

Large-Scale Robotic 3D Printing of Polymer Composites

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Contents

- **Motivation**
- **State of the art**
- **Goals and scientific questions**
- **Results and methods by article**
- **Discussion**



A verification print during the thesis

Motivation – Why print recycled composites

- 15.5 Mt of packaging plastic yearly in the EU
- Only 38% of waste gets recycled
- Repurpose as locally sourced material

WBCSD, Eurostat 2020



3D printed furniture made from recycled TetraPAK, Aectual 2022

Motivation – Printing recycled polymer composites

- High fill ratio allows the use of contaminated plastic
- Good material performance
- Buildability for complex parts
- Problems in large scale printing



*Thermwood,
ABS+CF*



*Dar 5m Smart Bridge,
PETG + GF – Autodesk*

State of the art

MATERIAL BEHAVIOUR IN 3D PRINTING

3D PRINTING PROCESS

- **Printpath planning**
- **Methods of multiaxis printing**

PROCESS PARAMETER VARIATION

State of the art – Material processing

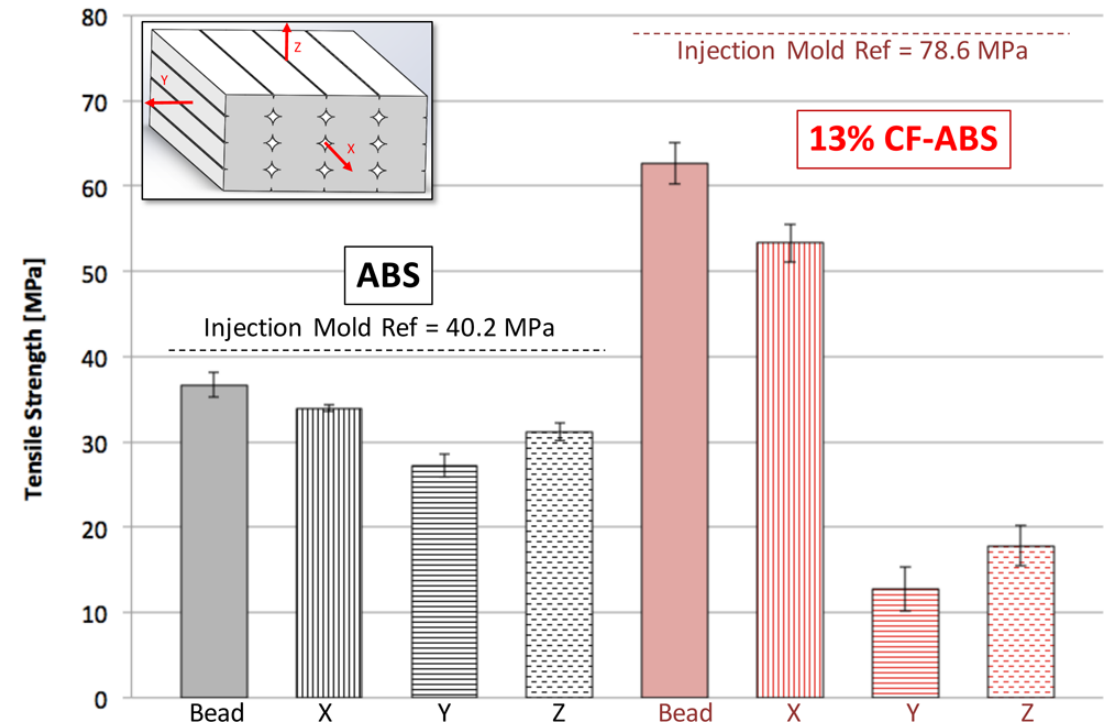
- Semicrystalline plastic shrinkage of 2-5%
- Fibre fill reduces deformation - 84%
- Fibre fill increases porosity and anisotropy (up to 5x)

F. Ning et al., 2015
C. E. Duty et al., 2017

- Particle fill decreases deformation by max. 46%

D. Stoof and K. Pickering, 2018

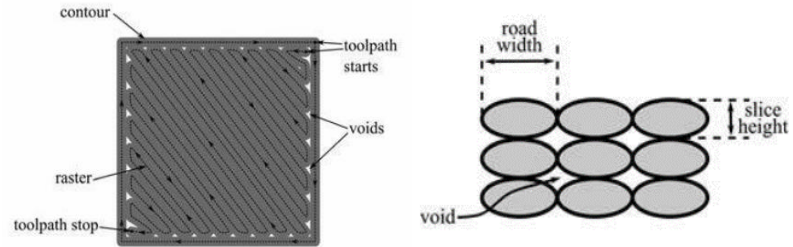
Tensile Strength of BAAM Materials



Anisotropy increase in fibre filled materials
(Duty, 2017)

State of the art - Process

- Line-by-line process effects



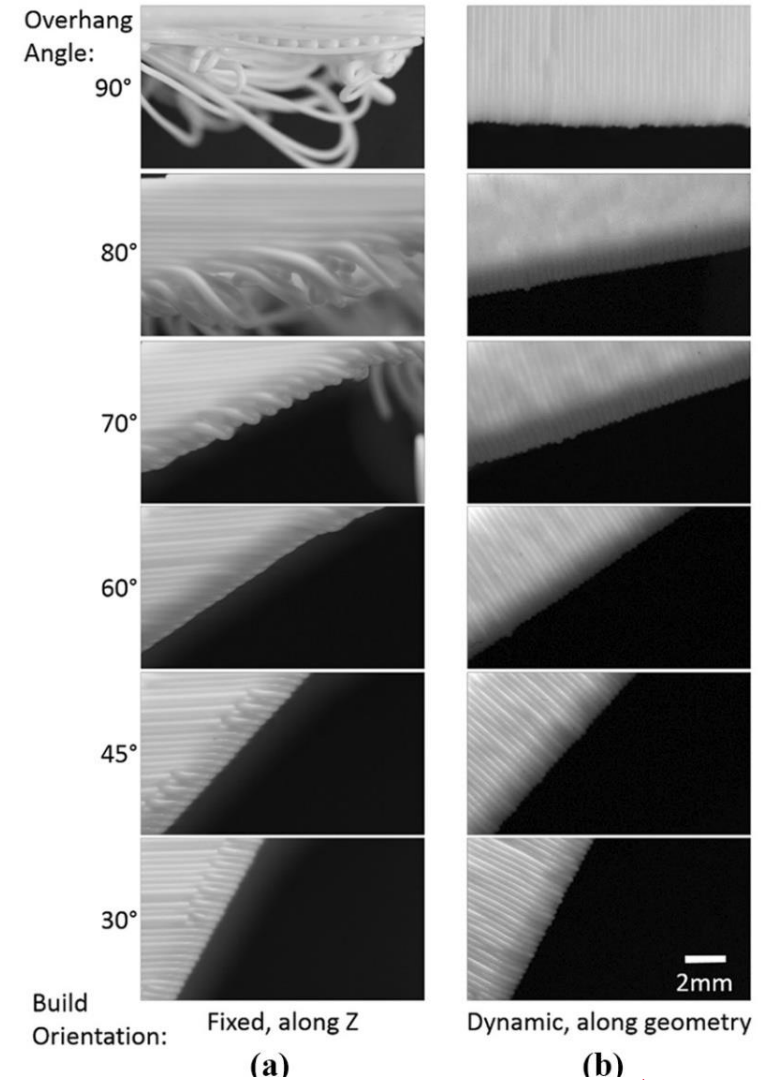
B. N. Turner, R. Strong, and S. A. Gold, 2014, 2015

- Problems with large scale single wall printing

Material failure at buildability limit



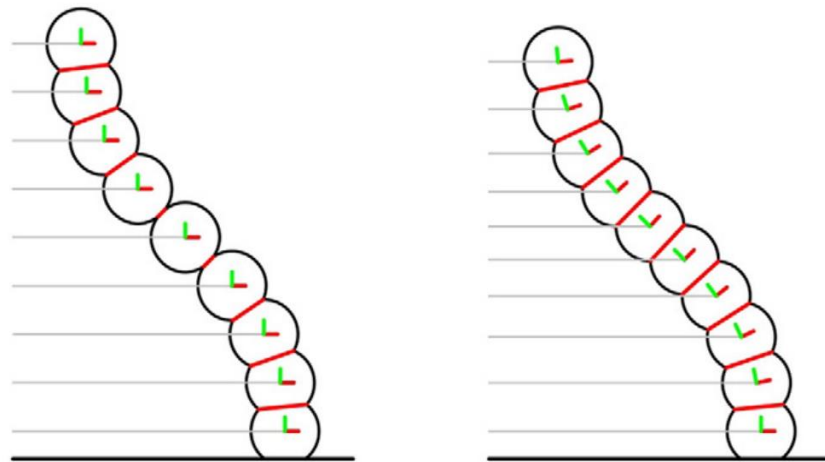
Large-Scale Robotic 3D Printing of Polymer Composites



Fry N., et al., 2020

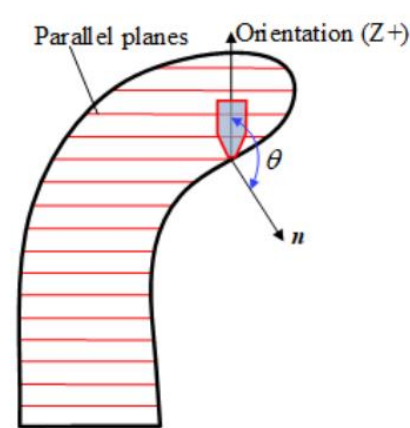
7/33'

State of the art – Multiaxis printing methods

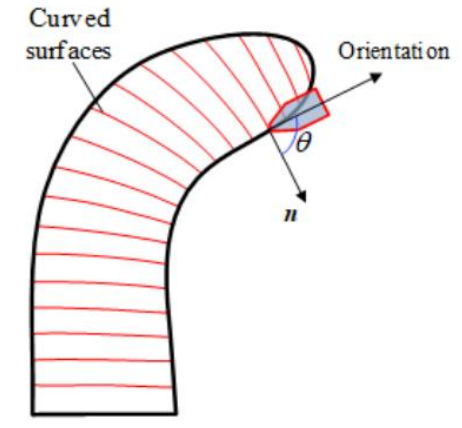


Constant layer height

Curved layer



Conventional



Nonplanar oriented printing

- First described as CLFDM
- Constant contact patch width
- Often combined with oriented printing

Chakraborty, et al., 2008

C. Gosselin, et al., 2016

Li Y., et al., 2021

State of the art – Nonplanar printing

- Expanded buildability, improved surface quality and strength (up to 6x)

Fang et al., 2020

- Isoparametric slicing limited in geometry
- Modern methods are voxel or field based

Dai C. et al., 2018



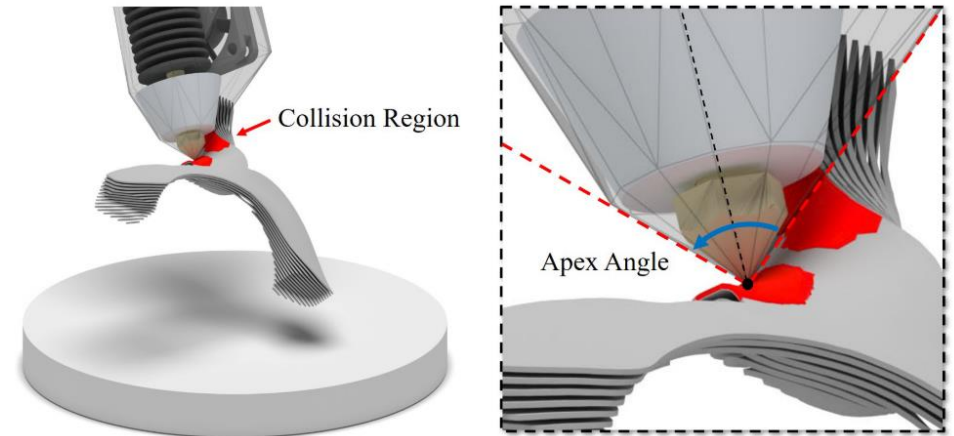
Model	Force F_{bk} at Failure Point (Unit: kN)		
	Planar Layers		Optimized Curved Layers
	Natural Ort.	Optimized Ort.	
Bunny head	0.24	1.07	1.52
Topo-opt	0.79	1.71	3.47

Nonplanar layers (Dai et al 2020, Fang et al 2020)

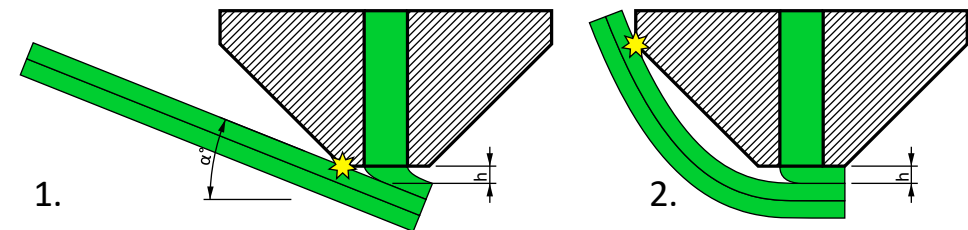


State of the art – Multiaxis printing

- Collision avoidance
- Oriented printing for reach
- A slicer without geometry limitation was first described in a research article at the end of 2022 (Zhang T., S3_DeformFDM)



Collision due to nonplanar layers (Fang et al 2020)



1. Nozzle collision due to slope 2. Collision with surrounding geometry

State of the art – Parameter variation

- Variation in layer height for printing top and bottom surfaces

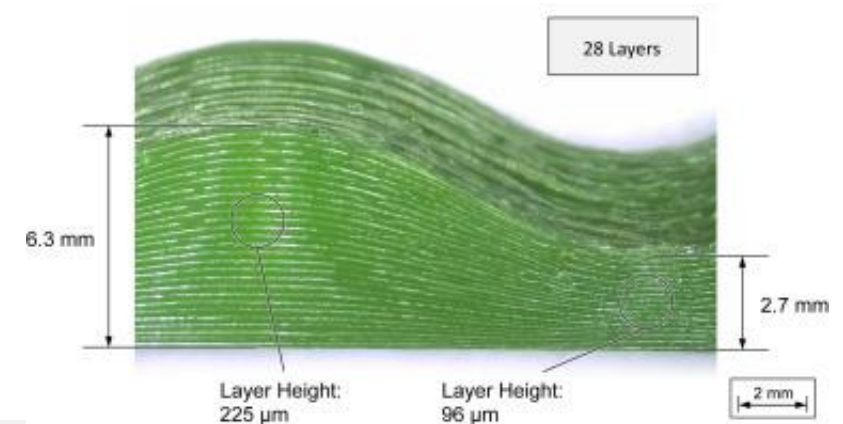
Pelzer L., Hopmann C., 2021

- Method of varying print path width (CONVEX)

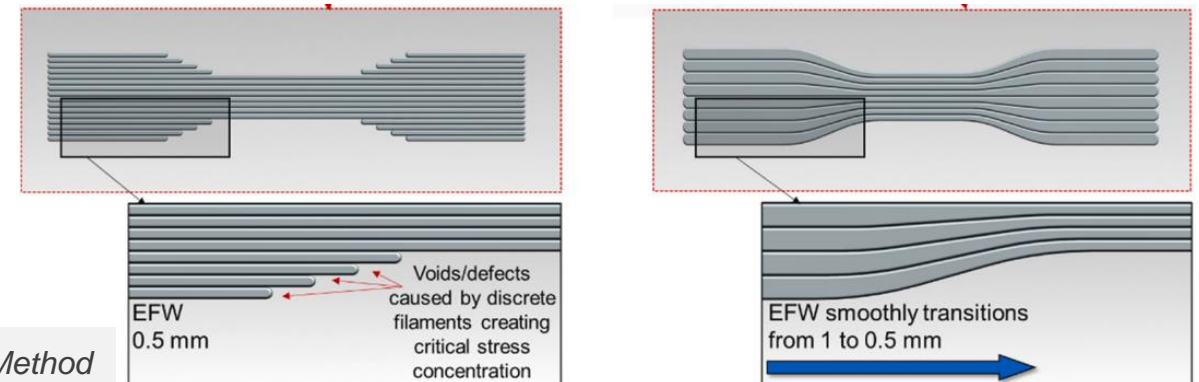
Moetazedian A, et al., 2021

- Used to fix failure in an isoparametric nonplanar slicing

G. Schuh et al., 2020

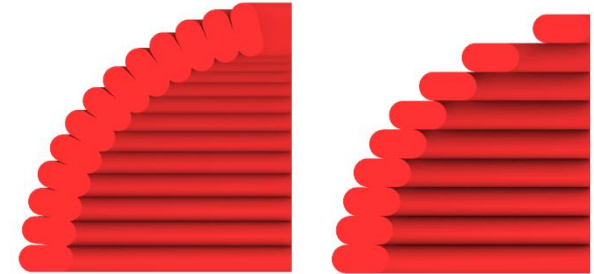


Top surfaces by nonplanar printing (Pelzer, 2021)



Analysis

- Thermoplastic composite is suitable for large scale 3D printing
- Screw extrusion, anisotropy, porosity, buildability
- Multiaxis 3D printing to improve buildability of single perimeter extrusion
- Blank space in literature exploring variation in process parameters



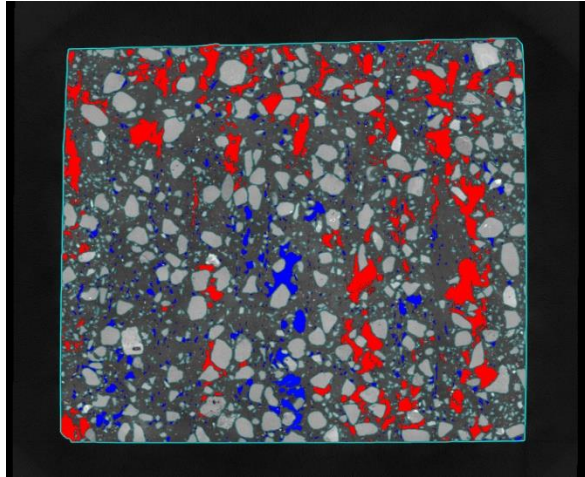
Goals - Large-Scale Robotic 3D Printing of Polymer Composites

The main goal is the development of a 3D printing process for large scale printing of complex, functional parts using polymer composites.



Print in progress

Scientific questions - Large-Scale Robotic 3D Printing of Polymer Composites



**Characterization of
printed properties**



**Effects of multiaxis and
nonplanar methods**



**Intralayer height
variation**

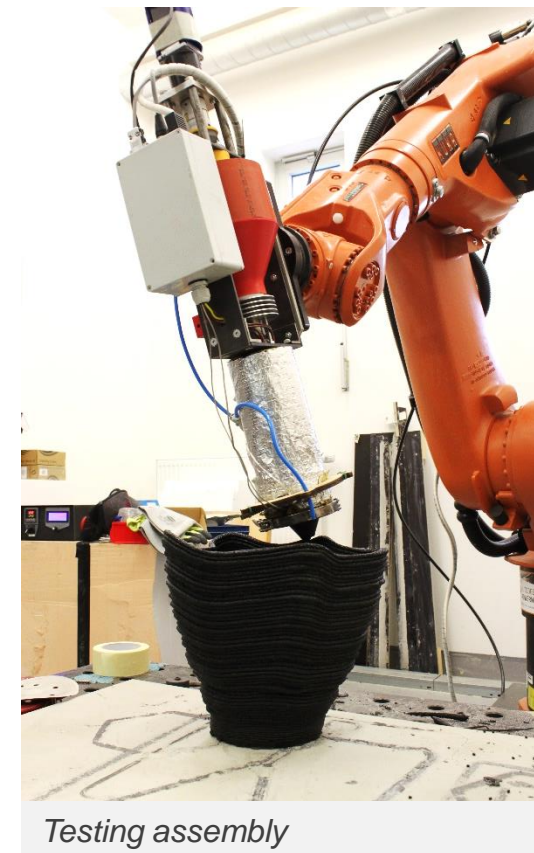
Question 1 – Characterization of printed properties

Scientific questions:

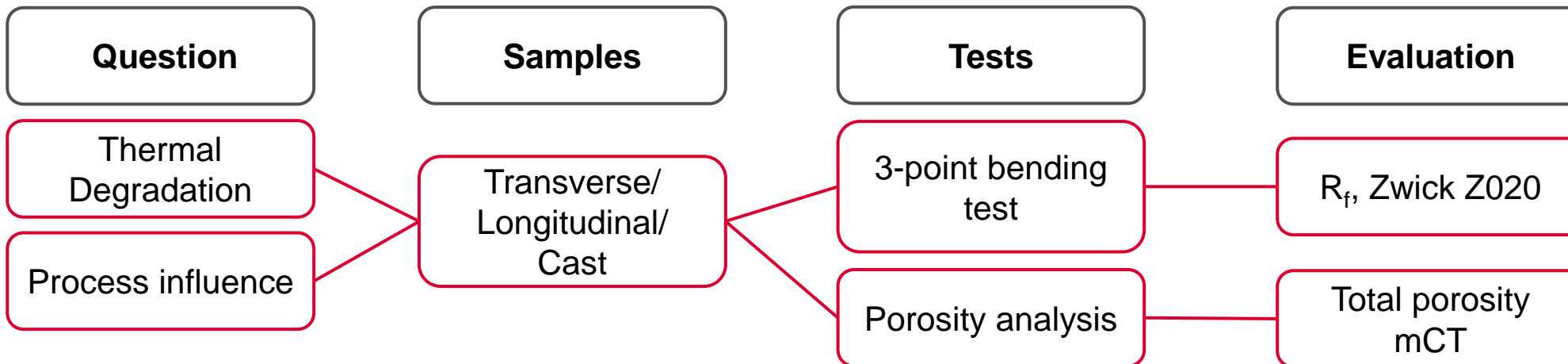
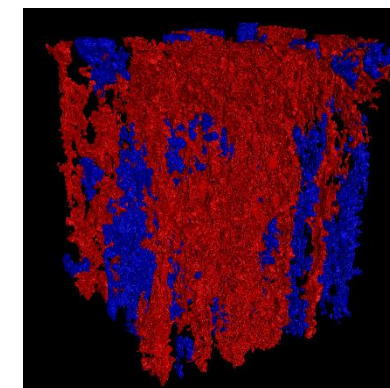
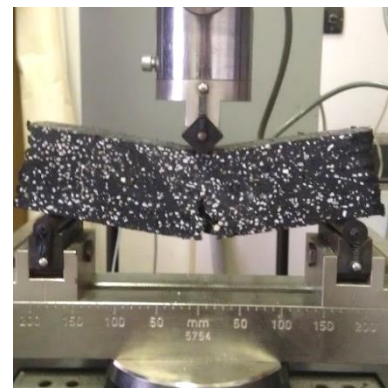
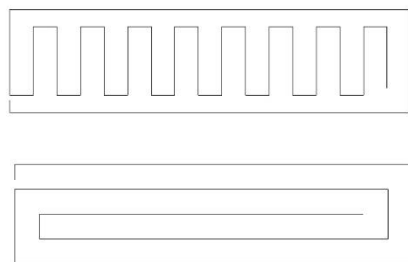
Are the material properties after 3D printing at a level that allows the material to be used for the manufacture of functional objects?

Which source of degradation is prevalent in the 3D printing process, if any, and to what degree?

H1: Mechanical properties of polymer concrete are reduced due to thermal degradation, porosity, or other factors of the 3DP process.



Q. 1 – Materials and methods



Q. 1 – Results

- Similar performance for Longitudinal and Cast

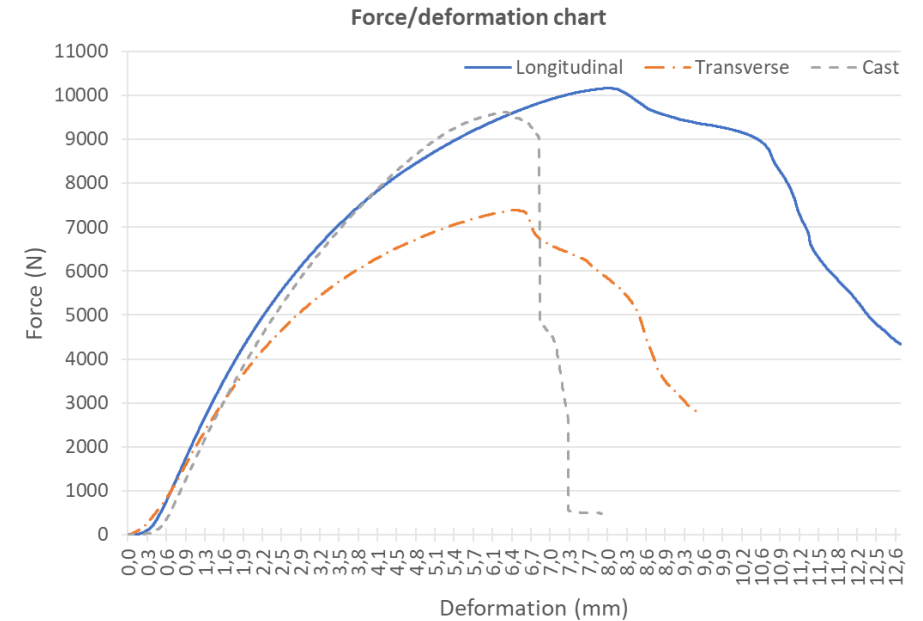
	R_f (MPa)	σ (MPa)
Logitudinal	19,5	0,631
Transverse	14,9	0,265
Cast	19,7	0,194

3-point bend test strength

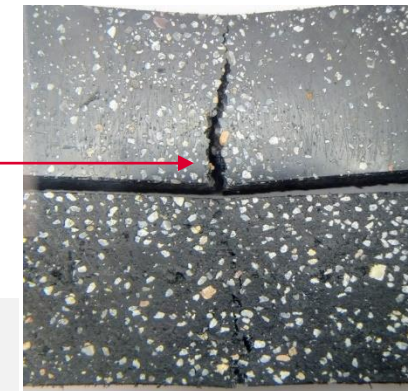
- Significant porosity found in 3DP samples

Porosity:

1. Longitudinal 12,59%
2. Transverse 10,54%
3. Cast 1,58%

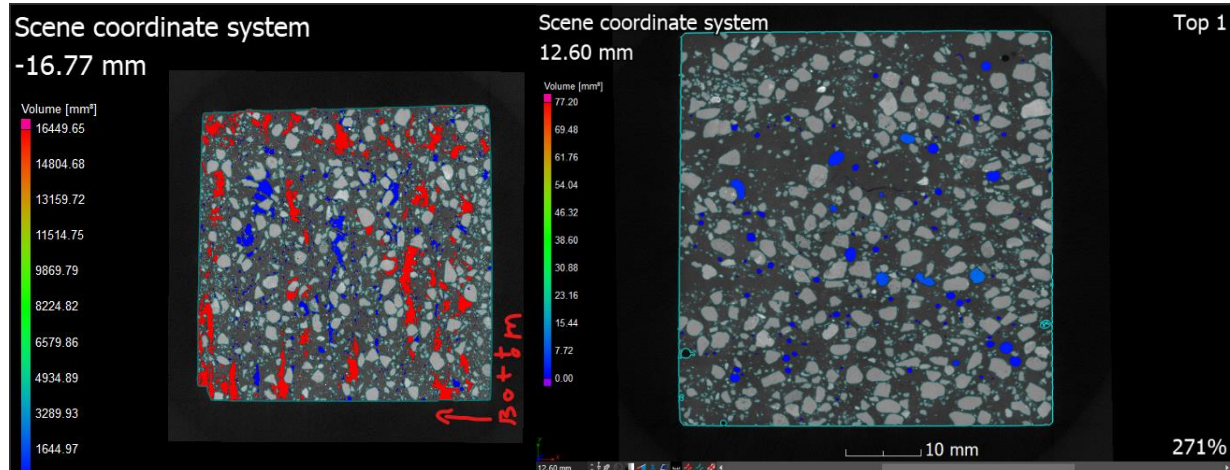


Cast brittle fracture

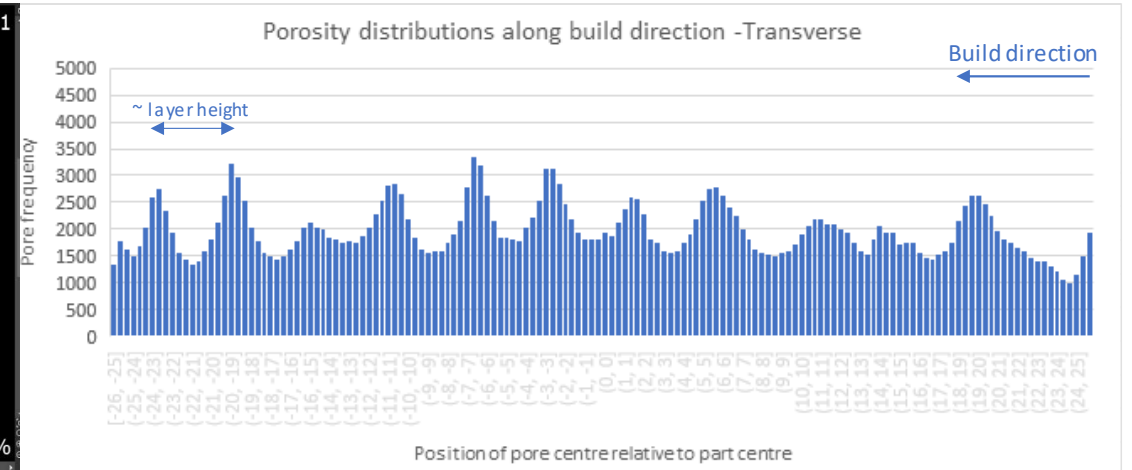


Cracks in 3D and cast samples

Q. 1 – Discussion



Porosity visualization Left: 3D printed, Right: Cast



Porosity by height chart

- Despite increases in porosity, material was able to keep its strength and ductility

*KRČMA, Martin, et al.; Use of polymer concrete for large-scale 3D printing; Rapid Prototyping Journal; 2021
doi:10.1108/RPJ-12-2019-0316; (JIF 3.9)*

Question 2 – Comparison of multiaxis methods

Scientific question:

Will the oriented printing method improve buildability and surface quality for large scale 3DP?

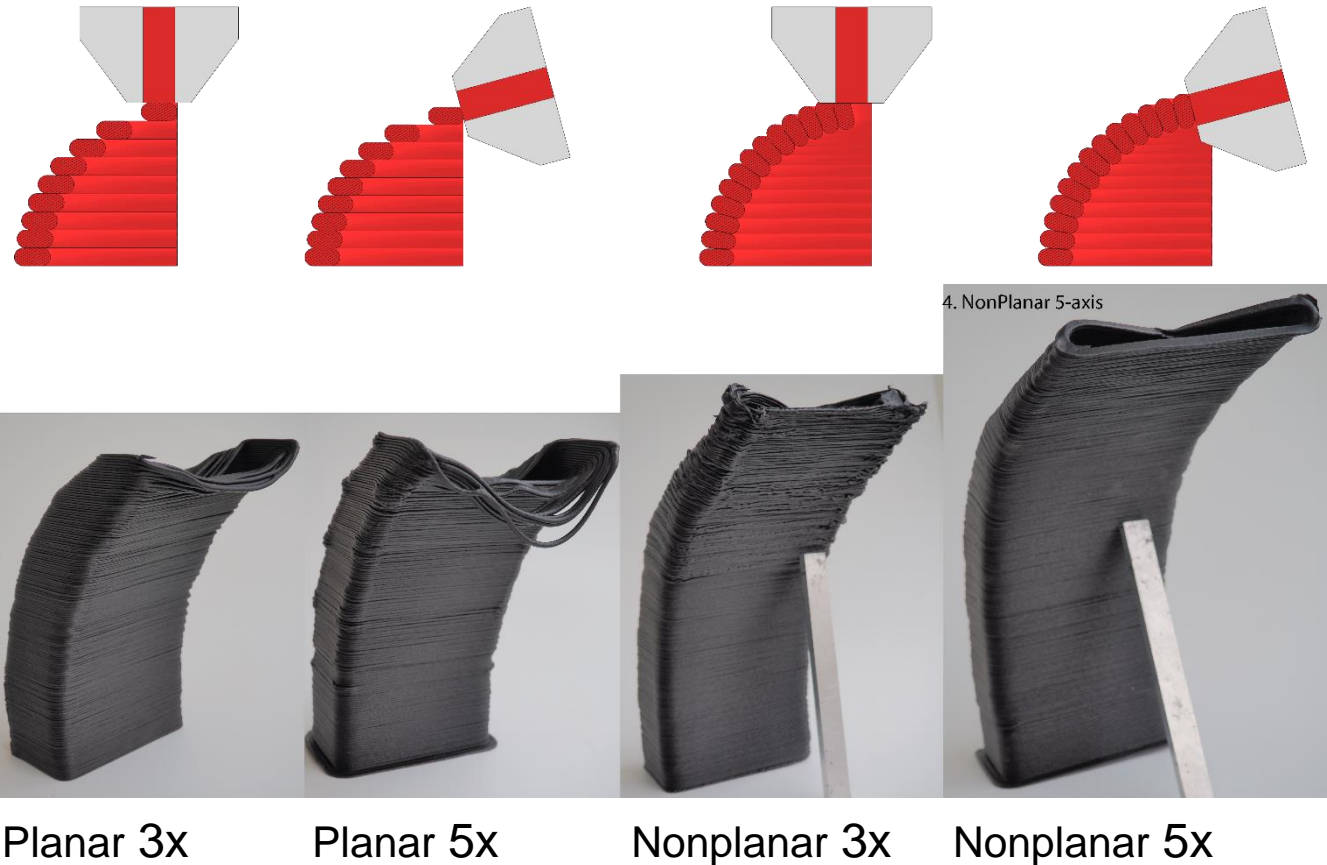
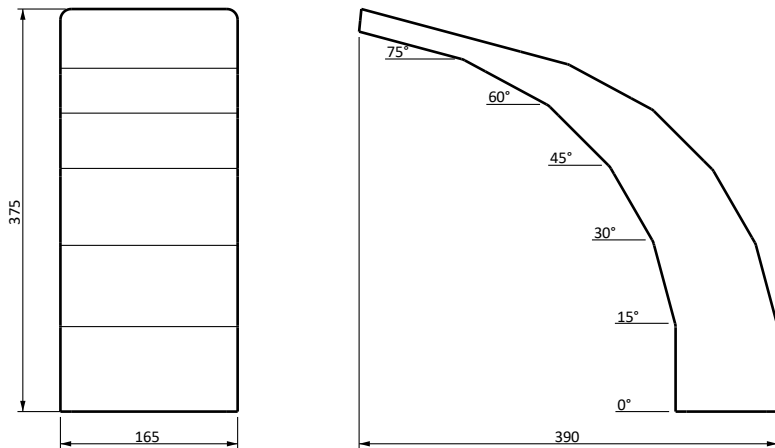
H2: Oriented 3DP improves buildability and surface quality compared to 3-axis printing, with the same benefits for large-scale 3D printing as desktop-scale.



Nonplanar oriented print

Q. 2 – Material and methods

- 4 sample groups
- Effects on buildability, surface quality and strength
- 3D scanning and mechanical testing



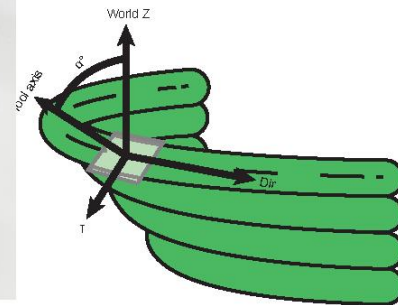
Q. 2 – Materials and methods



Slicing



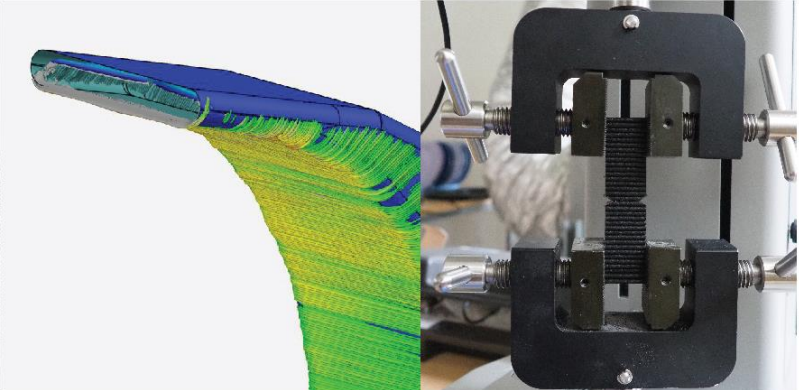
Orientation



Processing



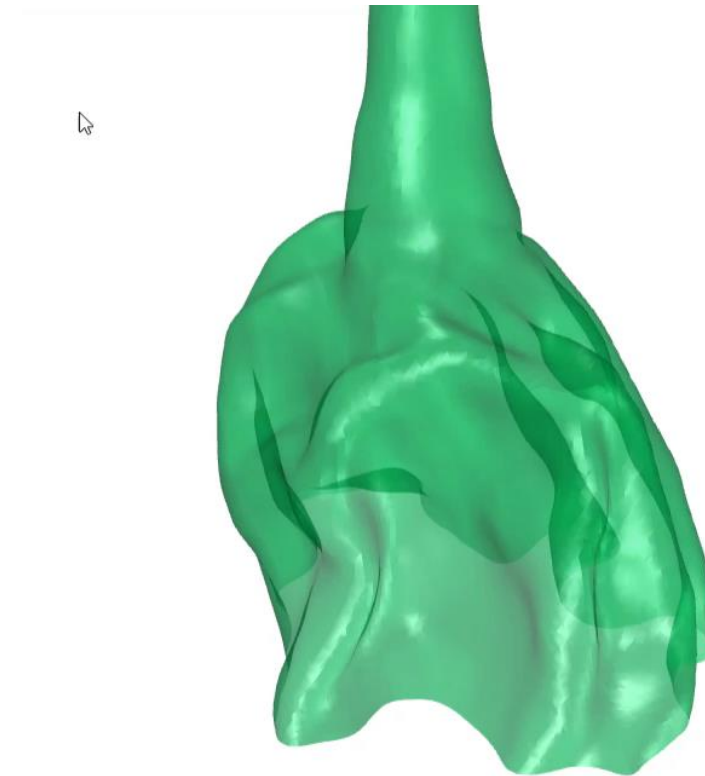
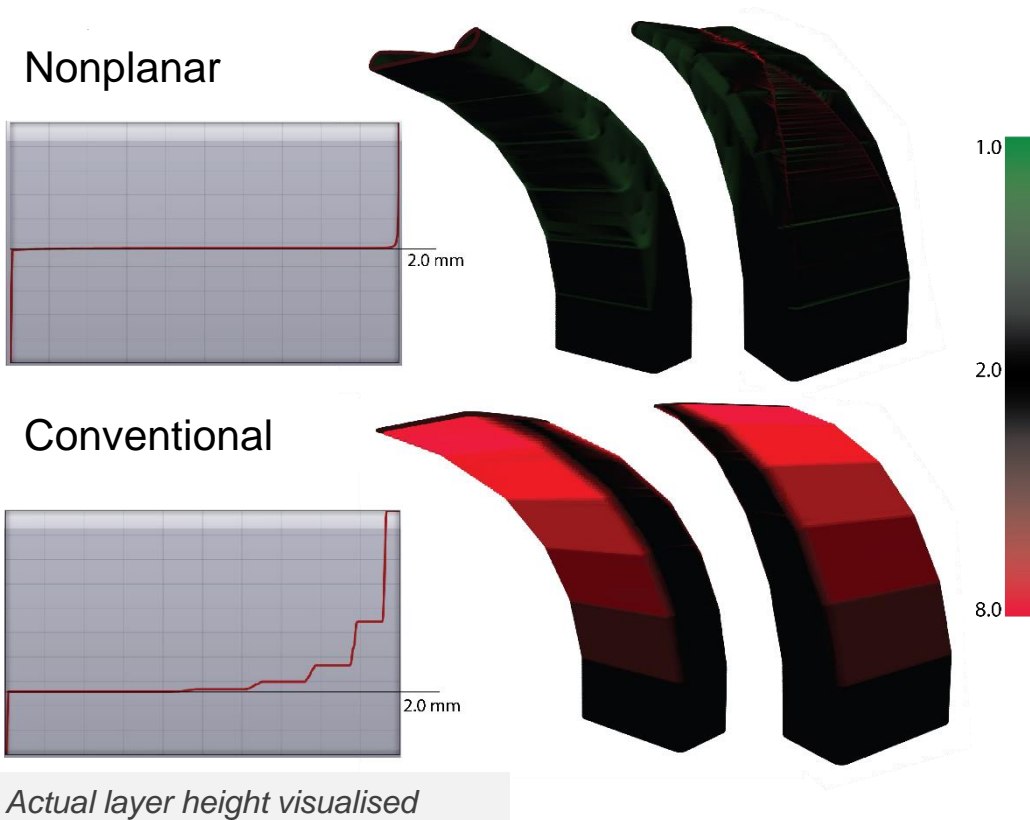
Prints



Processing

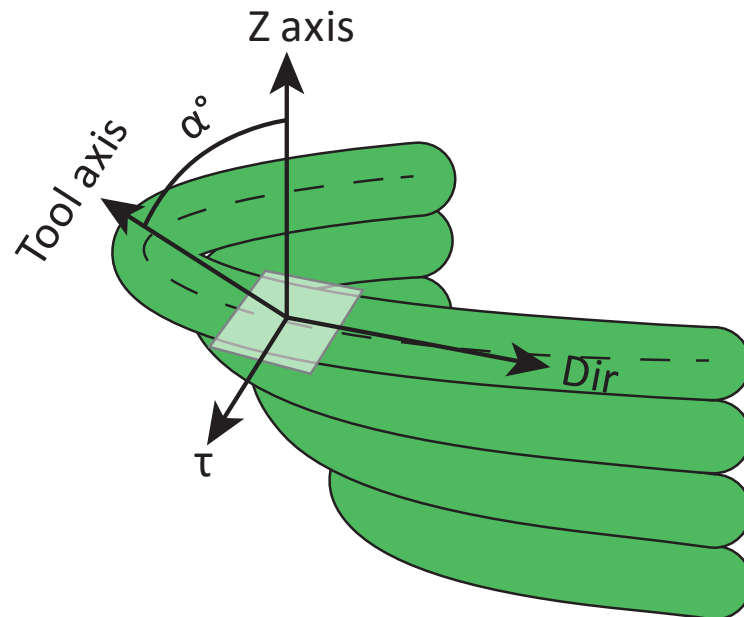
Evaluation

Q. 2 – Nonplanar path generation method

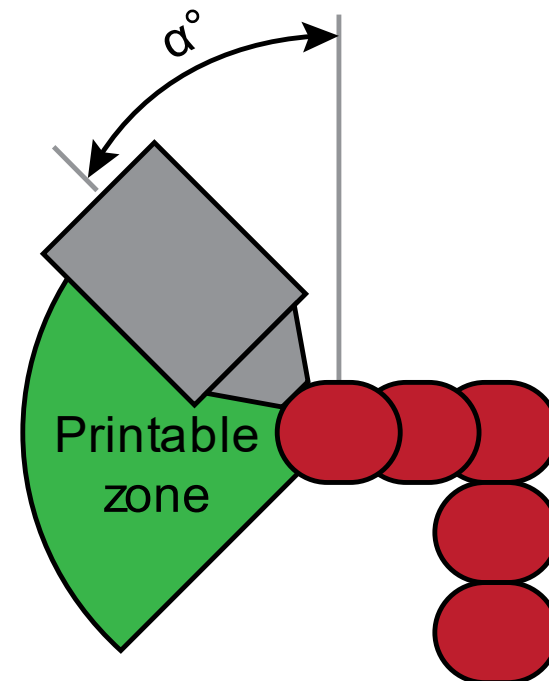


Q. 2 – Materials and methods

- Limited tilt method developed to increase reach



Tilt angle definition



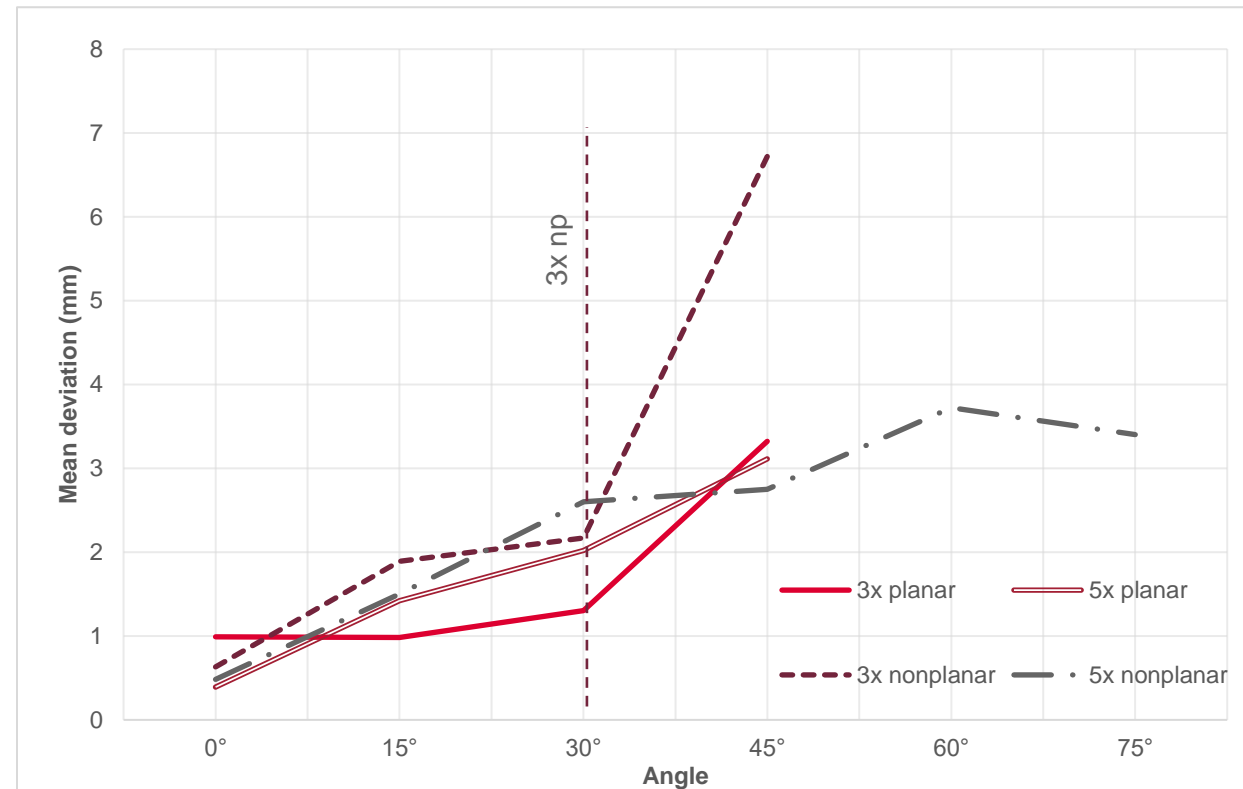
Printable zone

Q. 2 - Results

- Buildability of at least 75° by NP

	0°	15°	30°	45°	60°	75°
3-x planar	ok	ok	ok	ok	fail	fail
5-x planar	ok	ok	ok	ok	fail	fail
3-x nonplanar	ok	ok	ok	fail	fail	fail
5-x nonplanar	ok	ok	ok	ok	ok	ok

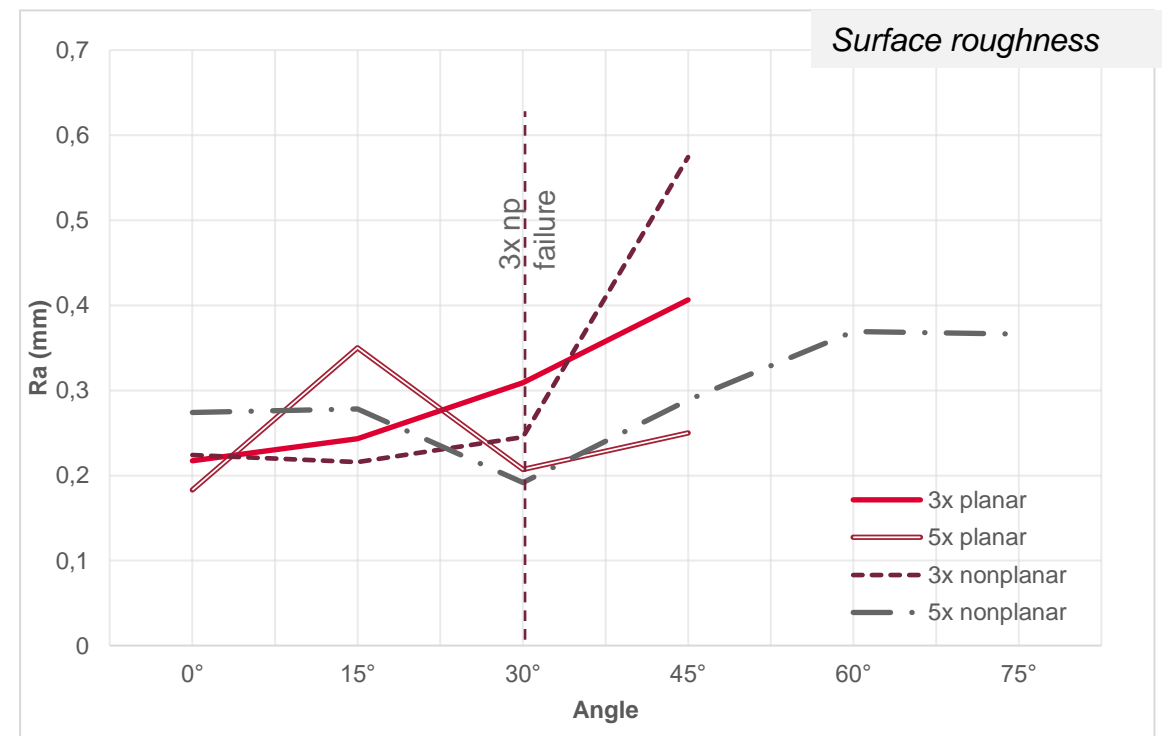
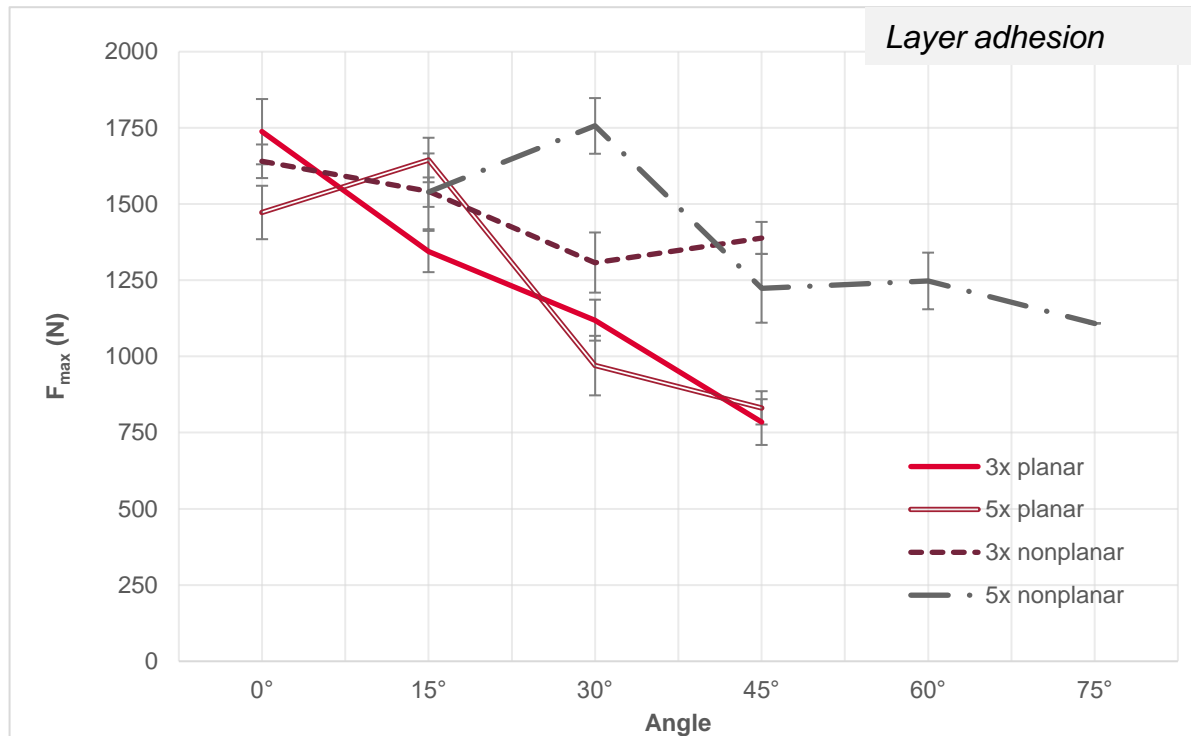
Buildability by method



Mean deviation

Q. 2 - Results

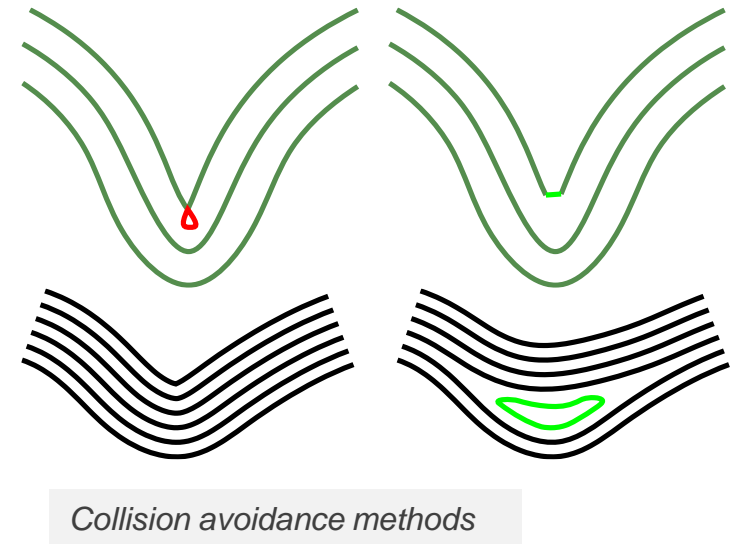
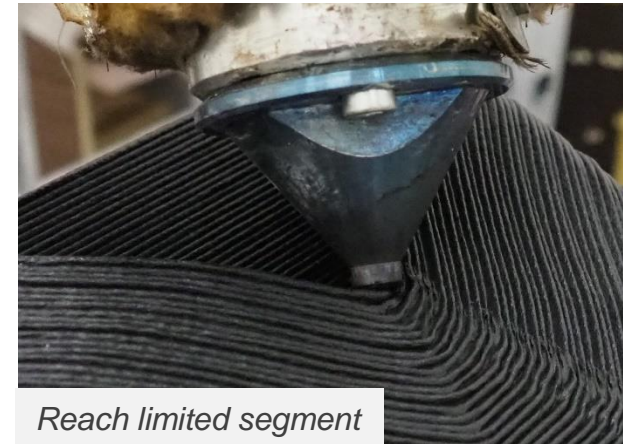
- Oriented printing on its own only benefits surface quality
- Surface quality and strength are increased for overhang angles over 15° by NP



Q. 2 - Discussion

- Limitations of nonplanar slicing due to reachability
- Oriented printing for increasing reach of nonplanar methods
- The “actual layer height” measure

KRČMA, Martin a David PALOUŠEK. Comparison of the effects of multiaxis printing strategies on large-scale 3D printed surface quality, accuracy, and strength. *The International Journal of Advanced Manufacturing Technology* [online]. 2022, doi:10.1007/s00170-022-08685-4; (JIF 3.4)

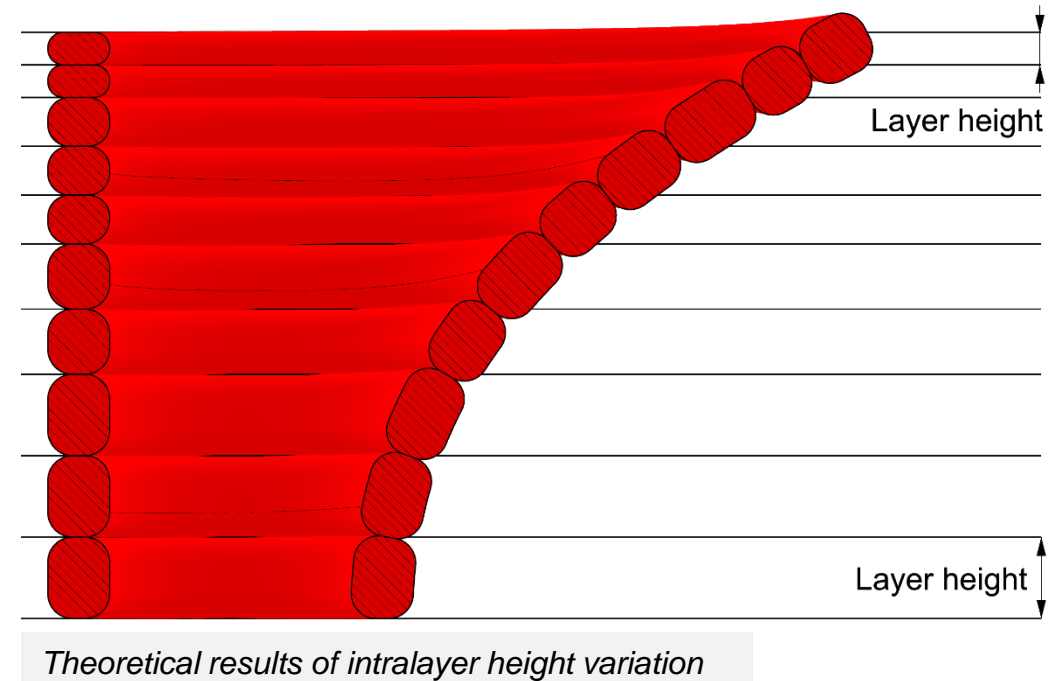


Question 3 – Intra layer height variation

Scientific question:

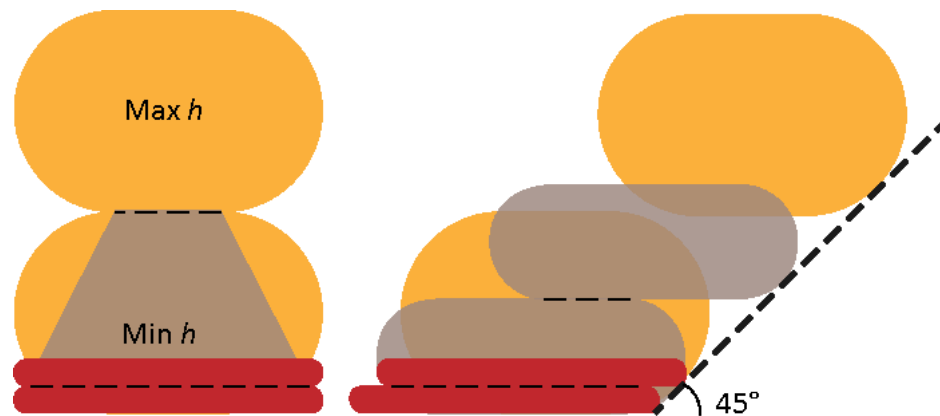
If reduction in material quantity in overhanging areas is compensated for, can planar printing achieve the same buildability without the drawbacks of nonplanar methods?

H3: Planar slicing combined with compensation for changes in actual layer height improves buildability like nonplanar slicing.

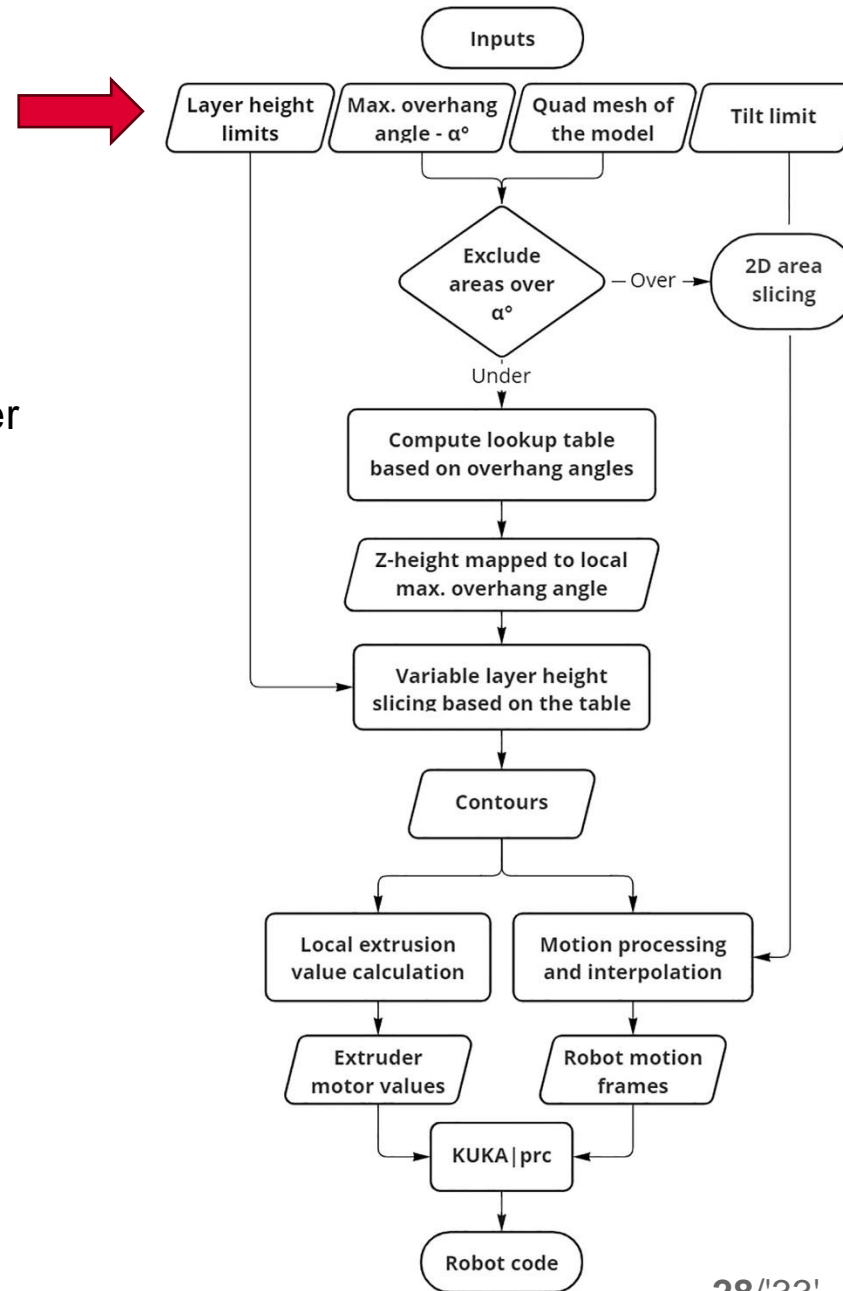


Q.3 - Results

- Buildability limit of $>82^\circ$ of overhang
- Layer height boundaries are 10-75% of nozzle diameter

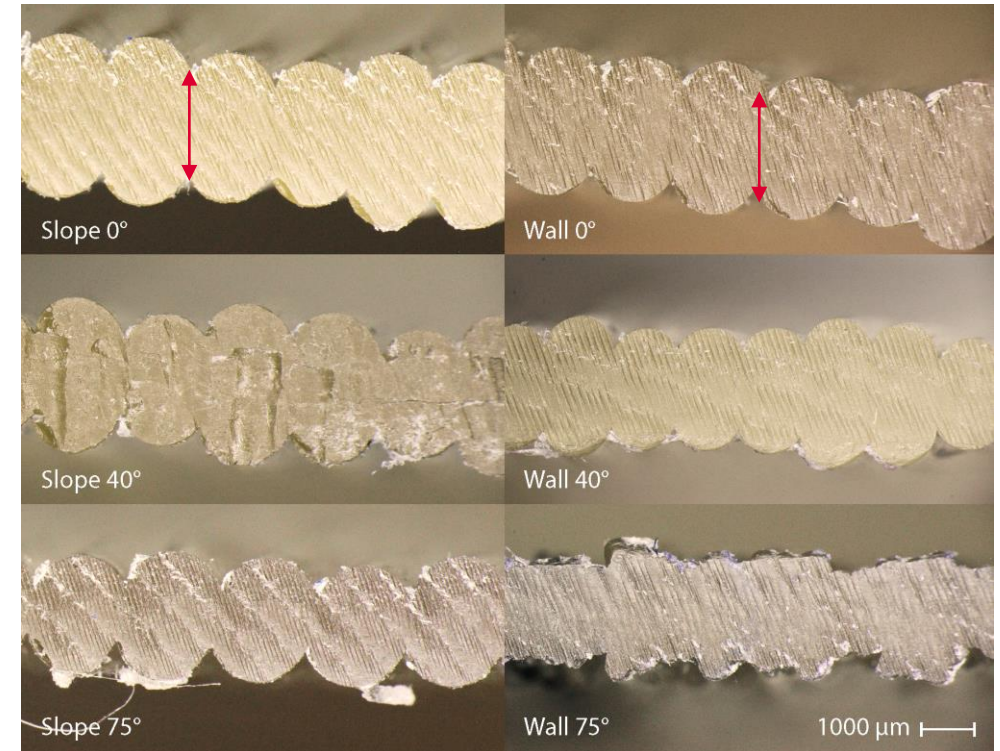
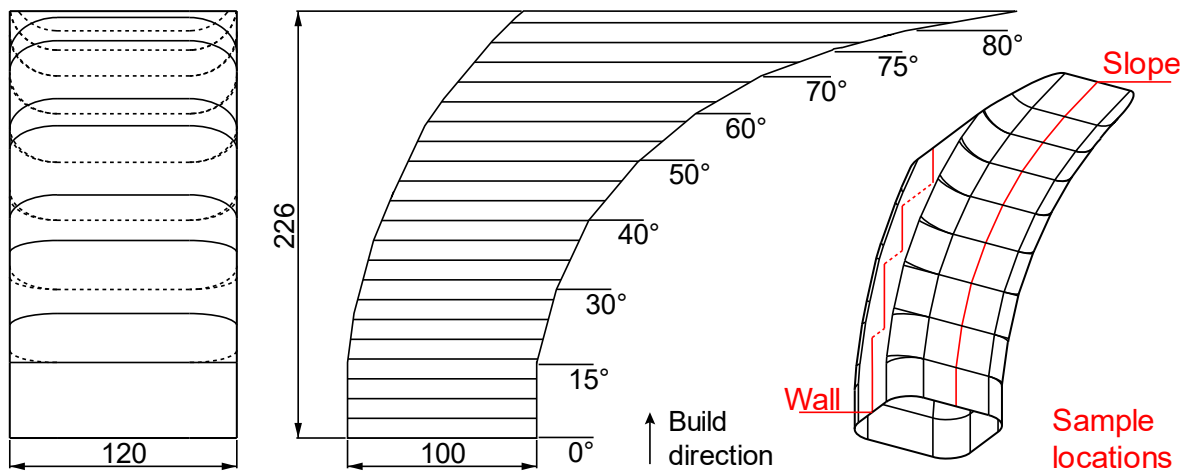


Boundary conditions of the new method



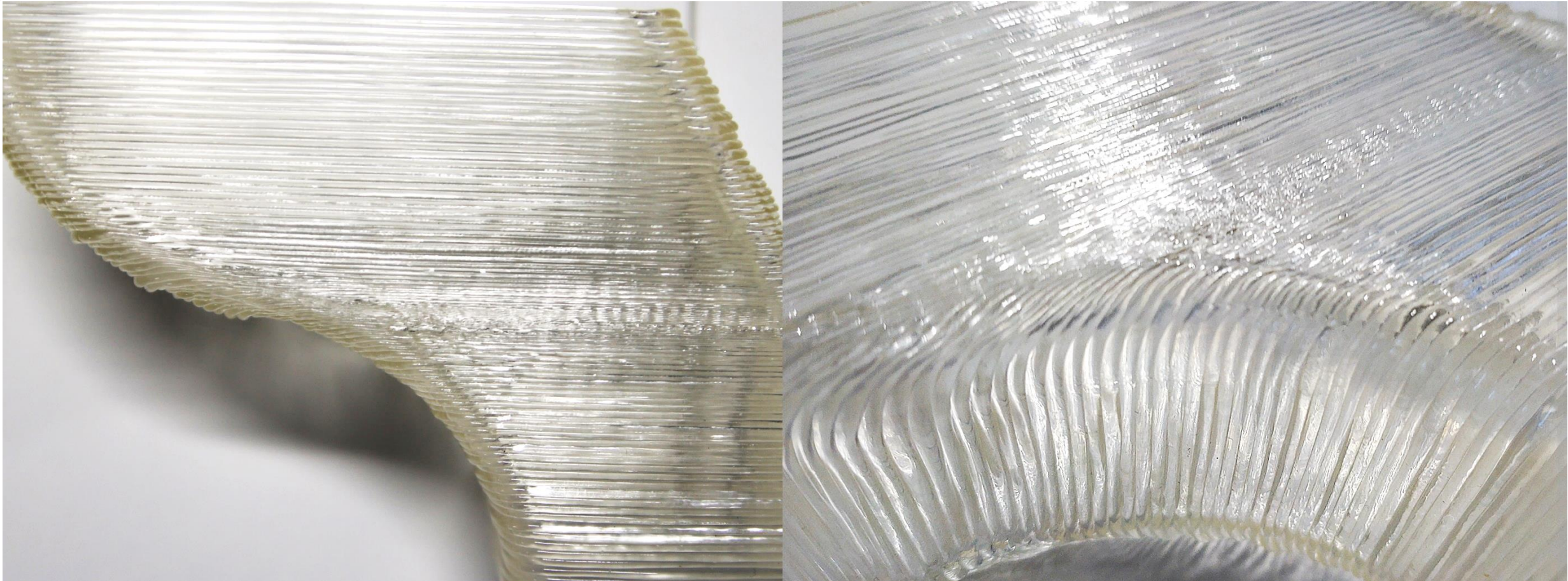
Q.3 - Results

- Single wall printing
- Verified by large scale pellet extrusion
- Wall thickness measured by optical microscopy



Wall samples cut from different locations

Q.3 - Results



Q.3 - Discussion

- Consistent performance due to consistent wall thickness
- Method works on objects with varying topology



Verification prints

KRČMA, Martin; et al.; *Method of Multiaxis Three-Dimensional Printing with Intralayer Height Variation for Stairstep Effect Compensation*. *3D Printing and Additive Manufacturing*. 2022. ISSN 2329-7662. Available at: <https://doi.org/10.1089/3dp.2022.0097>.; (JIF 3.1)

Conclusion – Scientific questions

- Q1: Polymer concrete was verified as a 3DP material
- Q2: The importance of nonplanar printing was shown
- Q3: New method of printing based upon actual layer height

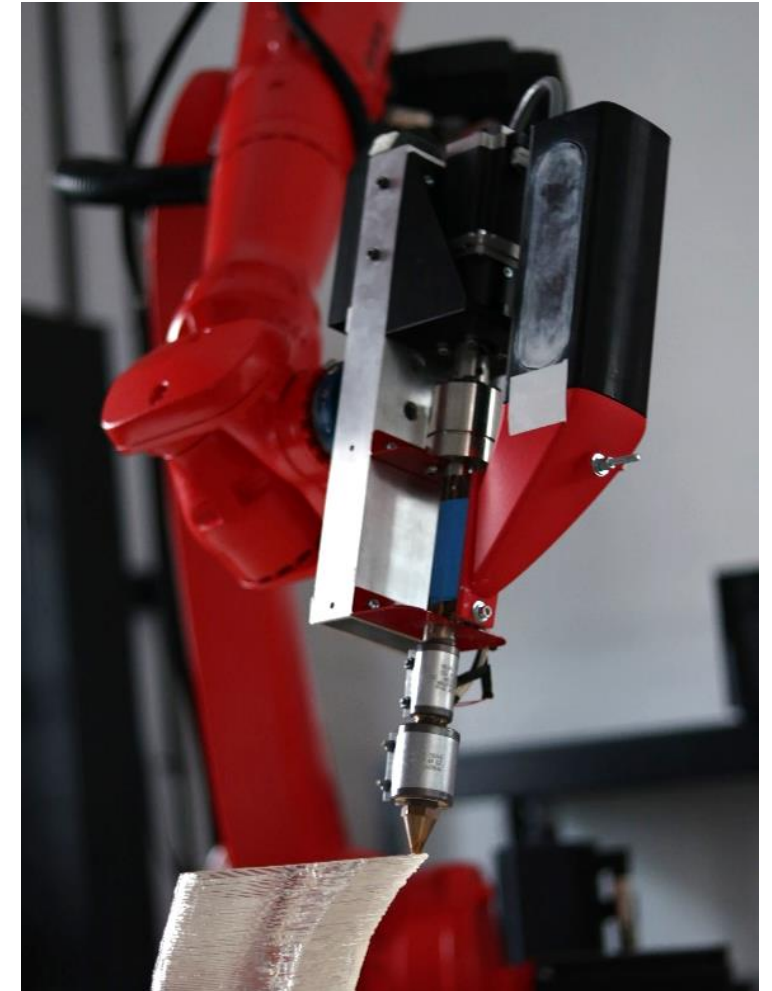


Intralayer height variation

Krčma 2022

Conclusion

- 3D printing large scale polymer composite
- Developed methods for multiaxis processing
- The interlayer height variation method enables efficient 3D printing of complex forms for a variety of extrusion processes



Krčma, 2022



THANK YOU FOR YOUR ATTENTION

Martin Krčma

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24.10.2023



ÚSTAV
KONSTRUOVÁNÍ

www.ustavkonstruovani.cz

Publications

WOS Journals:

KRČMA, Martin, David ŠKAROUPKA, Petr VOSYNEK, Tomáš ZIKMUND, Jozef KAISER a David PALOUSEK. Use of polymer concrete for large-scale 3D printing. Rapid Prototyping Journal [online]. 2021, 2021-02-27, 27(3), 465-474 [cit. 2023-09-14]. ISSN 1355-2546., doi:10.1108/RPJ-12-2019-0316; (JIF 3.9)

KRČMA, Martin a David PALOUŠEK. Comparison of the effects of multiaxis printing strategies on large-scale 3D printed surface quality, accuracy, and strength. The International Journal of Advanced Manufacturing Technology [online]. 2022, 119(11-12), 7109-7120 [cit. 2023-09-14]. ISSN 0268-3768., doi:10.1007/s00170-022-08685-4; (JIF 3.4)

KRČMA, Martin; PALOUŠEK, David; ŠKAROUPKA, David; BRAUMANN, Johannes a KOUTNÝ, Daniel. Method of Multiaxis Three-Dimensional Printing with Intralayer Height Variation for Stairstep Effect Compensation. 3D Printing and Additive Manufacturing. 2022. ISSN 2329-7662., <https://doi.org/10.1089/3dp.2022.0097.>; (JIF 3.1)

Conference proceedings:

Martin Krčma, doc. David Paloušek, PhD, Structural Members Manufactured By Freeform Deposition Of Polymer Concrete, BE.AM 2020, ISBN 9798561621192, Darmstadt, pp. 126-127 2020

Martin Krčma, David Škaroupka, PhD, Polybet, BE.AM 2020, ISBN 9798561621192, pp. 120-121 Darmstadt, 2020

Activities

Project Involvement:

- ZÉTA TJ01000034, Development of process parameters for additive manufacturing of highly filled waste thermoplastics
- TREND FW01010513, Development of a production system for large-format additive manufacturing of highly filled waste thermoplastics
- ZÉTA TJ04000408, Development of technology and strategies for robotic additive manufacturing of large-scale truss structures

Work on projects and economic contracts unrelated to the topic. E.g:

- Science Fund Project FV 2019-03
- OP PIK – Aplikace - Increasing the shear and bending strength of composite profiles by using 3D guiding and shaping jigs for mats
- MSV, 3D EXPO Bratislava 2019, Prototyp 2018, Noc vědců, 120 let VUT

Courses taught:

- Engineering Drawing Fundamentals 1K/ 156 h
- Engineering Drawing - 2K/ 156 h
- CAD - basic - 3CD/ 104 h
- Design and CAD- 4KC/ 26 h
- CAD Modeling - ZM1/ 120h
- Generative Design and Digital Production– YRP/ 91 h
- Plastic prototypes - ZPP/ 52 h
- Team project - ZKP/ 42h

Research stay: Kunstuniversität Linz, Austria, 1.9.2021 - 1.12.2021

Polymer concrete further development

- 1) New extruder built ensuring good mixing and minimizing losses and porosity when printing premixed material
- 2) Final material composition consisting of recycled automotive PP, recycled mineral wool and foundry sand
- 3) First functional objects were printed

