Mechanical behavior of MQXF cable stacks at room temperature

C. Fichera, G. Vallone, P. Ferracin, M. Guinchard, Ó. Sacristán

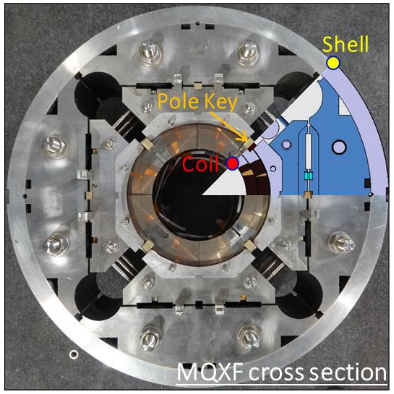
ENGINEERING
DEPARTMENT

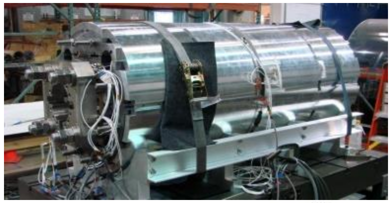
Outline

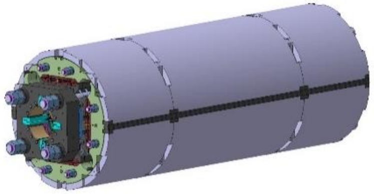
- MQXF and Nb_3Sn cable
- Test campaign planning
- Cable stack production
- Experimental results
- Conclusion

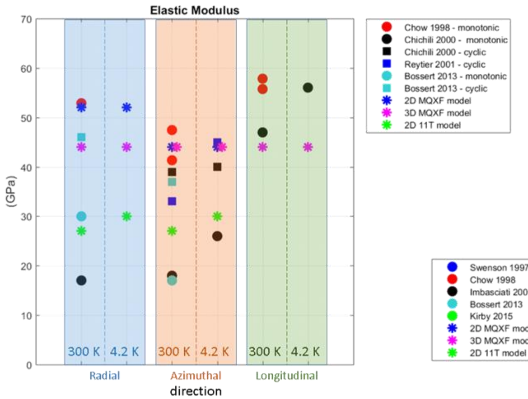
Introduction

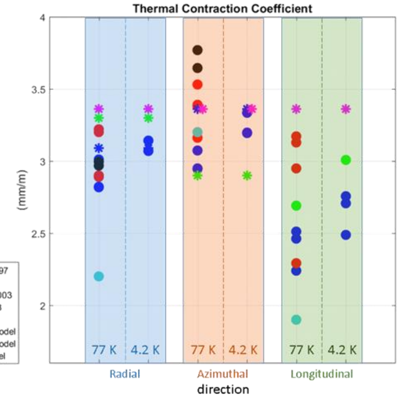
- The coil behavior is a crucial information for the structural assessment of magnets and prediction of conductor performance:
  - Mechanical properties at room and cryogenic temperature
  - Thermal properties from room temperature down to cryogenic
- Knowledge of coil properties shows uncertainty:
  - Different testing configurations (constrains, measurement technique)
  - Different cable configurations (epoxy, fiberglass, Mica, etc.)
  - Large scattering in material properties (thermal/mechanical)
- In FE models bad numerical-experimental comparison with impregnated MQXF coils.

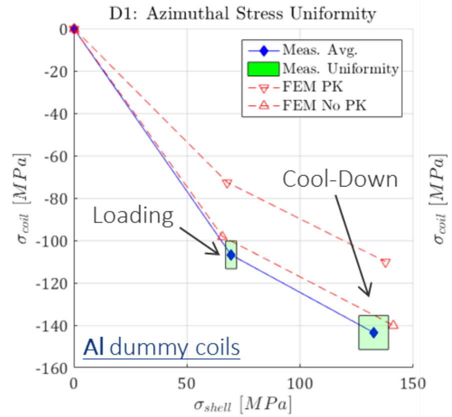


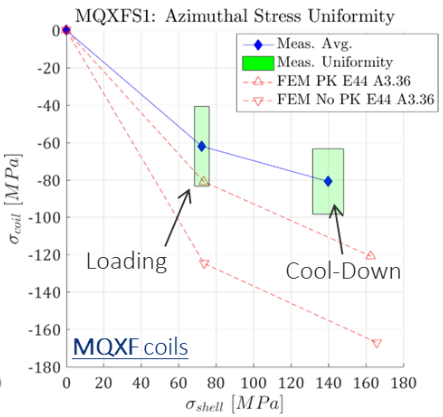








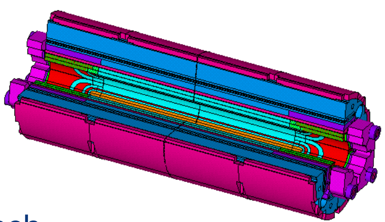




Test campaign planning

- Where the mismatch between the experimental and the numerical results with real coils comes from?
  - Tolerances (as for dummy coils)
  - Measurement technique (as for dummy coils)
  - Coil properties

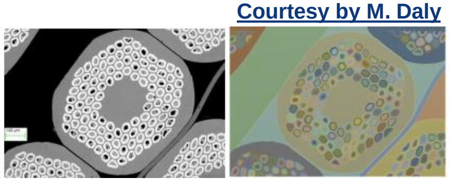
- How to reproduce the coil response in FE model?
  - Macroscale approach (Solid block)



  - Sub-modelling approach

  - Microscale approach

Courtesy by M. Daly



Experimental Test	Sample	Temperature	Loading Direction	Measurements
Free Compression	PIT 10-stack Reacted + Impregnated	300 K	Azimuthal	E_{yy}, ε_{yy}, ν_{yx}, ν_{yz}
			Radial	E_{xx}, ε_{xx}, ν_{xy}, ν_{xz}
			Longitudinal	E_{zz}, ε_{zz}, ν_{zx}, ν_{zy}
		77 K	Azimuthal	E_{yy}, ε_{yy}, ν_{yx}, ν_{yz}
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	RRP 10-stack Reacted + Impregnated	300 K	Azimuthal	E_{yy}, ε_{yy}, ν_{yx}, ν_{yz}
			Radial	E_{xx}, ε_{xx}, ν_{xy}, ν_{xz}
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		77 K	Azimuthal	E_{yy}, ε_{yy}, ν_{yx}, ν_{yz}
			Radial	E_{xx}, ε_{xx}, ν_{xy}, ν_{xz}
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Cable stack

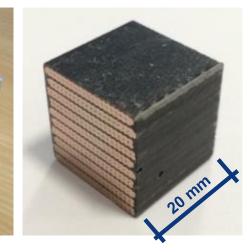
Parameter	Unit	MQXF
Strand diameter	mm	0.85
Fabrication process		RRP, PIT
Number of filaments		132, 192
Nominal sub-element diameter	um	<50
RRR after full heat treatment		>150
Cu/non-Cu		1.2
Minimum Ic (15 T, 4.222 K)*	A	361
Number of strands		40
Cabling degradation	%	<5
Cable bare width	mm	18.15
Cable bare mid-thickness	mm	1.525
Keystone angle	Deg.	0.55

- The study of the mechanical properties must be carried out on representative samples of the coil.
  - Dedicated moulds for reaction and impregnation (1.2% width and 4.5% thickness growth considered);
  - Fiberglass: TEX 636, ceramic binder: CTD-1202, epoxy: CTD-101K;
  - 18.7×18.85×150 mm long cable stack (RRP coil 106, PIT coil 203).

Reaction Mould

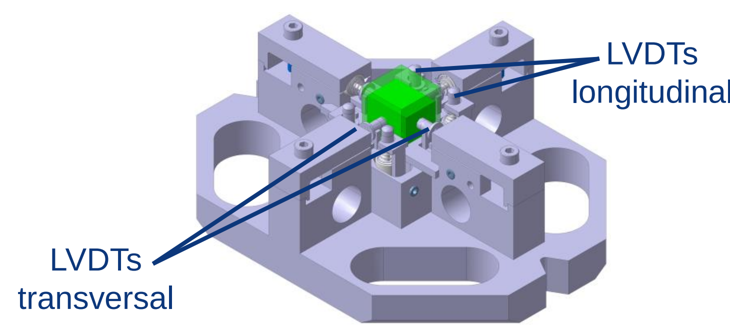
Impregnation Mould

Cutting tool



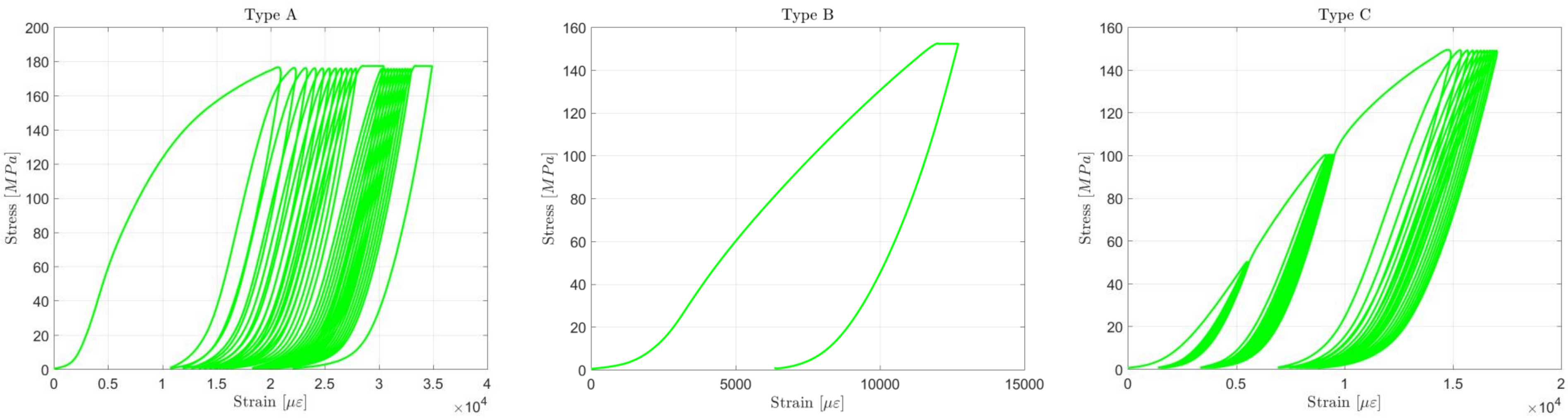
10-Cables stack

- Dedicated and validated test bench equipped with 8 LVDTs to measure:
  - Stress-strain relationship in all directions;
  - Transverse-longitudinal strain relationship.



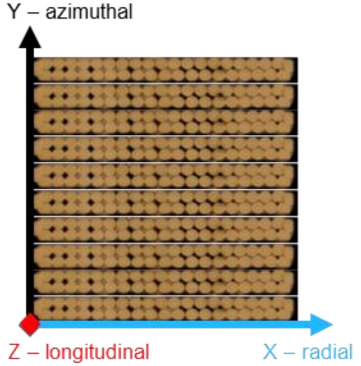
Experimental tests

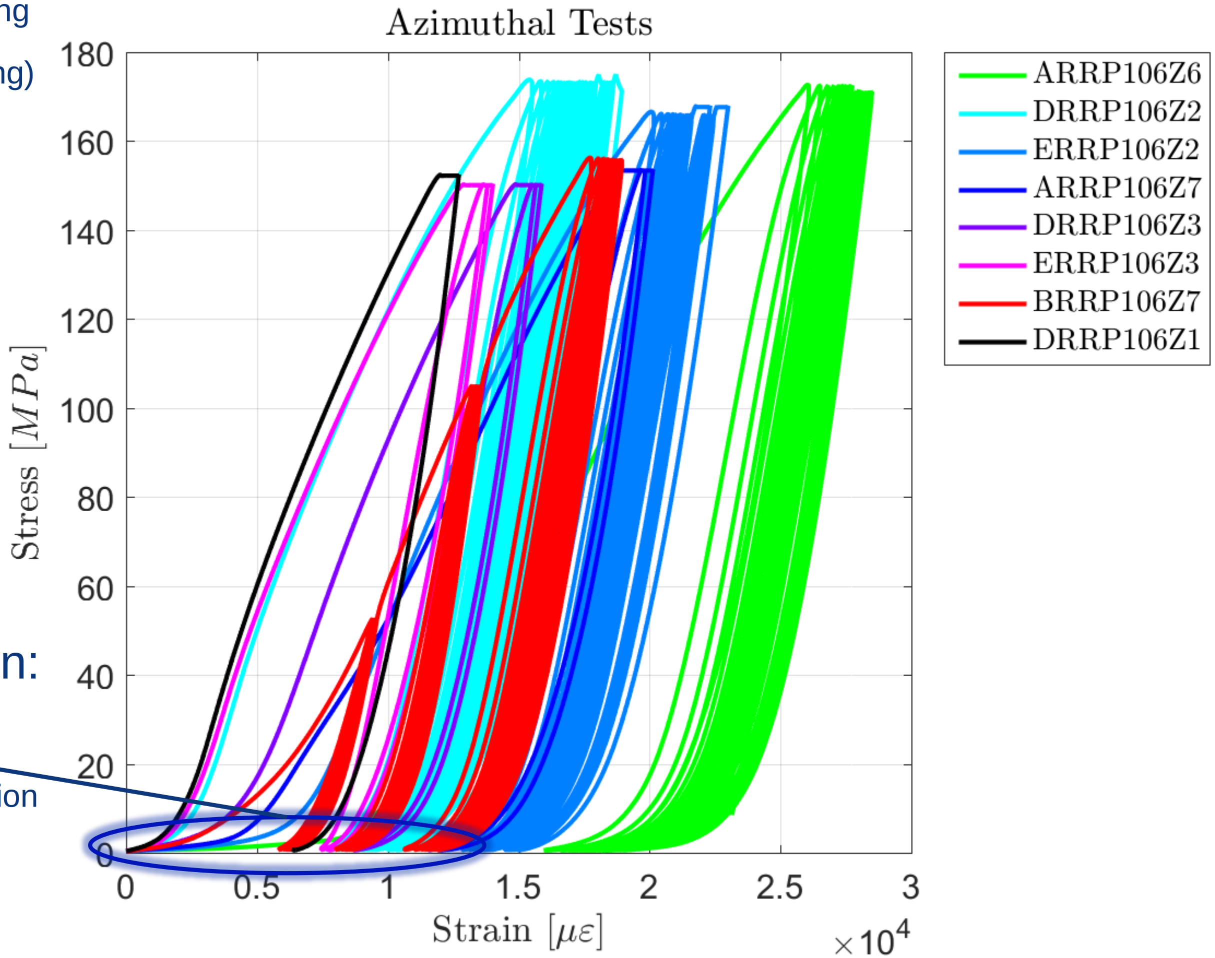
- Different test typologies to study the cable stack behavior during loading, unloading and cycling phases.
  - **Type A**: Single step load and cycling
  - **Type B**: Single step load (no cycling) + load holding
  - **Type C**: Multistep load and cycling



Experimental results – Azimuthal (1)

- 8 tests in azimuthal direction have been performed.
  - **3 of type A**: Single step load and cycling
  - **4 of type B**: Single step load (no cycling)
  - **1 of type C**: Multistep load and cycling





- Significant initial deformation:
  - Cable stack compaction
  - Pre-load does not reduce data dispersion
  - Cycling phases look very similar

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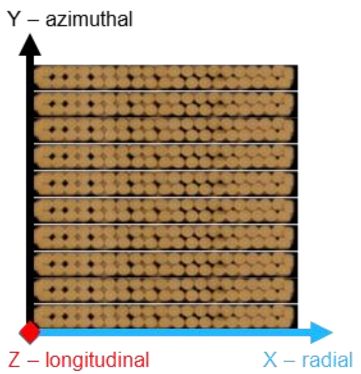

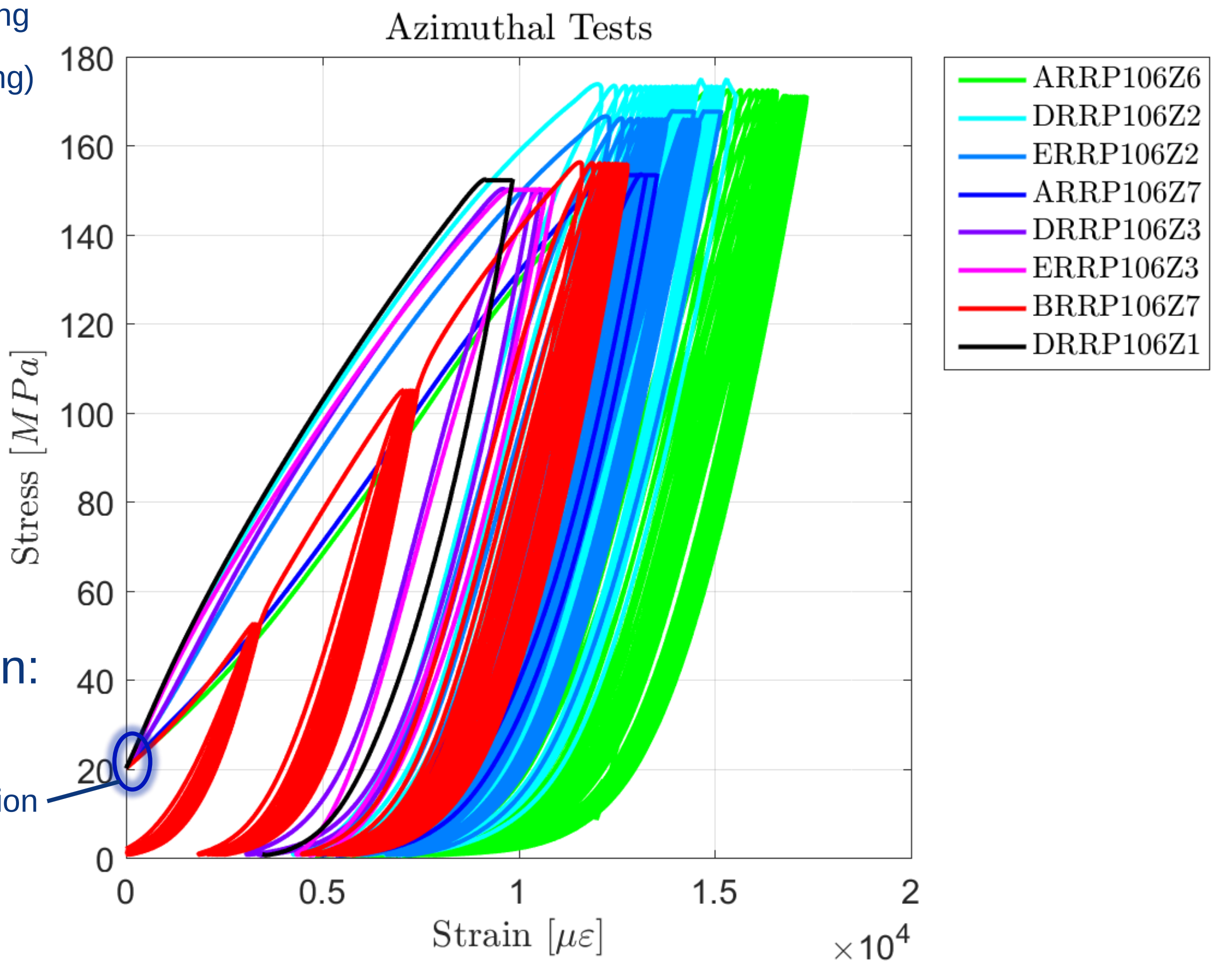

- Significant initial deformation:
  - Cable stack compaction
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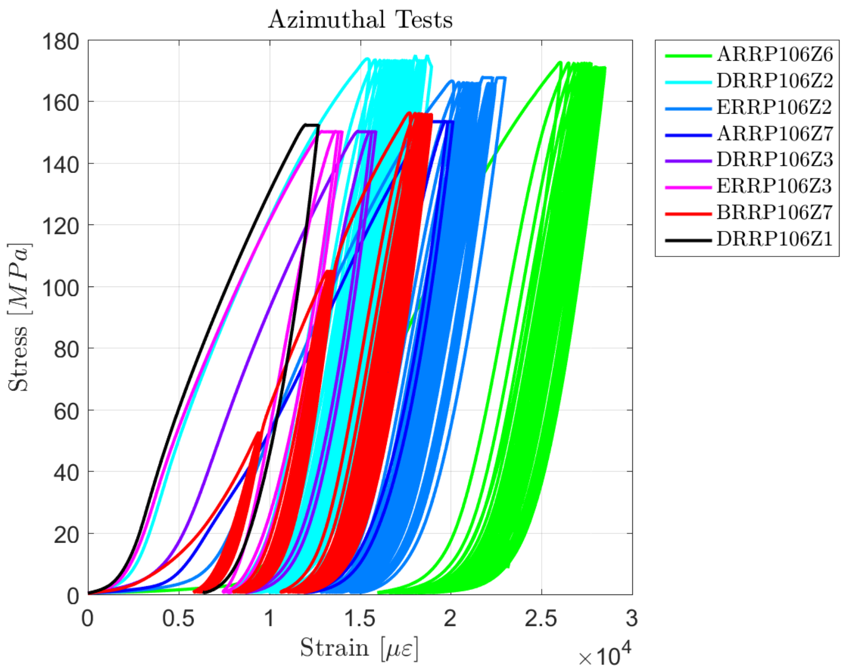
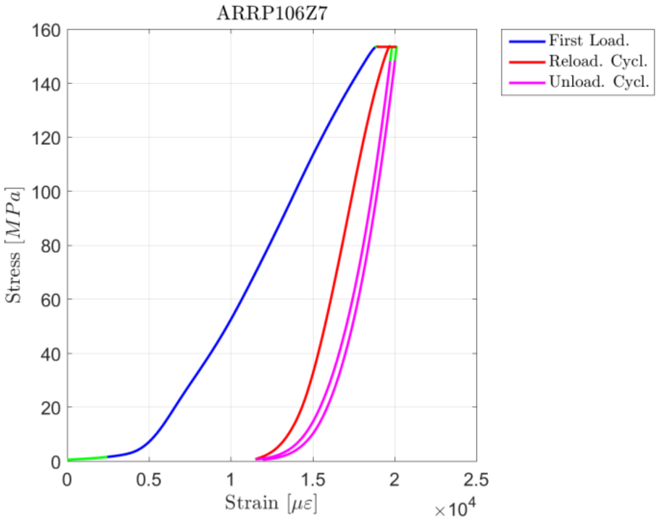
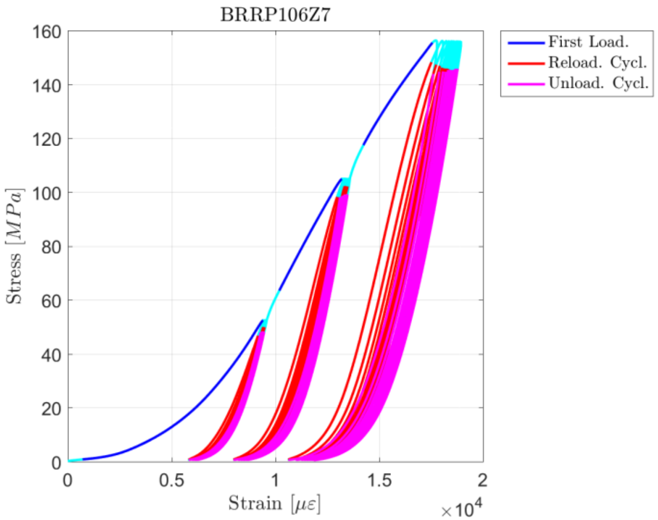
Experimental results – Azimuthal (2)

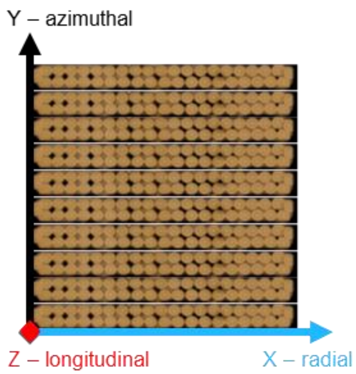
- Splitting the curves in three phases simplifies the data analysis:
  - First loading phase
  - Unloading cyclic phase
  - Reloading cyclic phase

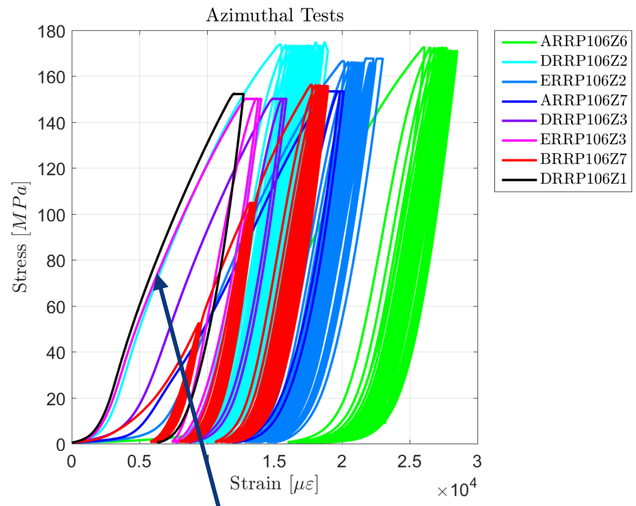






Experimental results – Azimuthal (3)





By definition, the material stiffness is the slope of the stress-strain curve:

$$K = \frac{d\sigma}{d\varepsilon}$$

If K is constant, linear elastic assumption is valid and K is known as elastic modulus or Young's modulus (E).

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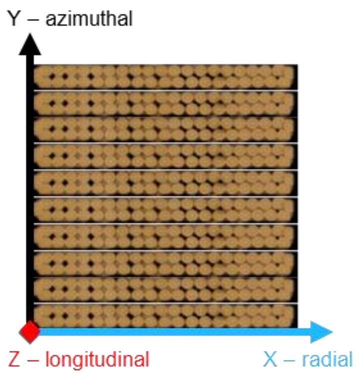

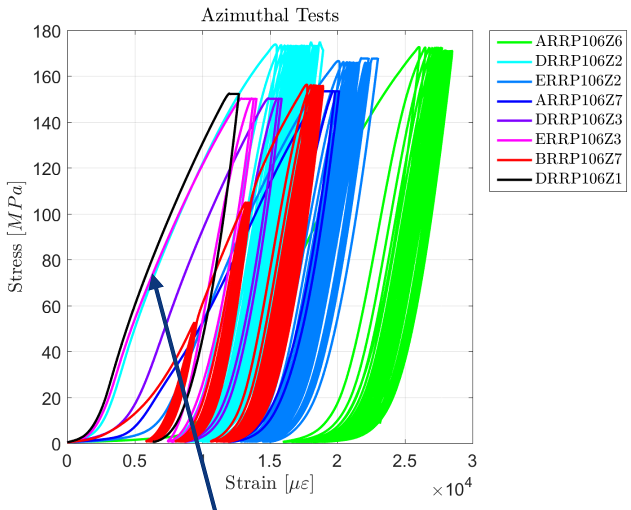

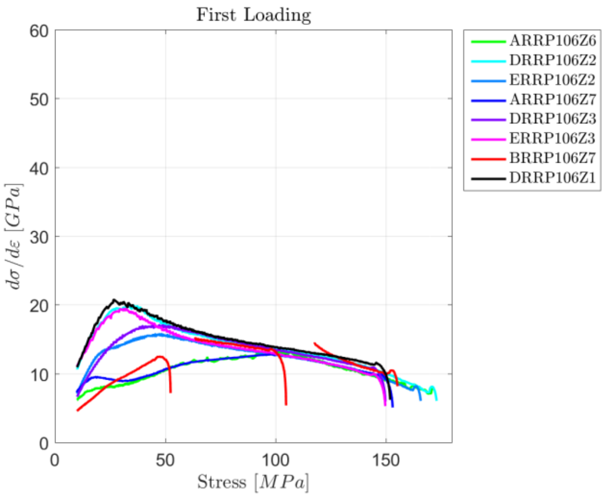

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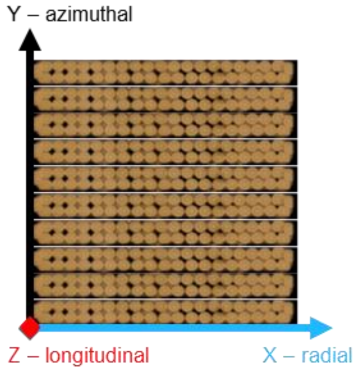

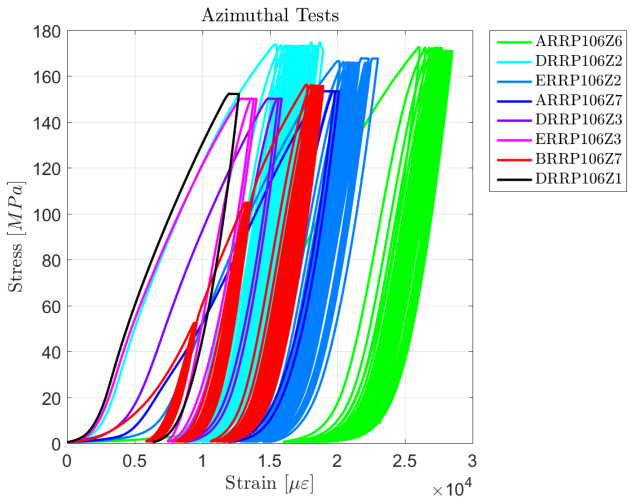

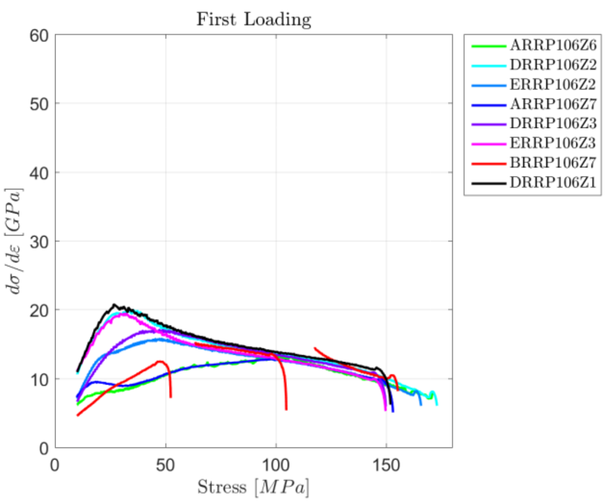

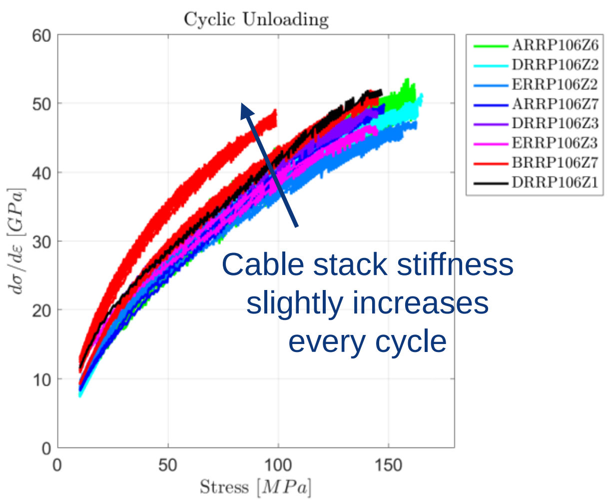

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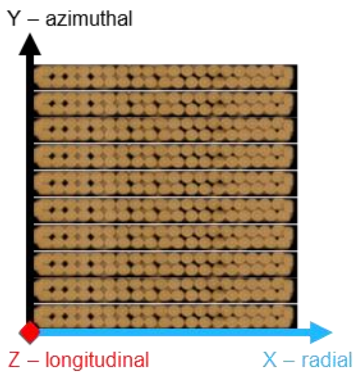

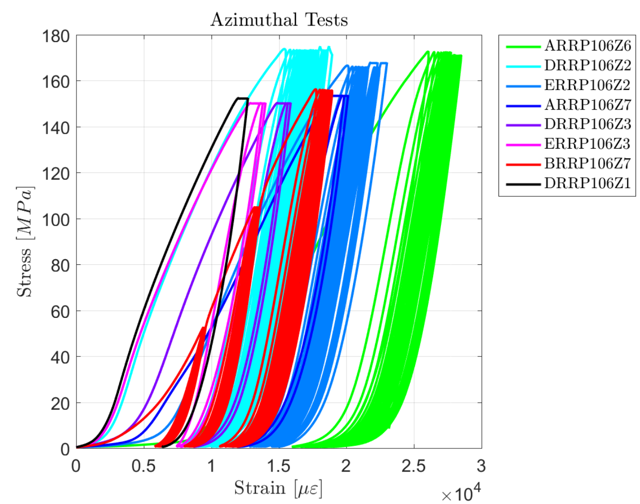

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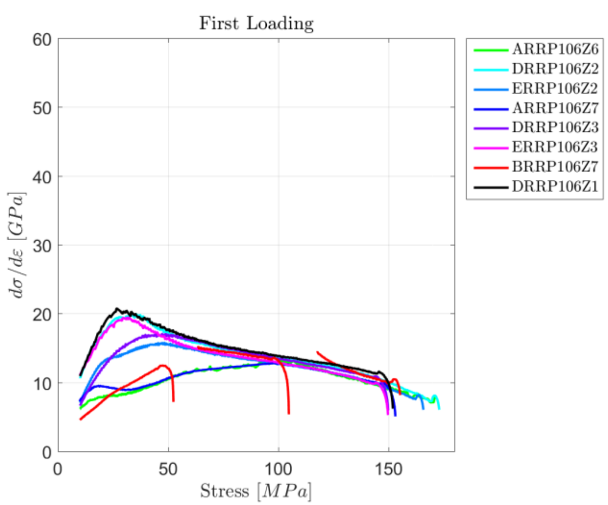
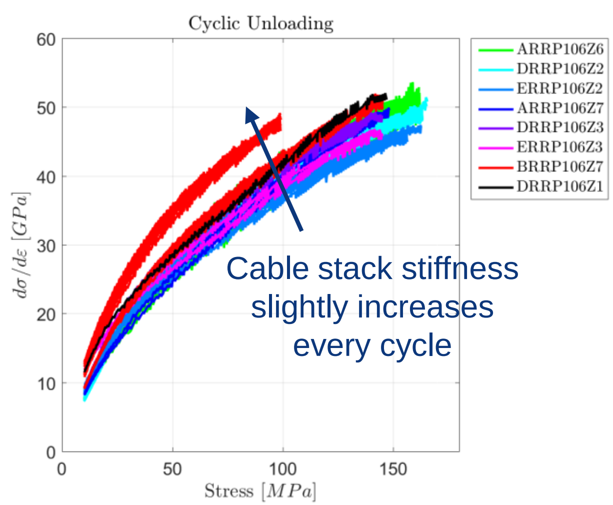
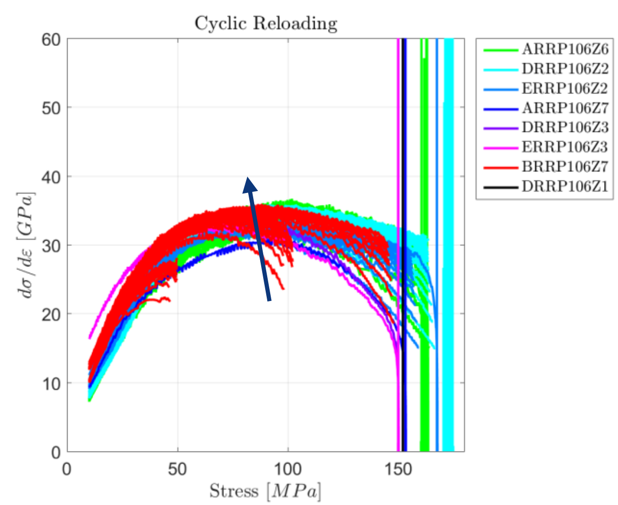
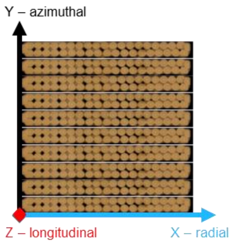
- Elastic assumptions are not recommended to reproduce this behavior.

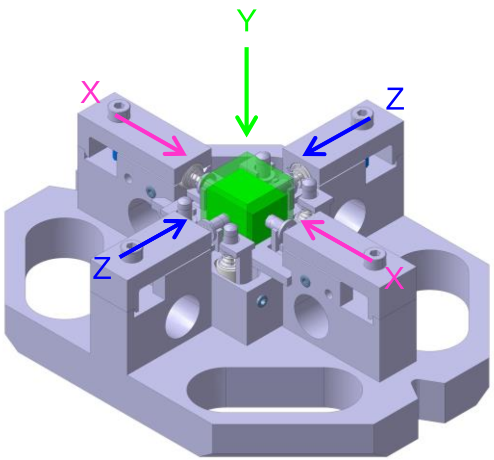






Experimental results – Azimuthal (4)



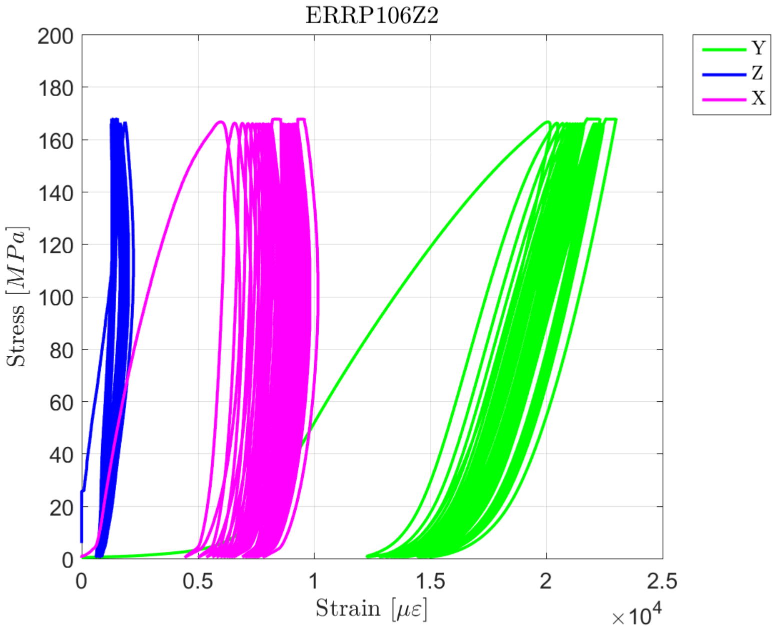


The relationship between the vertical and lateral deformations is commonly defined by:

$$\nu_{XY} = -\frac{\varepsilon_X}{\varepsilon_Y}$$

$$\nu_{ZY} = -\frac{\varepsilon_Z}{\varepsilon_Y}$$

If ν is constant, linear elastic assumption is valid and ν is known as Poisson's ratio.



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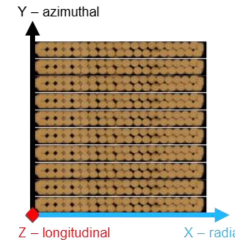

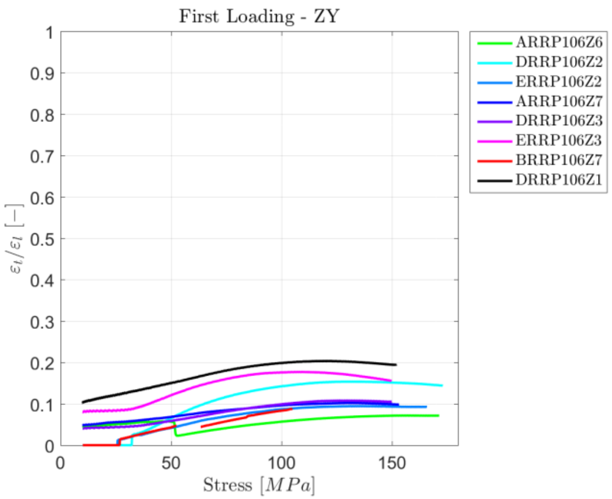

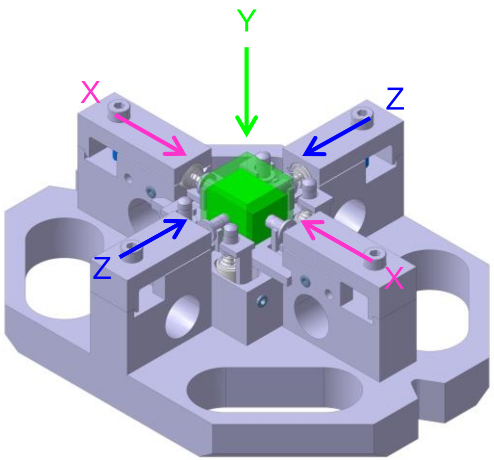

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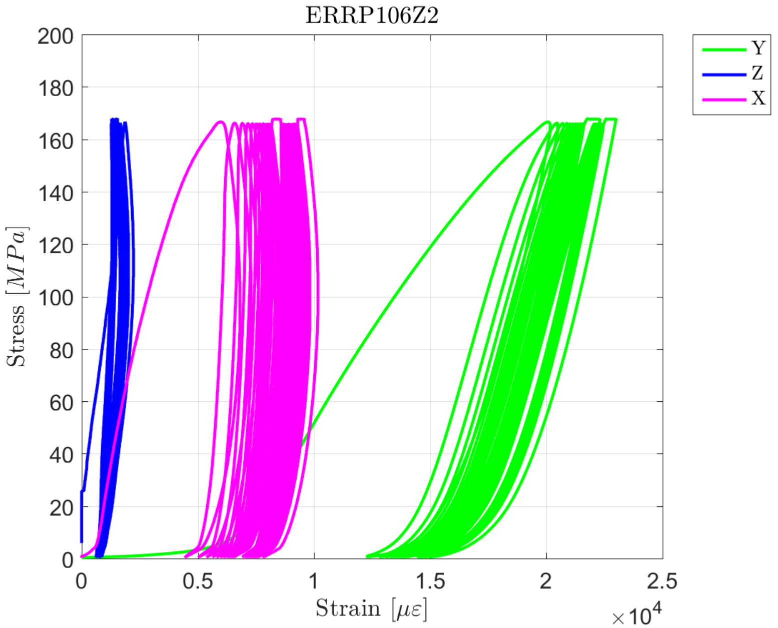

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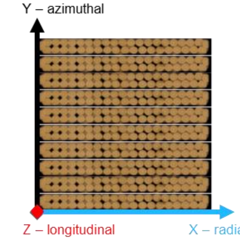
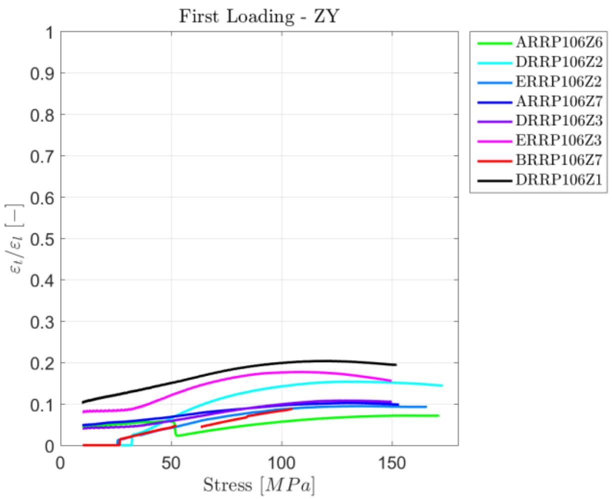
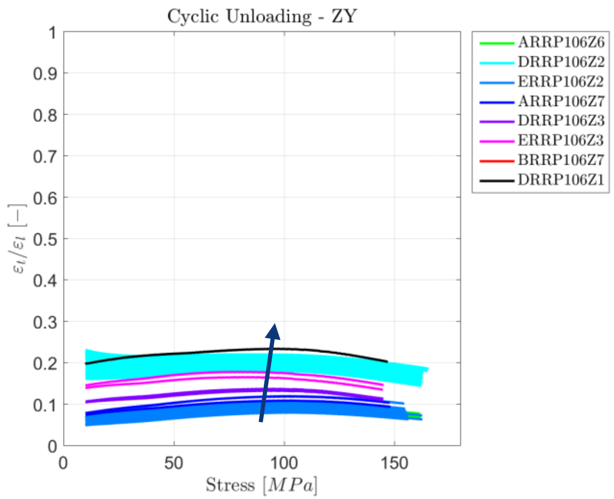
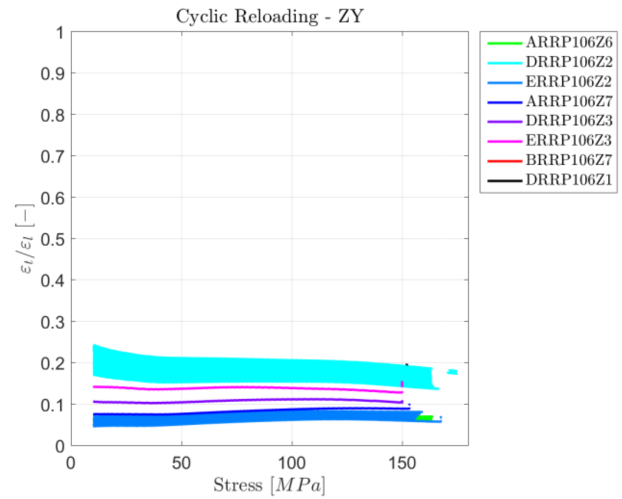


- Longitudinal-Azimuthal strain relationship:







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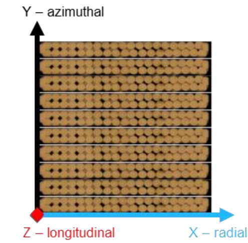

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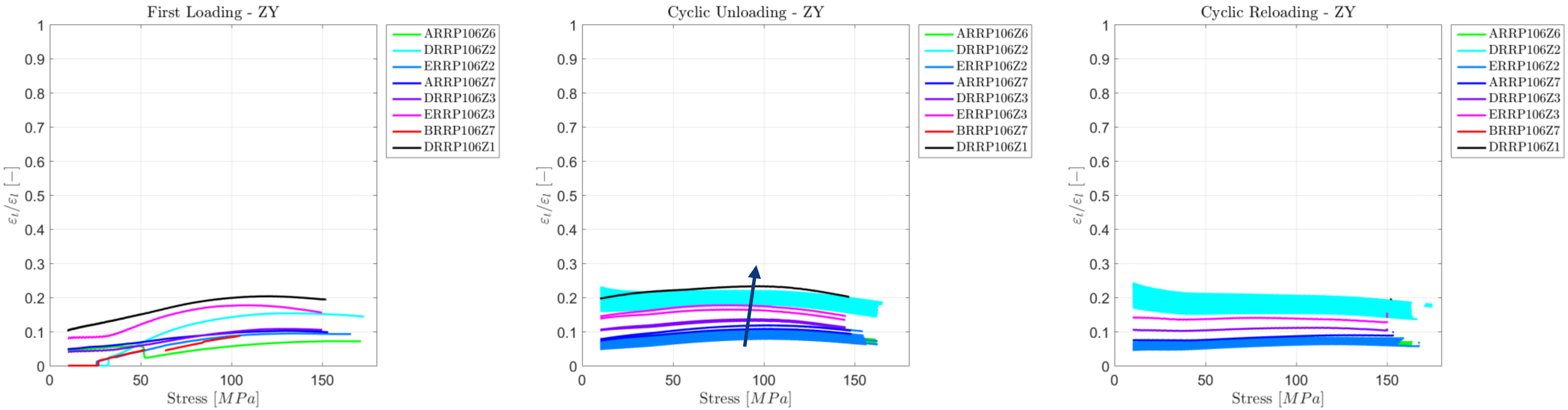
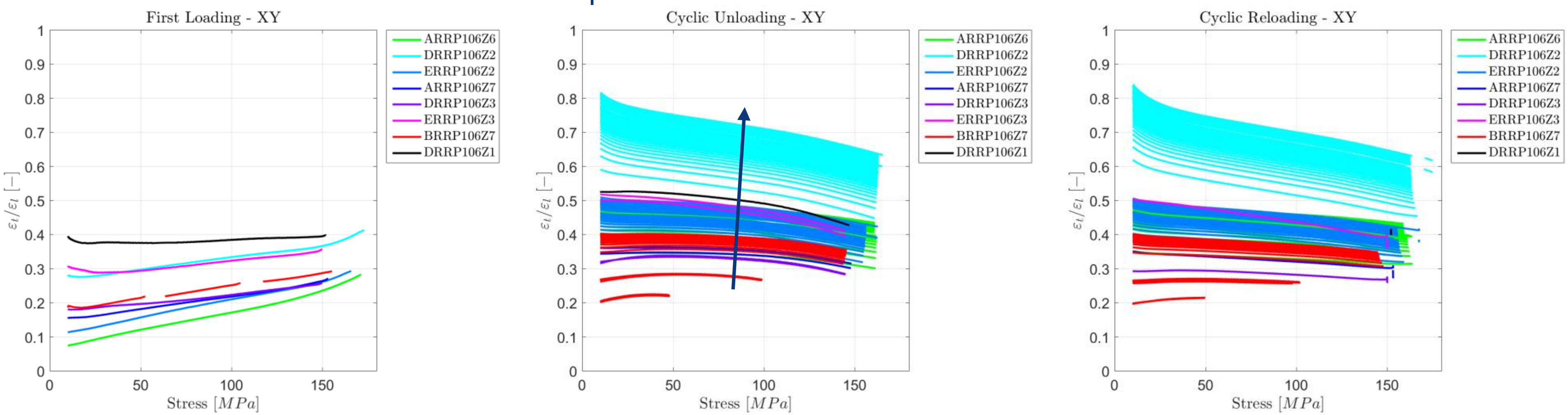
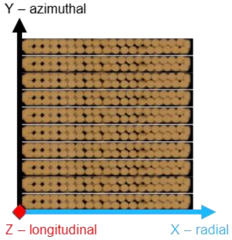


- Radial-Azimuthal strain relationship:



Experimental results – Radial (1)



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  - **3 of type A**:

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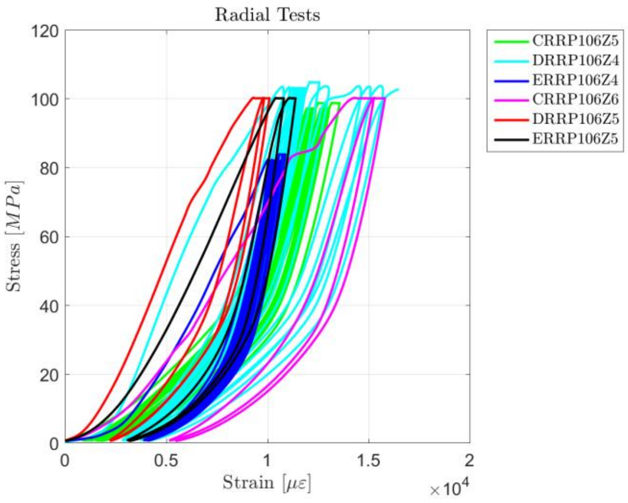
    Single step load (no cycling)



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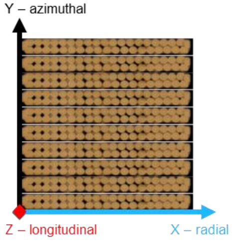

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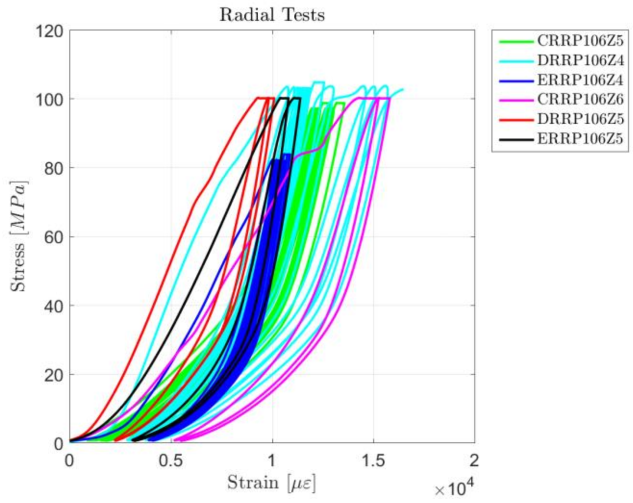

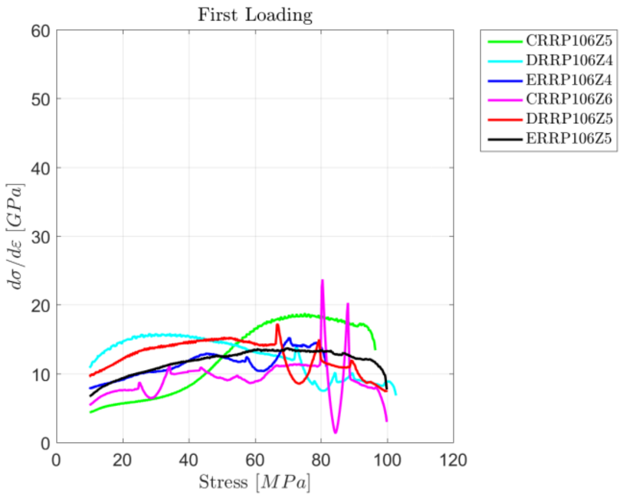

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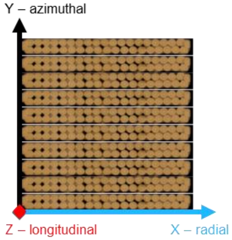

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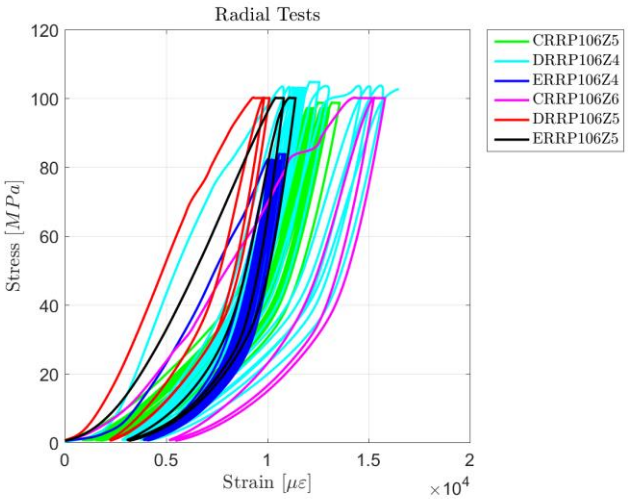

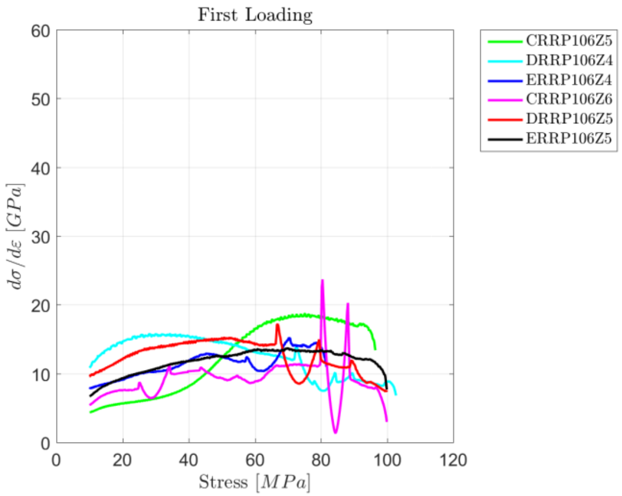

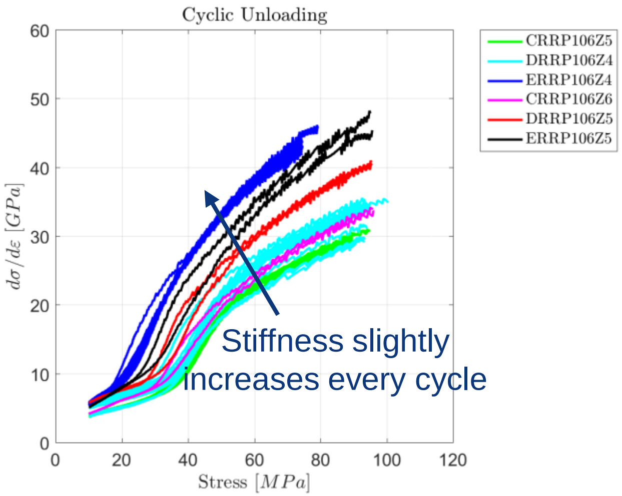

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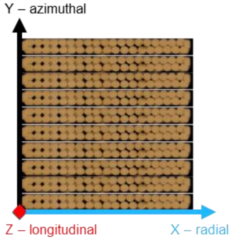

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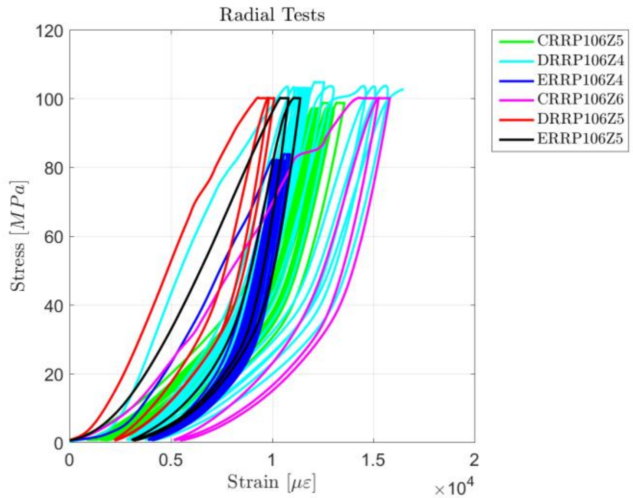
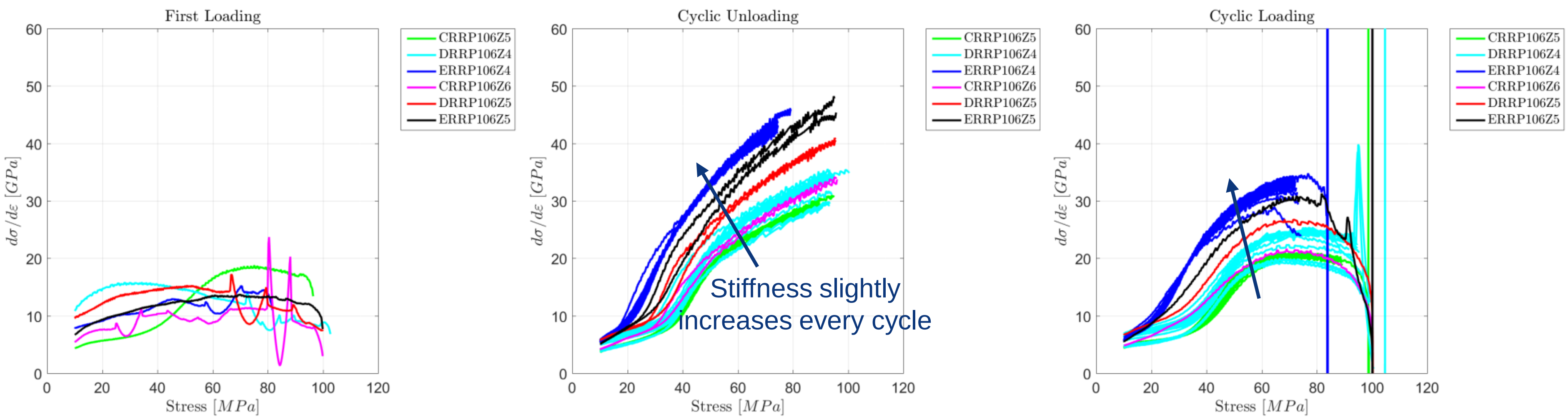
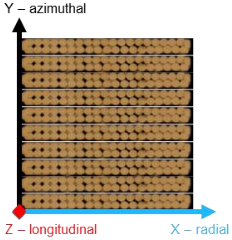


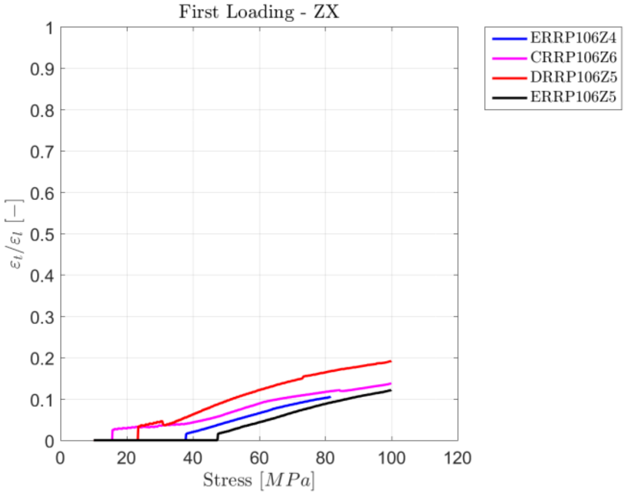
- The cable stack stiffness is strongly depended by the stress level.
- Elastic assumptions are not recommended to reproduce this behavior.
- Cable stack delamination at low stresses.

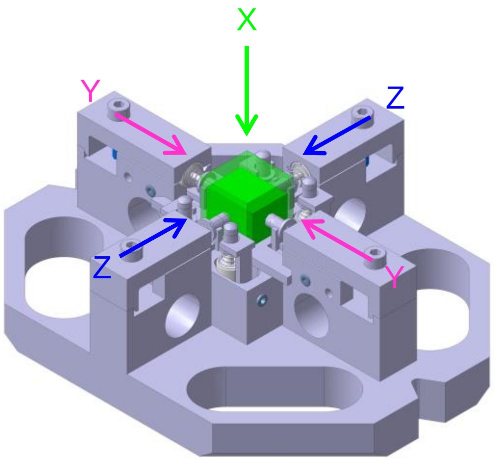


Experimental results – Radial (2)



- Longitudinal-Radial strain relationship:





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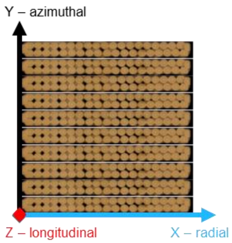
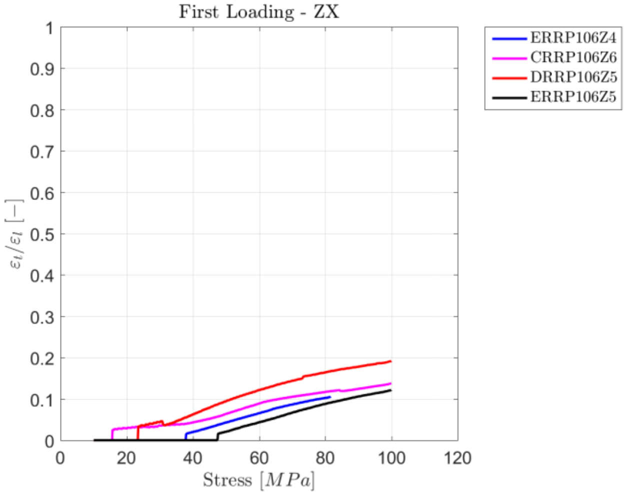
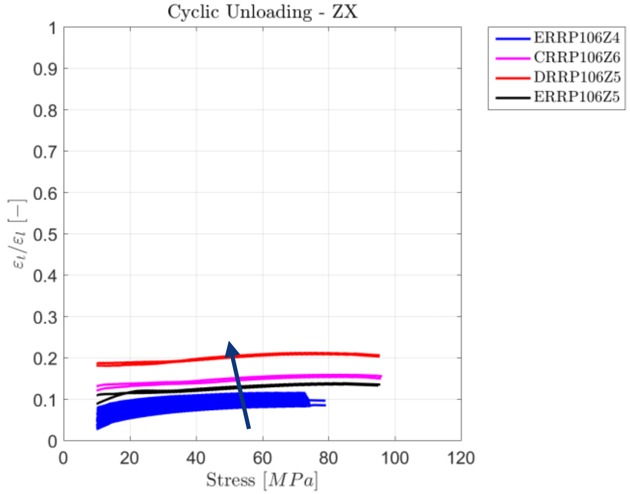
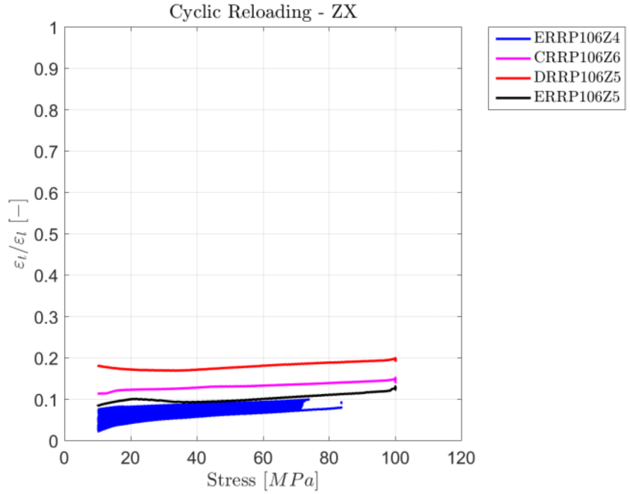
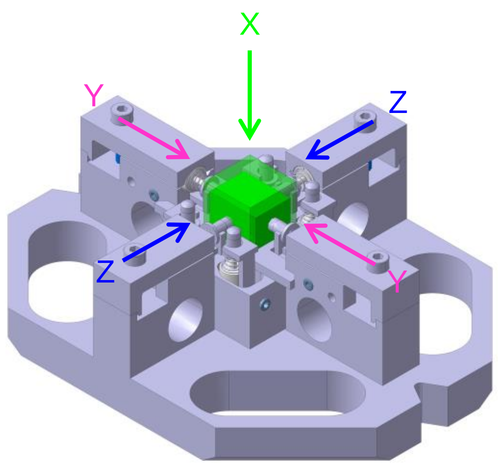


- Longitudinal-Radial strain relationship:

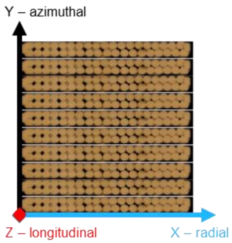




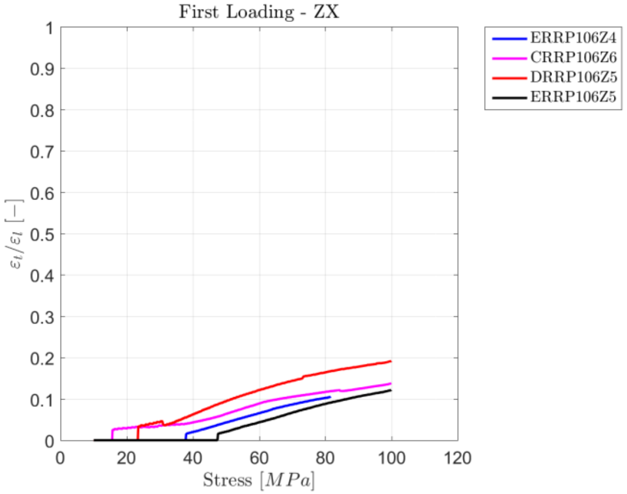


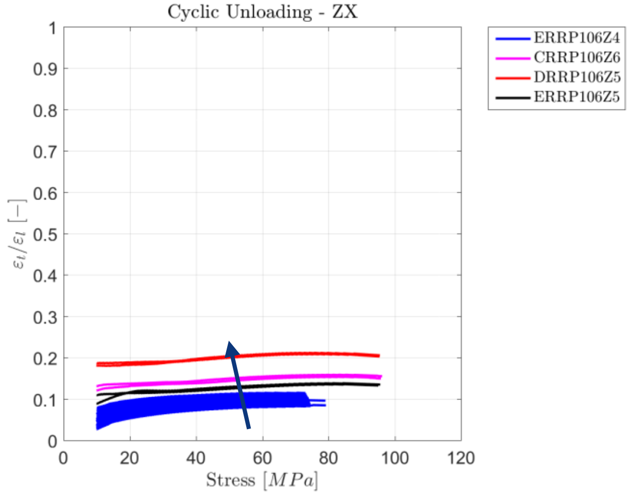


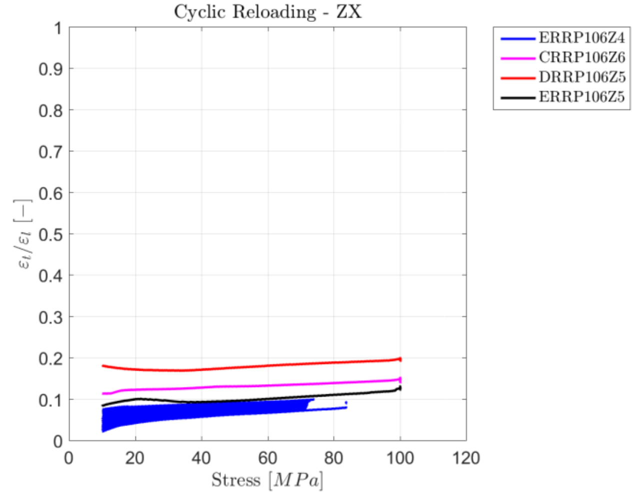
Experimental results – Radial (2)



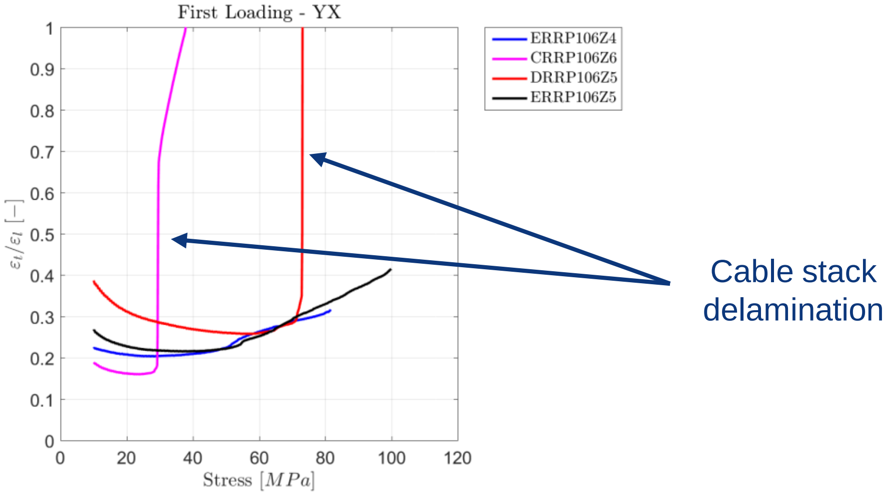
- Longitudinal-Radial strain relationship:



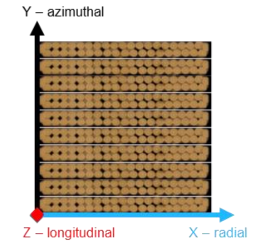




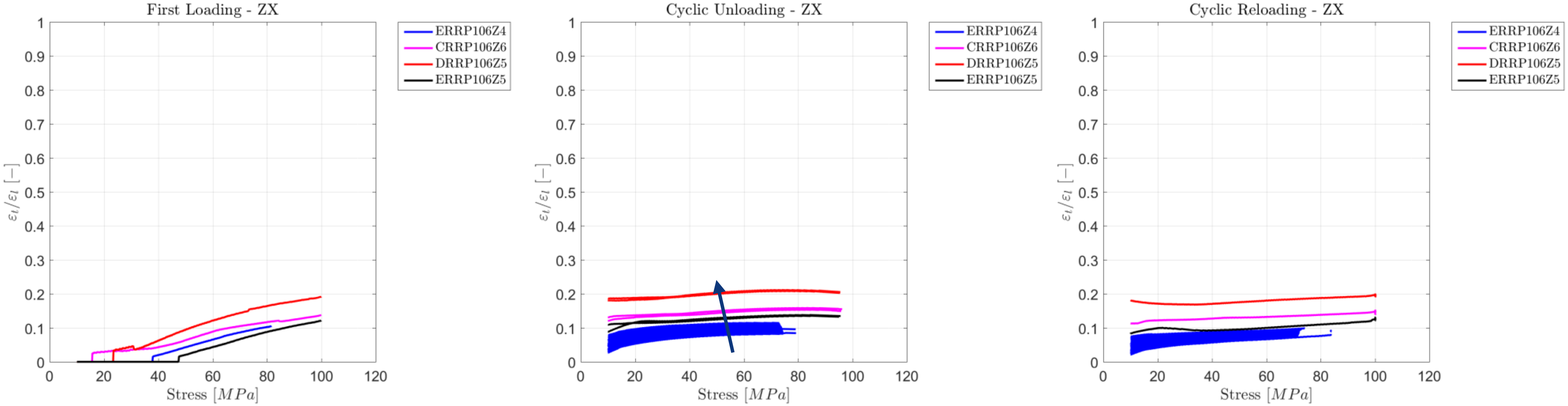
- Azimuthal-Radial strain relationship:



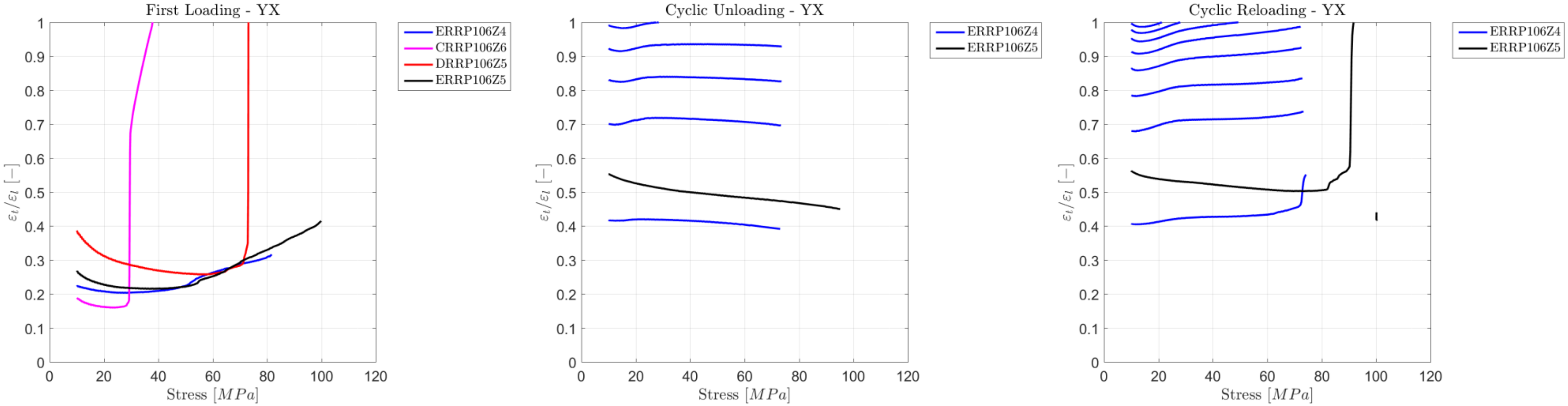
Experimental results – Radial (2)



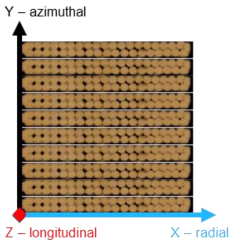
- Longitudinal-Radial strain relationship:



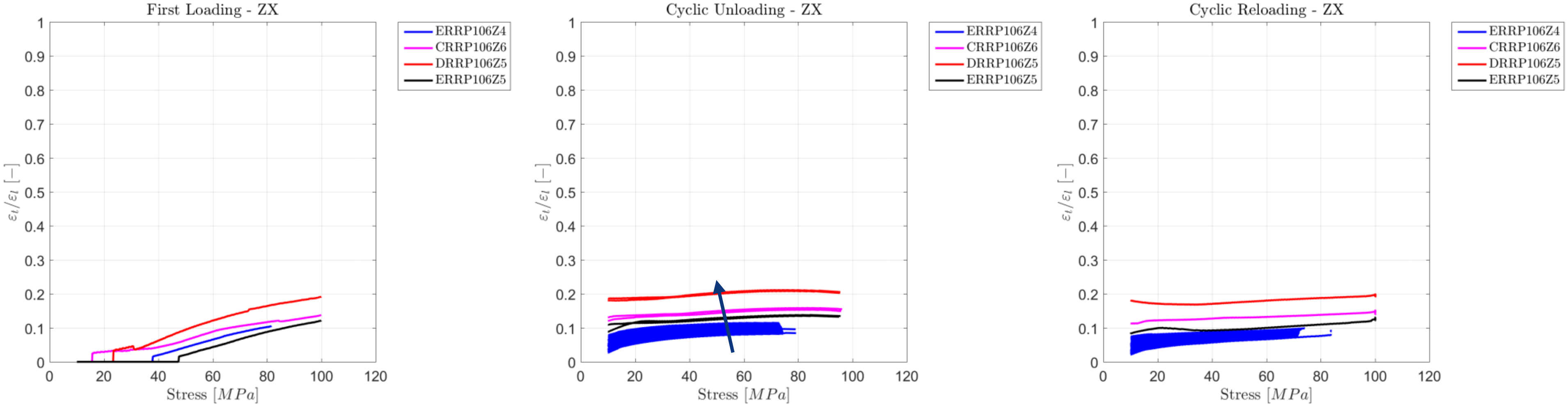
- Azimuthal-Radial strain relationship:



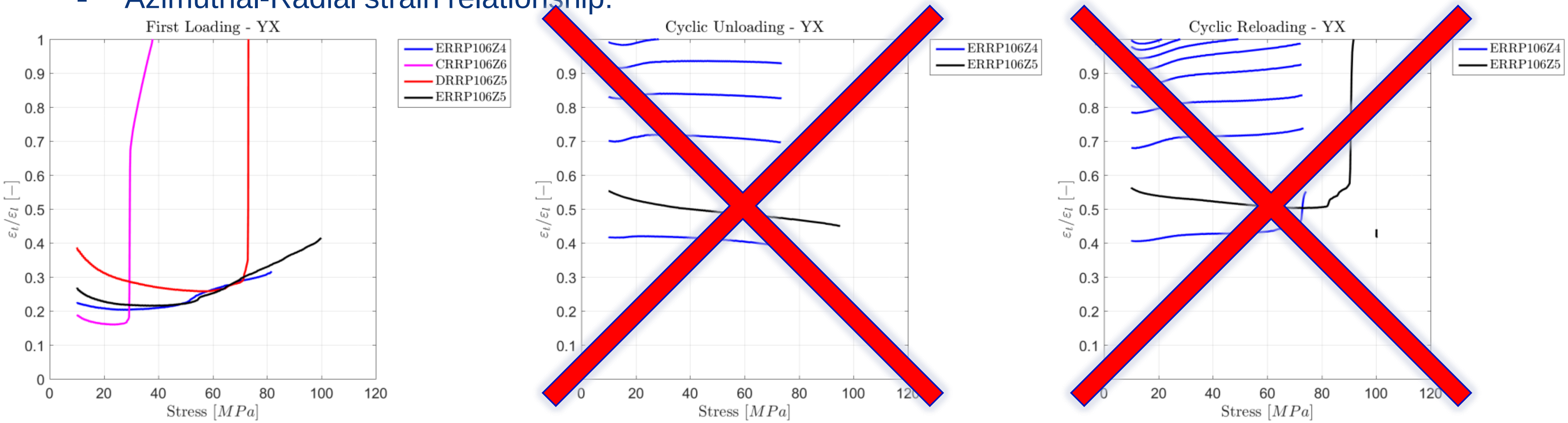
Experimental results – Radial (2)



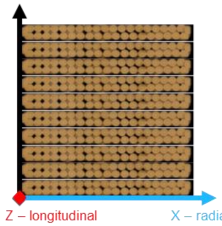
- Longitudinal-Radial strain relationship:



- Azimuthal-Radial strain relationship:



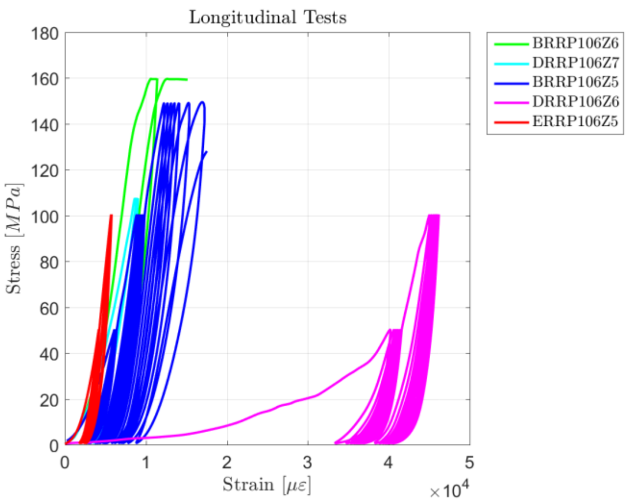
Experimental results – Longitudinal



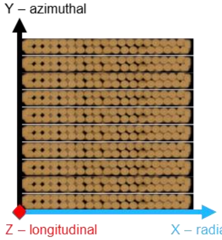
- 5 tests in radial direction have been performed.
  - **2 of type B**:

    Single step load (no cycling)
  - **3 of type C**:

    Multistep load and cycling



Experimental results – Longitudinal



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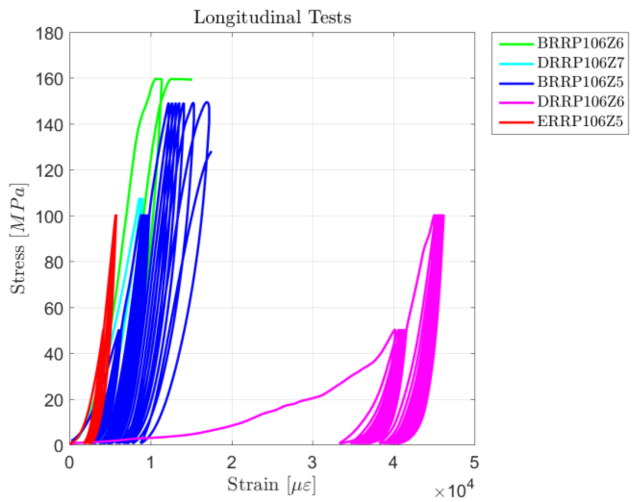
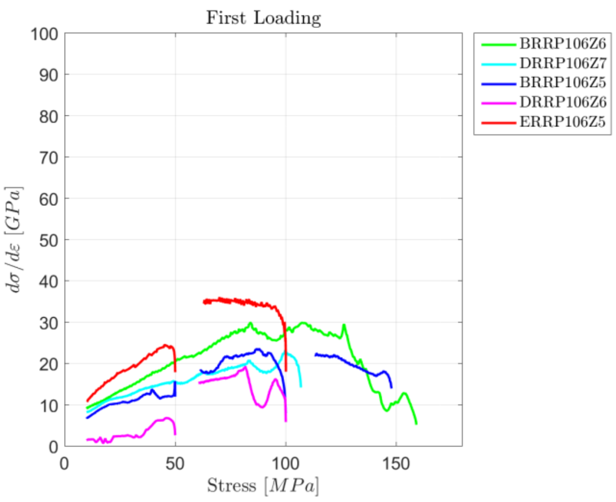
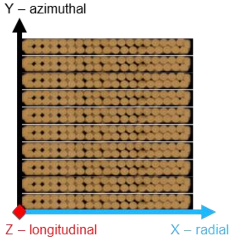




Experimental results – Longitudinal



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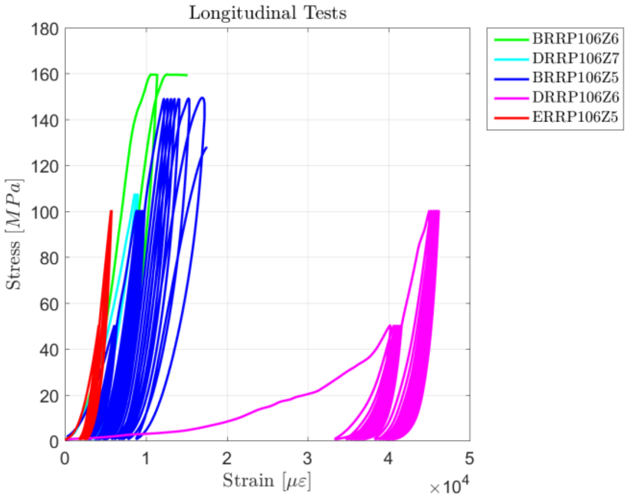
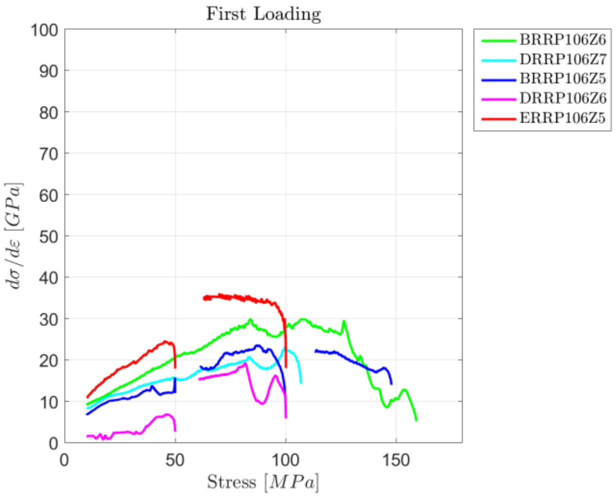
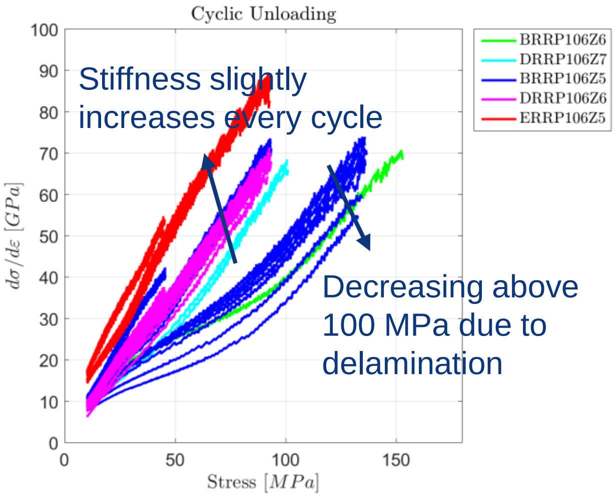
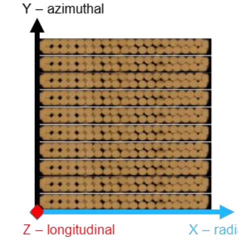






Experimental results – Longitudinal



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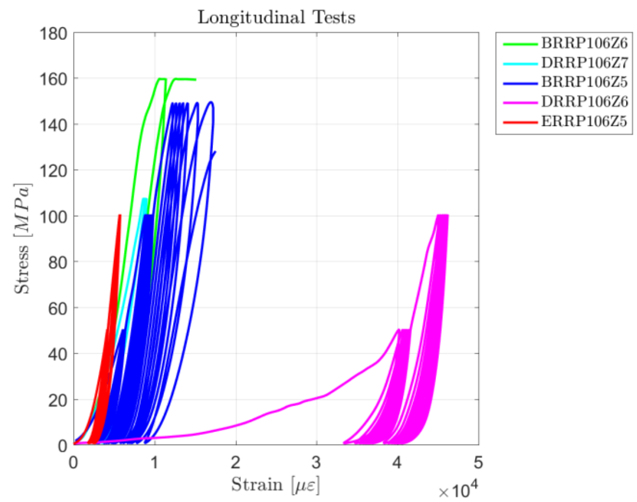
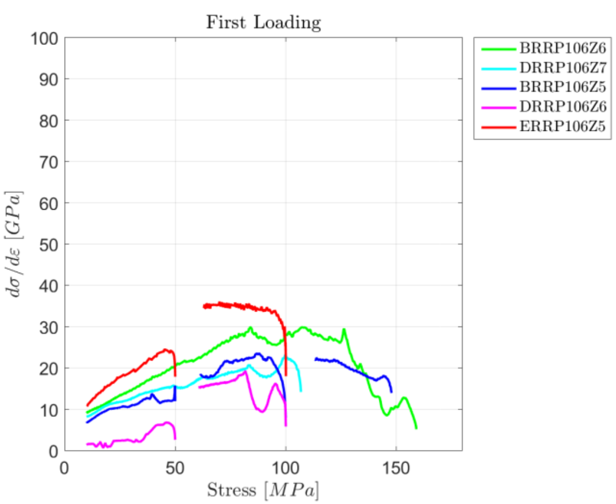
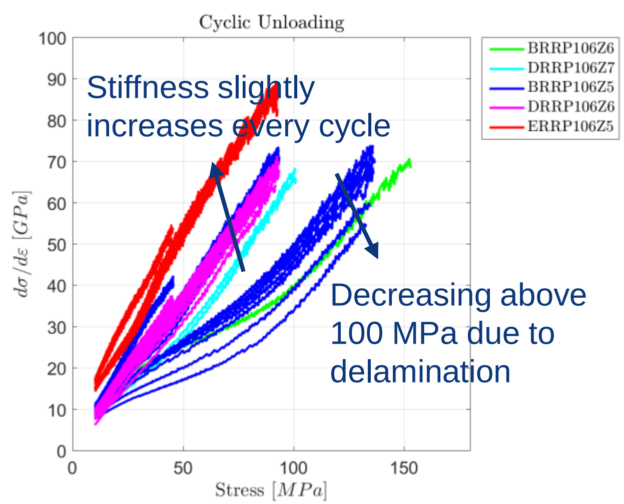
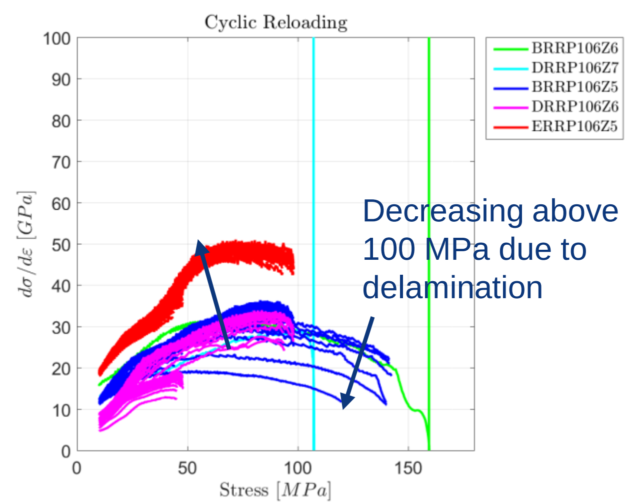


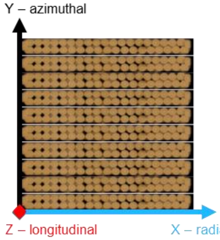
- The cable stack stiffness is strongly depended by the stress level.
- Elastic assumptions are not recommended to reproduce this behavior.
- Cable stack delamination at low stresses.
- Cable stack length could affect the results.



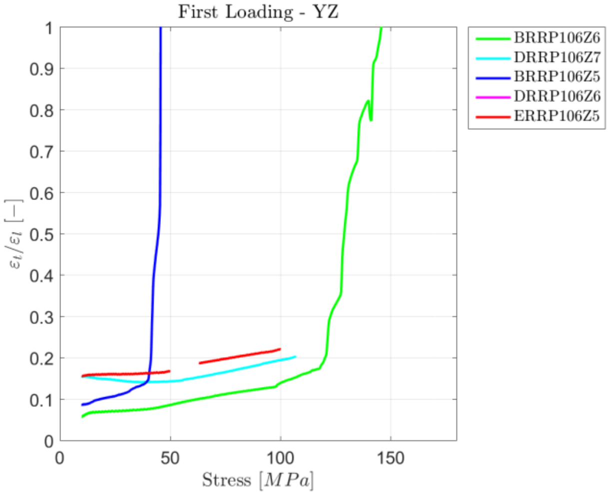


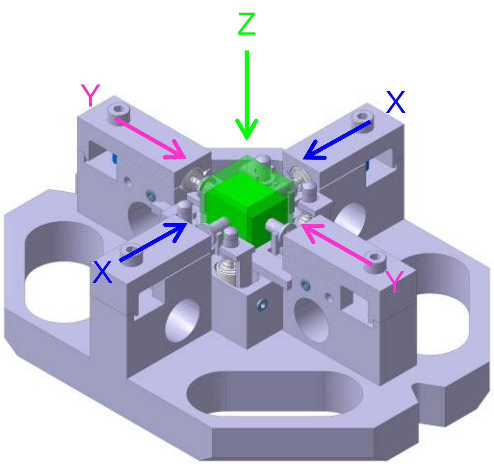


Experimental results – Longitudinal

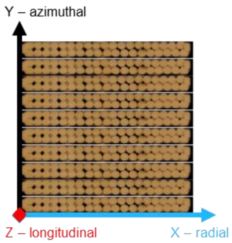


- Azimuthal-Longitudinal strain relationship:

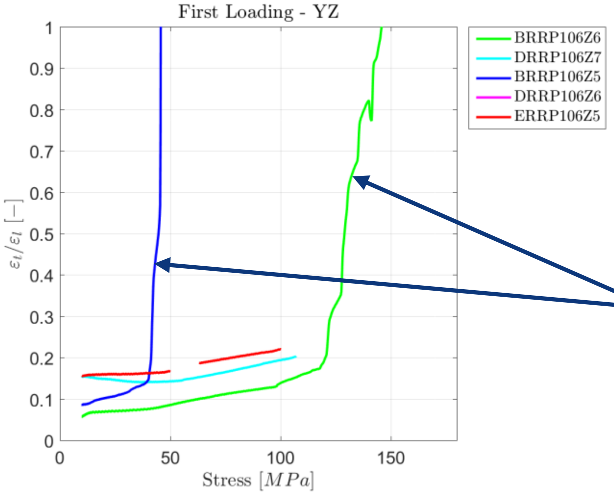


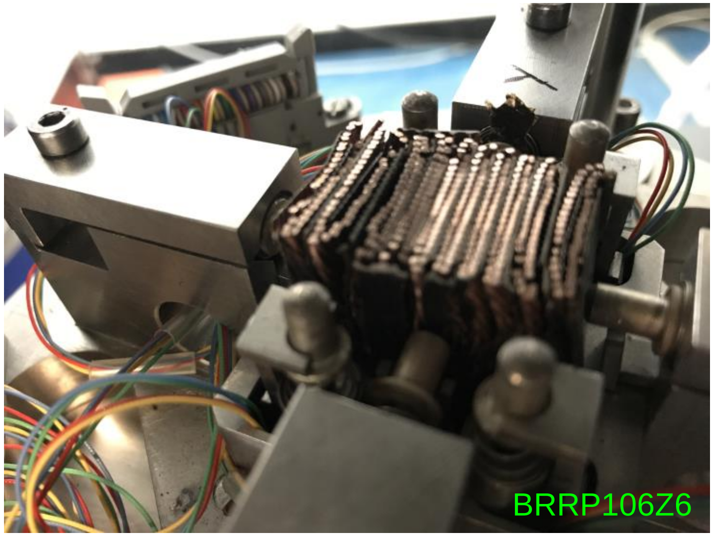


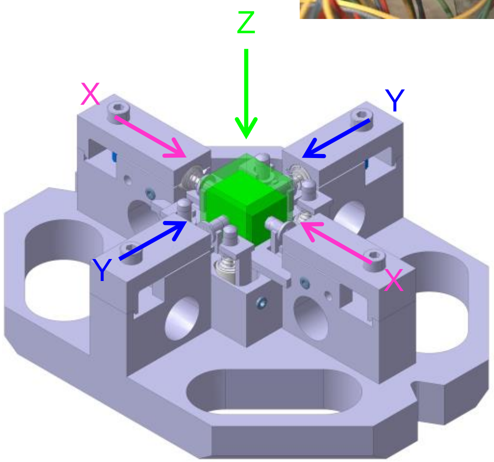
Experimental results – Longitudinal



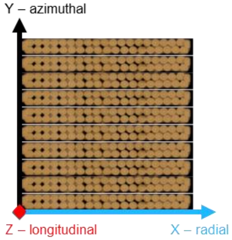
- Azimuthal-Longitudinal strain relationship:



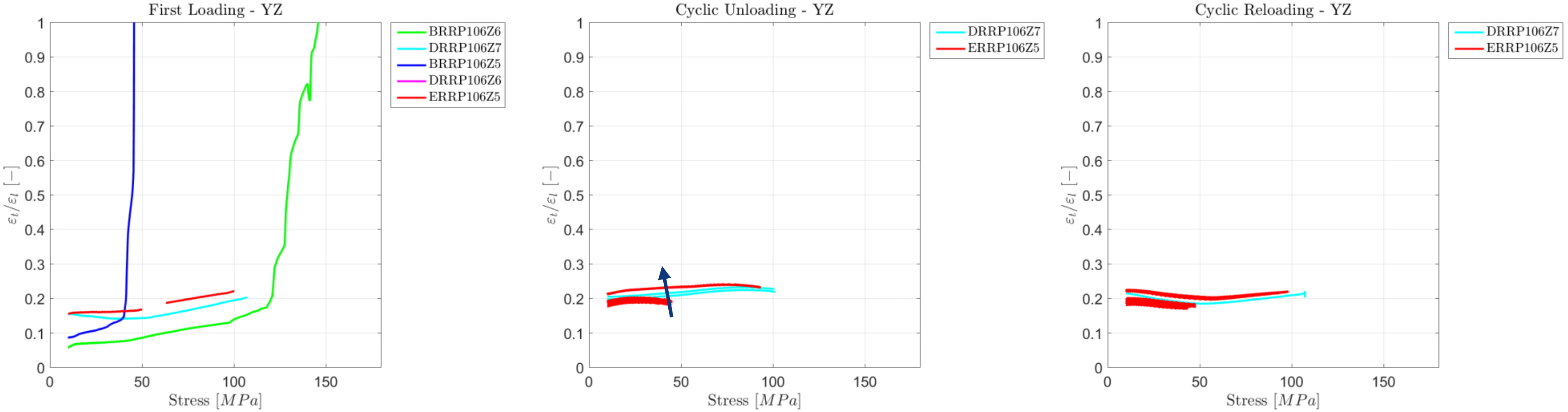


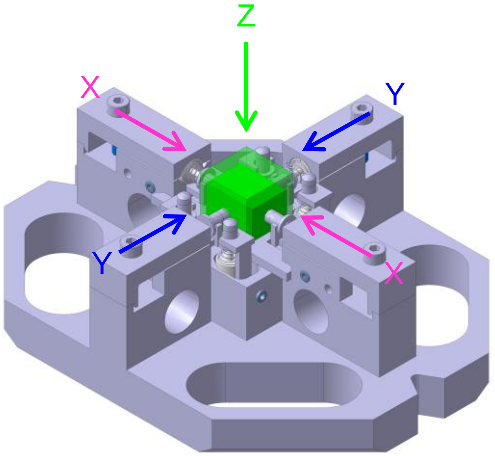


Experimental results – Longitudinal

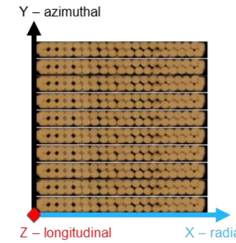


- Azimuthal-Longitudinal strain relationship:

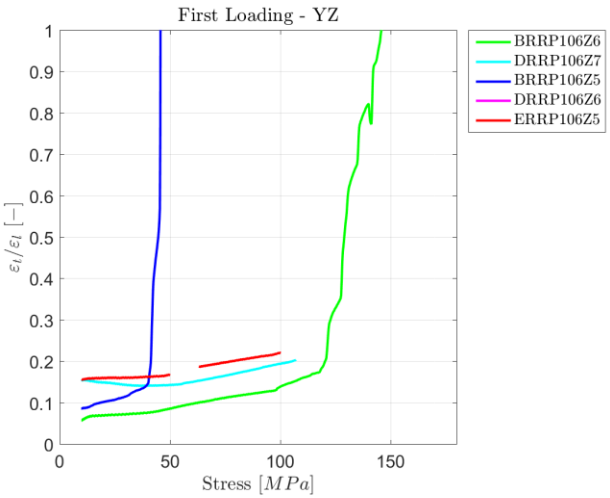


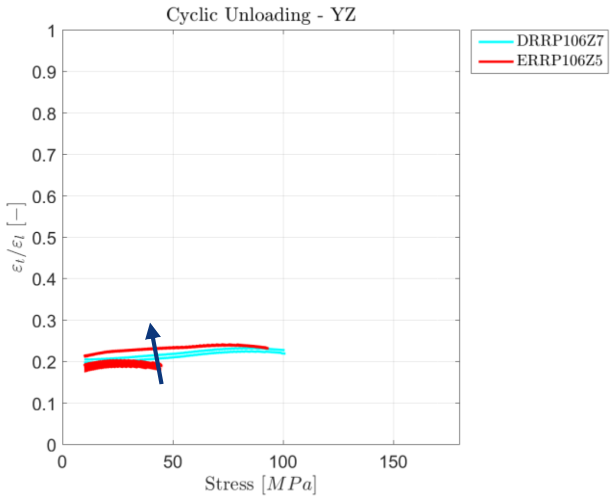


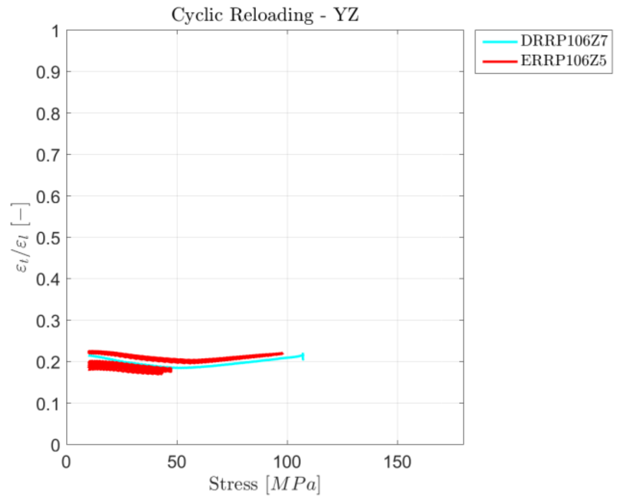
Experimental results – Longitudinal



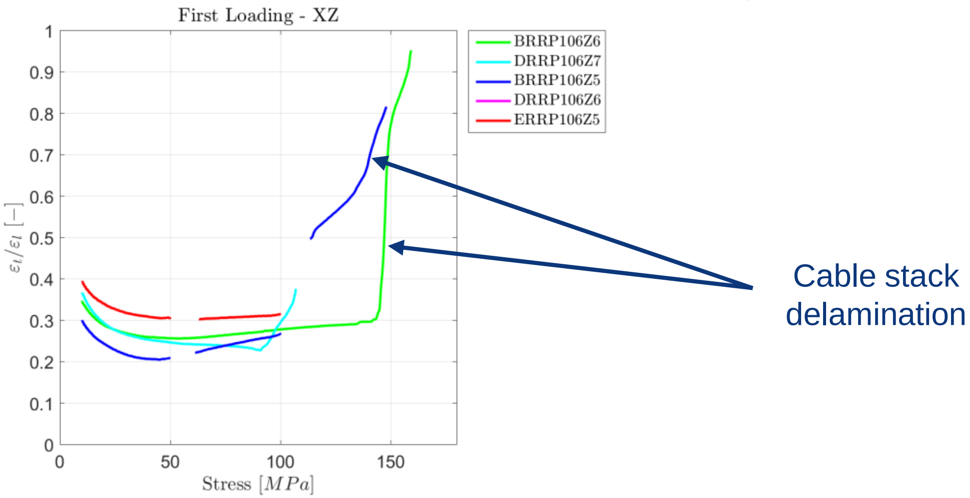
- Azimuthal-Longitudinal strain relationship:



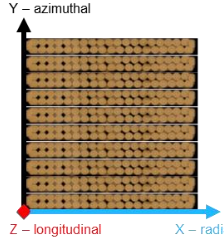




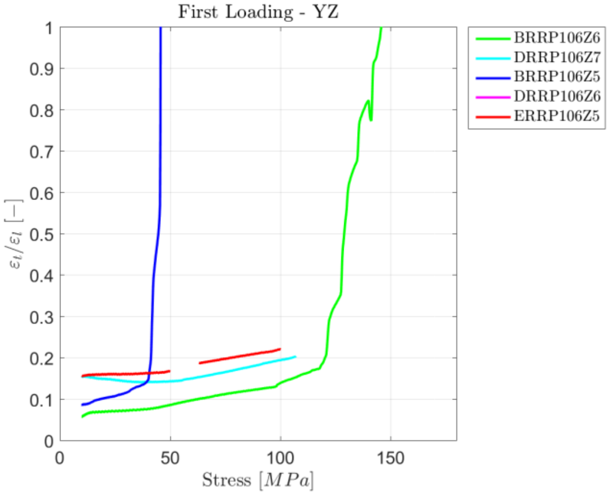
- Radial-Longitudinal strain relationship:

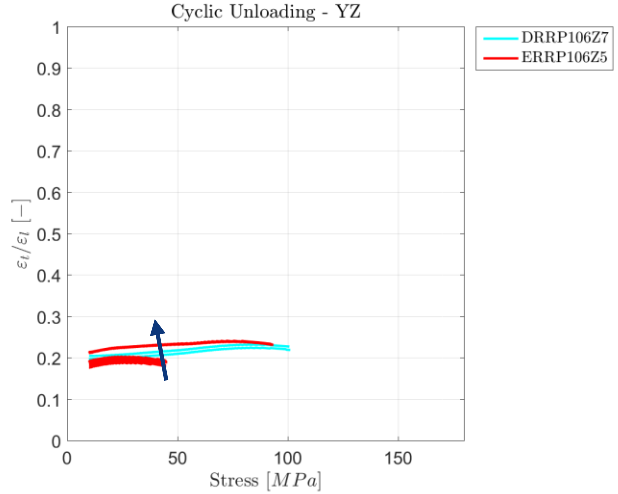


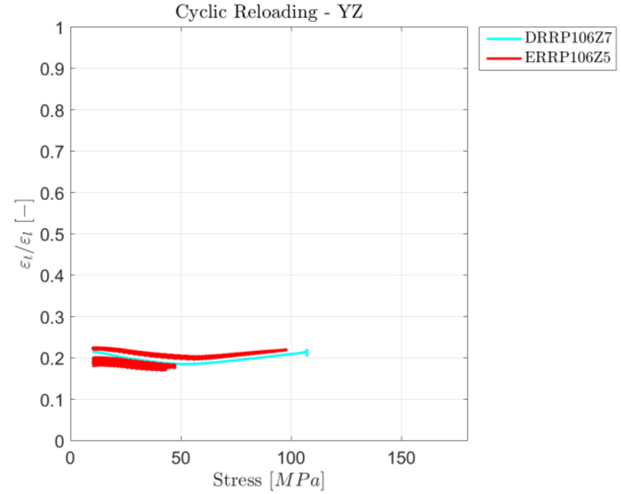
Experimental results – Longitudinal



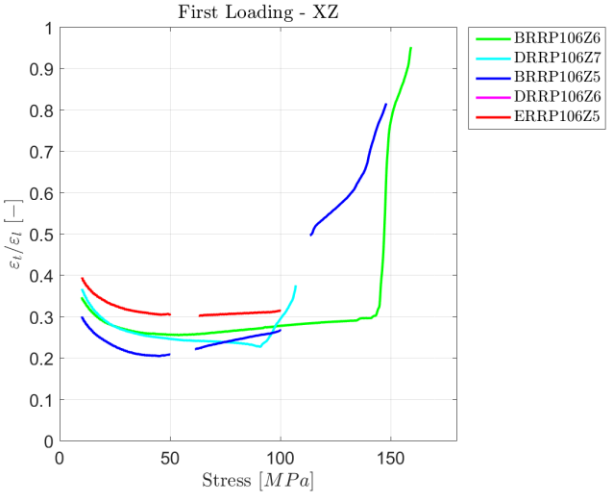
- Azimuthal-Longitudinal strain relationship:

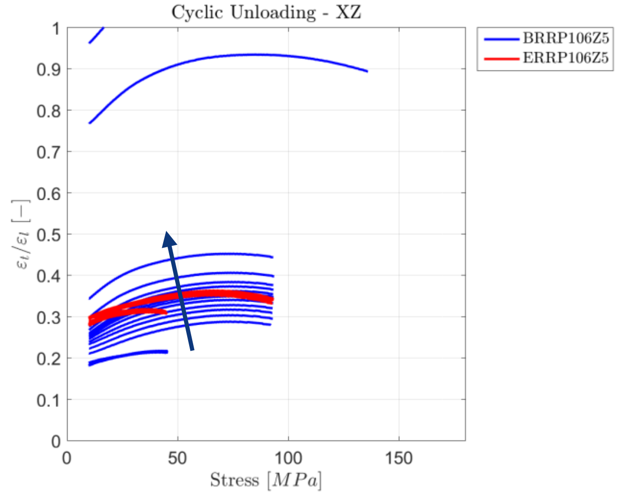


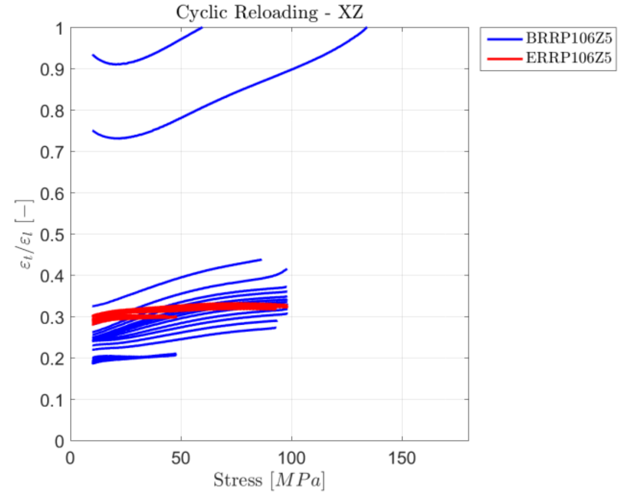




- Radial-Longitudinal strain relationship:







Conclusion

- An extended test campaign has been carried out at CERN to study the overall behavior of impregnated MQXF cable stacks.
- Stress-strain relationships have been analyzed in free compression tests.
- In all directions (X,Y,Z) the cable stack shows strongly not linear elastic behavior.
- The experimental results give information about the cable stack behavior and different inputs how to reproduce it.

Next

- What about PIT cable?
- What about cryogenic temperatures?
- What about thermal properties?

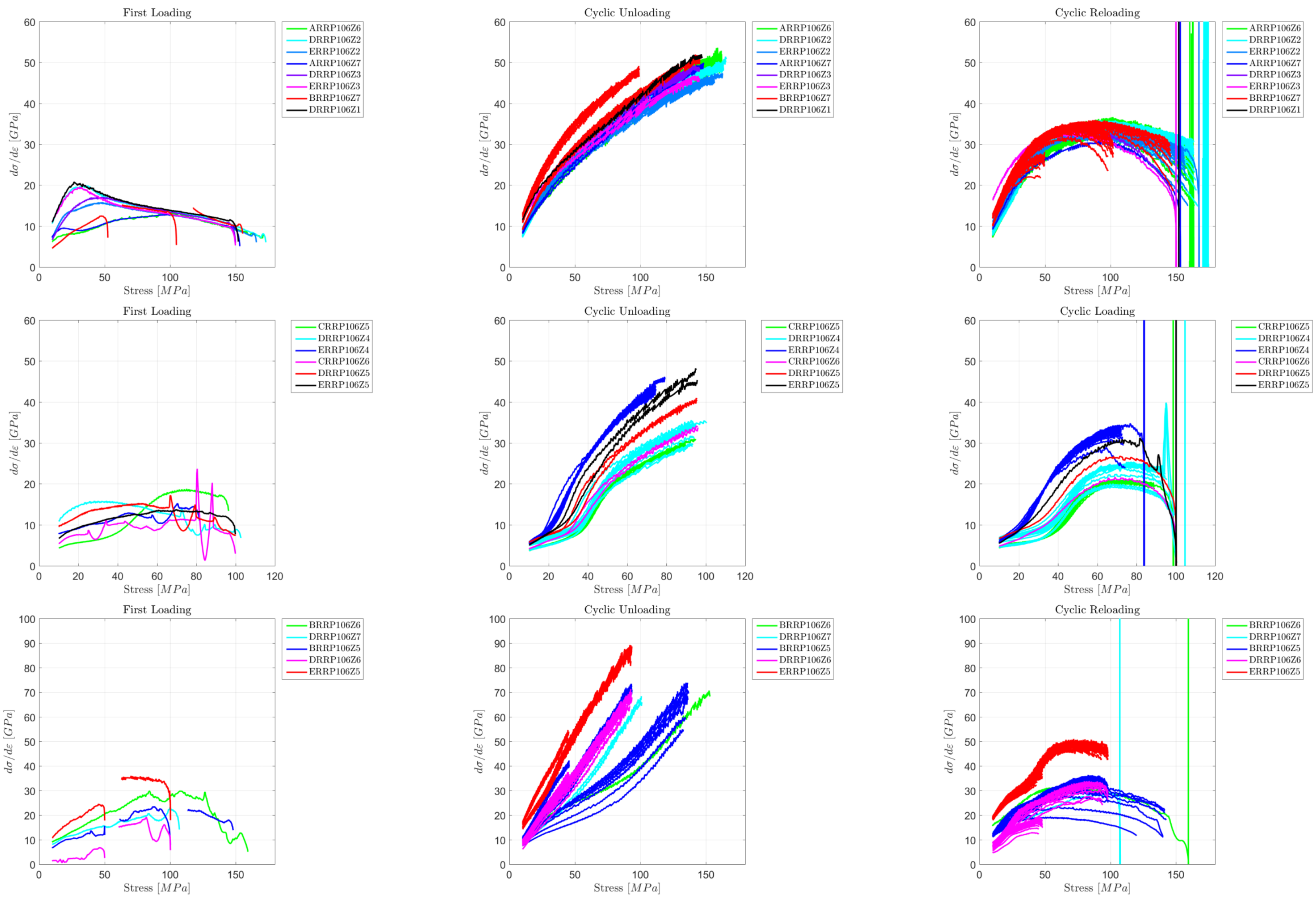
Thank you

Experimental results

Azimuthal

Radial

Longitudinal



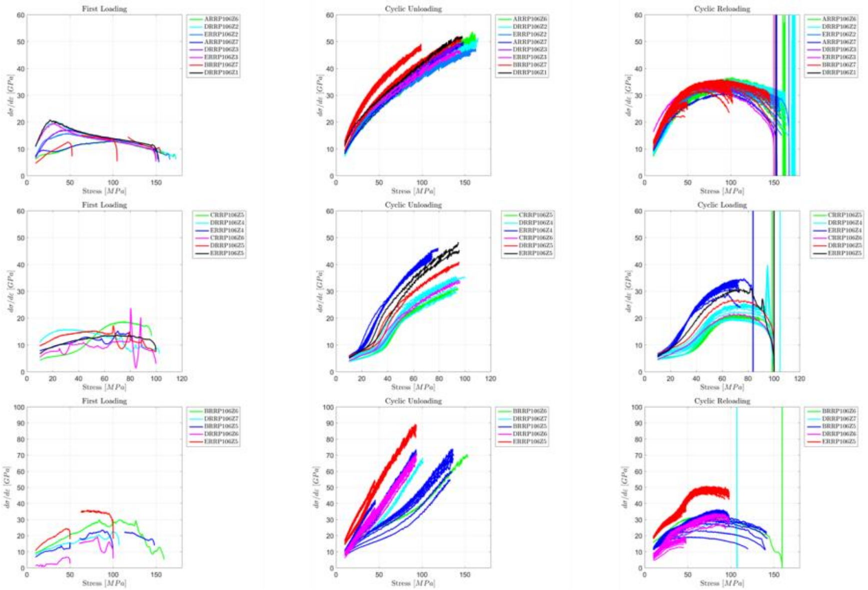
Experimental results

First Loading | Cyclic Unloading | Cyclic Loading

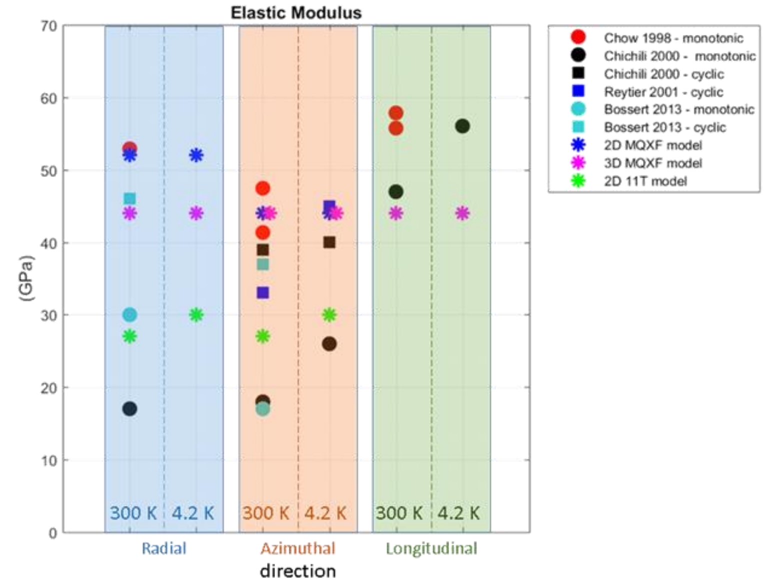
Azimuthal

Radial

Longitudinal



- Data from literature:



- Summary of the test campaign:

	Azimuthal			Radial			Longitudinal		
	$d\sigma/d\varepsilon$	$\varepsilon_Z/\varepsilon_Y$	$\varepsilon_X/\varepsilon_Y$	$d\sigma/d\varepsilon$	$\varepsilon_Z/\varepsilon_X$	$\varepsilon_Y/\varepsilon_X$	$d\sigma/d\varepsilon$	$\varepsilon_Y/\varepsilon_Z$	$\varepsilon_X/\varepsilon_Z$
	(GPa)			(GPa)			(GPa)		
First Loading	5÷20	0.05÷0.2	0.1÷0.4	5÷25	0.05÷0.15	~0.2	10÷25	~0.16	0.2÷0.3
Cyclic Unloading	10÷50	0.05÷0.2	0.2÷0.5	5÷40	0.1÷0.2	N/A	10÷70	~0.2	0.2÷0.3
Cyclic Loading	10÷35	0.05÷0.2	0.2÷0.5	5÷30	0.05÷0.15	N/A	10÷35	~0.2	0.2÷0.3