

Optimized Digital Design and Production: Continuous-fiber- reinforced 3D printing of polyamides

Aalto University & VTT

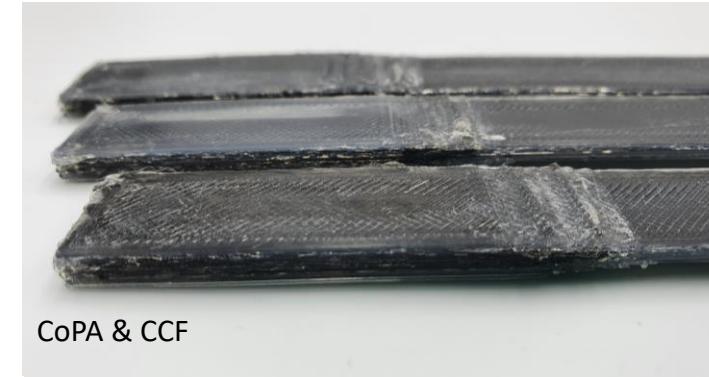
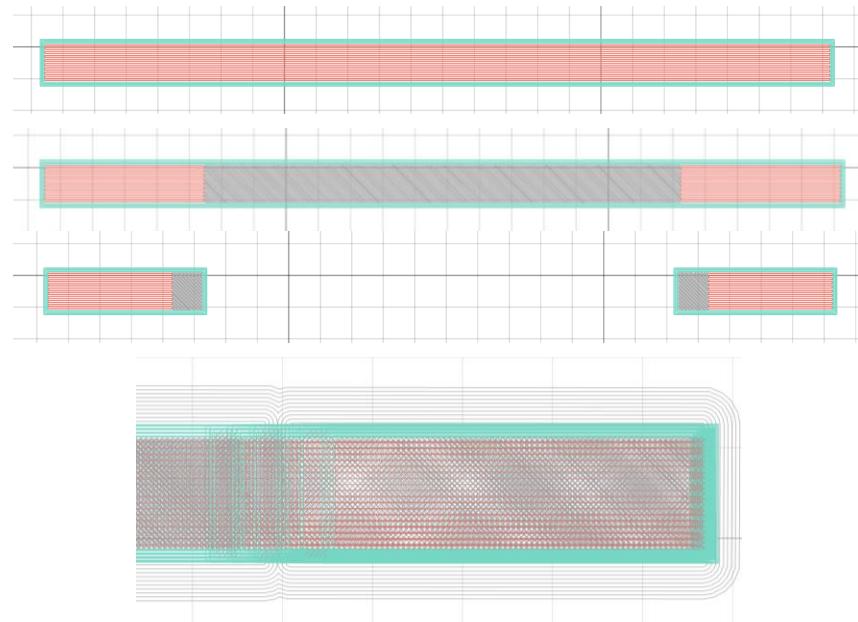
ValueBioMat WP1-WP2

A”

Aalto University
School of Engineering

Optimized Digital Design and Production

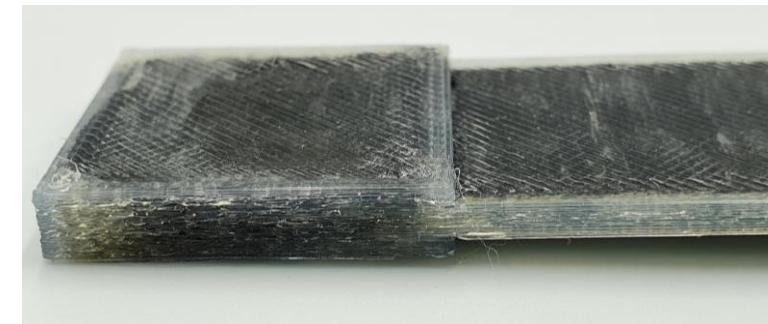
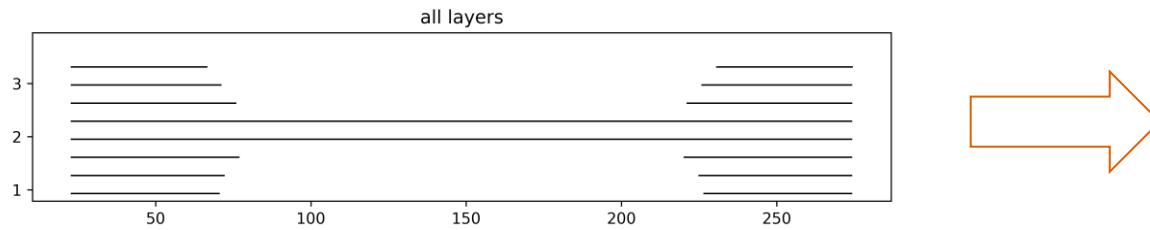
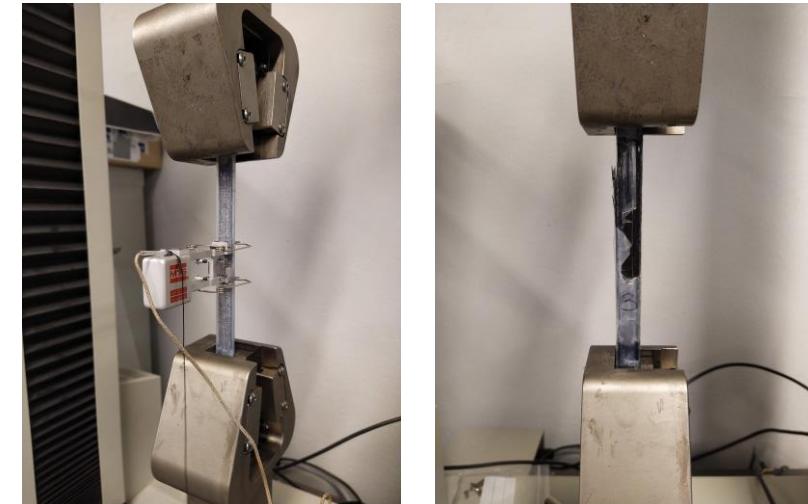
- Fiber-reinforced extrusion of polyamides
 - Commercial copolyamide filament: BASF Ultrafuse
 - Continuous carbon fiber infill
 - 3DP at 240 °C utilizing Anisoprint Composer A4



CCF reinforced Copolyamide: test specimen
Longitudinal tension (tensile_0)
Transverse tension (tensile_90)
In-plane shear (+45)

Simulation

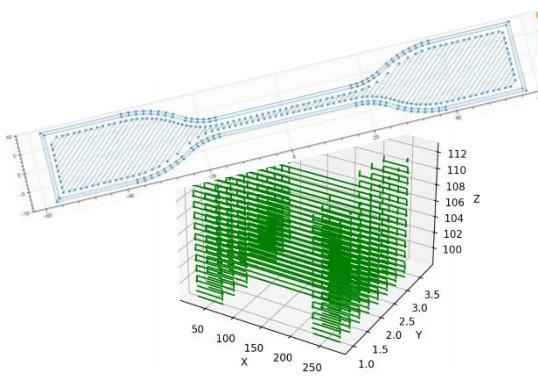
- *ORIENT subroutine to convert gcode into .inp file
- Model strictly following 3D printing
- Displacement-based
- Simulation based on the continuum damage mechanics (CDM) model
- The effect of different fiber orientations on the tensile strength were studied both experimentally and numerically.
- Hashin failure criteria



Done: FE-Model generation

Gcode → FE-model → Simulation

- Read Gcode
- Geometry
- Fiber orientation



Fibers in printed specimen

- Generate FE-Mesh
- Input fiber orientations

```

In [18]: M1 = m1*m1
          M2 = m2*m2
          M12_tan = M12_tan*M12_tan
          WD = 1.0

Out[18]:
W1 = 1.0
M12_tan = M12_tan*(epsilon_tan*trace(M12_tan))**2/2 + mu*(epsilon_tan*trace(M12_tan)*trace(M12_tan))
M12_tan = sqrt((W1*epsilon_tan*trace(M12_tan))**2)
alpha = alpha*(epsilon_tan*trace(M12_tan))**2
WD = WD/sqrt(alpha)

Out[19]:
W1 = 1.0
M12_tan = M12_tan*(epsilon_tan*trace(M12_tan))**2
alpha = alpha*(epsilon_tan*trace(M12_tan))**2
WD = WD/sqrt(alpha)

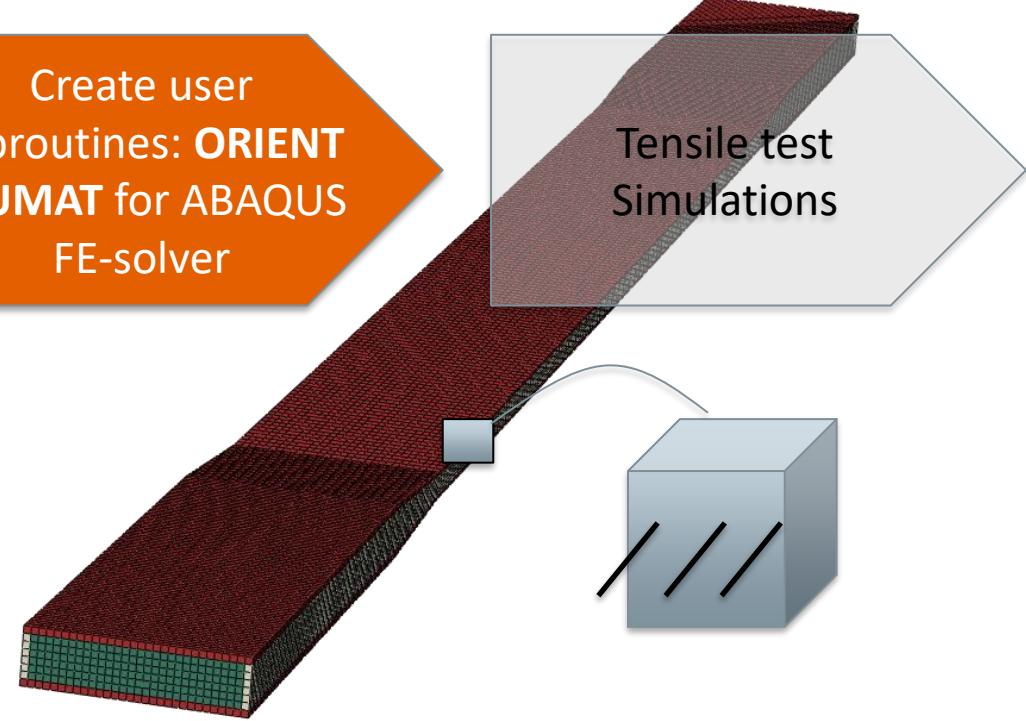
Out[20]:
alpha(c1) + c21 + c31) * (M1[c11] + M1[M1c12] + M1[M1c13] + M2[c22] + M2[M2c23] + M3[c33]) + mu(2*c11 + c12 + c13 + 2*c22 + c23 + 2*c33)/2
+ mu(M1[c11] + M1[M1c12] + M1[M1c13] + M2[c22] + M2[M2c23] + M3[c33])**2/(2*c11 + c12 + c13 + 2*c22 + c23 + 2*c33)**2
+ mu(2*c11 + c12 + c13 + 2*c22 + c23 + 2*c33)/2
+ beta(M1[c11] + M1[M1c12] + M1[M1c13] + M2[c22] + M2[M2c23] + M3[c33])
+ beta(M1[c11] + M1[M1c12] + M1[M1c13] + M2[c22] + M2[M2c23] + M3[c33])**2/(2*c11 + c12 + c13 + 2*c22 + c23 + 2*c33)**2
+ beta(2*c11 + c12 + c13 + 2*c22 + c23 + 2*c33)/2

Out[21]:
# lasketaan seuraava ja komplikaatioinen derivoituna epäyhtälökuvausta
# Jokaista komponenttia tarvitaan energian energian derivointi vektoriin
# komplikaatio = sp.Matrix(vector('phi').energy(M1,epsilon_tan).vek)
komplikaatio = sp.MatrixMatrixMatrixFromEnergy('phi',epsilon_tan,vek)

Out[22]:
# tarkistellaan komponenttien lähtökohtaisesta lauseesta
# koodissa
# 1. M1[M1c11] + 2M1[M1c12] + 2M1[M1c13] + 2M1[M1c12] + 2M1[M1c13] + 2M1[M1c11] + M1[M1c11] + M1[M1c12] + M1[M1c13]
# 2. M1[M1c12] + 2M1[M1c13] + M1[M1c12] + M1[M1c13] + M1[M1c11] + 2M1[M1c12] + 2M1[M1c13] + 2M1[M1c11]
# 3. M1[M1c13] + 2M1[M1c11] + M1[M1c12] + M1[M1c13] + M1[M1c11] + 2M1[M1c12] + 2M1[M1c13] + 2M1[M1c11]
# 4. M2[M2c22] + 2M2[M2c23] + 2M2[M2c21] + M2[M2c23] + 2M2[M2c21] + M2[M2c22] + M2[M2c23] + 2M2[M2c21]
# 5. M2[M2c23] + 2M2[M2c21] + M2[M2c23] + 2M2[M2c21] + M2[M2c22] + M2[M2c23] + 2M2[M2c21]
# 6. M2[M2c21] + M2[M2c23] + 2M2[M2c22] + M2[M2c23] + 2M2[M2c21] + M2[M2c22] + M2[M2c23] + 2M2[M2c21]
# 7. M3[M3c33] + 2M3[M3c31] + M3[M3c32] + M3[M3c31] + M3[M3c32] + M3[M3c33] + 2M3[M3c31] + 2M3[M3c32] + 2M3[M3c33]
# 8. M3[M3c31] + 2M3[M3c32] + M3[M3c33] + M3[M3c31] + M3[M3c32] + M3[M3c33] + 2M3[M3c31] + 2M3[M3c32] + 2M3[M3c33]
# 9. M3[M3c32] + 2M3[M3c33] + M3[M3c31] + M3[M3c32] + M3[M3c33] + 2M3[M3c31] + 2M3[M3c32] + 2M3[M3c33]
# 10. M1[M1c11] + M1[M1c12] + M1[M1c13] + M2[M2c22] + M2[M2c23] + M2[M2c21] + M3[M3c33] + M3[M3c31] + M3[M3c32]
# 11. M1[M1c11] + M1[M1c12] + M1[M1c13] + M2[M2c22] + M2[M2c23] + M2[M2c21] + M3[M3c33] + M3[M3c31] + M3[M3c32]
# 12. M1[M1c11] + M1[M1c12] + M1[M1c13] + M2[M2c22] + M2[M2c23] + M2[M2c21] + M3[M3c33] + M3[M3c31] + M3[M3c32]
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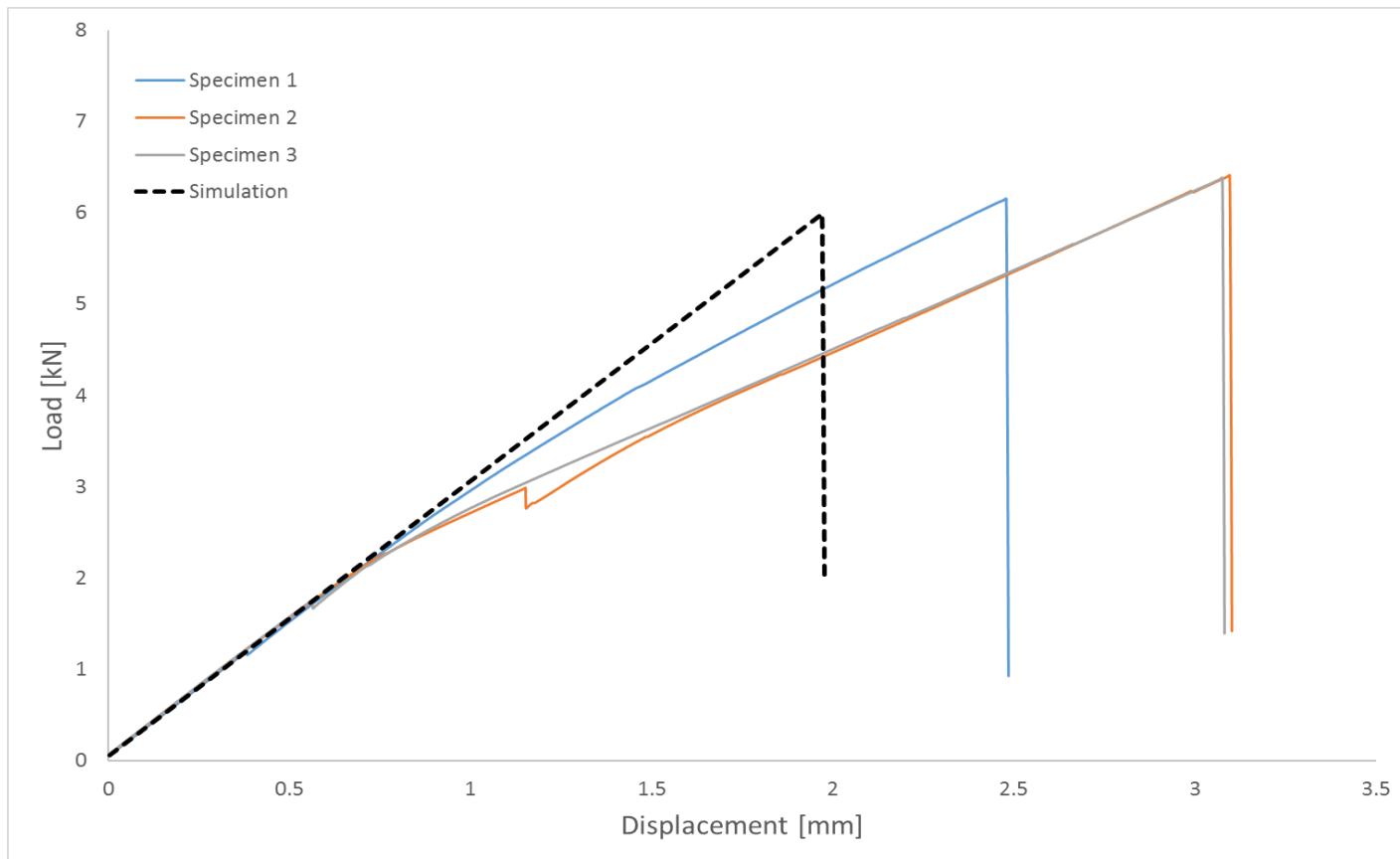
Python Coding

Create user subroutines: **ORIENT** & **UMAT** for ABAQUS FE-solver

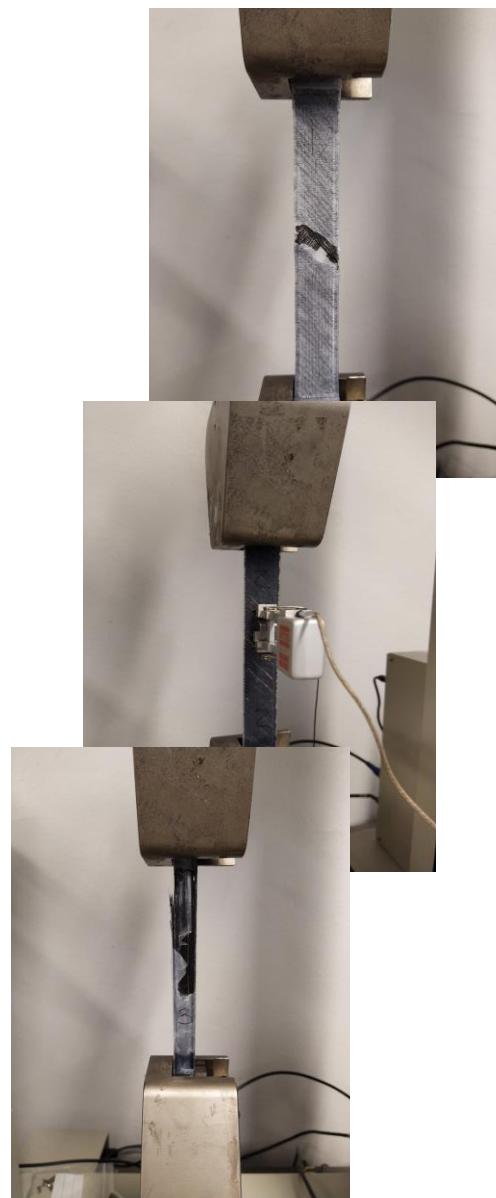


FE- Model & Fiber orientation

Material properties: tensile 0°



- The figure here illustrates tensile tests results for specimens where the fibre orientation is perpendicular to the direction of tension.
- Dashed line shows the simulated result. Despite the non linear deformation before failure, simulation is well in line with the experimental results.

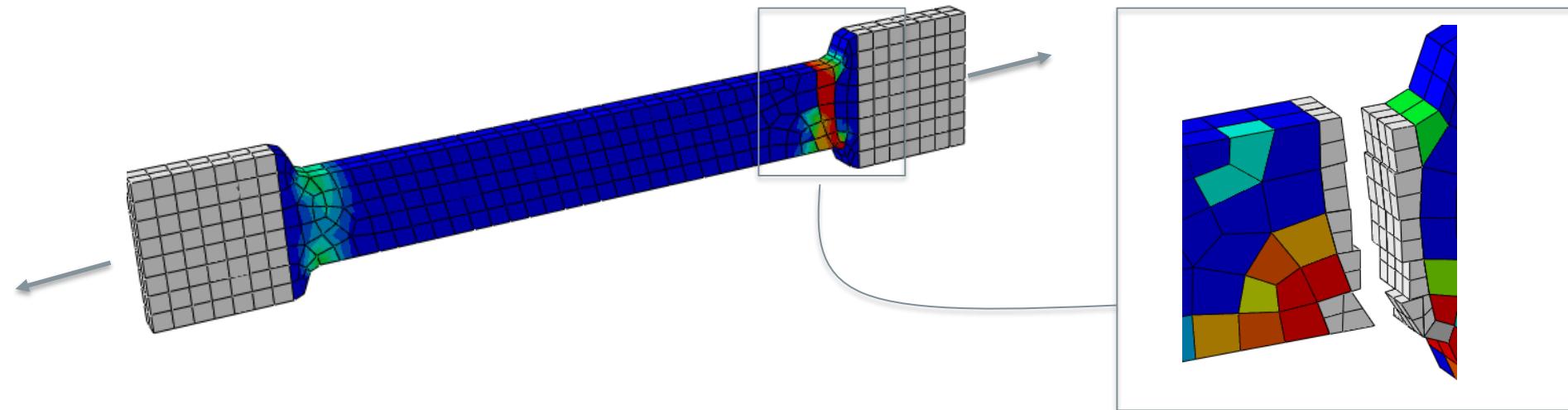


Mechanical properties: Summary

Property	Description	Value
E_1 [GPa]	Longitudinal elastic modulus	19.5 ± 0.4
E_2 [GPa]	Transverse elastic modulus	2.2 ± 0.1
G_{12} [GPa]	In-plane shear modulus	2.0 ± 0.1
ν_{12}	Major Poisson's ratio	0.21 ± 0.03
X_T [MPa]	Longitudinal tensile strength	240.2 ± 47.4
Y_T [MPa]	Transverse tensile strength	20.8 ± 0.5
S [MPa]	In-plane shear strength	48.3 ± 1.3

To be done: Fracture & Damage Modell

Further develop and verify models for 3D printed CF reinforced composites



To be done: Optimised printing

FE - simulation

Optimised fiber orientation & Specimen shape

?
Printed specimen

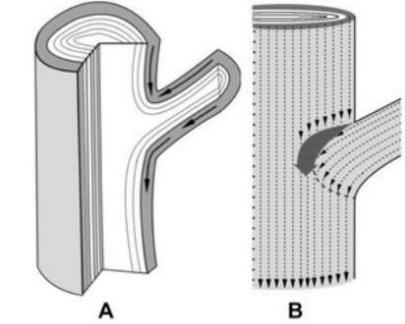
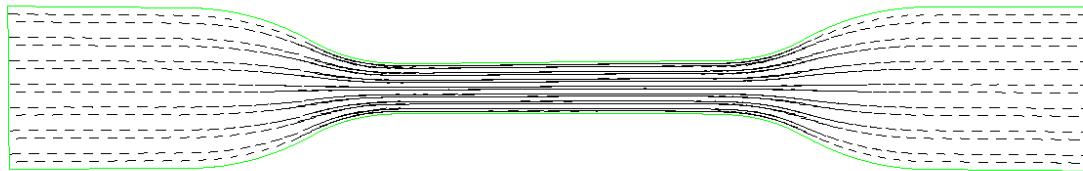


Fig by DOI:[10.14214/sf.1461](https://doi.org/10.14214/sf.1461)



Fiber orientations based FEM analysis & Principal stresses

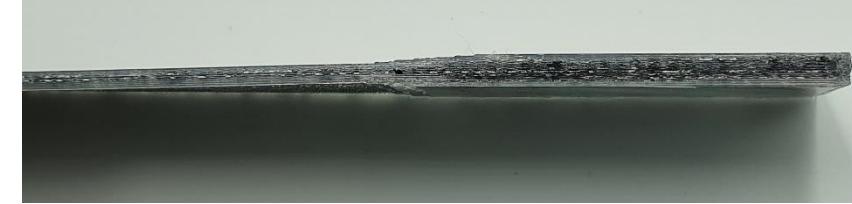
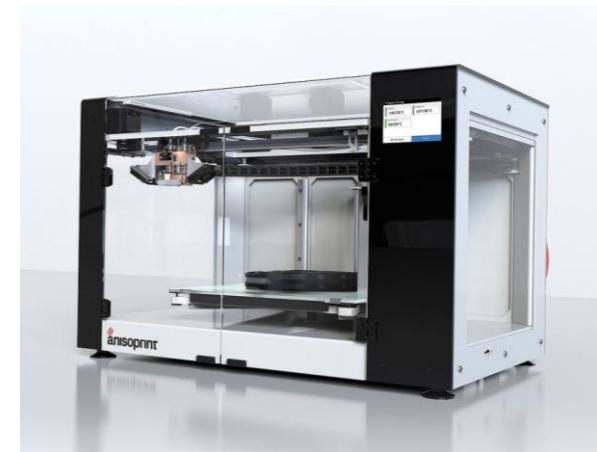


Fig. by Aalto (Sid)

Optimized Digital Design and Production

- Fiber-reinforced extrusion of polyamides
 - Bio-based PA11, Rilsan Besno
 - Filament made at VTT
 - Continuous carbon fiber perimeters
 - 3DP at 210°C utilizing Anisoprint Composer A4



PA 11 & CCF

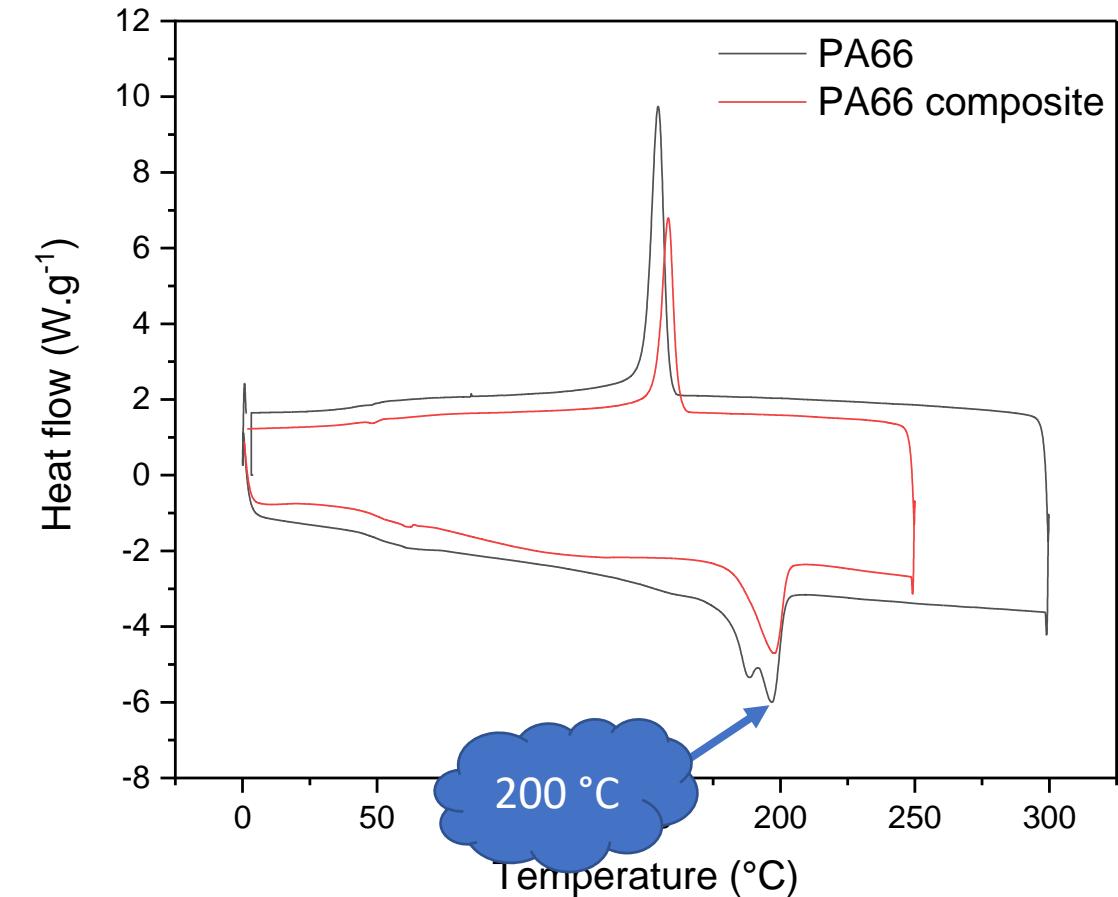
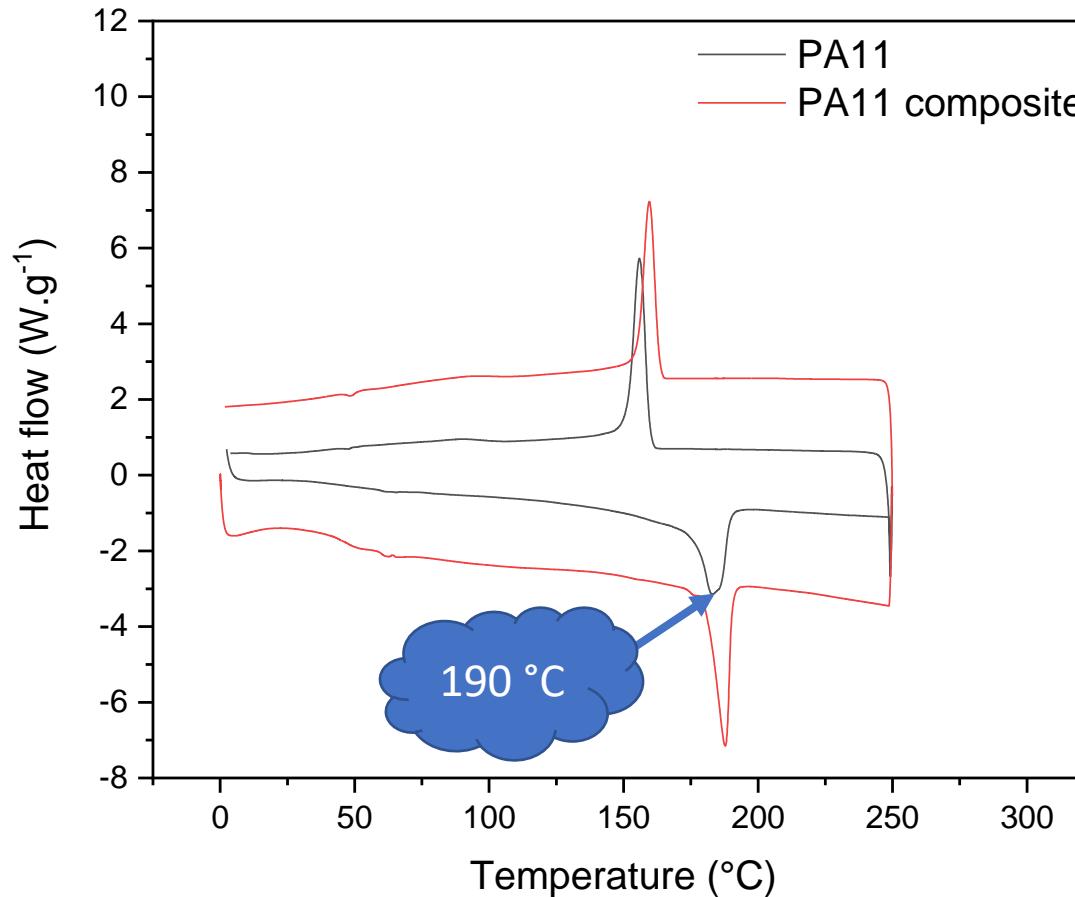


PA 11 & CCF

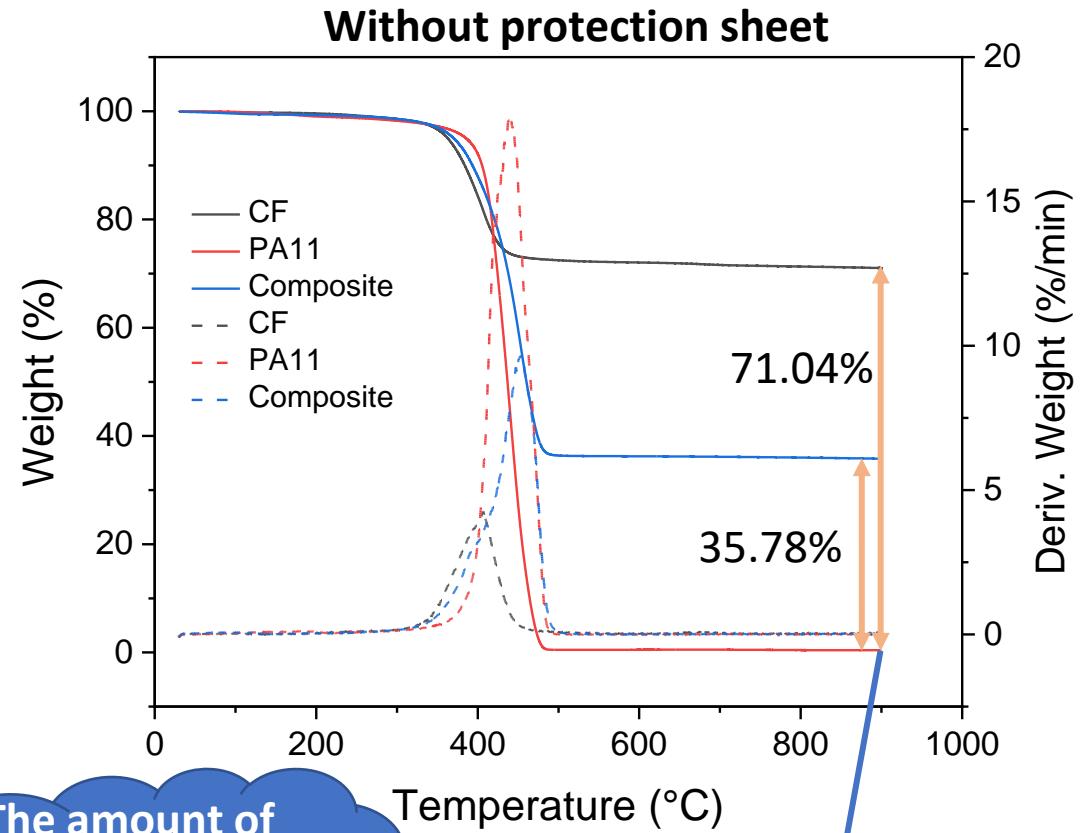


PA 11 & CCF

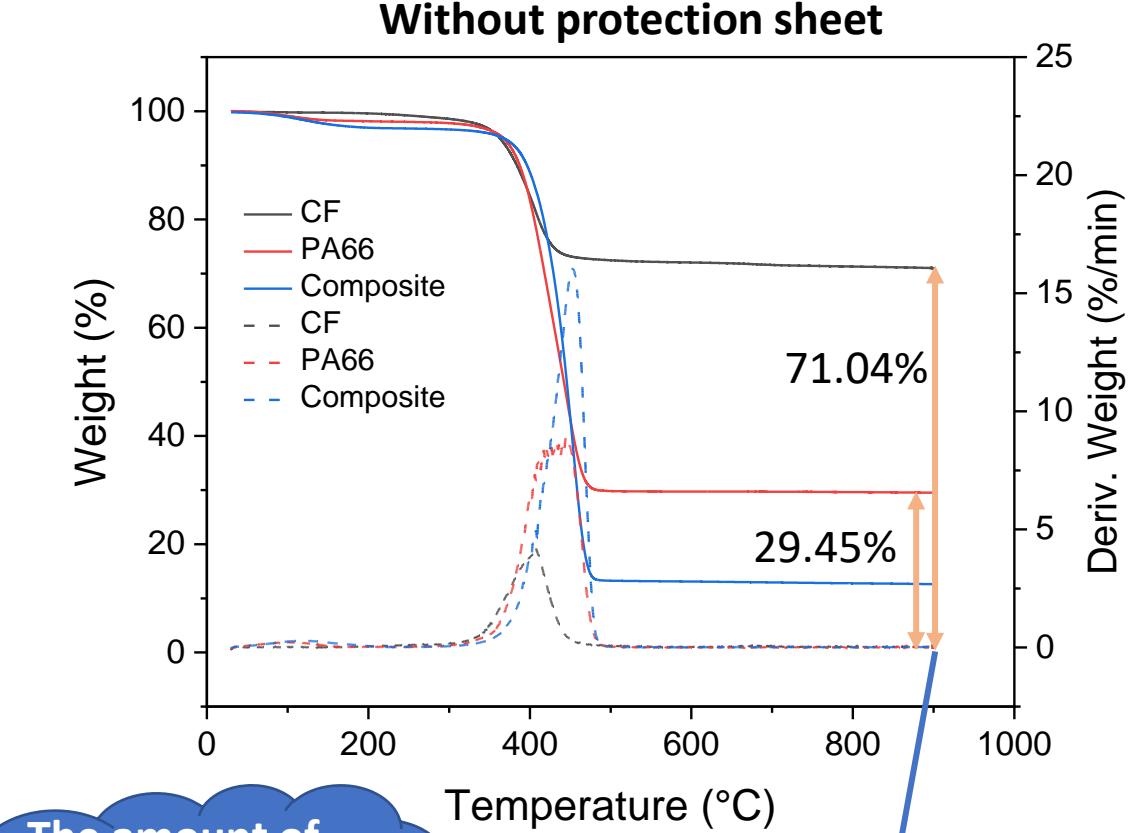
Material Characterization: DSC



Material Characterization: TGA

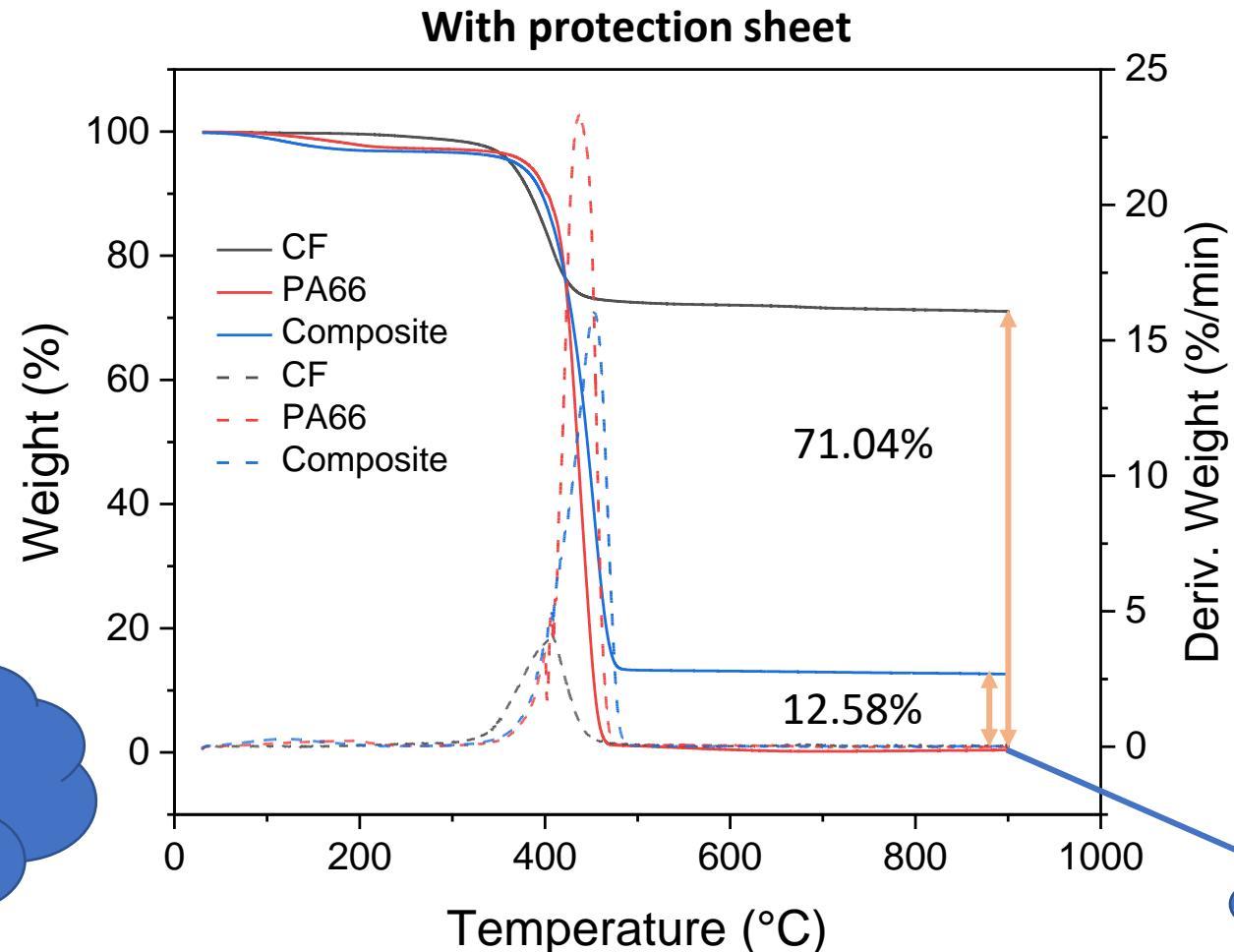


The amount of CF in the composite is around 50%
06/08/2022



The amount of CF in the composite is around 41%

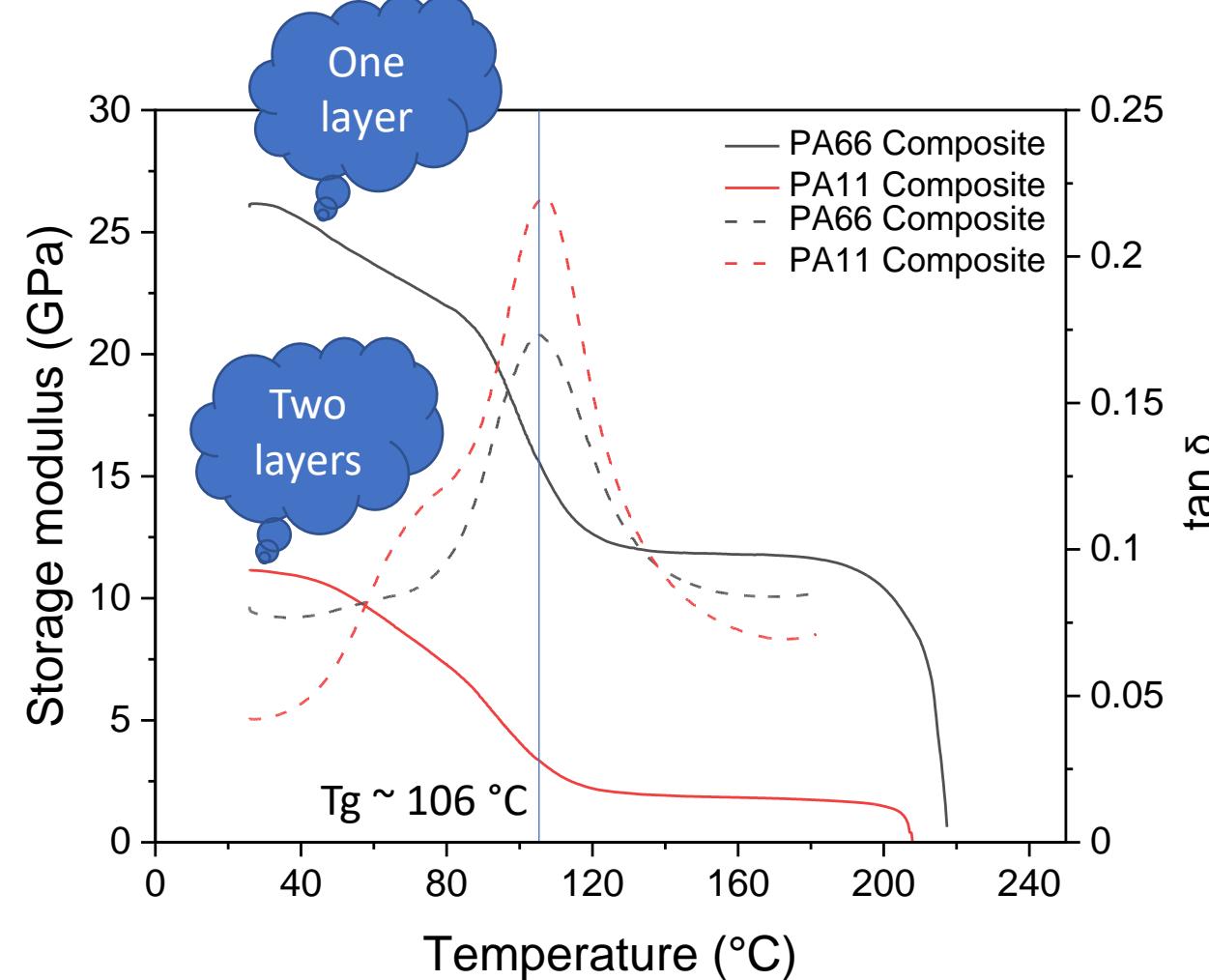
Material Characterization: TGA

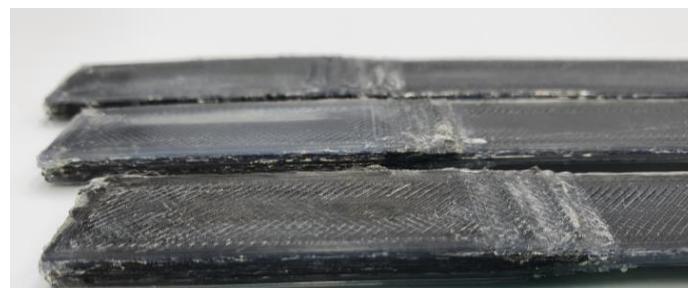


The amount of
CF in the
composite is
around 17%

Material Characterization: DMA

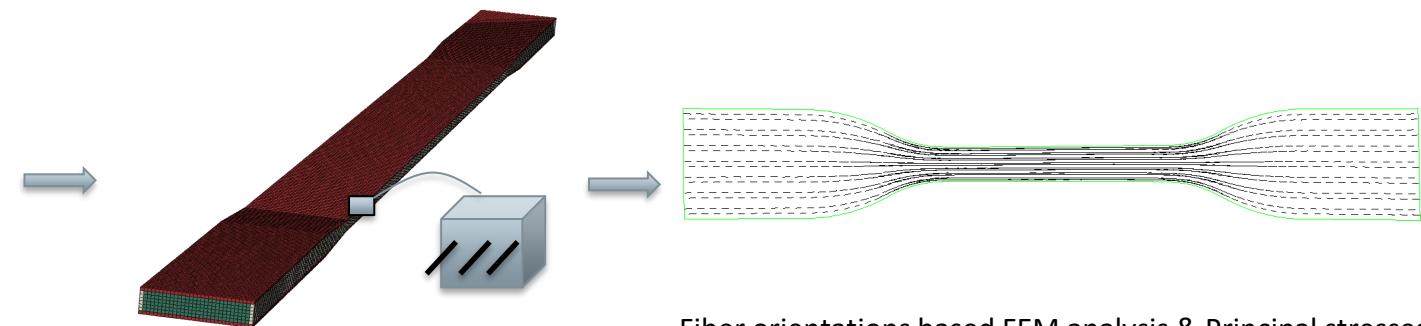
Both sample
without
protection
sheet





CoPA-CCF tensile specimen

FE- Model & Fiber orientation



Fiber orientations based FEM analysis & Principal stresses



PA 11 & CCF

