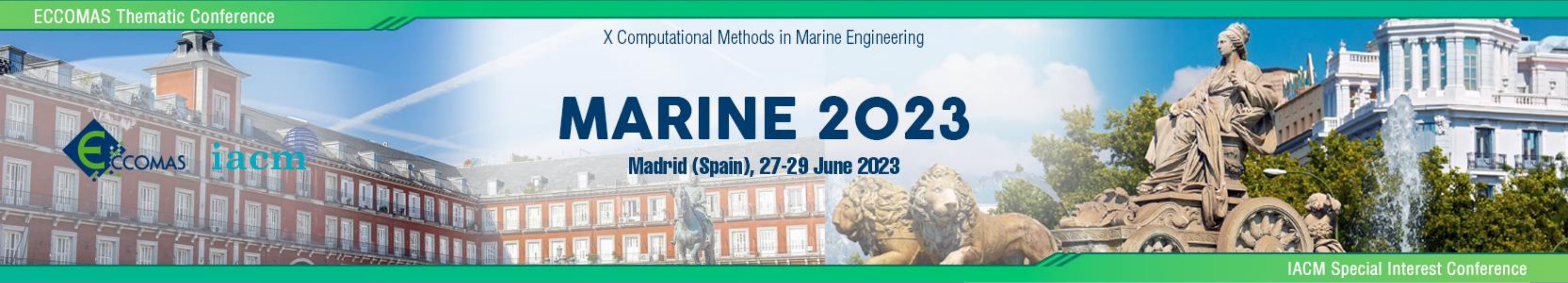

COMPOSITES AND ADVANCED MATERIALS FOR MULTIFUNCTIONAL STRUCTURES (CAMMS)

NUMERICAL MODEL FOR THE CHARACTERIZATION OF 3D PRINTED COMPOSITES

CIMNE
EXCELENCIA SEVERO OCHOA

FIBRE4YARDS
SHIPYARD FOR THE FUTURE

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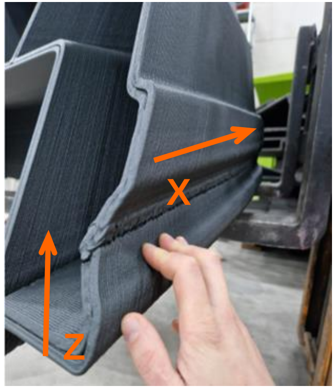
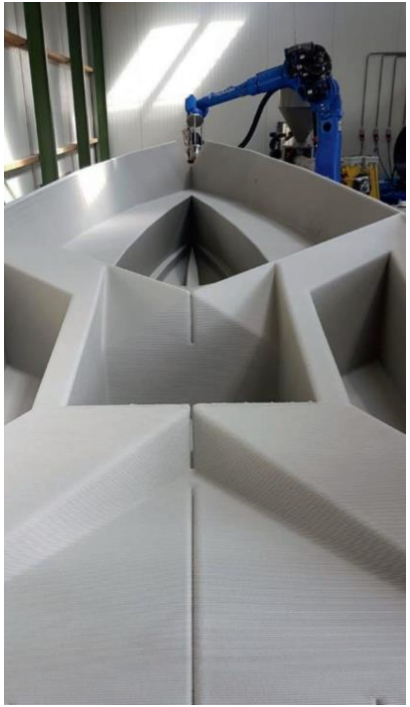
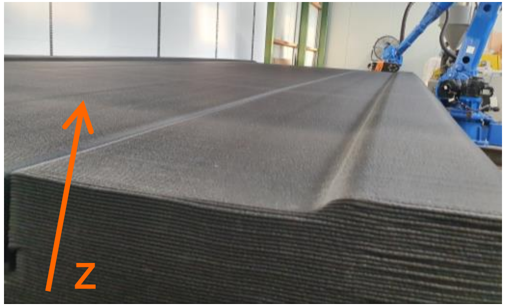
INTRODUCTION

01

INTRODUCTION







INTRODUCTION

Objective:
Simulate a 3D printed material considering the anisotropy produced by the manufacturing process using the Space Mapping constitutive model

- The **anisotropy** present in the resin that bonds the different manufacturing planes will be taken into consideration in the model through the implementation of a resin constitutive model.
- Therefore: Anisotropy will be included in the model though the resin constitutive model.
- A methodology based on **Space Mapping** is proposed to overcome the difficulties in simulating the orthotropic nonlinear behavior of 3D printed composites. This methodology allows the use of known nonlinear isotropic formulations and offers numerical advantages.
- The constitutive model used for the characterization of the material is the **serial-parallel mixing theory**.

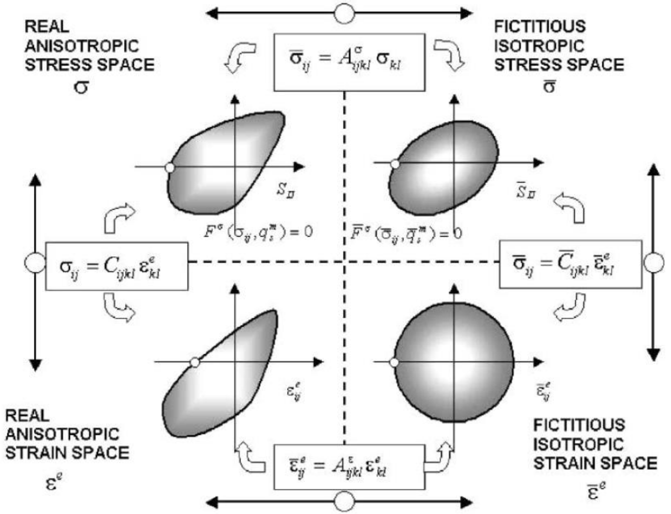
FORMULATION

02

FIBRE4YARDS SHIPYARD FOR THE FUTURE

CIMNE EXCELENCIA SEVERO OCHOA

FORMULATION SPACE MAPPING



Relation between the fictitious isotropic and the real anisotropic spaces

FEMUSS

$$\bar{\sigma}_{IJ} \doteq A^{S}_{IJKL}\,\sigma_{KL}$$

$$\left(A^{S}_{IJKL}\right)^{-1} = B^{\sigma}_{IJKL} = W_{IJKL}w_{RSKL}$$

$$W_{IJKL}w_{RSKL} = \omega_{IK}\omega_{JL}$$

$$\omega_{IJ} = Diag\{\omega_{xx};\omega_{yy};\omega_{zz}\} = Diag\left\{\sqrt{\frac{f_x}{f}};\sqrt{\frac{f_y}{f}};\sqrt{\frac{f_z}{f}}\right\}$$

$$\bar{E}_{IJ} \doteq A^{E}_{IJKL}\,E_{KL}$$

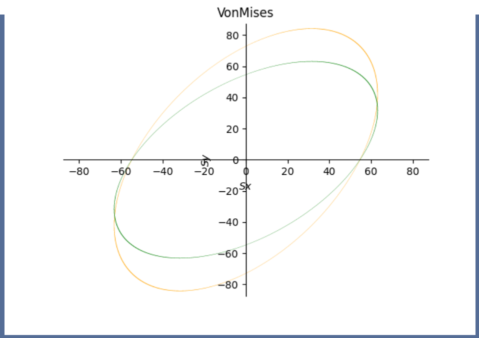
Sergio Oller, Eduardo Car, and Jacob Lubliner. "*Definition of a general implicit orthotropic yield criterion*". In: Computer Methods in Applied Mechanics and Engineering 192.7-8 (2003), pp. 895–912. ISSN: 00457825. DOI: 10.1016/S0045-7825(02)00605-9.

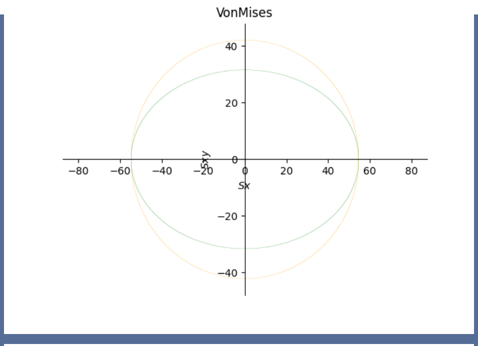
FIBRE4YARDS SHIPYARD FOR THE FUTURE CIMNE EXCELENCIA SEVERO OCHOA

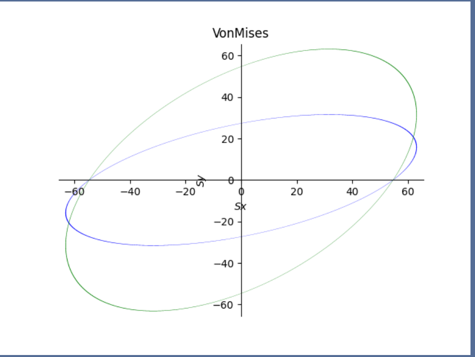
SPACE MAPPING BEHAVIOUR

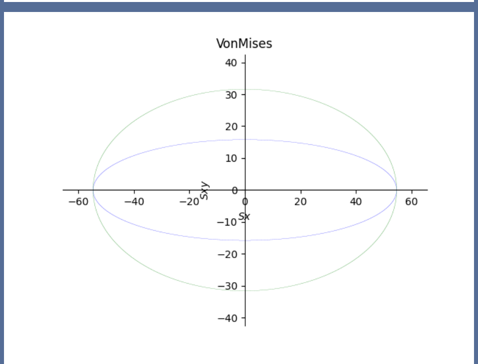
$\frac{\bar{\sigma}_x}{\sigma_x}$	$\frac{\bar{\sigma}_y}{\sigma_y}$	$\frac{\bar{\sigma}_z}{\sigma_z}$	$\frac{\bar{\tau}_{xy}}{\tau_{xy}}$	$\frac{\bar{\tau}_{xz}}{\tau_{xz}}$	$\frac{\bar{\tau}_{yz}}{\tau_{yz}}$
1.0	2.0	2.0	2.0	1.0	1.0
1.0	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
1.0	0.75	0.75	0.75	1.0	1.0

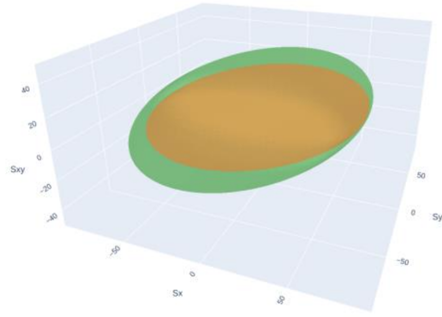
By modifying the **compressive strength** ratio, the anisotropic behaviour of the matrix is characterized.

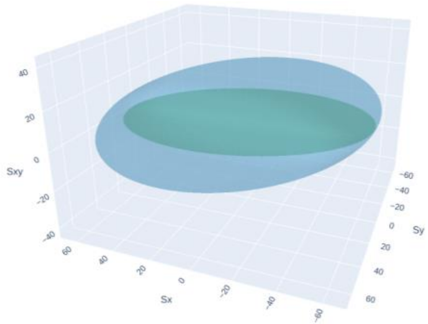






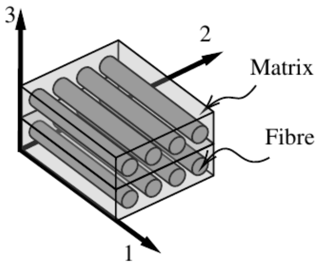






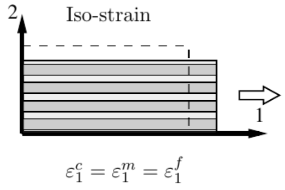
SP MIXING THEORY

- Numerical models for composite material characterization will be based on the Serial/Parallel mixing theory.
- Is a constitutive equation that provides the response of the composite by coupling the constitutive equations of its components.



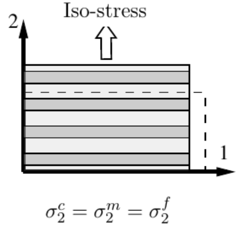
Parallel behavior

$$\begin{cases} {}^{c}\varepsilon_P = {}^{m}\varepsilon_P = {}^{f}\varepsilon_P \\ {}^{c}\sigma_P = {}^{m}k\, {}^{m}\sigma_P + {}^{f}k\, {}^{f}\sigma_P \end{cases}$$



Serial behavior

$$\begin{cases} {}^{c}\varepsilon_S = {}^{m}k\, {}^{m}\varepsilon_S + {}^{f}k\, {}^{f}\varepsilon_S \\ {}^{c}\sigma_S = {}^{m}\sigma_S = {}^{f}\sigma_S \end{cases}$$



EXPERIMENTAL SETUPS

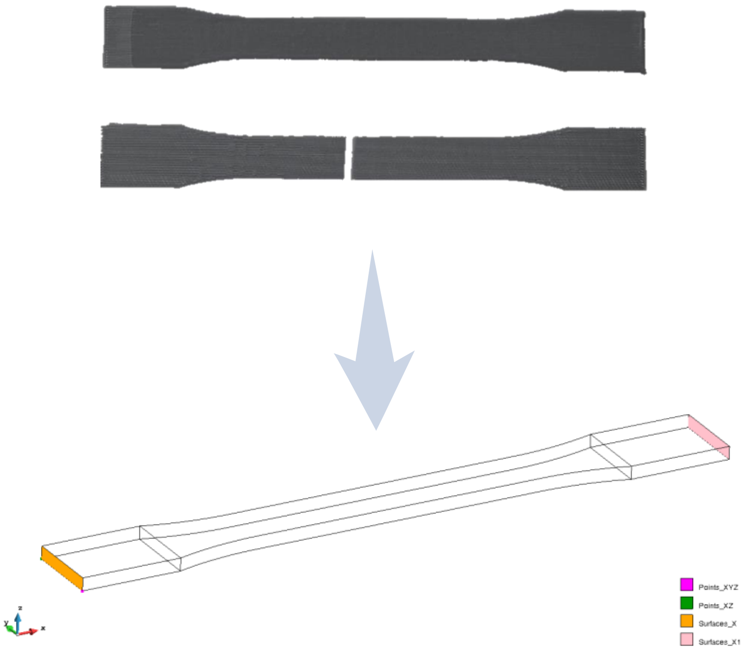
03

FIBRE4YARDS SHIPYARD FOR THE FUTURE

CIMNE EXCELENCIA SEVERO OCHOA

MATERIAL DEFINITION

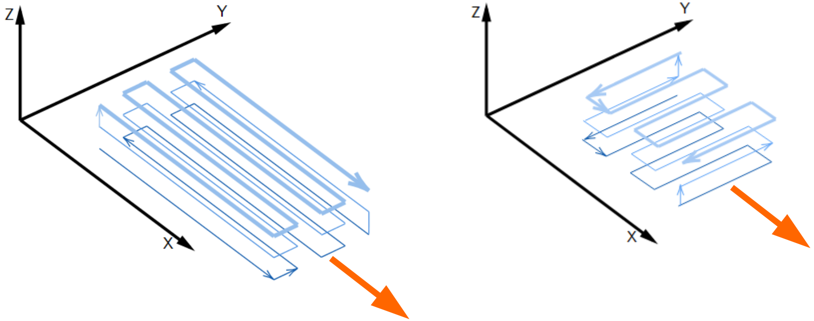
- The objective is to numerically simulate material testing experiments obtained from literature.
- Literature provides mechanical properties of materials in their raw form and the properties achieved through additive manufacturing.
- Mechanical properties of printed materials are influenced by the anisotropy of the printing process.
- Anisotropy parameter is determined using space mapping.
- The focus is on calibrating the spatial mapping values for resin.

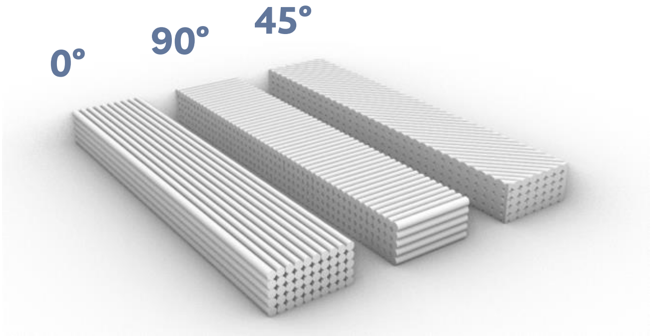


MATERIAL DEFINITION

- Analysis will be performed for
  - Resin
  - Resin with short fibres
  - Resin with continuous fibres.

- Analyses are made for 3 cases:
  - Parts printed at 0°.
  - Parts printed at 90°.
  - Parts printed at 45°





MATERIAL DEFINITION – PLA

	Direction	PLA
Tensile modulus (MPa)	E_1 (0°)	3376
	E_2 (90°)	3125
In-plane Shear Modulus (MPa)	G_{12}	1092
Poisson coefficient	ν_{12}	0.331
	ν_{23}	0.325
Tensile Strength (MPa)	σ_1 (0°)	54.7

$\frac{\overline{\sigma_x}}{\sigma_x}$	$\frac{\overline{\sigma_y}}{\sigma_y}$	$\frac{\overline{\sigma_z}}{\sigma_z}$	$\frac{\overline{\tau_{xy}}}{\tau_{xy}}$	$\frac{\overline{\tau_{xz}}}{\tau_{xz}}$	$\frac{\overline{\tau_{yz}}}{\tau_{yz}}$
1	1.475	1.475	1.75	1	1

Ratio of compressive strengths

	Direction	PLA
Tensile modulus (MPa)	E_1 (0°)	3376
	E_2 (90°)	3125
In-plane Shear Modulus (MPa)	G_{12}	1092
Poisson coefficient	ν_{12}	0.331
	ν_{21}	0.325
Tensile Strength (MPa)	σ_1 (0°)	54.7
	σ_2 (90°)	37.1
In-plane Shear Strength (MPa)	τ_{12}	18.0

Experimental mechanical properties

RESULTS

04

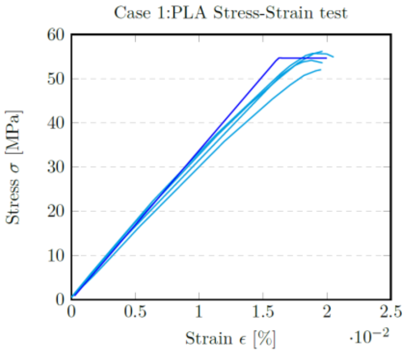
FIBRE4YARDS SHIPYARD FOR THE FUTURE

CIMNE EXCELENCIA SEVERO OCHOA

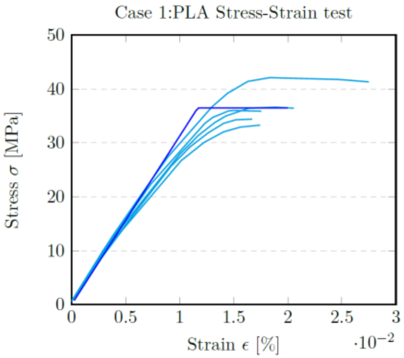
RESULTS – PLA

$\frac{\overline{\sigma_x}}{\sigma_x}$	$\frac{\overline{\sigma_y}}{\sigma_y}$	$\frac{\overline{\sigma_z}}{\sigma_z}$	$\frac{\overline{\tau_{xy}}}{\tau_{xy}}$	$\frac{\overline{\tau_{xz}}}{\tau_{xz}}$	$\frac{\overline{\tau_{yz}}}{\tau_{yz}}$
1	1.475	1.475	1.75	1	1

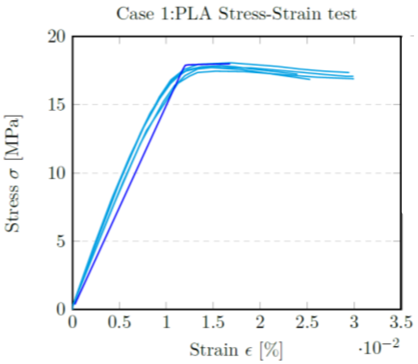
Stress-Strain 0°

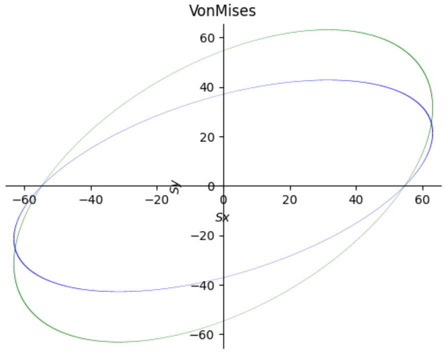


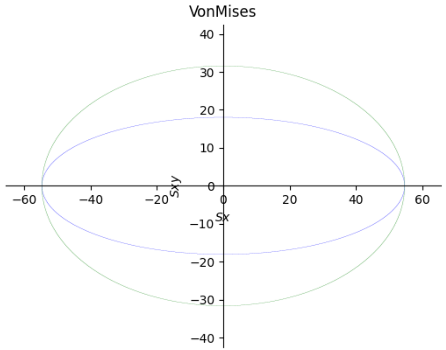
Stress-Strain 90°



Stress-Strain ±45°







Graph data
Experimental sample
Numerical

MATERIAL DEFINITION – PLA & Short CF

	Direction	PLA + 15% CF
Tensile modulus (MPa)	E_1 (0º)	7541
	E_2 (90º)	3920
In-plane Shear Modulus (MPa)	G_{12}	1268
Poisson coefficient	ν_{12}	0.400
	ν_{23}	0.150
Tensile Strength (MPa)	σ_1	53.4

Material	$\frac{\overline{\sigma_x}}{\sigma_x}$	$\frac{\overline{\sigma_y}}{\sigma_y}$	$\frac{\overline{\sigma_z}}{\sigma_z}$	$\frac{\overline{\tau_{xy}}}{\tau_{xy}}$	$\frac{\overline{\tau_{xz}}}{\tau_{xz}}$	$\frac{\overline{\tau_{yz}}}{\tau_{yz}}$
PLA	1	1.475	1.475	1.75	1	1
PLA & CF	1	1.51	1.51	1.63	1	1

Ratio of compressive strengths

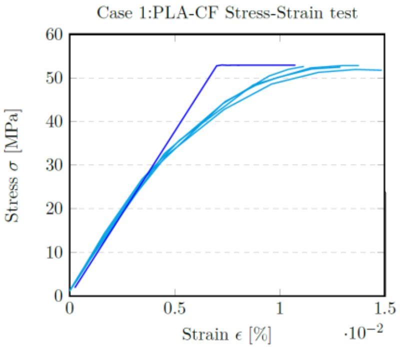
	Direction	PLA + 15% CF
Tensile modulus (MPa)	E_1 (0º)	7541
	E_2 (90º)	3920
In-plane Shear Modulus (MPa)	G_{12}	1268
Poisson coefficient	ν_{12}	0.400
	ν_{21}	0.150
Tensile Strength (MPa)	σ_1 (0º)	53.4
	σ_2 (90º)	35.4
In-plane Shear Strength (MPa)	τ_{12}	18.9

Experimental mechanical properties

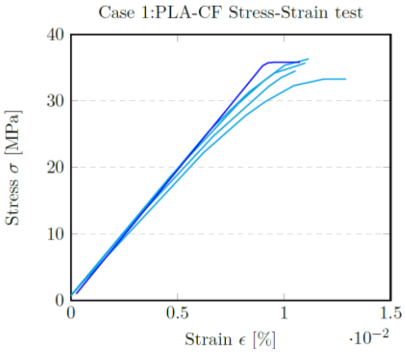
RESULTS – PLA & Short CF

$\frac{\overline{\sigma_x}}{\sigma_x}$	$\frac{\overline{\sigma_y}}{\sigma_y}$	$\frac{\overline{\sigma_z}}{\sigma_z}$	$\frac{\overline{\tau_{xy}}}{\tau_{xy}}$	$\frac{\overline{\tau_{xz}}}{\tau_{xz}}$	$\frac{\overline{\tau_{yz}}}{\tau_{yz}}$
1	1.51	1.51	1.63	1	1

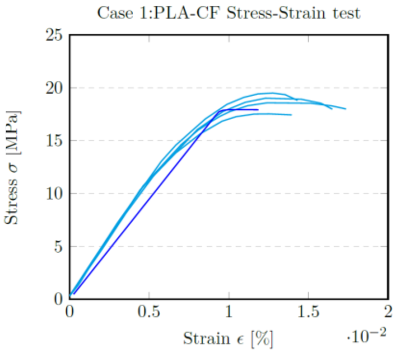
Stress-Strain 0°



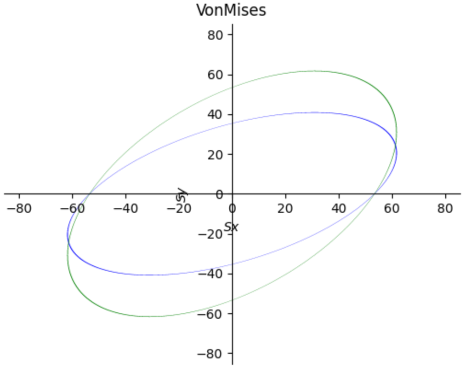
Stress-Strain 90°

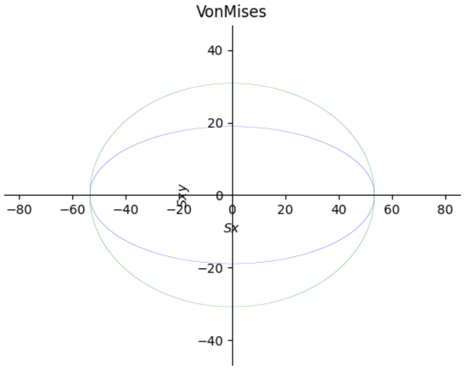


Stress-Strain ±45°

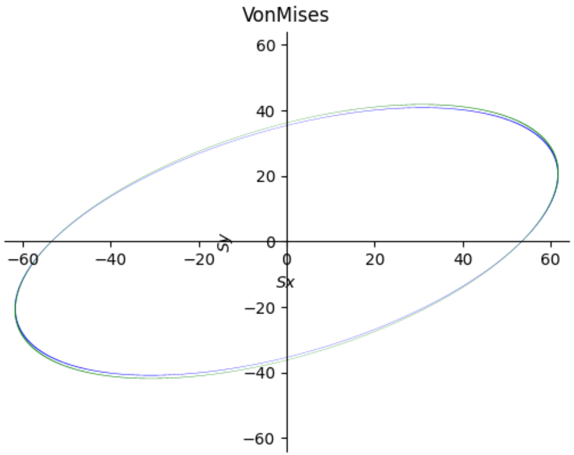


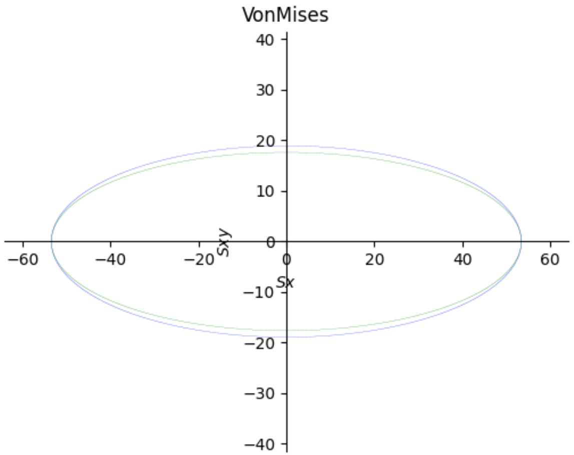
Graph data
- Experimental sample
- Numerical





RESULTS – PLA & PLA + Short CF





Material	$\frac{\overline{\sigma_x}}{\sigma_x}$	$\frac{\overline{\sigma_y}}{\sigma_y}$	$\frac{\overline{\sigma_z}}{\sigma_z}$	$\frac{\overline{\tau_{xy}}}{\tau_{xy}}$	$\frac{\overline{\tau_{xz}}}{\tau_{xz}}$	$\frac{\overline{\tau_{yz}}}{\tau_{yz}}$
PLA	1	1.475	1.475	1.75	1	1
PLA & CF	1	1.51	1.51	1.63	1	1

MATERIAL DEFINITION – Nylon & CF

	Direction	Nylon	Cont. CF
Tensile modulus (MPa)	E_1 (0º)	1000	136556
	E_2 (90º)		7187
In-plane Shear Modulus (MPa)	G_{12}		4000
Poisson coefficient	ν_{12}	0.35	0.27
	ν_{23}		0.40
Tensile Strength (MPa)	σ_1	45.5	1944
Volumetric participation		55%	45%

Material	$\frac{\overline{\sigma_x}}{\sigma_x}$	$\frac{\overline{\sigma_y}}{\sigma_y}$	$\frac{\overline{\sigma_z}}{\sigma_z}$	$\frac{\overline{\tau_{xy}}}{\tau_{xy}}$	$\frac{\overline{\tau_{xz}}}{\tau_{xz}}$	$\frac{\overline{\tau_{yz}}}{\tau_{yz}}$
Nylon + CF	1	5.5	1	1.8	1	1

Ratio of compressive strengths

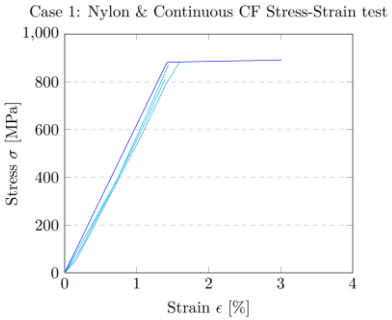
	Direction	Composite
Tensile modulus (MPa)	E_1 (0º)	62000
	E_2 (90º)	430
In-plane Shear Modulus (MPa)	G_{12}	1100
Tensile Strength (MPa)	σ_1 (0°)	875
	σ_2 (90º)	8.54
In-plane Shear Strength (MPa)	τ_{12}	21.8

Experimental mechanical properties

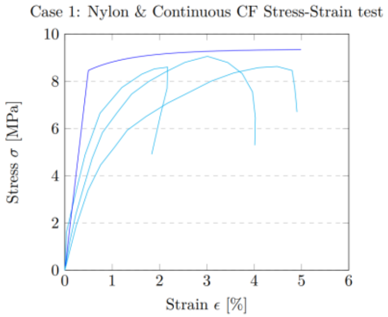
RESULTS – Nylon & CF

$\frac{\overline{\sigma_x}}{\sigma_x}$	$\frac{\overline{\sigma_y}}{\sigma_y}$	$\frac{\overline{\sigma_z}}{\sigma_z}$	$\frac{\overline{\tau_{xy}}}{\tau_{xy}}$	$\frac{\overline{\tau_{xz}}}{\tau_{xz}}$	$\frac{\overline{\tau_{yz}}}{\tau_{yz}}$
1	5.5	1	1.8	1	1

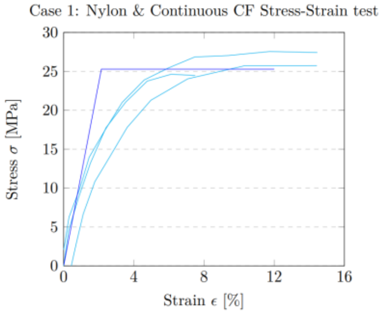
Stress-Strain 0°

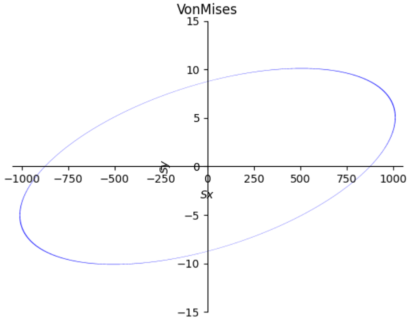


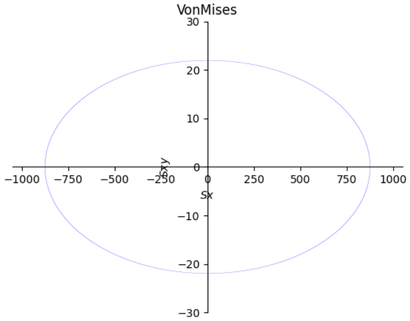
Stress-Strain 90°



Stress-Strain ±45°







Graph data
—— Experimental sample
—— Numerical

FIBRE4YARDS SHIPYARD FOR THE FUTURE
CIMNE EXCELENCIA SEVERO OCHOA

CONCLUSIONS

05

CONCLUSIONS

- Space Mapping allows to capture the anisotropy generated by the 3D printing process in isotropic materials.
- It is also effective in capturing anisotropy in composite materials.
- Using Space Mapping to define material behavior simplifies calculations, as isotropic formulations are faster than anisotropic ones.

ACKNOWLEDGEMENTS

This research was supported by the European Commission under grant agreement No 101006860.
We thank our colleagues from FIBRE4YARDS who provided insight and expertise that greatly assisted the research

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