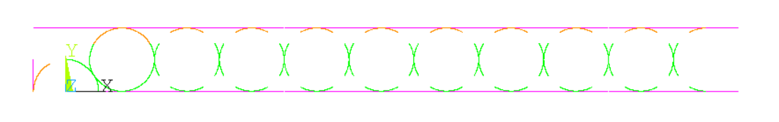
New contact elements



New analysis characteristics

- keystoning starts after a **spring-back** step
- not all the strands are loaded from the beginning

New contact elements

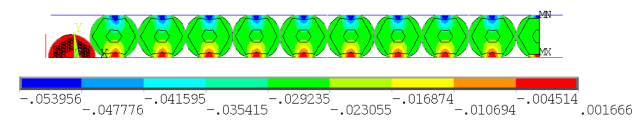


Use of different keyoptions for the contacts elements:

- **no separation** contact
- **unilateral contacts** with friction

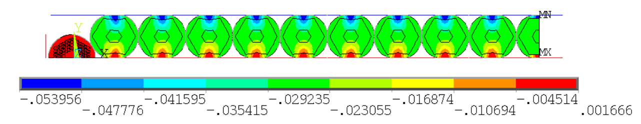
Spring-back

Displacement before spring-back

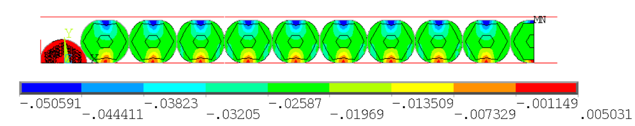


Spring-back

Displacement before spring-back

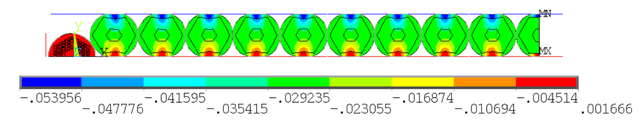


Displacement after spring-back

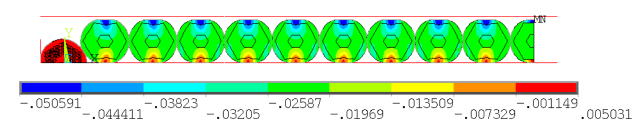


Spring-back

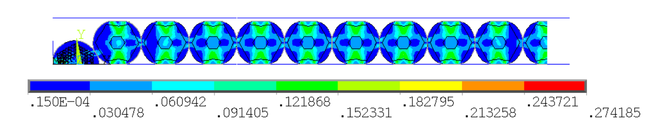
Displacement before spring-back



Displacement after spring-back

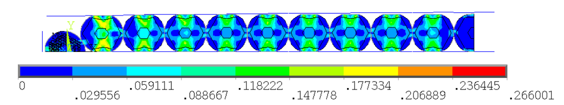


Plastic strain after spring-back



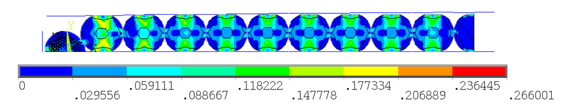
Keystoning step

$\alpha = 0.5\ ^\circ$

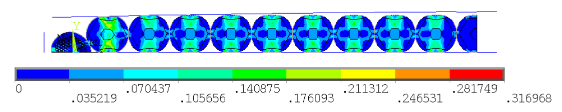


Keystoning step

$\alpha = 0.5\ °$

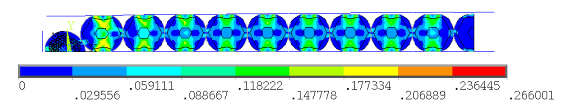


$\alpha = 0.75\ °$

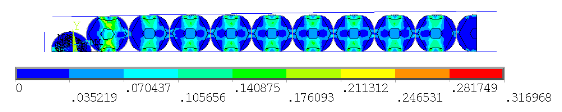


Keystoning step

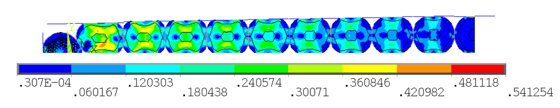
$\alpha = 0.5\ ^\circ$



$\alpha = 0.75\ ^\circ$

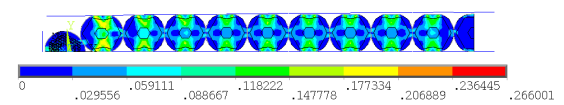


$\alpha = 1\ ^\circ$

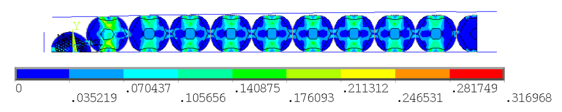


Keystoning step

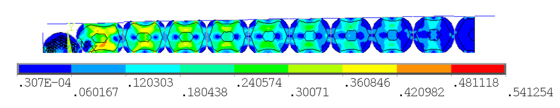
$\alpha = 0.5\ ^\circ$



$\alpha = 0.75\ ^\circ$



$\alpha = 1\ ^\circ$



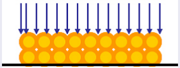
The most critical strand remains the second one even if other strands are higly deformed.

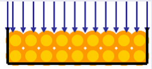
Workload steps

We want to obtain information about the **operative conditions**

Workload steps

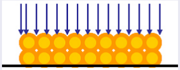
We want to obtain information about the **operative conditions**

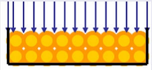




Workload steps

We want to obtain information about the **operative conditions**

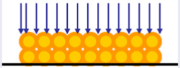


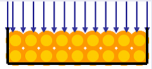


Additional timestep with different constraints and loads (200 MPa)

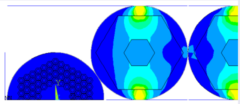
Workload steps

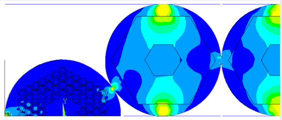
We want to obtain information about the **operative conditions**





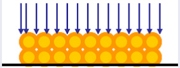
Additional timestep with different constraints and loads (200 MPa)

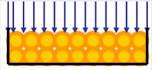




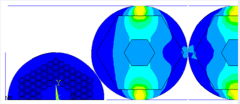
Workload steps

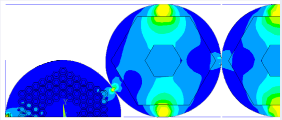
We want to obtain information about the **operative conditions**





Additional timestep with different constraints and loads (200 MPa)





Correlation between strain and cable critical current?

Conclusions and further developments

- A valid code for simulating core buckling, spring-back and keystoning has been written.

Conclusions and further developments

- A valid code for simulating core buckling, spring-back and keystoning has been written.
- It is now possible to make comparison between different cables' geometries.

Conclusions and further developments

- A valid code for simulating core buckling, spring-back and keystoning has been written.
- It is now possible to make comparison between different cables' geometries.
- A full simulation of the keystone cable has to be performed.

Conclusions and further developments

- A valid code for simulating core buckling, spring-back and keystoning has been written.
- It is now possible to make comparison between different cables' geometries.
- A full simulation of the keystone cable has to be performed.
- Work is ongoing to solve strands static sketches and create an analytical model.

Conclusions and further developments

- A valid code for simulating core buckling, spring-back and keystoning has been written.
- It is now possible to make comparison between different cables' geometries.
- A full simulation of the keystone cable has to be performed.
- Work is ongoing to solve strands static sketches and create an analytical model.
- Last step will be applying these techniques to $BSCCO - 2212$.

Thanks for your attention.

Thanks for your attention.

Questions?