Modelling process and performance of FFF (Fused Filament Fabrication)

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DSM Materials Science Center

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Outline

- Introduction
  - DSM Additive Manufacturing
  - Motivation
- Processing aspects of Fused Filament Fabrication
- Performance aspects of Fused Filament Fabrication
- Conclusions & outlook

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Introduction in DSM Materials Science Center

Brightlands Chemelot Campus

Employees

400

Scientists/technicians

350

Diversity
Male/female:

75/25

Nationalities

>20

Two sites:

Geleen (NL)

Shanghai (CN)

Main customers

DSM Engineering Plastics
DSM Dyneema
DSM Resins and Functional materials
DSM Additive Manufacturing
DSM Advanced Solar

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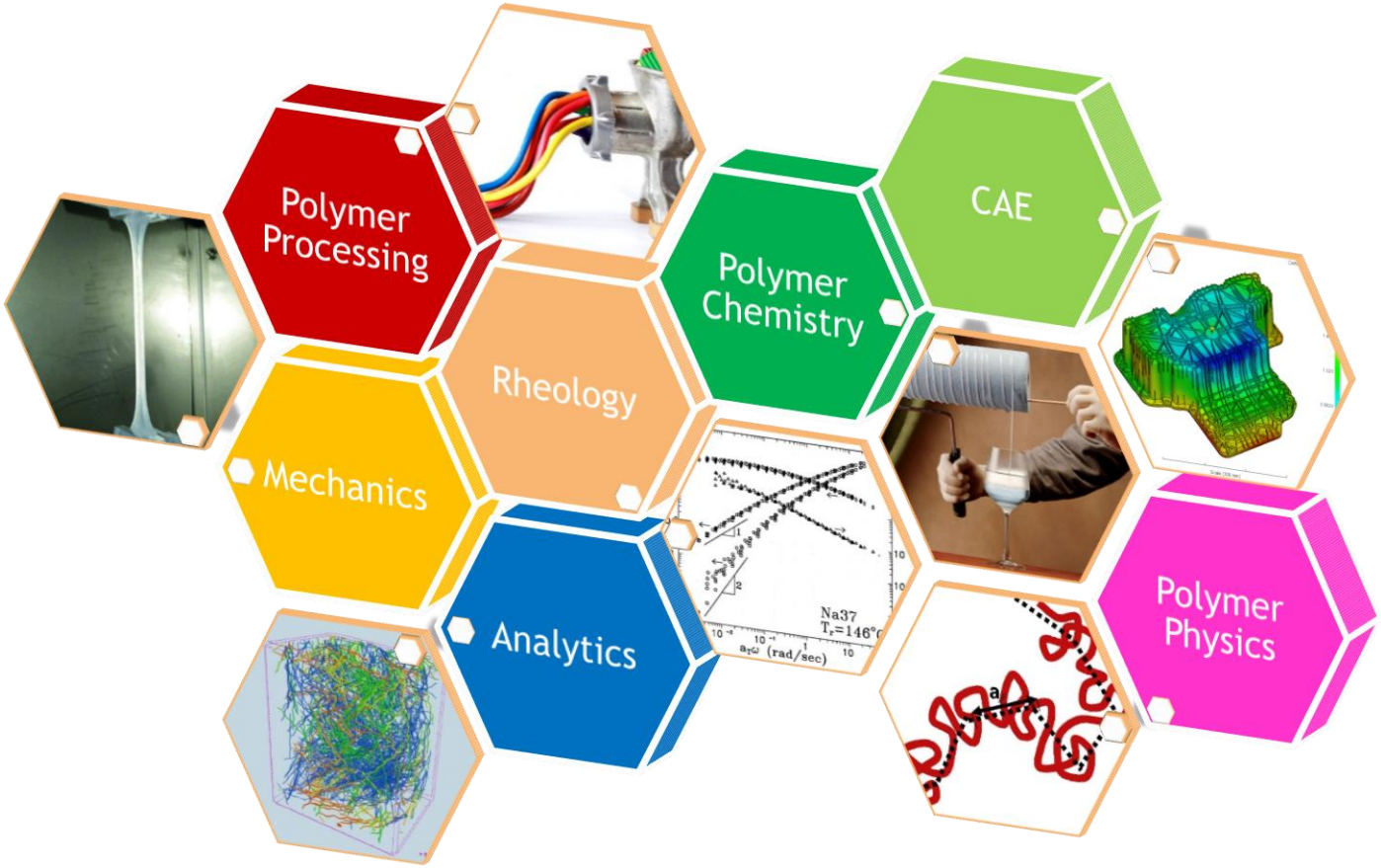
DMSC Competences



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DSM Additive Manufacturing

Engineering Plastics

Resins & Functional Materials

Additive Manufacturing

DSM Engineering Plastics

- Strong track record and application know-how in main industries
- 6 FFF grades commercially available
- New developments in FFF and SLS

DSM SOMOS

- Strong brand (25+ years) in 3D printing, rapid tooling
- Pioneer in photopolymers
- Technologically most-advanced materials in SLA
- Developments in DLP, Jetting, BinderJet, …

Portfolio of Engineering Materials across all technologies and application segments

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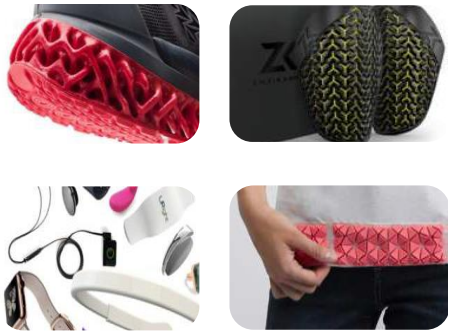
DSM Additive Manufacturing - 4 segments

Healthcare

- Medical Models
- On/In body
- Dental aligners
- Dental guides

Sports & Lifestyle



- Shoes
- Wearables
- Shields and Guards
- Printing of fabrics

Tools & Electronics

- Electronics
- Connectors
- Injection molding
- Jigs & Fixtures
- Investment casting

Transportation

- Motorsports/F1
- Small volume cars
- Aerospace/Trains
- Auto interior
- Under the hood

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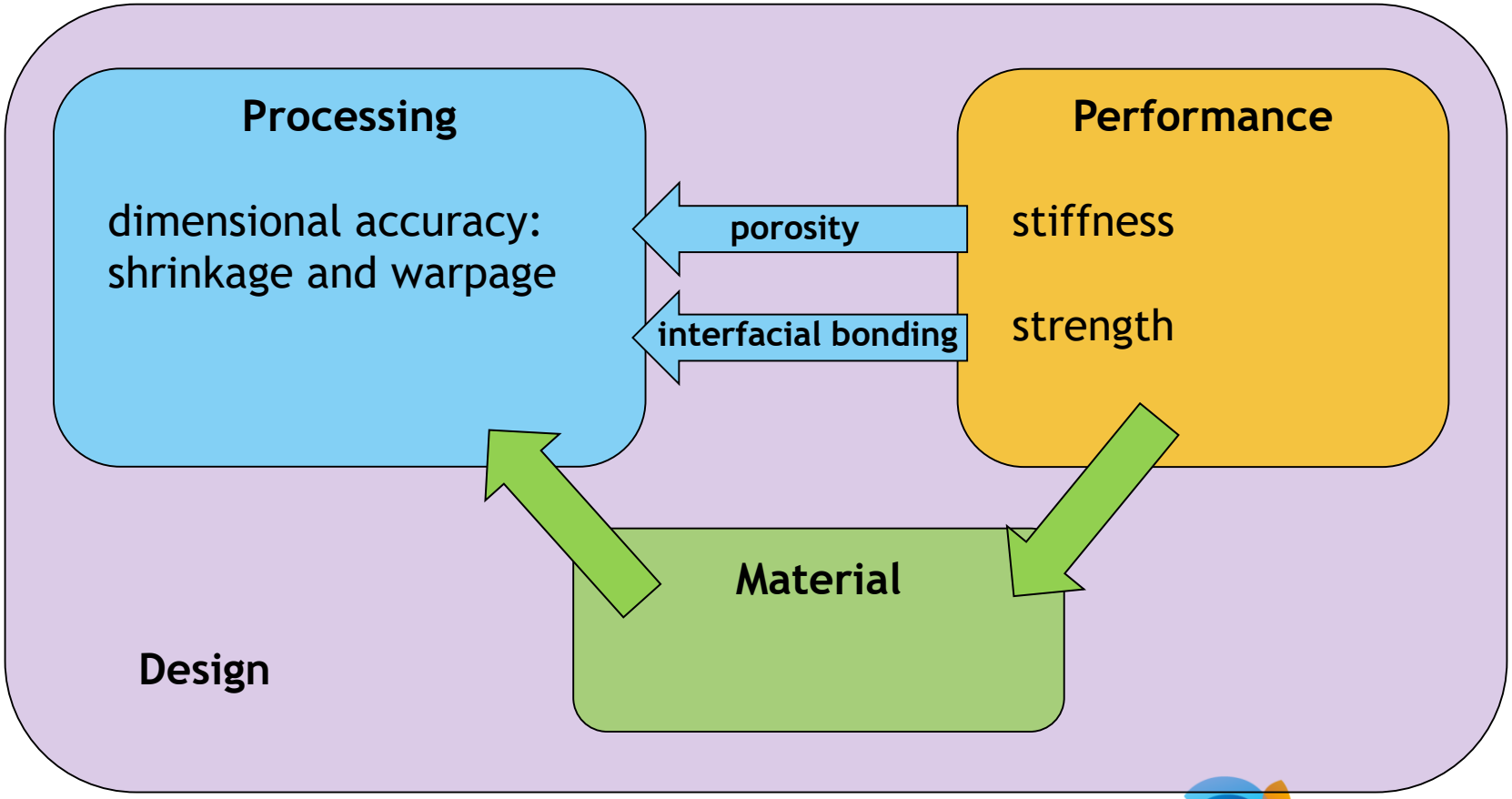
Motivation

- The FFF technology can only be successful if we are able to develop and apply accurate simulation tools that enable us to optimize design, process, and material.



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DSM, FFF grades:

- Novamid®
  - Novamid ID 1030: PA6/66
  - Novamid ID 1030 CF10: PA6/66 + CF
  - Novamid ID 1070: PA6
- Arnite®
  - Arnite ID 3040: PET

Material cards added to Digimat MX in V2019.0

- Arnitel®
  - Arnitel ID 2045: Thermoplastic Copolyester (TPC)
  - Arnitel ID 2060 HT: Thermoplastic Copolyester (TPC)

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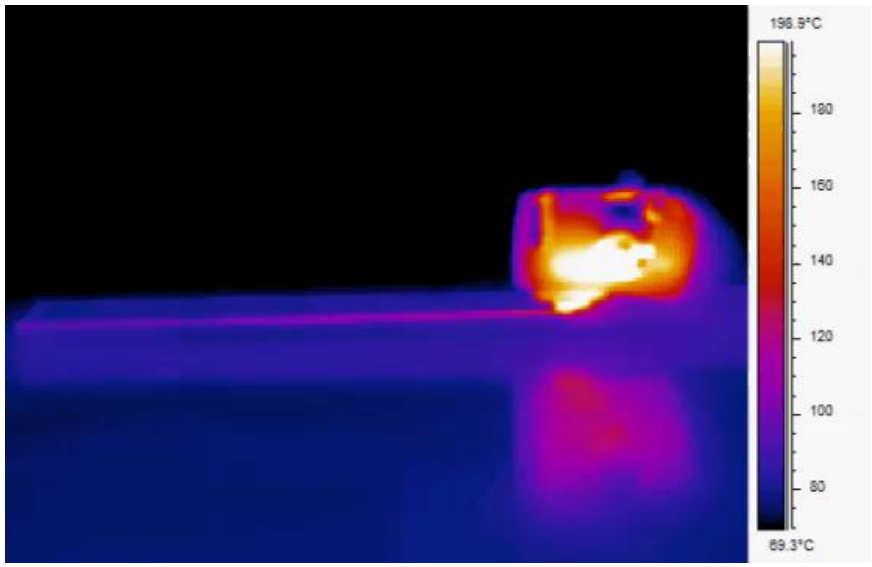
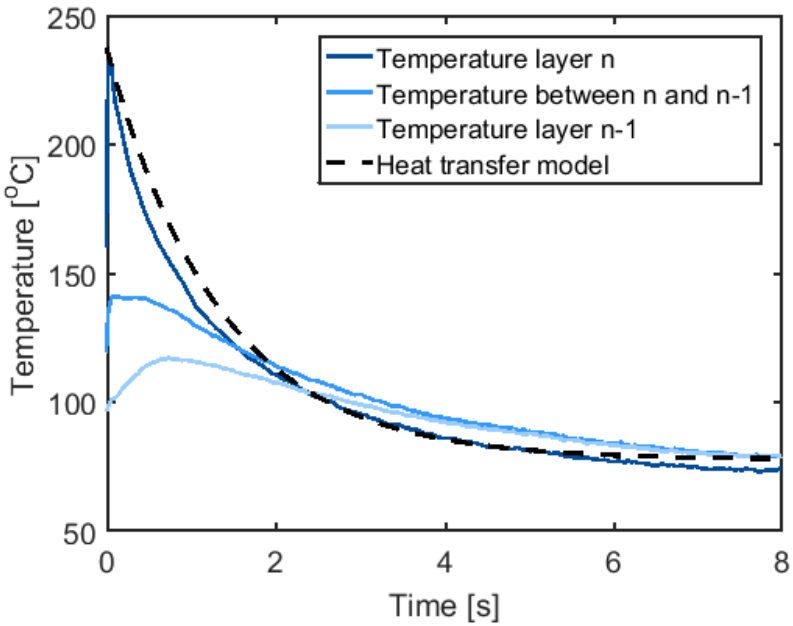
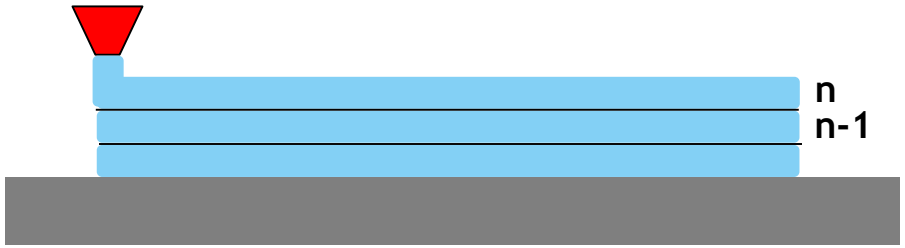
Processing of FFF

Infrared movie of FFF printing of a rectangular profile







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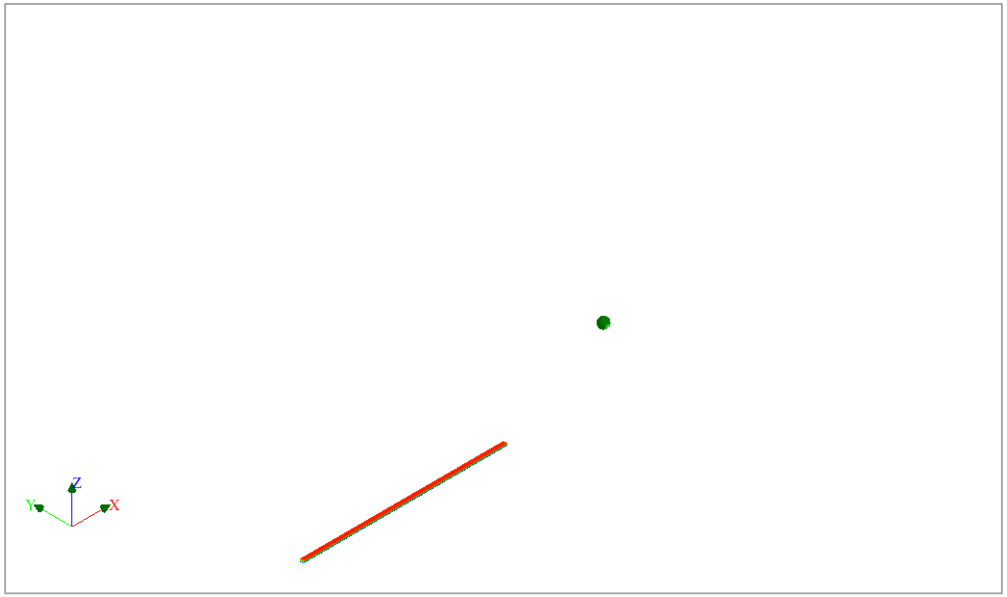
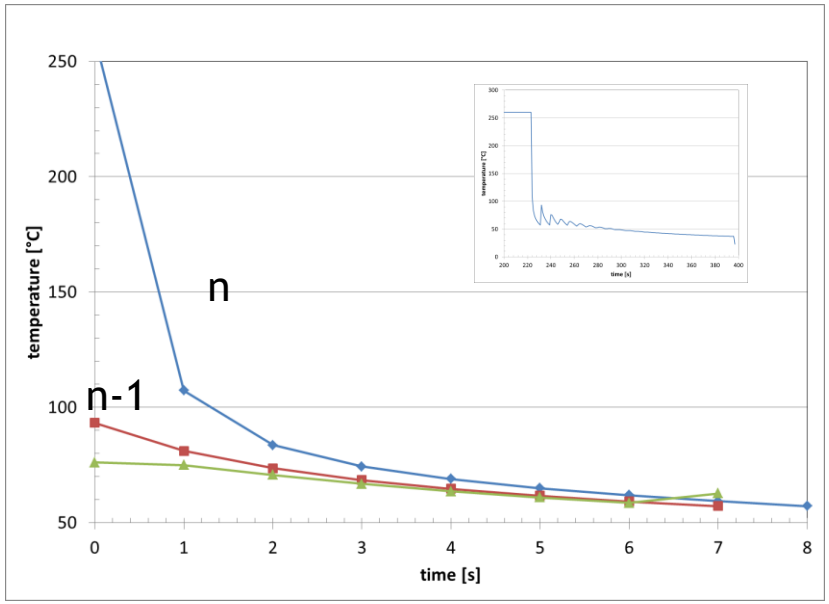
Temperature history





Temperature at designated location

T_{nozzle}=260°C, T_{bed}=80°C, T_{amb}=30°C, timestep = 1 s

Simulated temperature history agrees qualitatively well with experiment, improvement would be found in optimizing thermal boundary conditions

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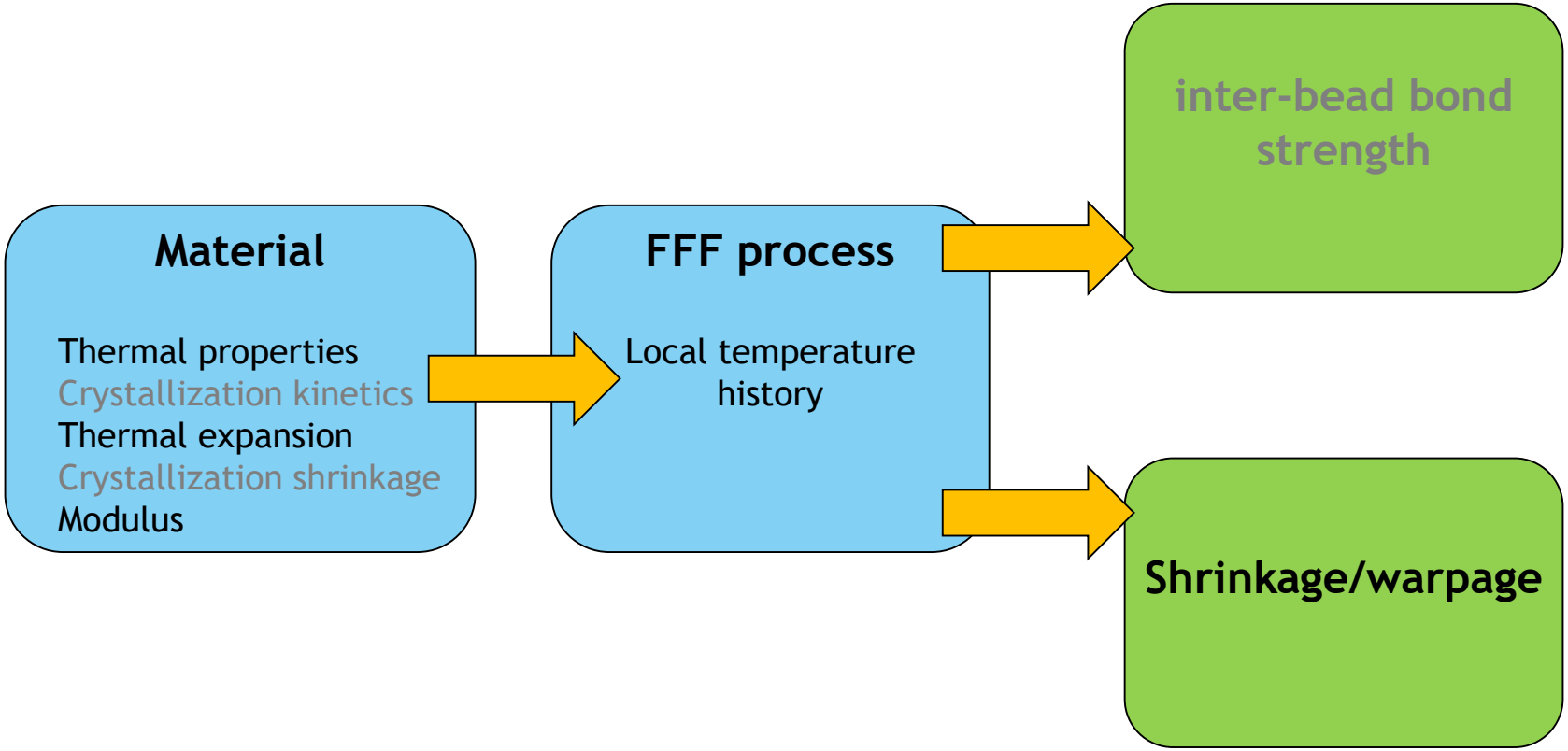
Modelling the FFF process with Digimat AM



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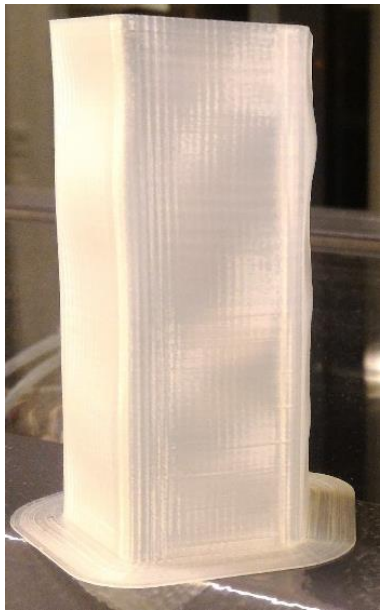
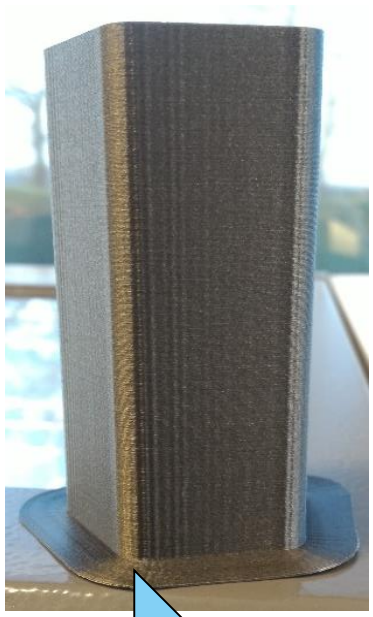
Warpage

Differential shrinkage during 3D-printing might cause warpage of the printed part. It manifests in deformation of thin walls or, most commonly, release from the build surface.

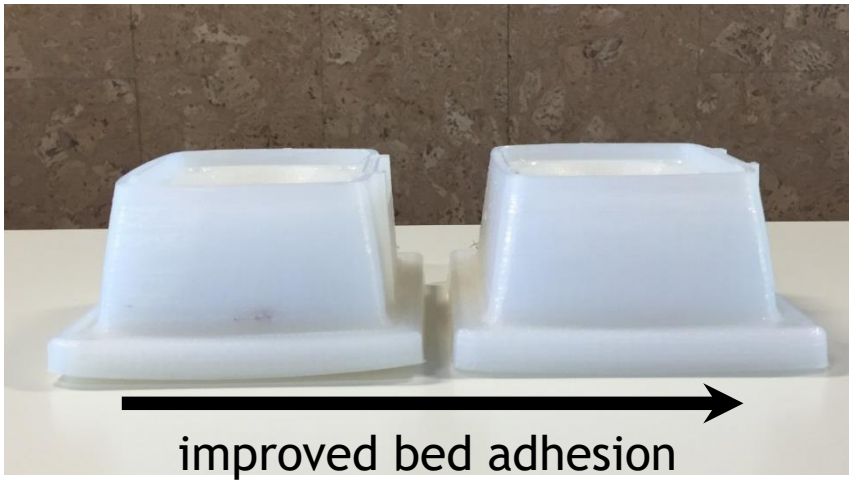
Deformation thin walled structure





Warpage improved by adding carbon fibers

Release from build surface



Important issue for polyamides!

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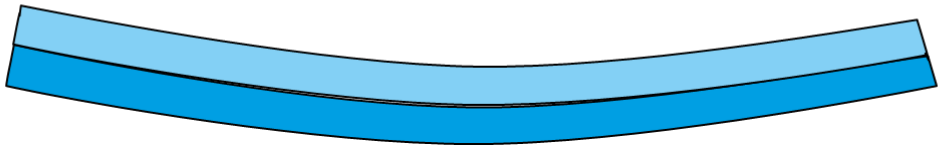
Warpage: principle

Polymer melt 2 is deposited on already solidified layer 1

Layer 2 shrinks during cooling, but is hindered by layer 1

As layer 2 is supposed to adhere well to layer 1, after releasing the print, the layered structure will bend upwards



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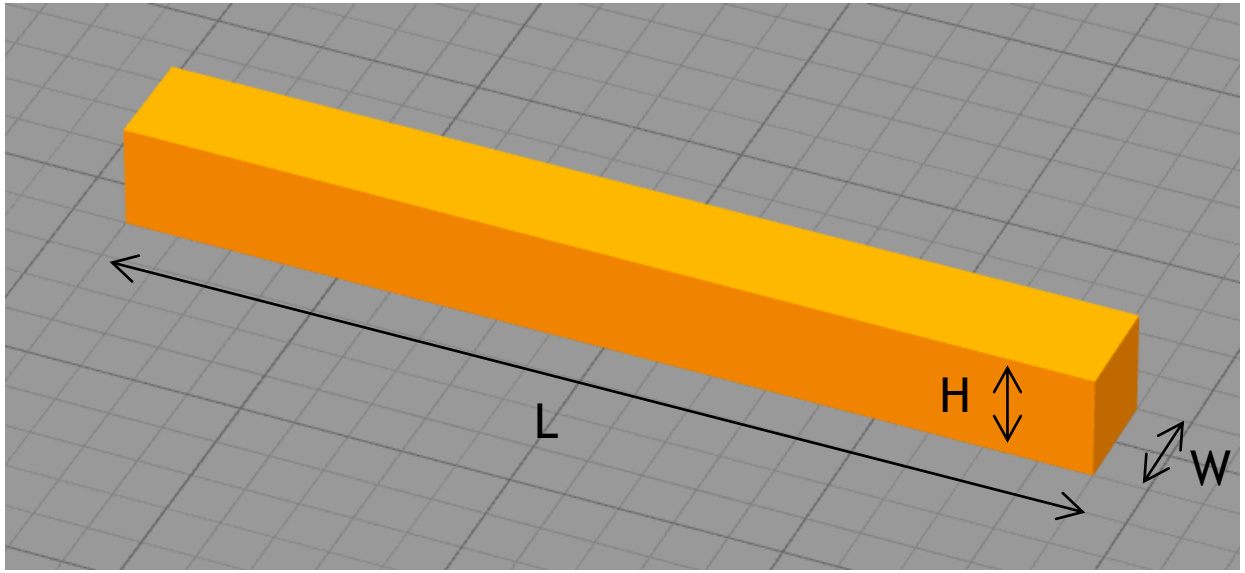
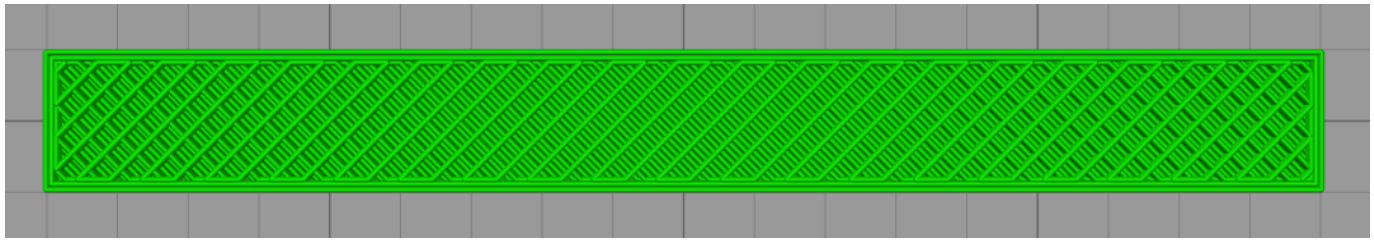
Warpage bar



L x W x H =
50/70/90 x 10 x 10 mm



25% infill -45°/45°

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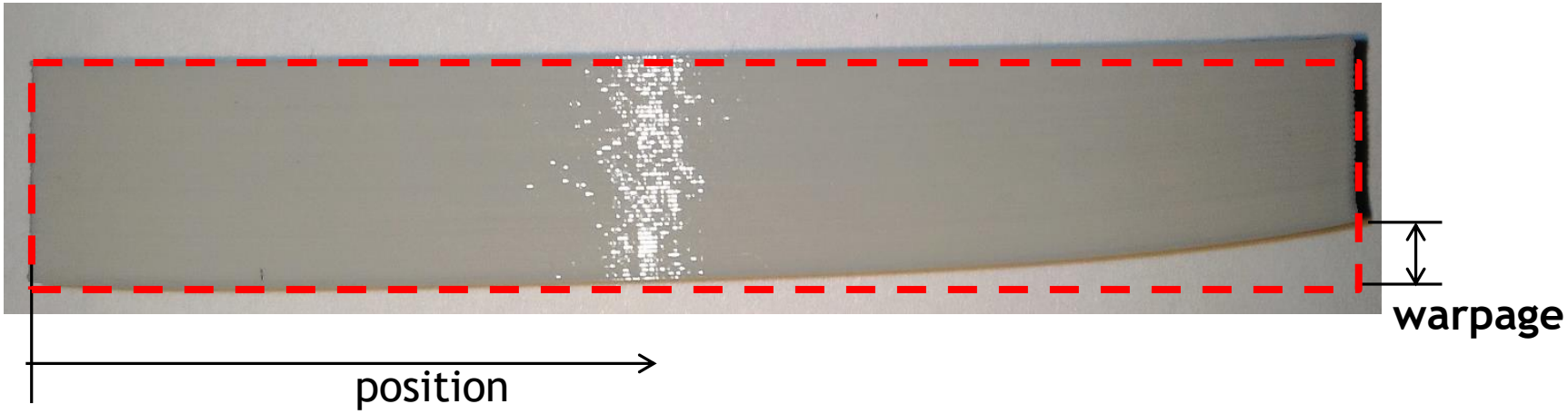
Warpage indicator

(L x W x H) = 90 x 10 x 10 mm



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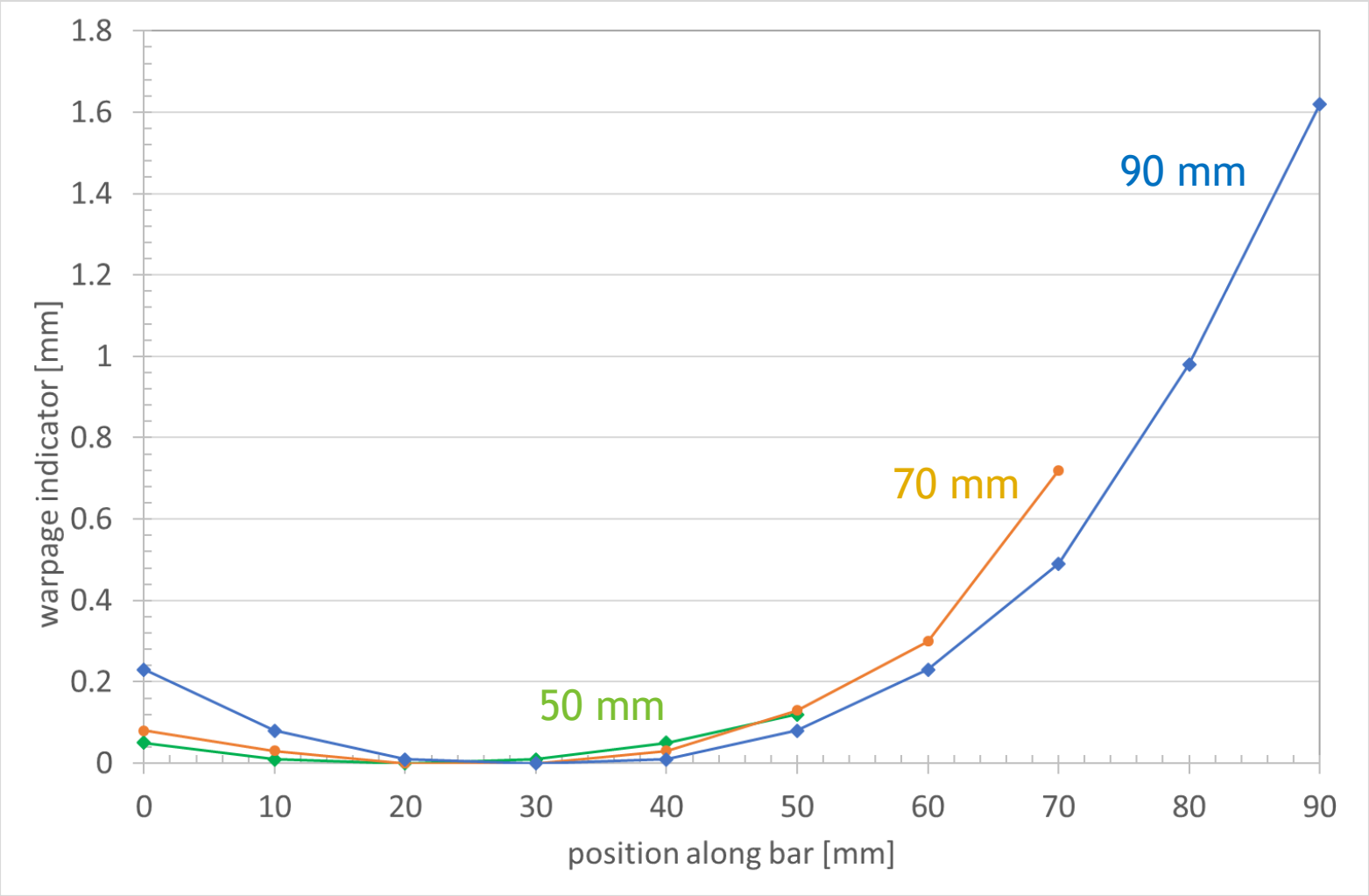
Results: Warped prints



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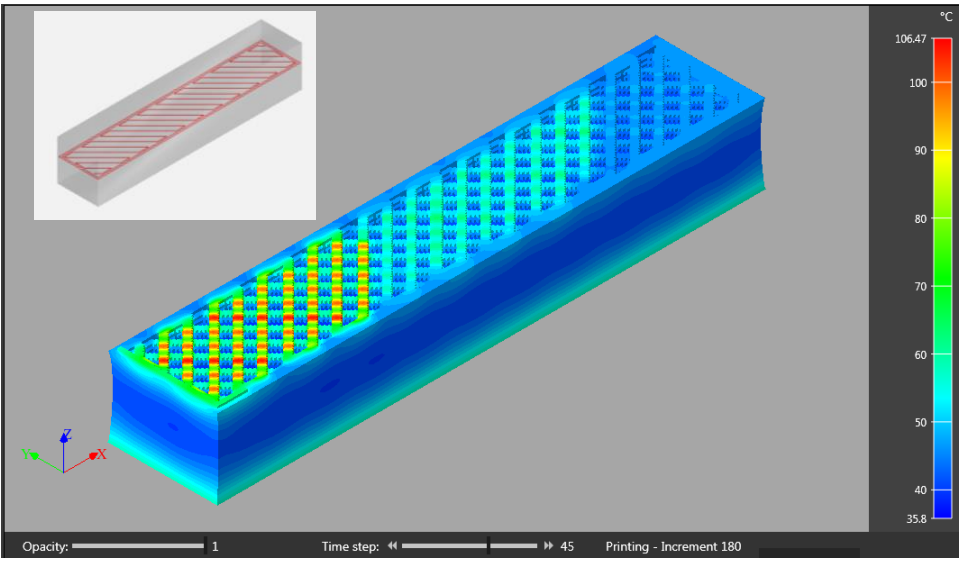
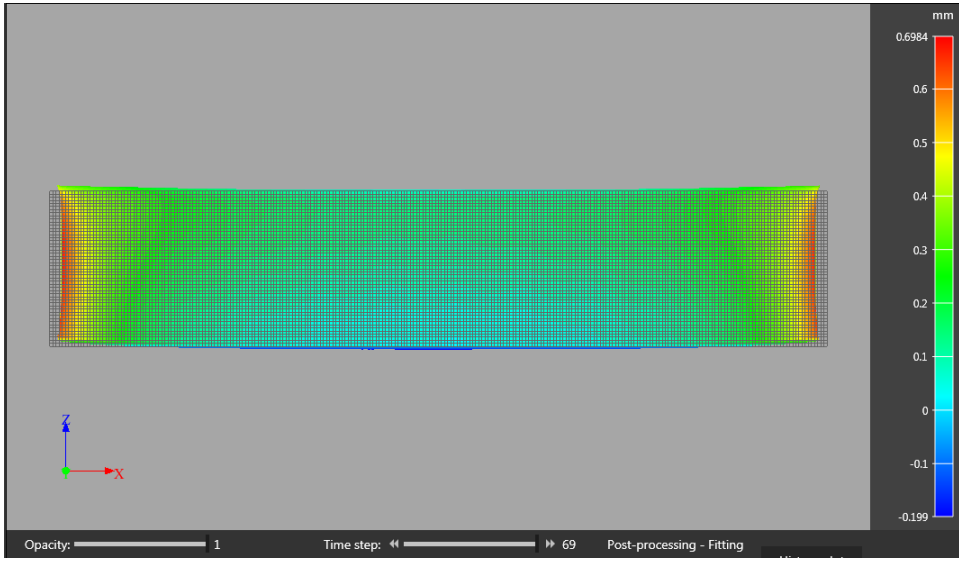
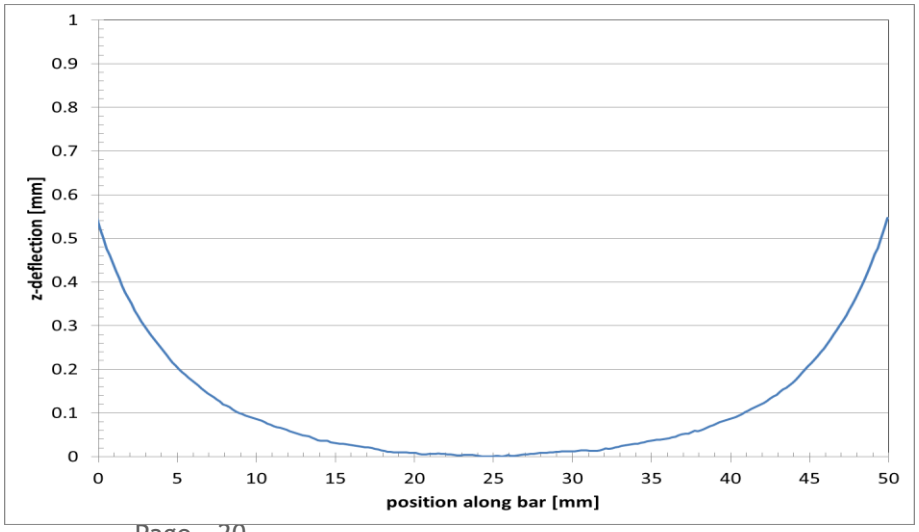
Results: comparison with Digimat AM results



Temperature distribution during printing



Deflection in z-direction after printing



Warpage is overpredicted, most likely caused by:

- Boundary conditions, e.g. adhesion to bed
- Experimentally release of part during printing

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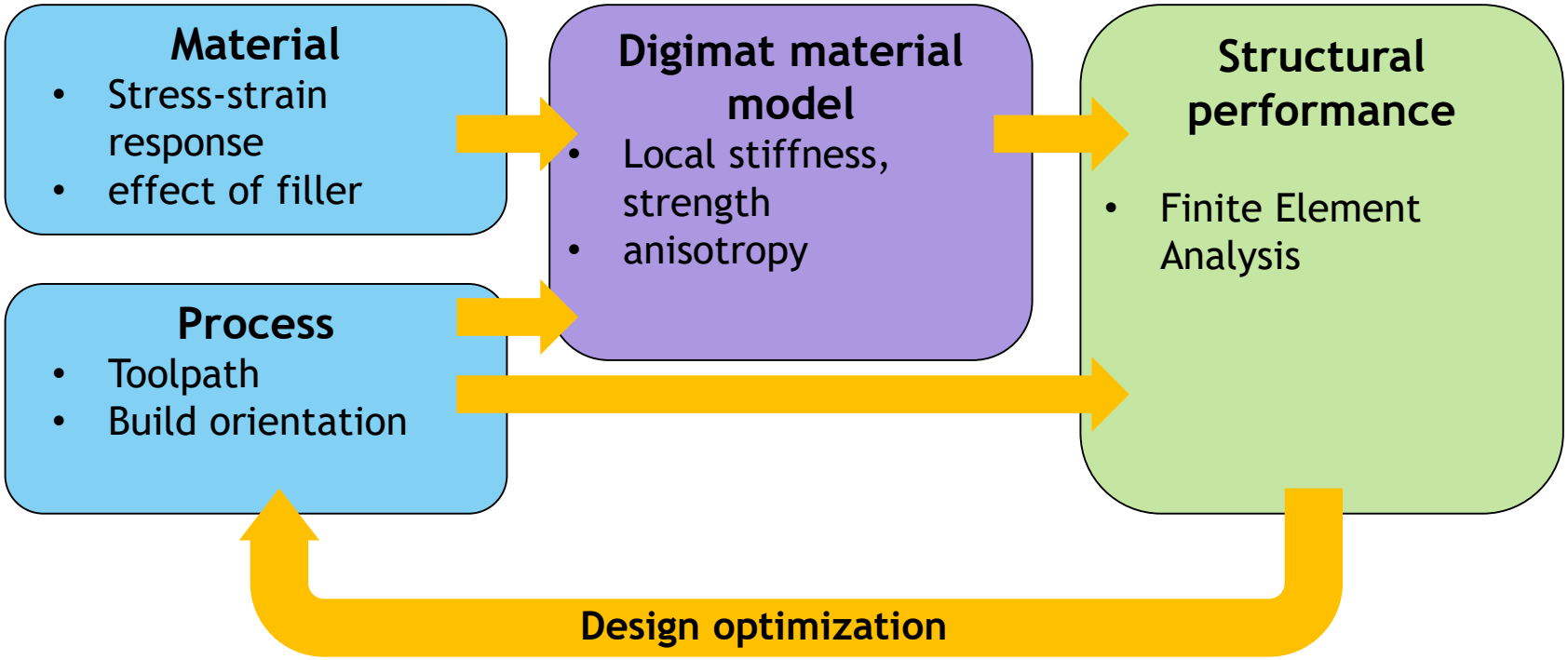
Structural performance FFF parts



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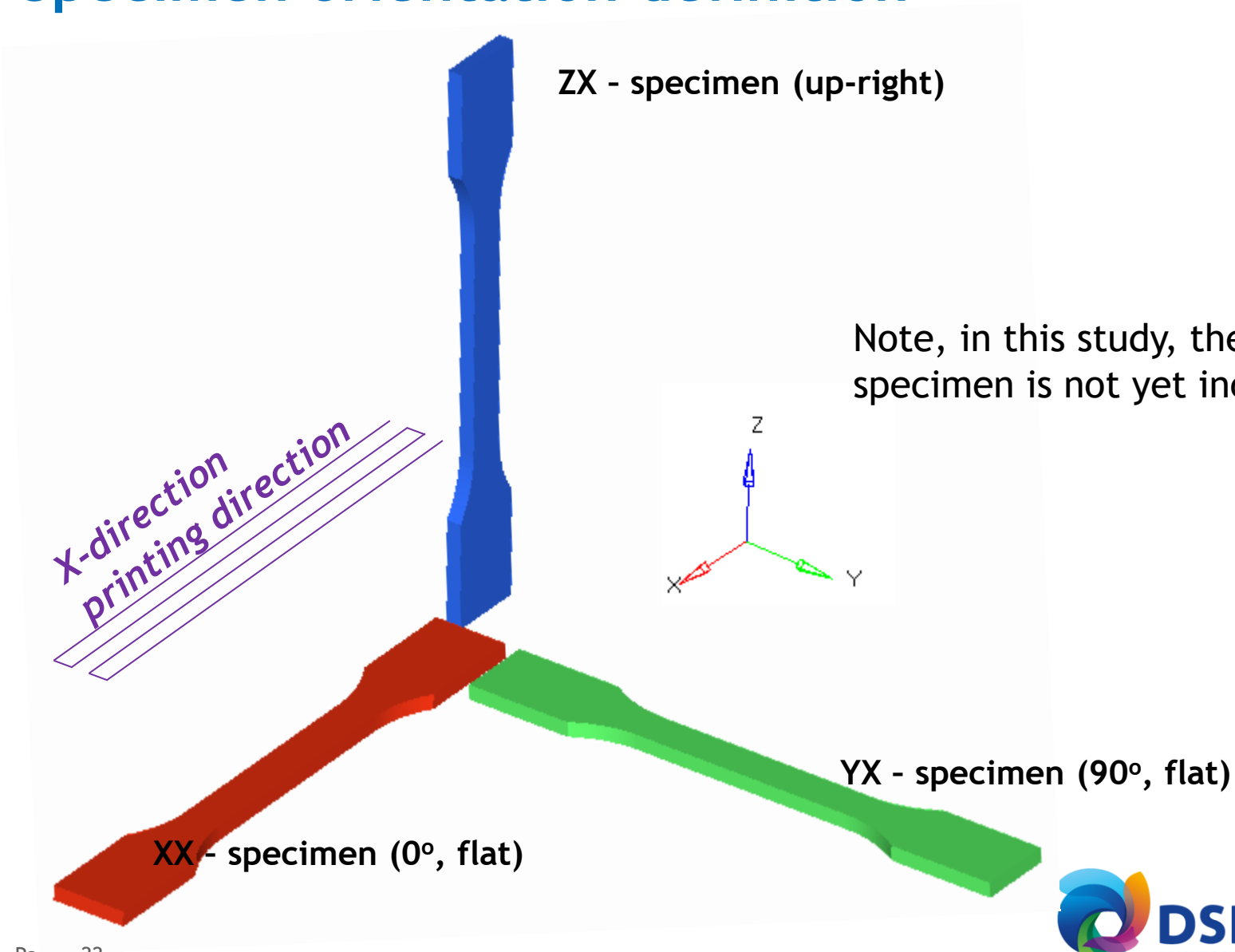
Specimen orientation definition



Note, in this study, the ZX - specimen is not yet included.

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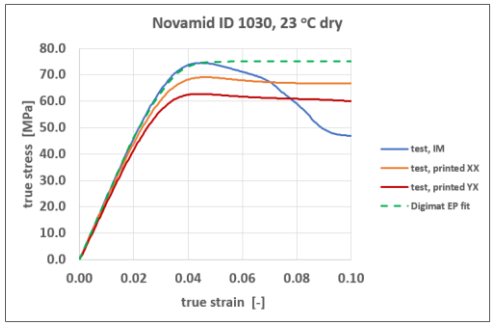
Calibration material model for unreinforced FFF

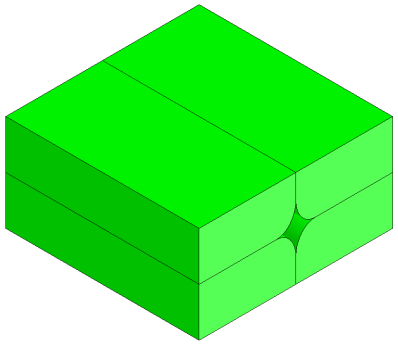
STEP 1
Fit the bulk stress-strain behavior with an Elasto-Plastic model

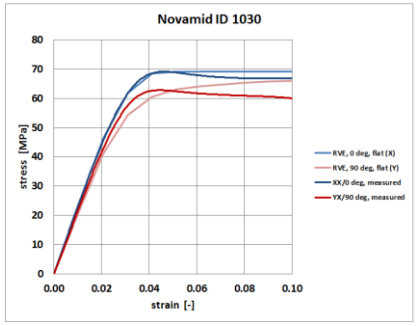
STEP 2
Digimat-FE:
Build RVE representing the FFF microstructure

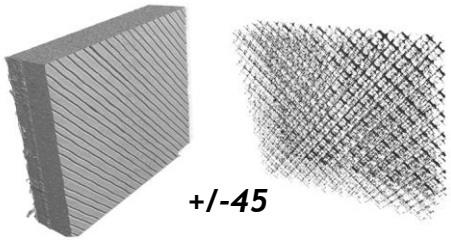
STEP 3
Calculate RVE stress-strain curves (micro FEA); compare stiffness and strength with printed specimens

optimization loop









input from print settings and or microscopy/ µCT scan

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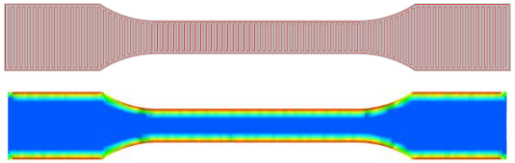
Calibration material model for unreinforced FFF

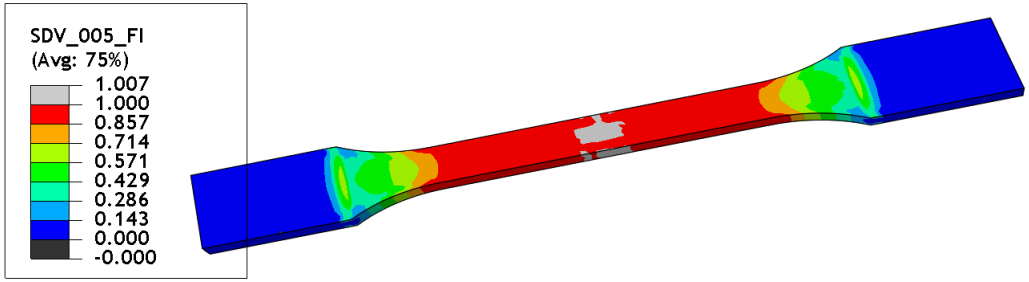
STEP 4
Digimat-MF:
Add and calibrate the failure indicator

STEP 5
Digimat-MAP:
Convert toolpath of printed tensile specimens into orientation file for FEA

STEP 6
Digimat-CAE:
Generate material card for FEA; run FE analysis of printed tensile specimens

Validation cases





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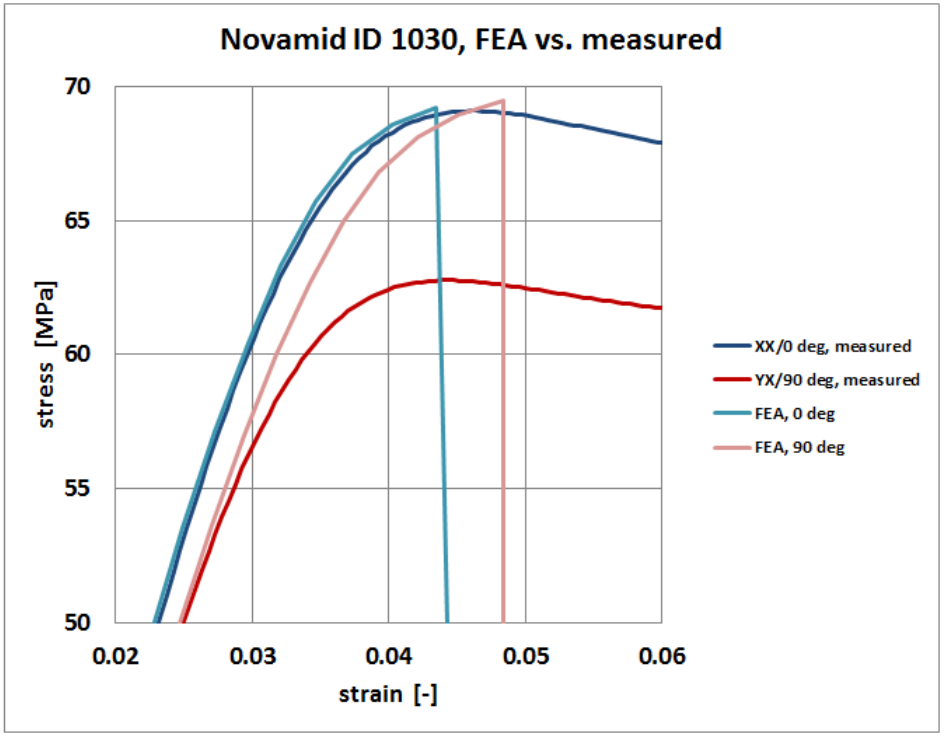
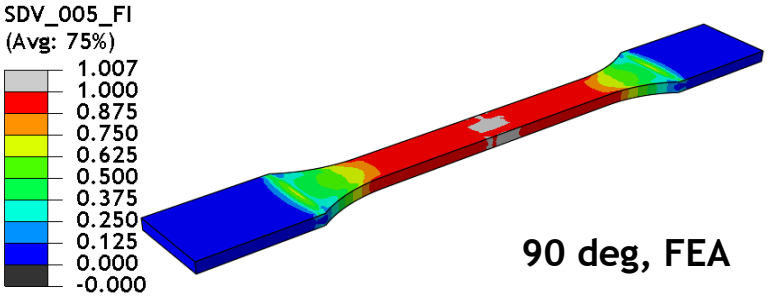
Calibration of material model for unreinforced FFF: STEP 6 → FEA results





- Good prediction of stiffness for both samples.
- Strength of the 90 degree specimen is over-predicted.

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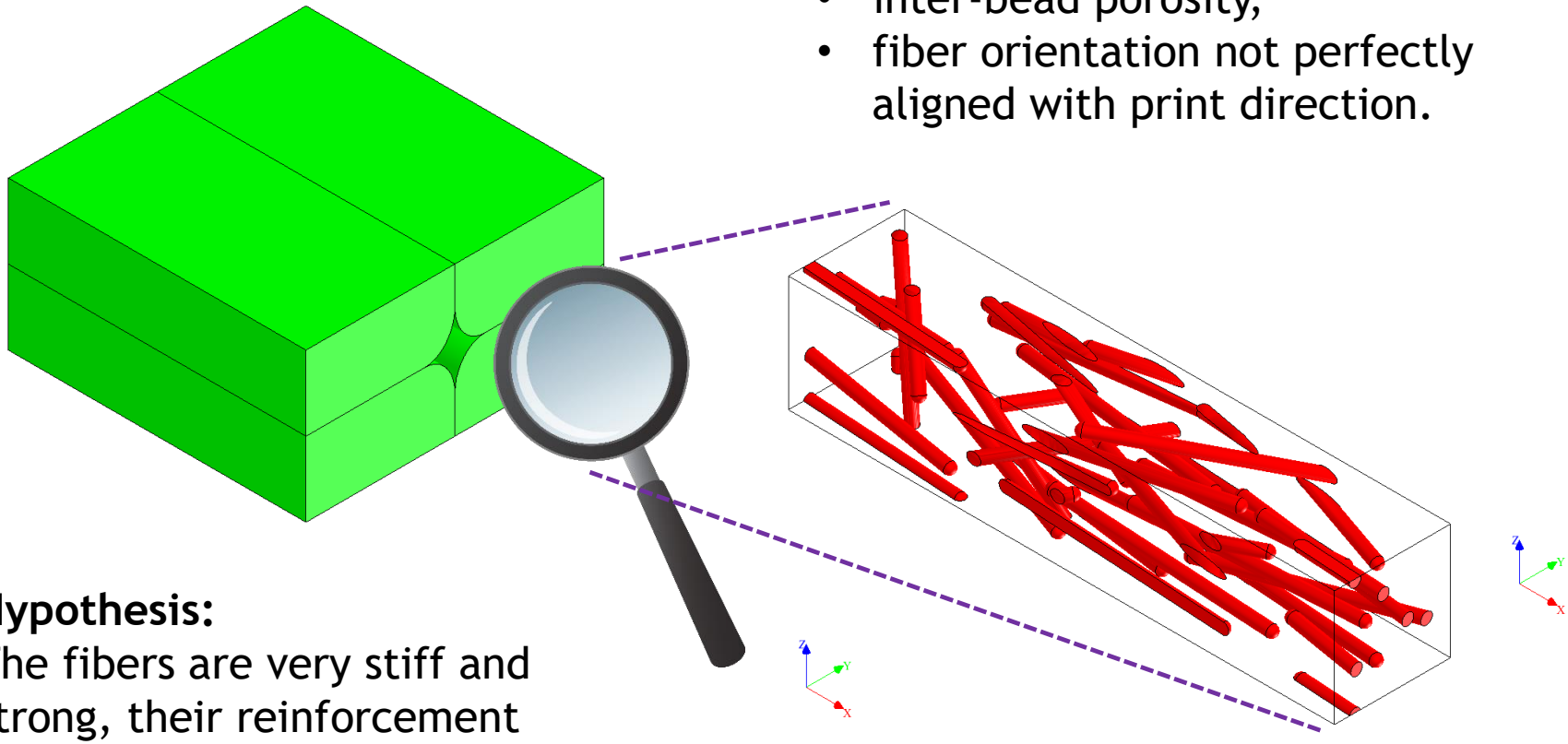
RVE for fiber reinforced FFF material

RVE features:

- inter-bead porosity,
- fiber orientation not perfectly aligned with print direction.



Hypothesis:
The fibers are very stiff and strong, their reinforcement overrule the effect of the inter-bead porosity → simplified RVE

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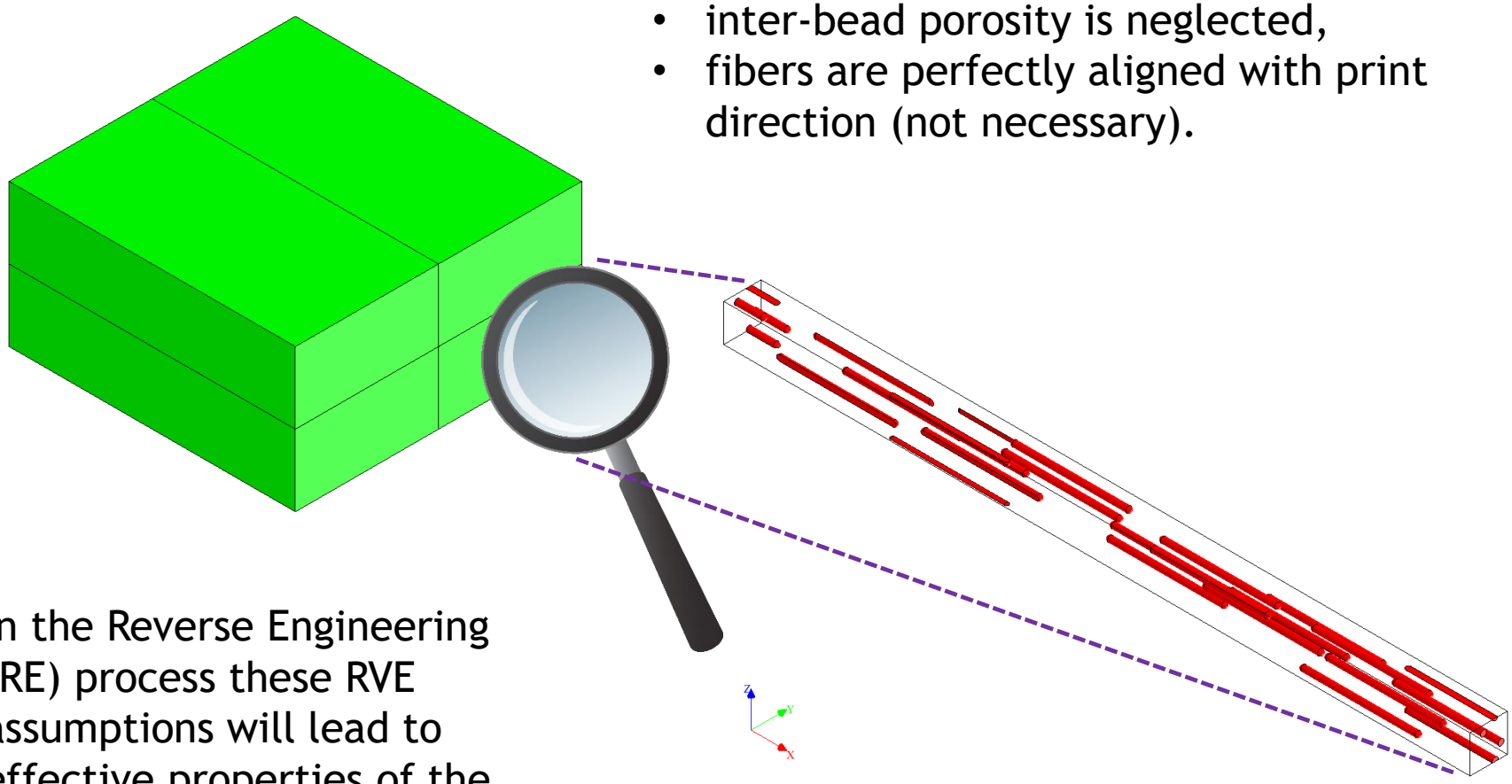
RVE for fiber reinforced FFF material

Simplified RVE:

- inter-bead porosity is neglected,
- fibers are perfectly aligned with print direction (not necessary).



In the Reverse Engineering (RE) process these RVE assumptions will lead to effective properties of the matrix+pores

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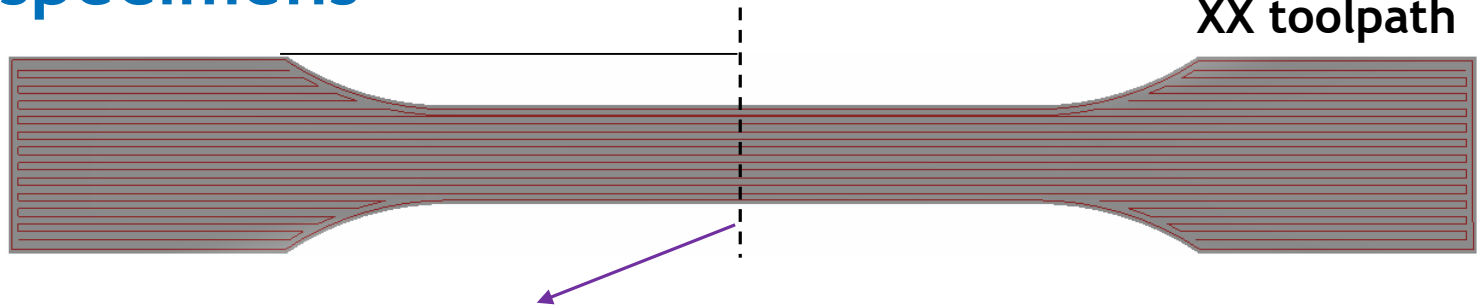
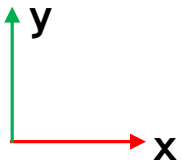
RVE for printed Novamid ID 1030-CF10 specimens

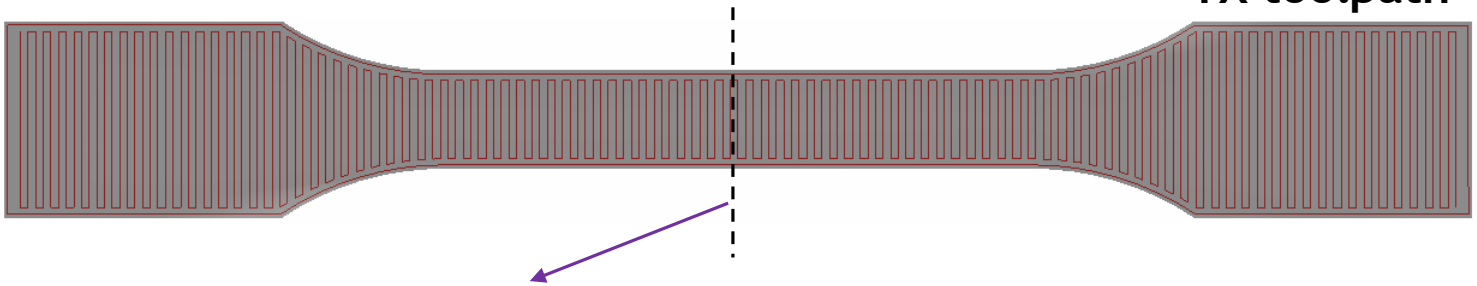
XX toolpath

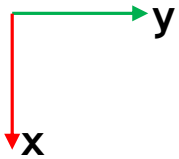




In a cross-section all beads are aligned with the tensile test direction: RVE is 100% aligned (0°)

YX toolpath





Outer bead: defining the specimen contour, it is aligned with the tensile test direction. A 2-layer RVE is defined:

- 76% of cross-section area: 90°
- 24% of cross-section area: 0°

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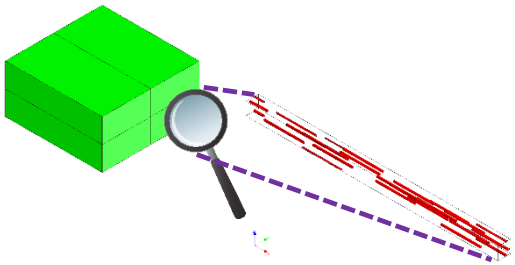
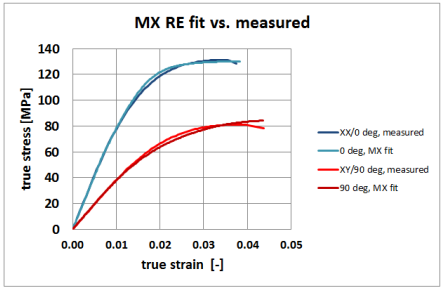
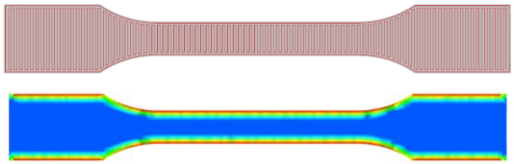
Calibration of material model for reinforced FFF







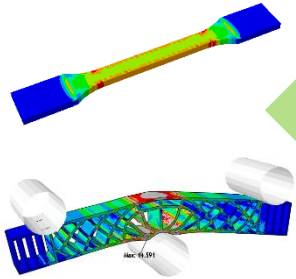
STEP 1
RVE assumptions for printed specimens

STEP 2
Digimat-MX:
Reverse engineer material model parameters including failure indicator

STEP 3
Digimat-MAP:
Convert toolpath of printed tensile specimens into orientation file for FEA

STEP 4
Digimat-CAE:
Generate material card for FEA; run FE analysis of printed tensile specimens

Validation cases



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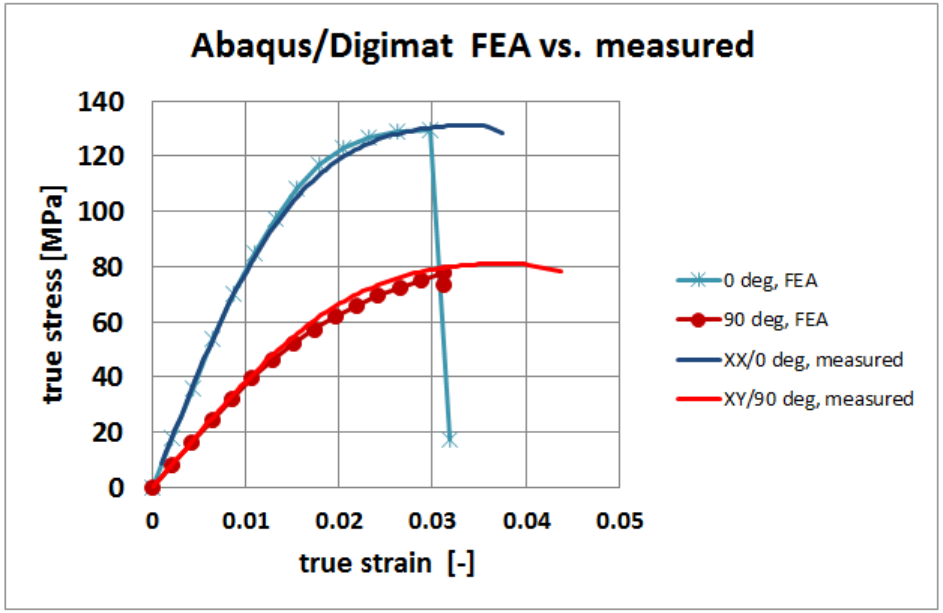
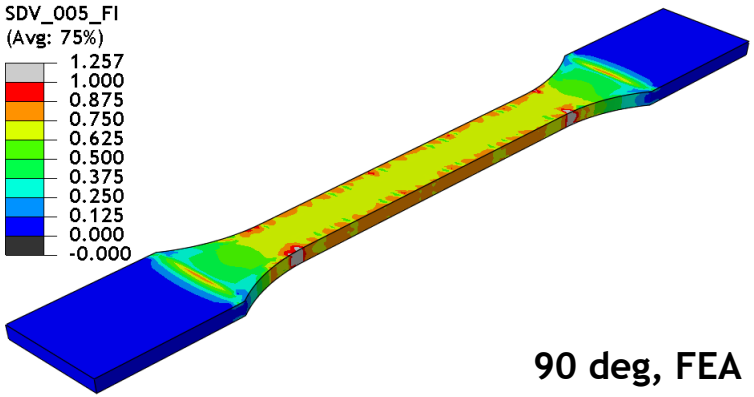
Calibration of material model for reinforced FFF: STEP 4 → FEA results specimens





90 deg, FEA

- Overall good correlation between FEA predictions and measured stress-strain curves.
- Failure in the FEA prediction is at lower strain values compared to measured values.

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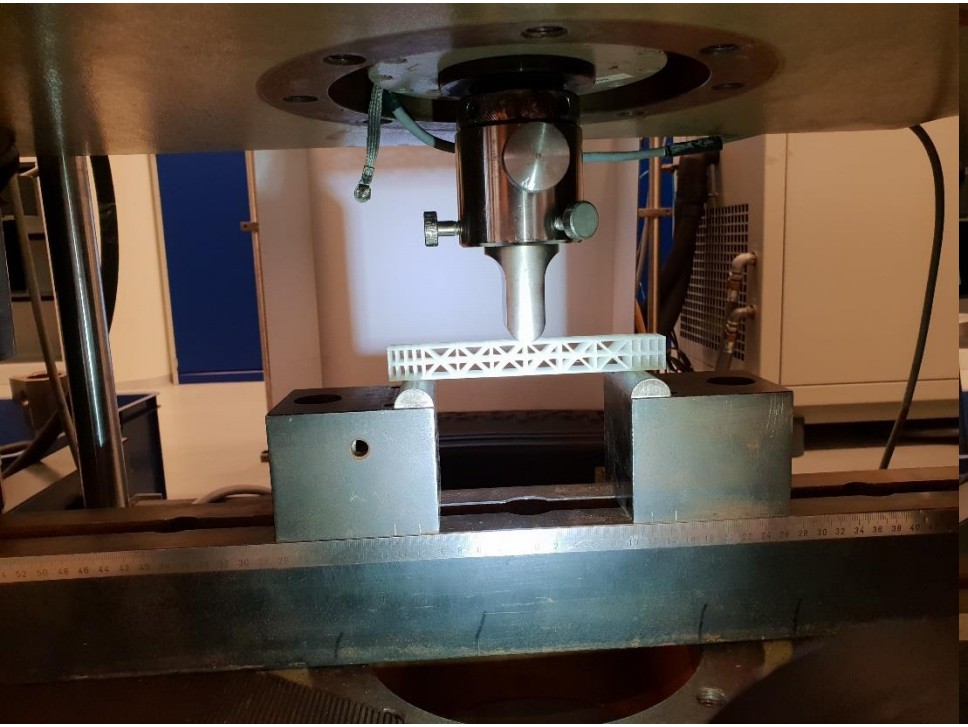
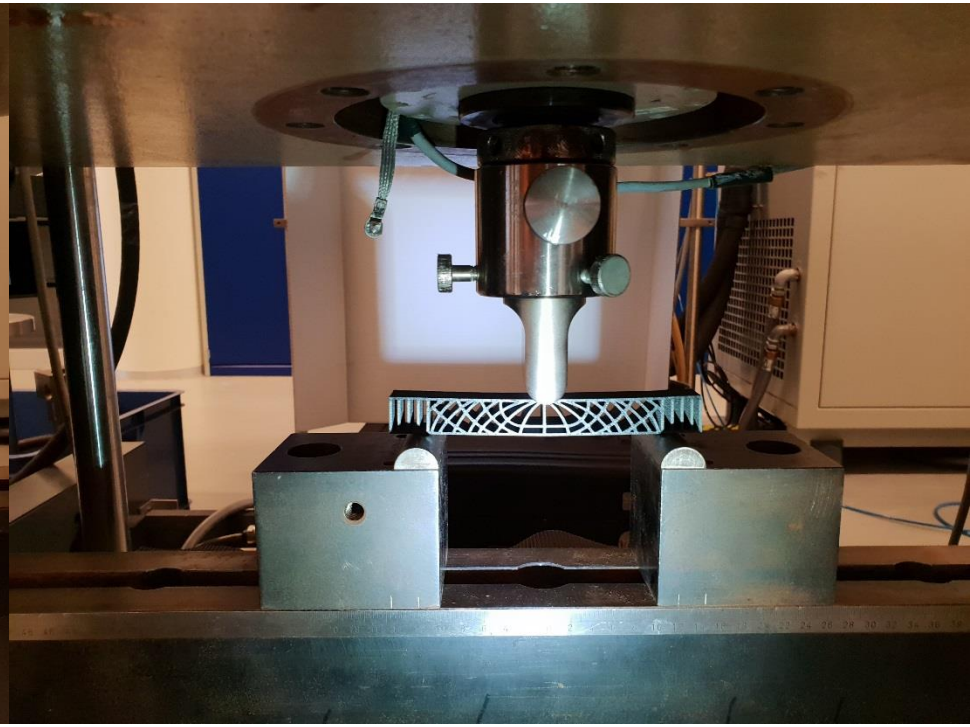
Validation case: 3 point bending

Two materials: Novamid ID 1030
Novamid ID 1030 CF10



STD beam design



OPTI beam design

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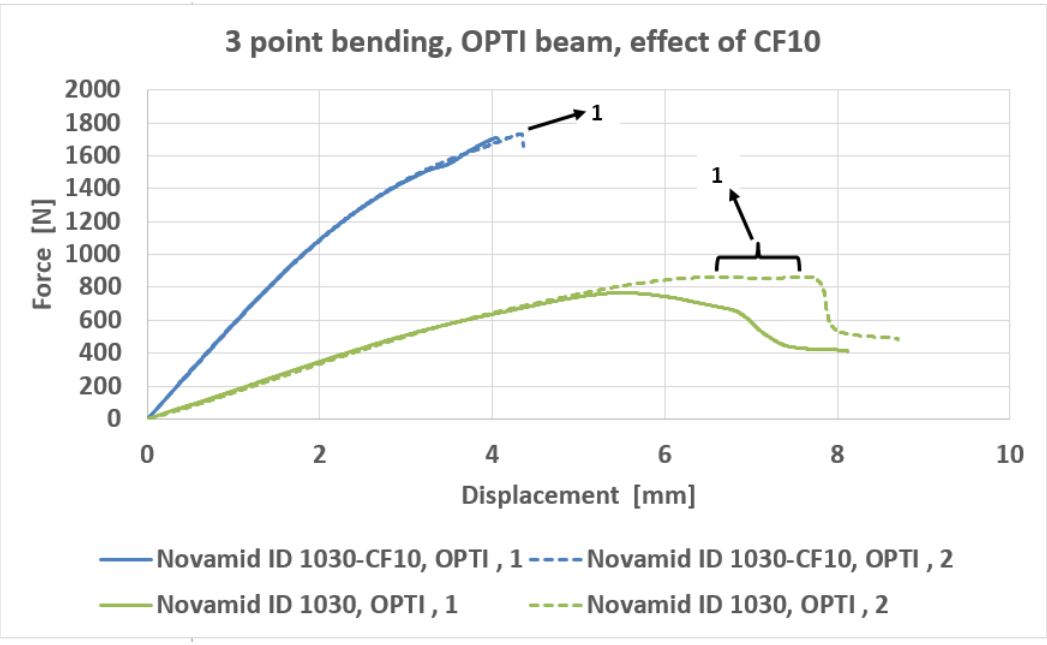
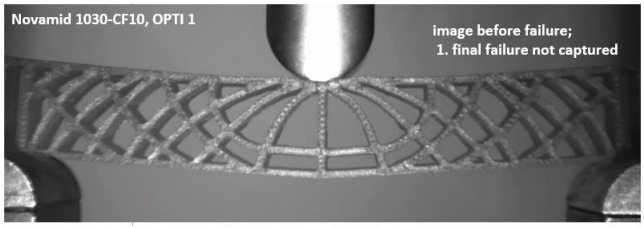
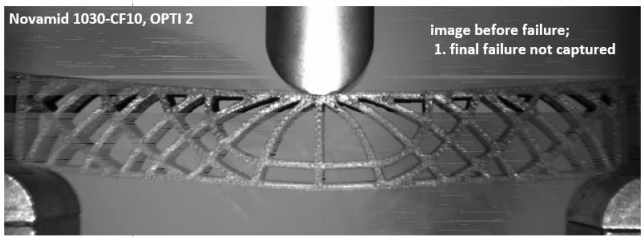
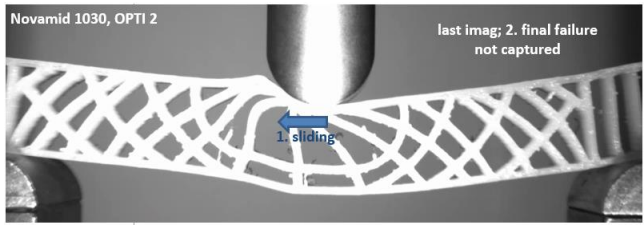
OPTI beams









- Stiffness increase for CF10 grade compared to unfilled is 3.5
- Strength of the beam is increased by a factor of 2

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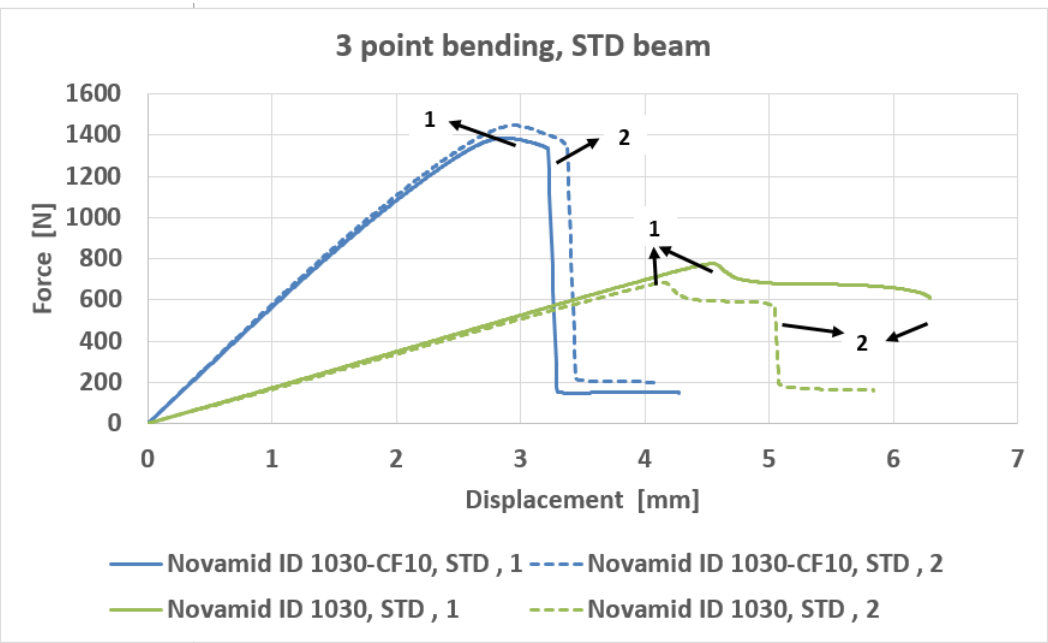
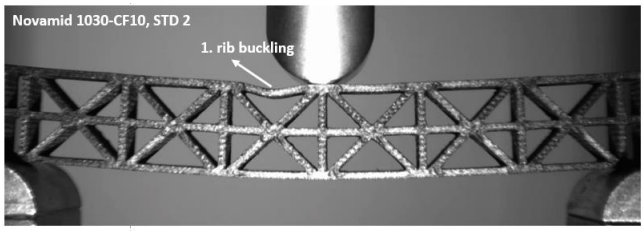
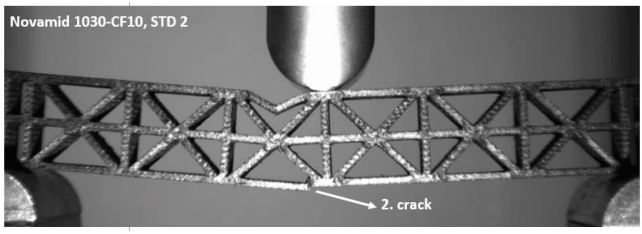
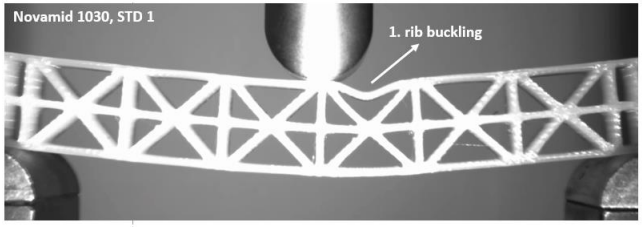
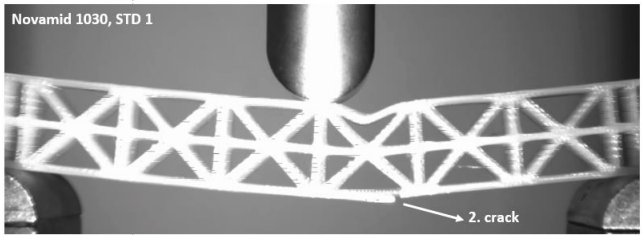
STD beams











- Stiffness increase for CF10 grade compared to unfilled is 3.5
- Strength of the beam is increased by a factor of 2

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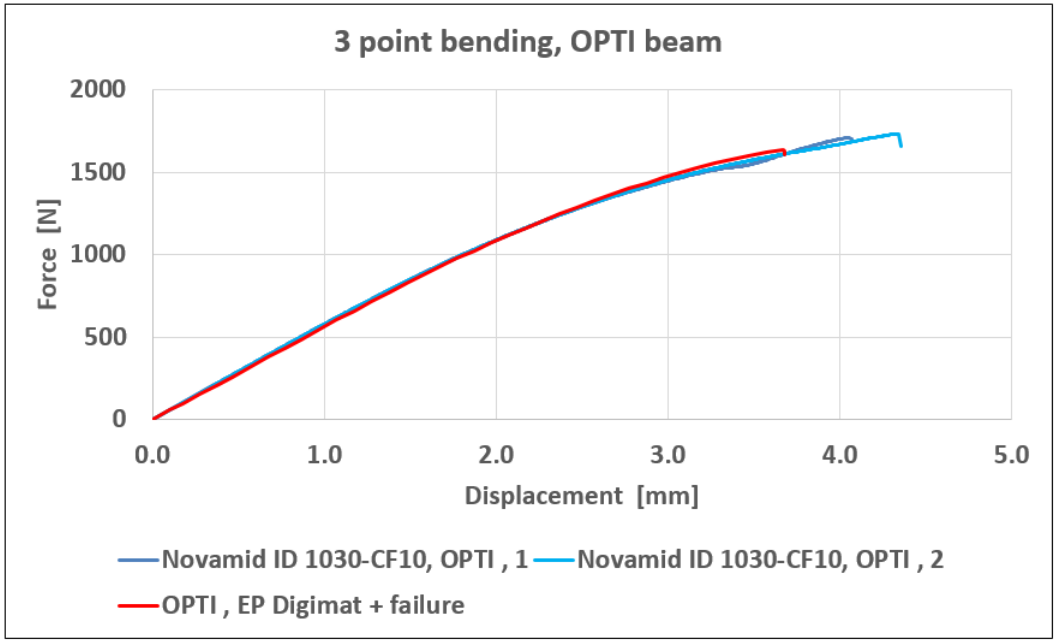
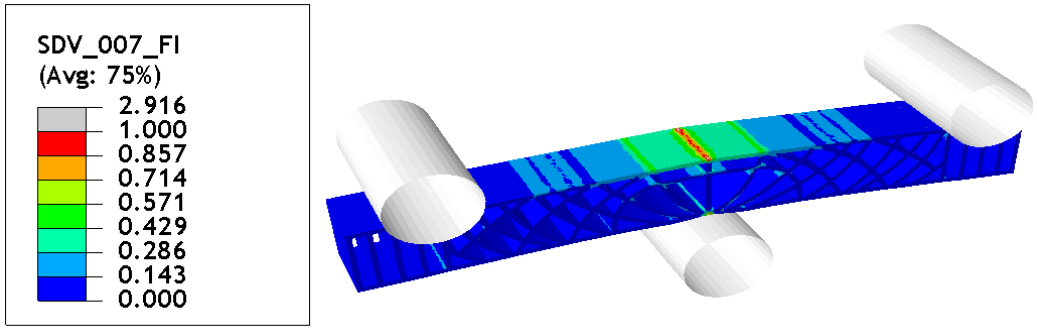
OPTI beam, Novamid ID 1030 CF10: FEA results



- Uni-directional approach for CF orientation.
- Good correlation for stiffness and strength.
- failure location is identified.



Contour plot of failure indicator at instance of failure: red area is predicted failure location(s)

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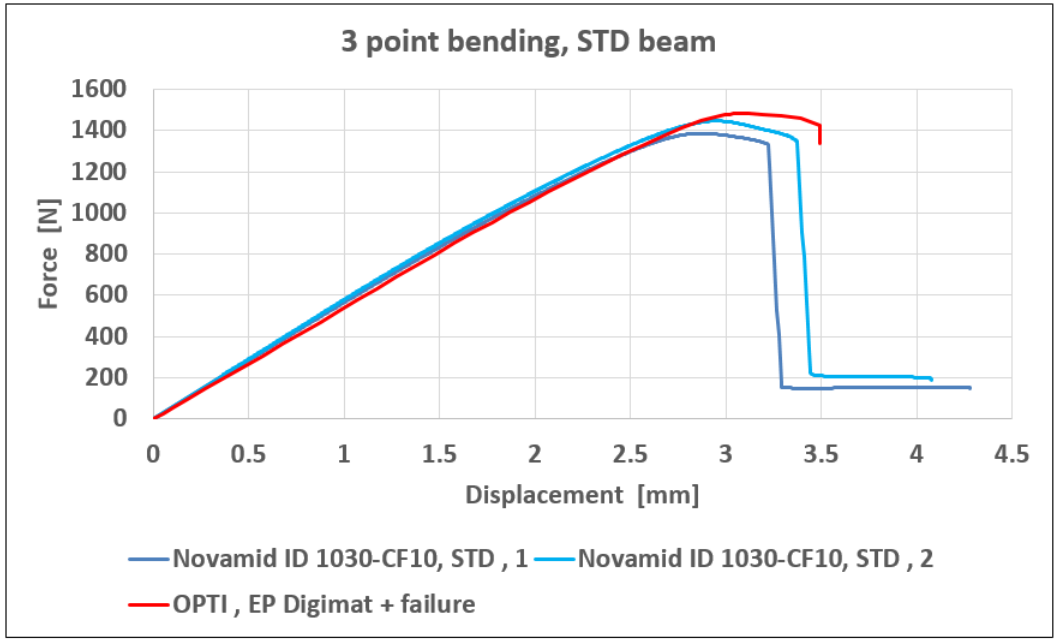
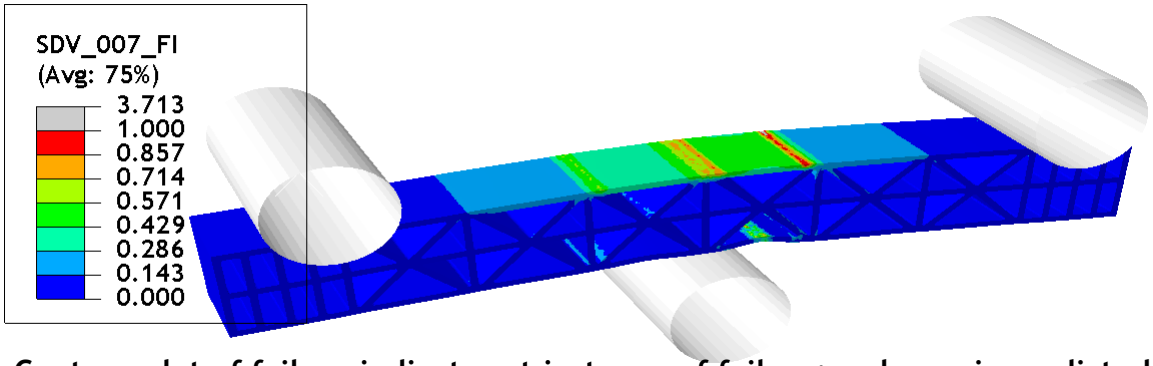
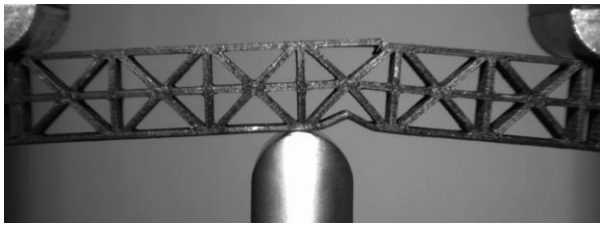
STD beam, Novamid ID 1030 CF10: FEA results



- Good correlation for stiffness and strength
- failure locations are identified





Contour plot of failure indicator at instance of failure: red area is predicted failure location(s)

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Conclusions & Outlook

- The Digimat AM tool is able to predict the trends for warpage observed in practice:
  - effect of tool path,
  - infill,
  - carbon fiber filled grades.

- Considering crystallization kinetics and crystallization shrinkage, will further enhance the accuracy.

- The first validations for the performance modelling of FFF grades shows excellent results.

- Once reliable experimental stress-strain data for the ‘up-right’ case are available we can improve the material models further.

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Acknowledgements

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