

COMPUTATIONAL MODELS FOR NON-LINEAR MECHANICAL LOADING ANALYSES OF LATTICE STRUCTURES MADE BY LPBF

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INSTITUTE OF MACHINE
AND INDUSTRIAL DESIGN

CONTENT

- Introduction and Motivation
- State of the Art
- Summary of Literature Review
- Aim of PhD thesis
- Materials and Methods
- Results and Discussion
- Conclusions

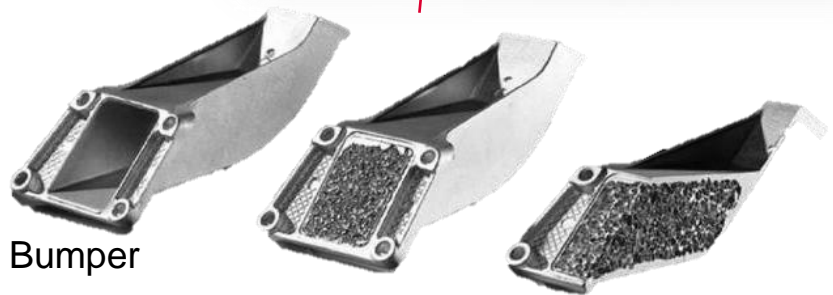
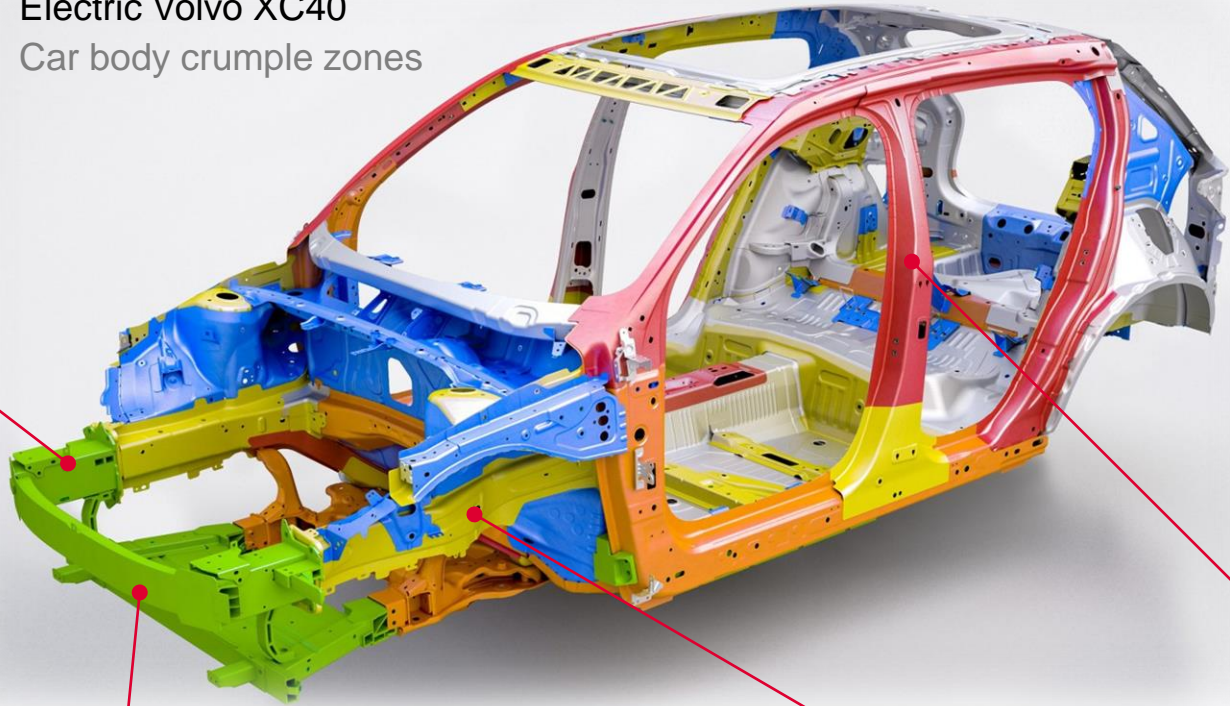
Introduction and Motivation

Electric Volvo XC40
Car body crumple zones

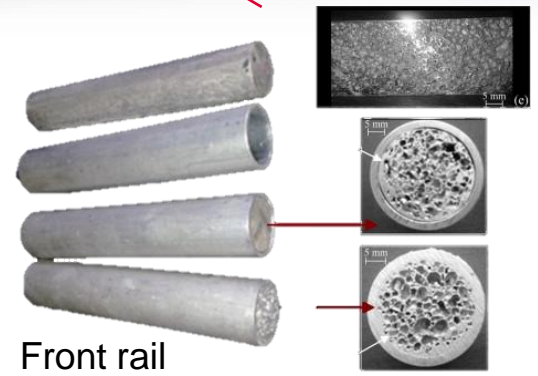
- Mild steel
- High strength steel
- Very high strength steel
- Extra high strength steel
- Ultra high strength steel
- Aluminium



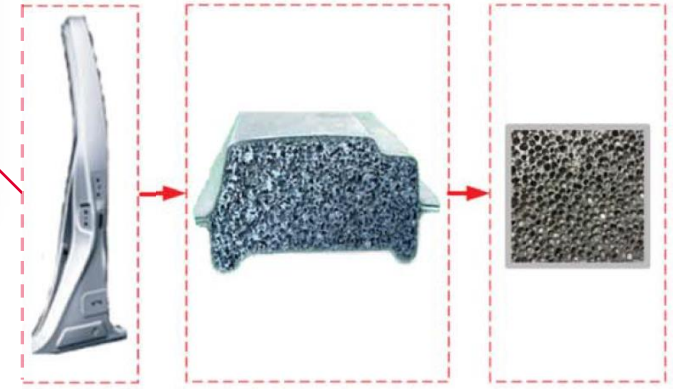
Crash box



Bumper



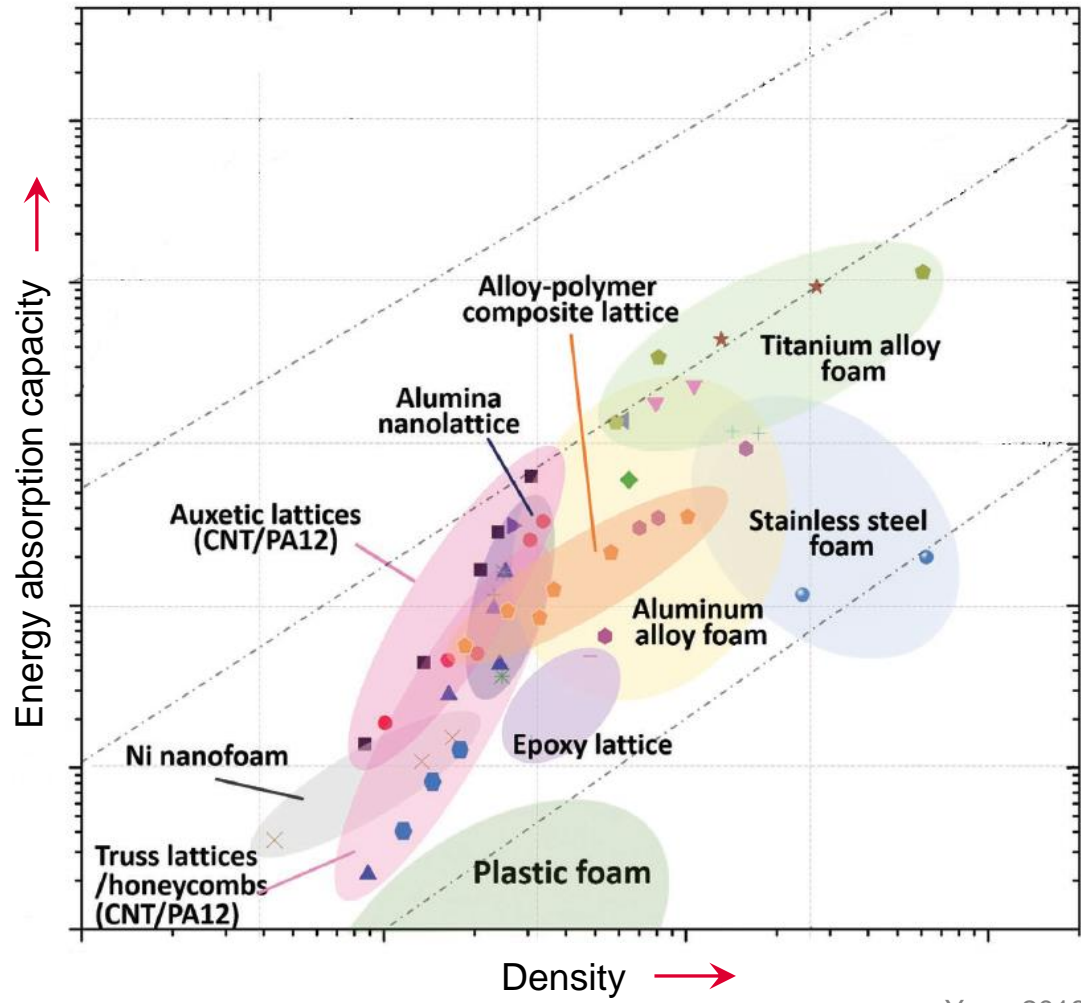
Front rail



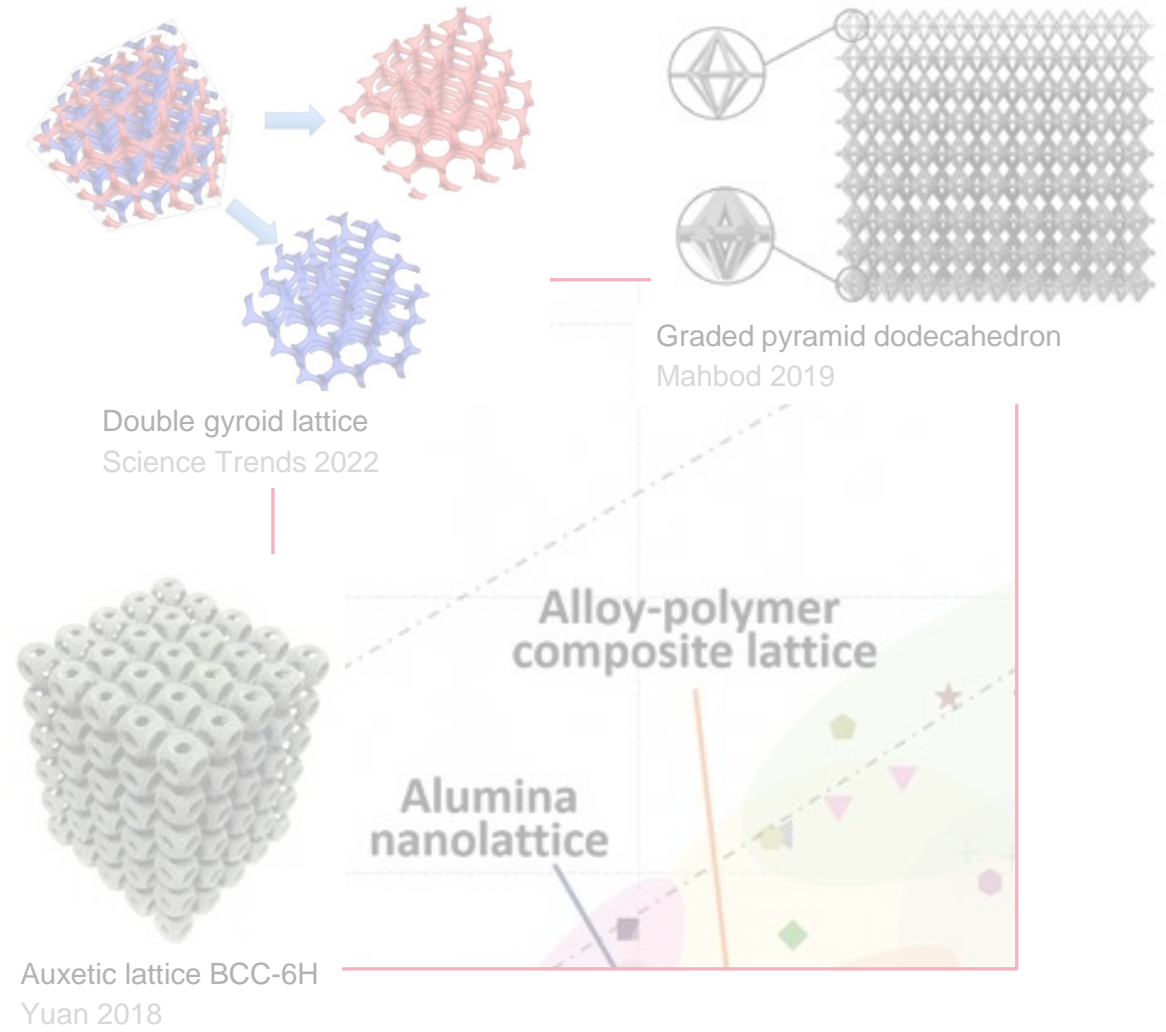
B pillar

Introduction and Motivation

Performance of metamaterials

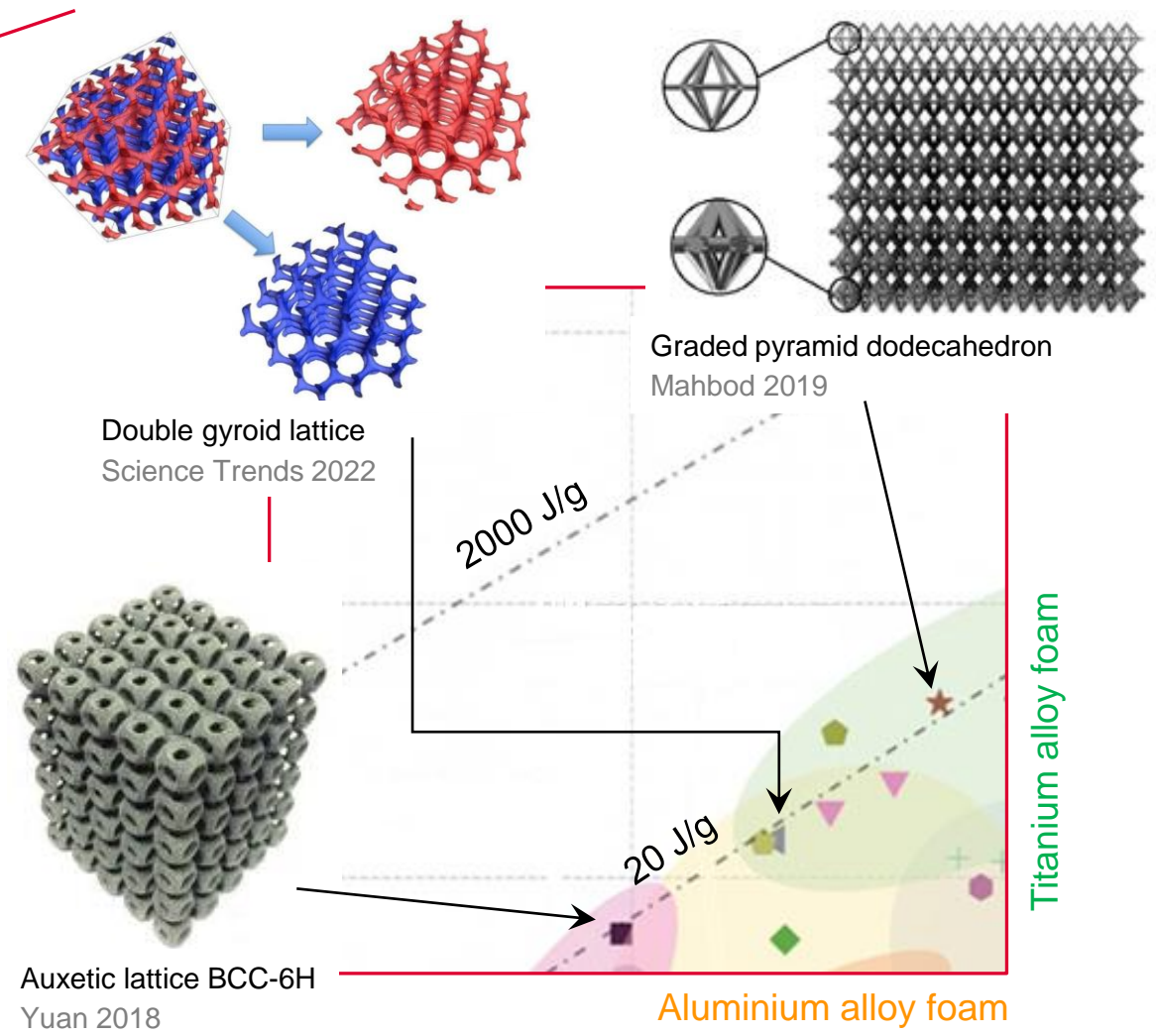
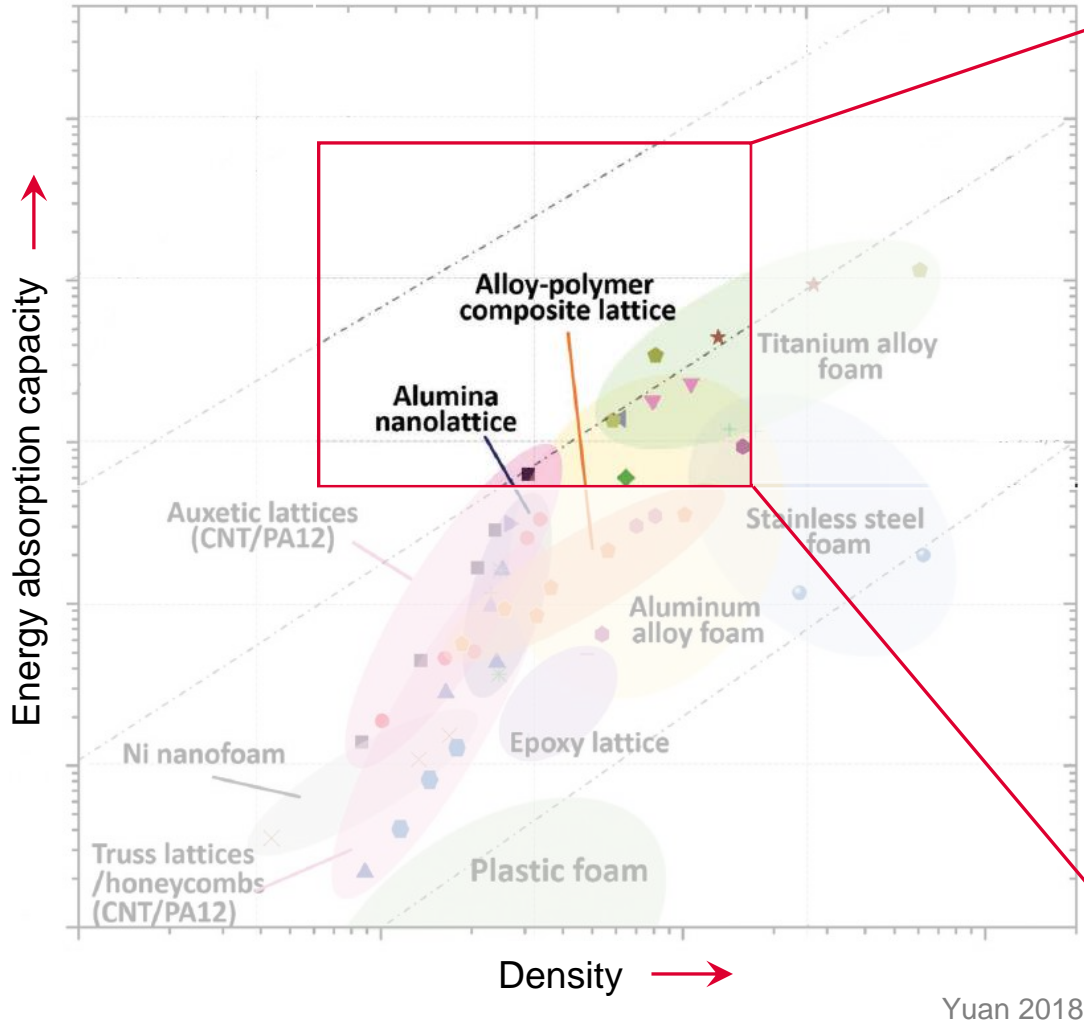


Yuan 2018

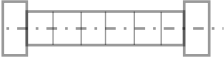


Introduction and Motivation


Performance of metamaterials



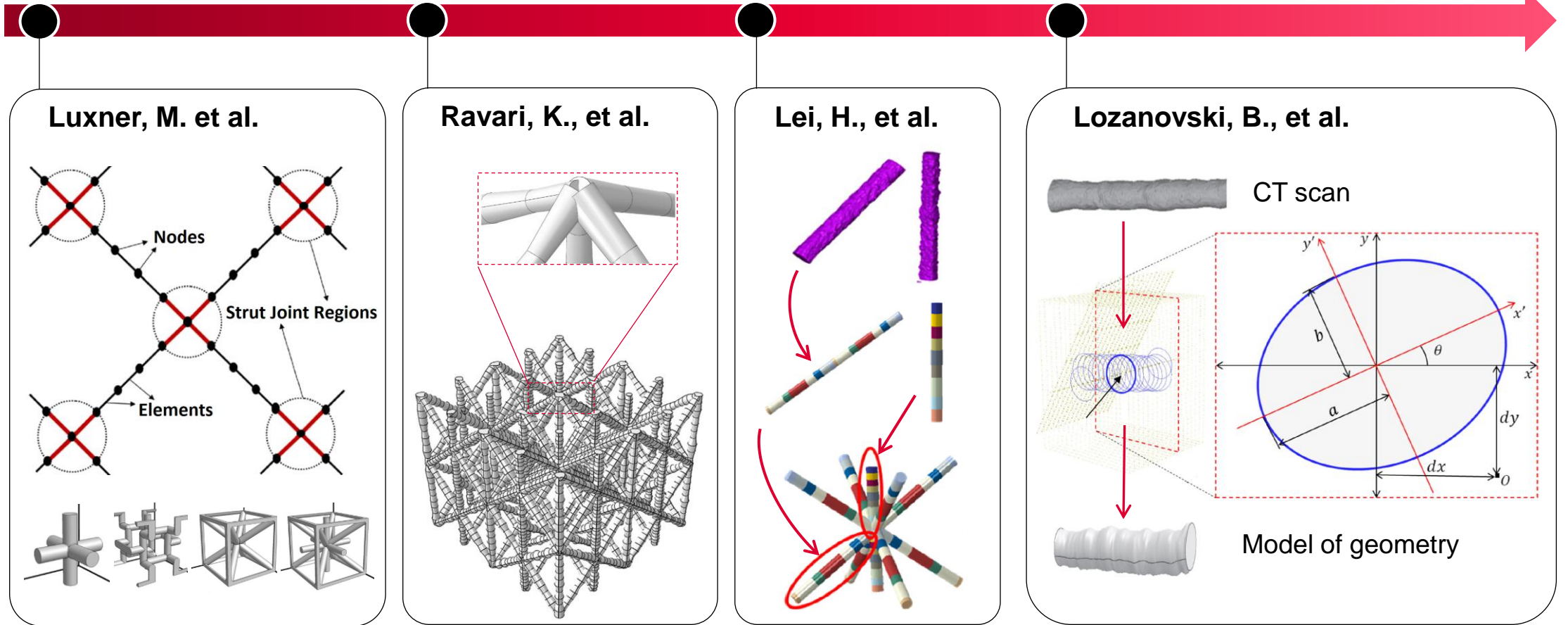
State of the Art – Computational approaches

2004 – 2009 

2014 

2018 

2019 



State of the Art – Model of material

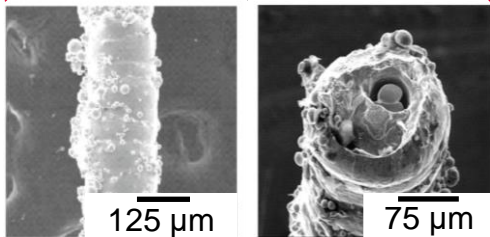
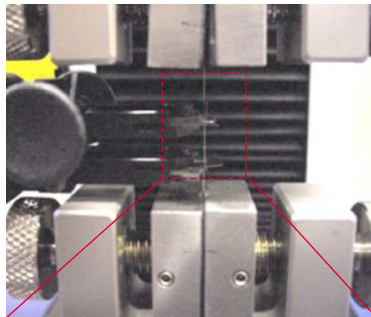
2010 – 2013

2014

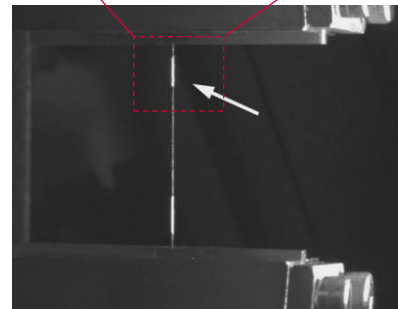
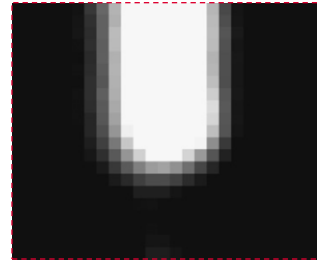
2018

2018

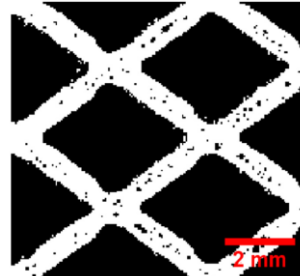
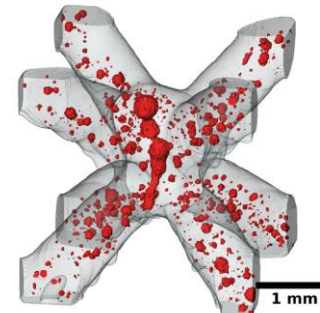
Tsopanos, S., Smith, M.



Li, P., et al.



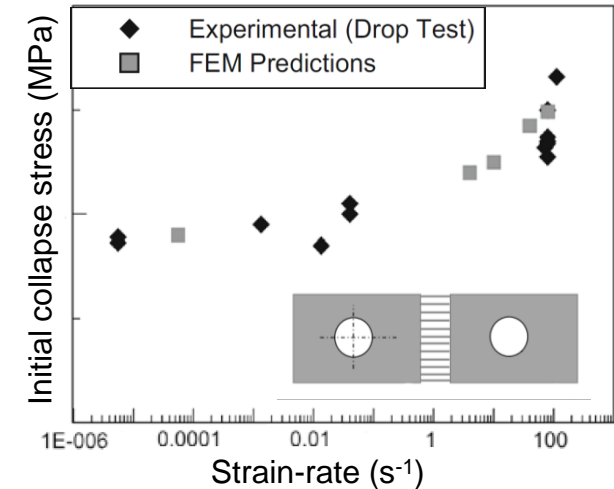
Amani, Y., et al.



Gümrük, R., et al.

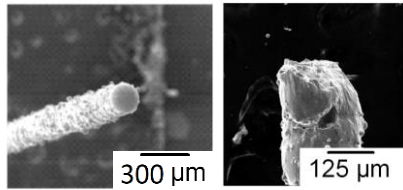
○ Cowper-Symonds model

Collapse stress of structure



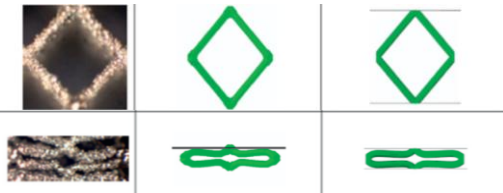
Summary of literature review

✓ Mech. properties of bulk material

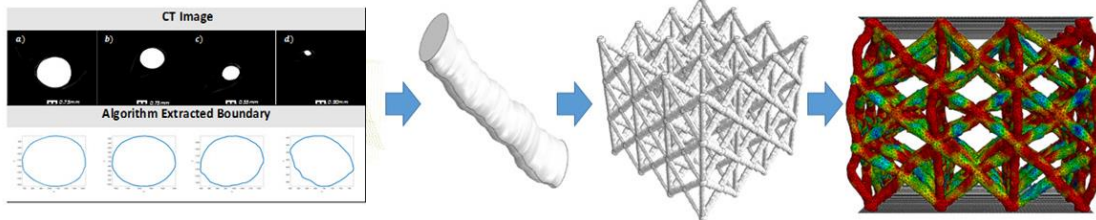


✓ Stiffness corrections near nodes

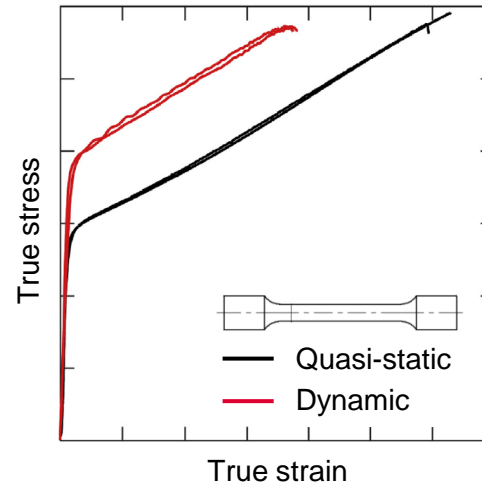
✓ Modeling of dynamic simulations



✓ Implementation of the significant geometrical imperfections

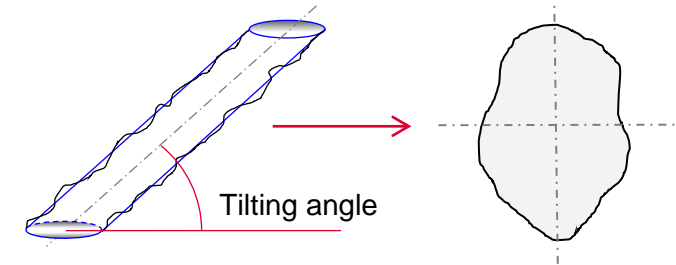


✓ Effect of the strain-rate sensitivity for bulk material

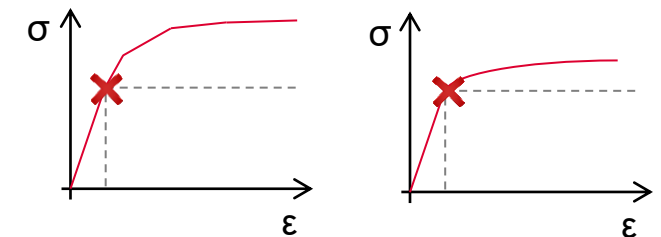


Analysis of unknown aspects

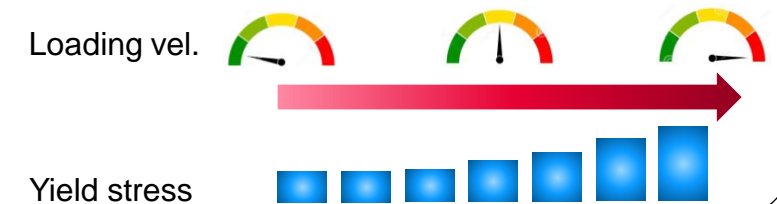
⚡ Influence of geometrical imperfections



⚡ Non-linear mat. model based thin struts



⚡ Strain-rate sensitivity of structure



Aim of PhD thesis

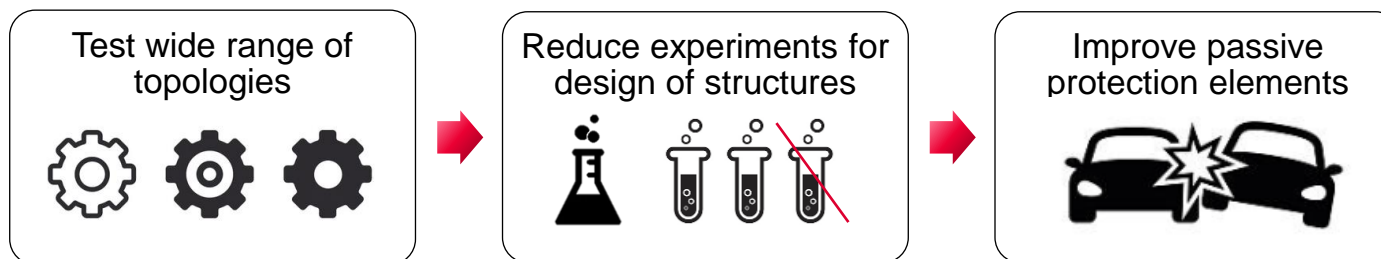
The main goal of the thesis

The thesis aims at development of the computational model that represents the deformational behavior of mechanically loaded lattice structures produced by SLM technology.

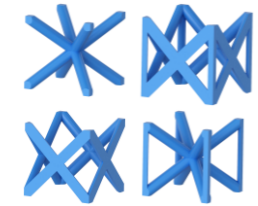
The benefit of the thesis

- Achieve higher absorption potential in comparison to experimental testing
- Precise design of lattice structure topology for wide range of applied loads
- Outperform conventionally produced metamaterials

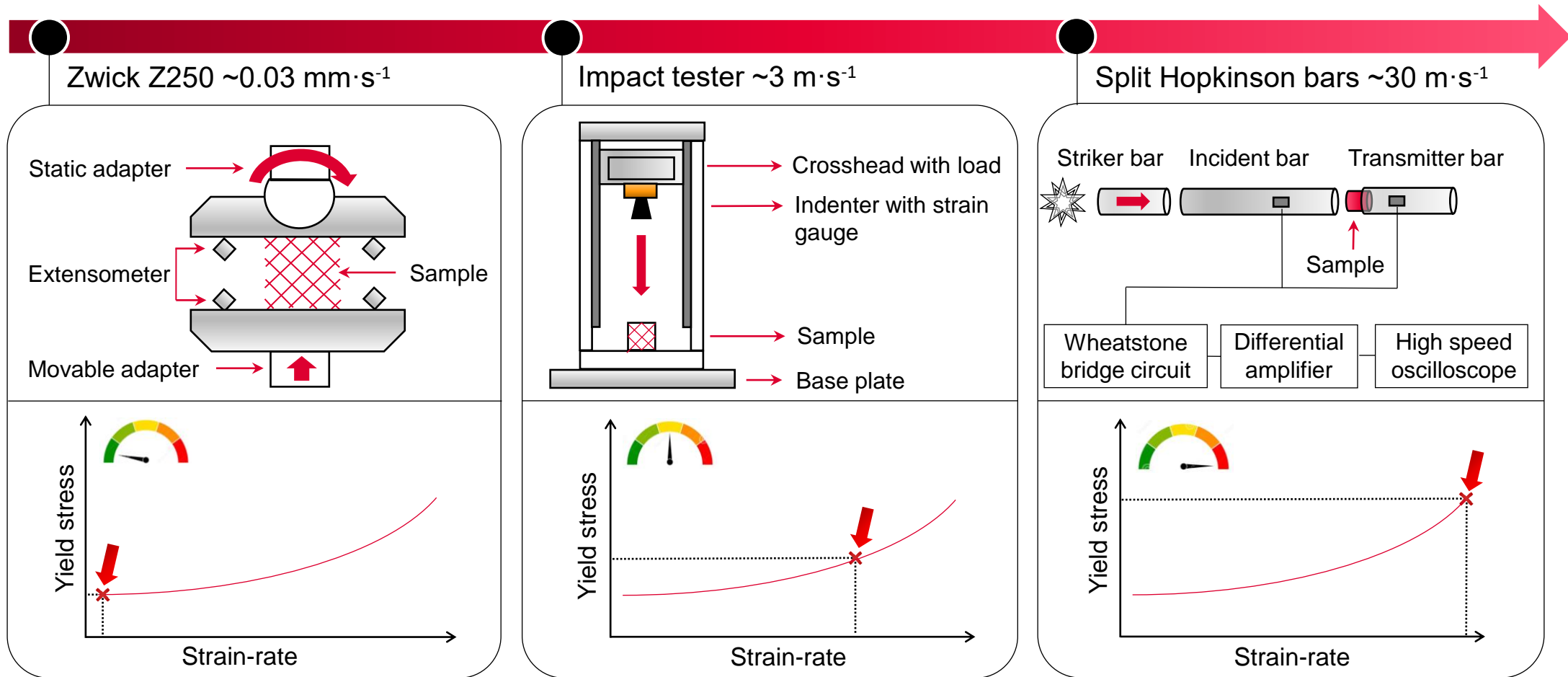
Application potential



Materials and methods



Loading velocities



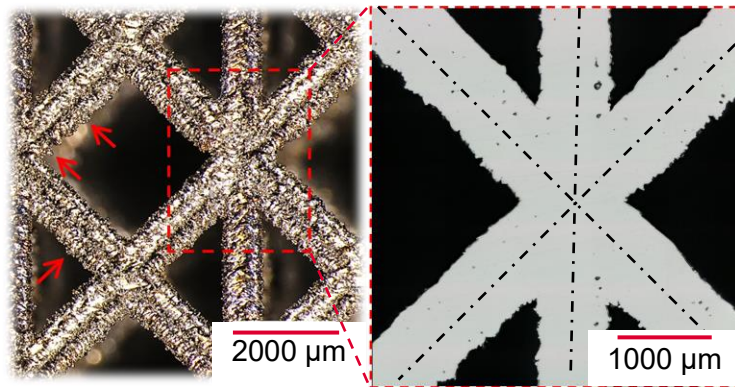
Scientific question and hypothesis

Scientific question

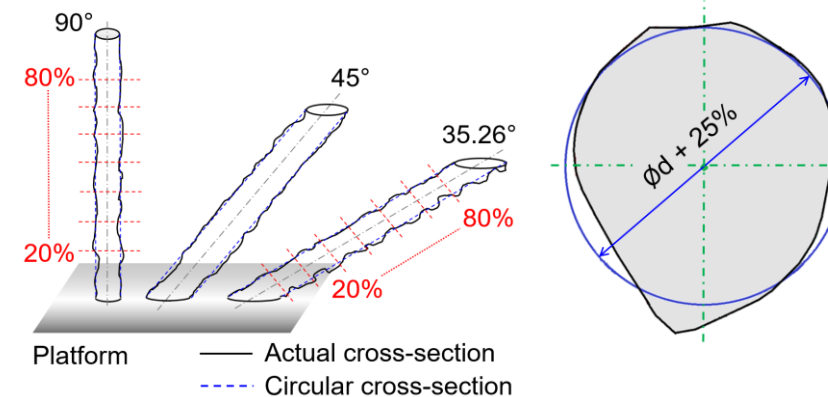
Q1: How do geometric imperfections affect the compression response of the structure?

Hypothesis

H1: Samples for dimensional analysis



Cross-section based on scans

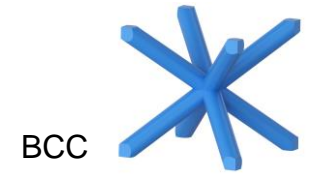


Tested prediction

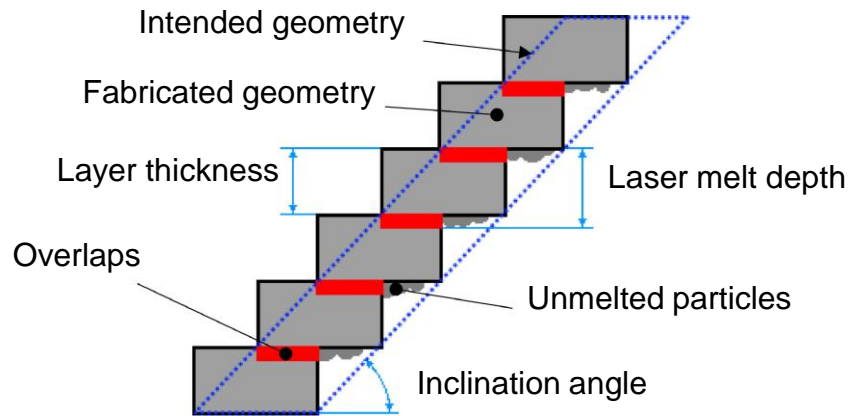
P1: Changes of the cross-sectional dimensions as a consequence of manufacturing imperfections strongly affect mechanical properties of lattice structures' response.

Results and discussion

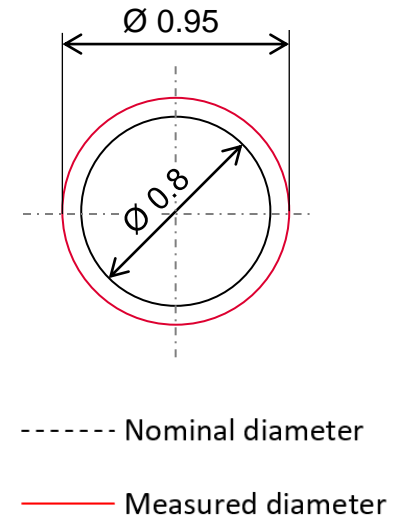
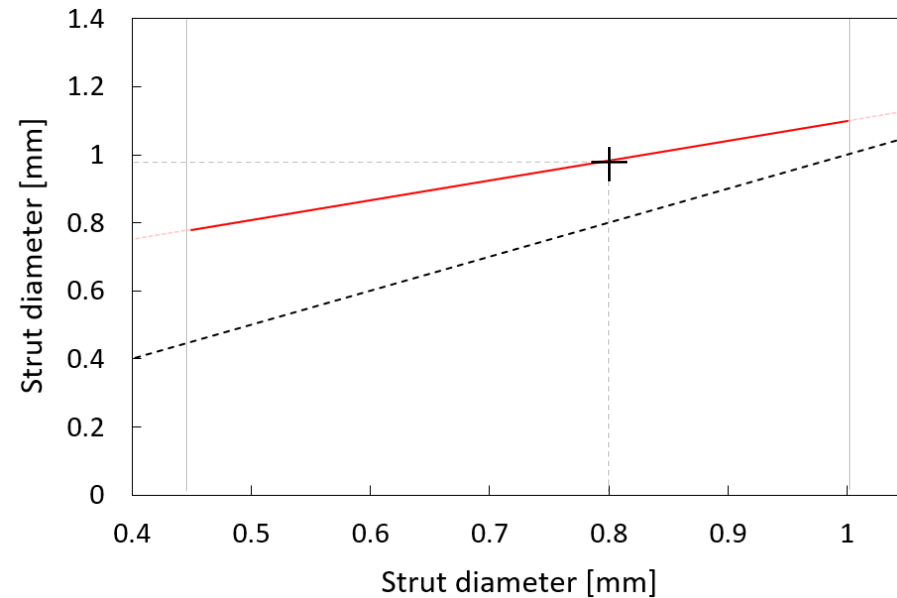
Tested prediction 1 – quasi-static loading 10^{-3} s^{-1}



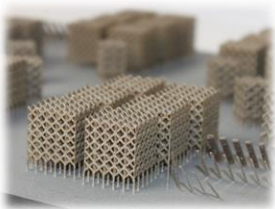
Dimensional inspection of lattice structures



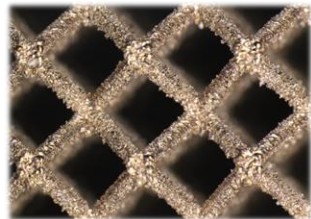
AlSi₁₀Mg trend of measured diameters



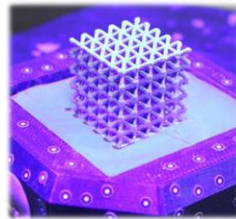
Production



Post-processing



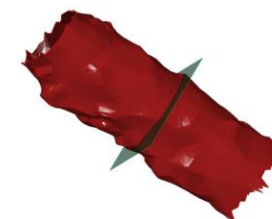
Digitization



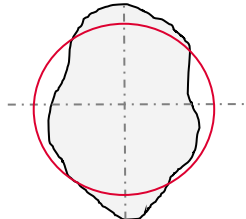
Polygonization



Measurement

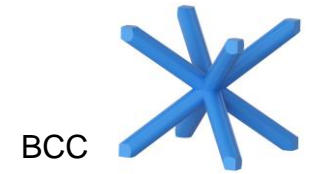


Evaluation



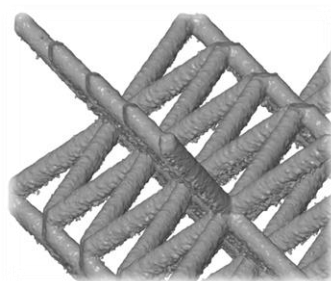
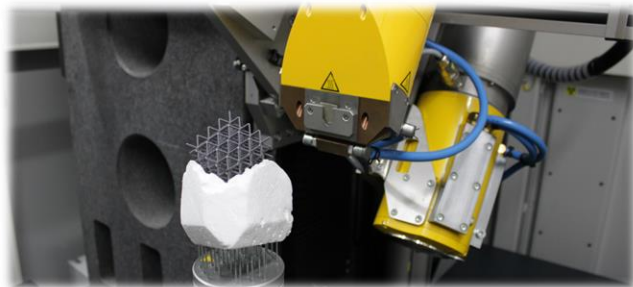
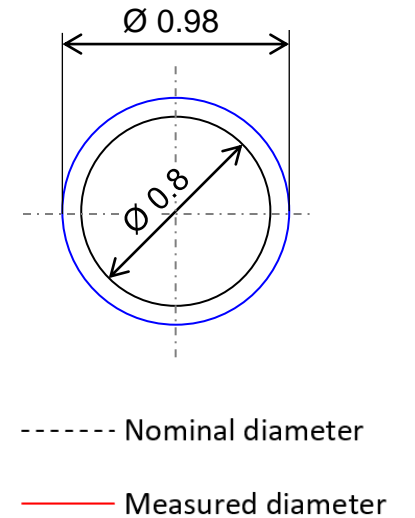
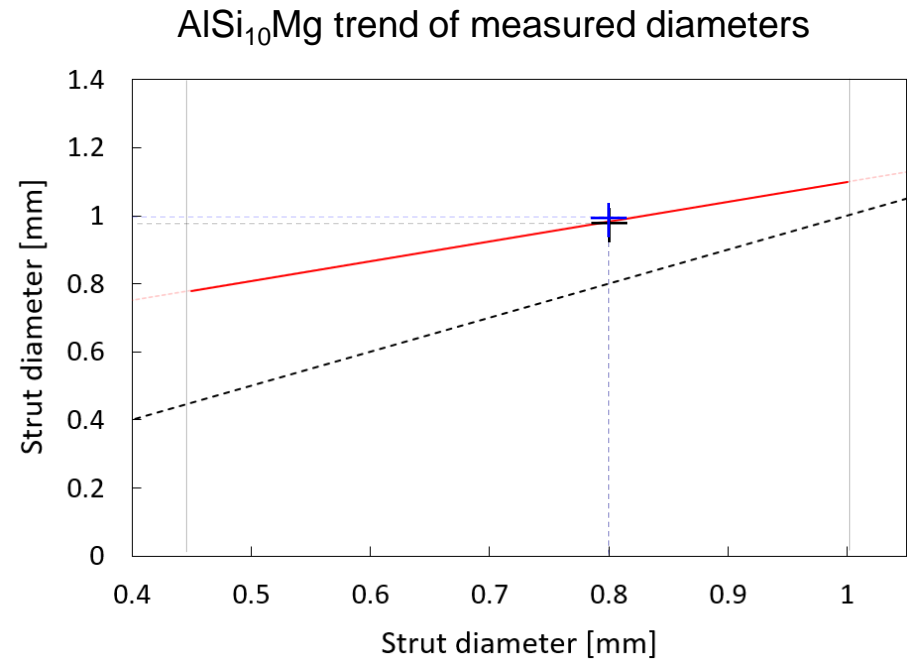
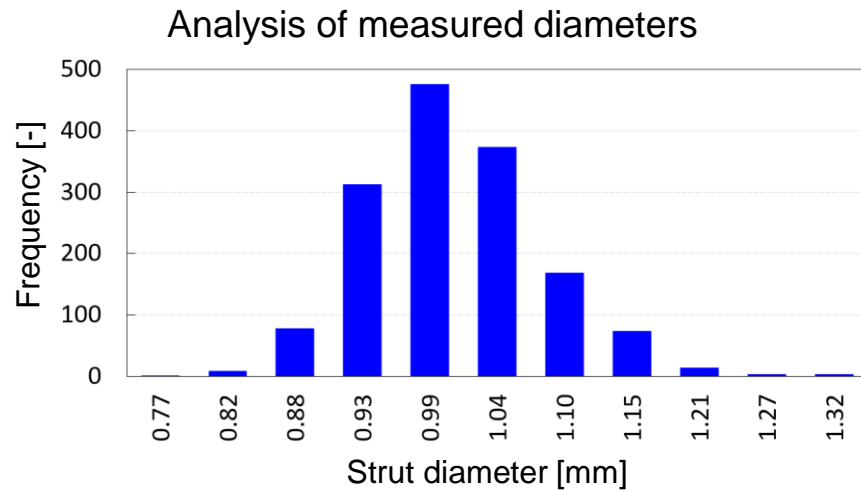
Results and discussion

Tested prediction 1 – quasi-static loading 10^{-3} s^{-1}



Dimensional inspection of lattice structures

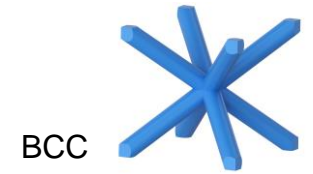
- Measured with CT (15 μm minimal voxel size)



- Average of 1600 measured cross-sections
- Check for specific strut diameter 0.8 mm
- Semi-automated script for evaluation

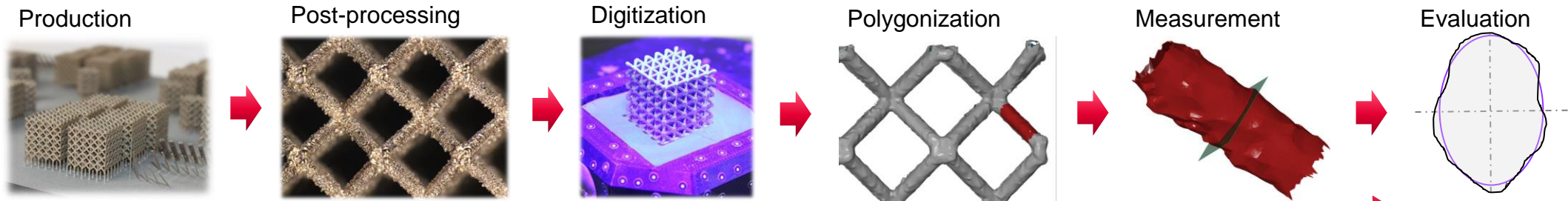
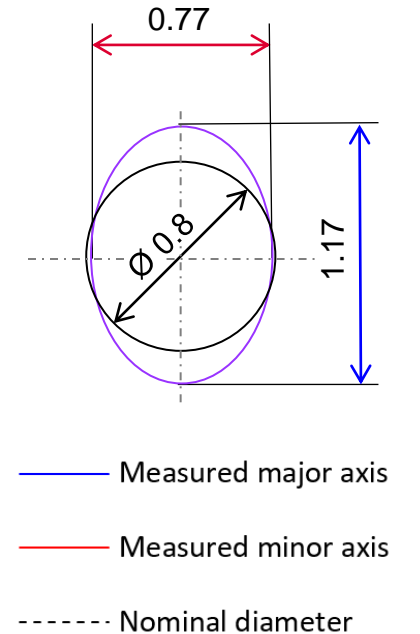
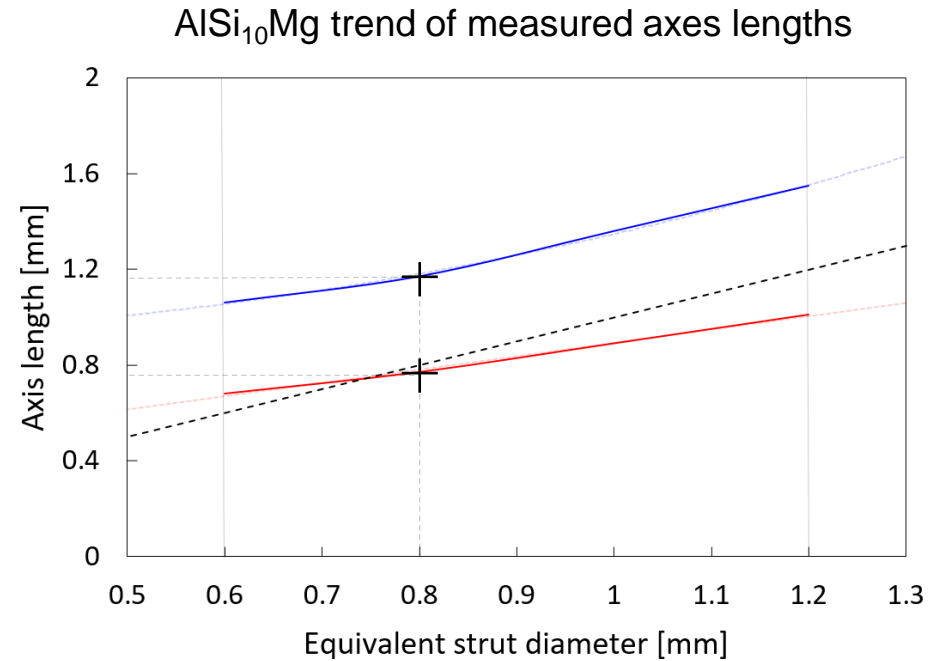
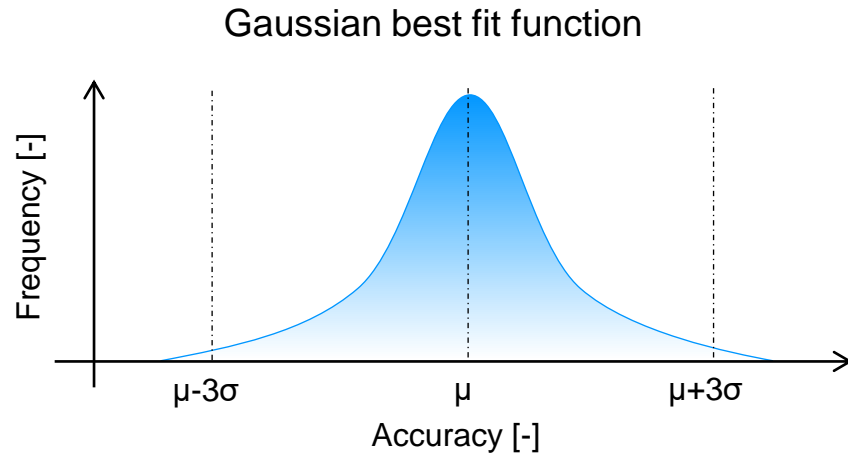
Results and discussion

Tested prediction 1 – quasi-static loading 10^{-3} s^{-1}



Dimensional inspection of lattice structures

- Optical digitization with $\pm 5 \mu\text{m}$ accuracy



Results and discussion

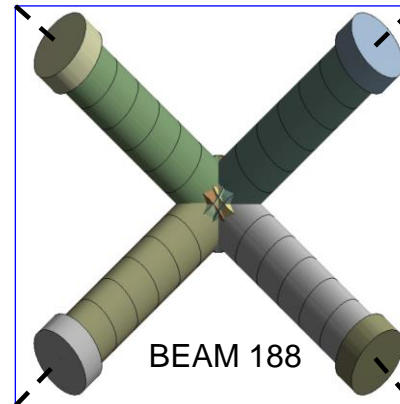
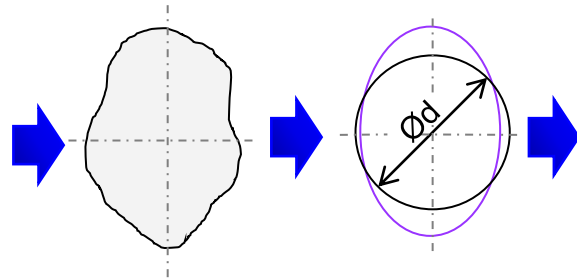
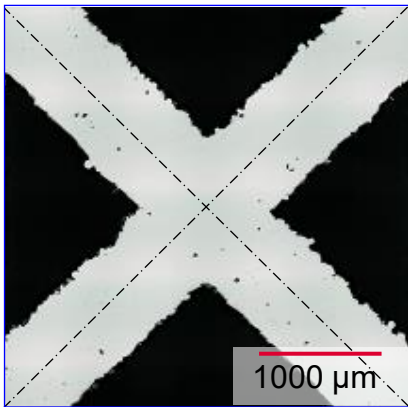
Tested prediction 1 – quasi-static loading 10^{-3} s^{-1}


Phenomena capturing

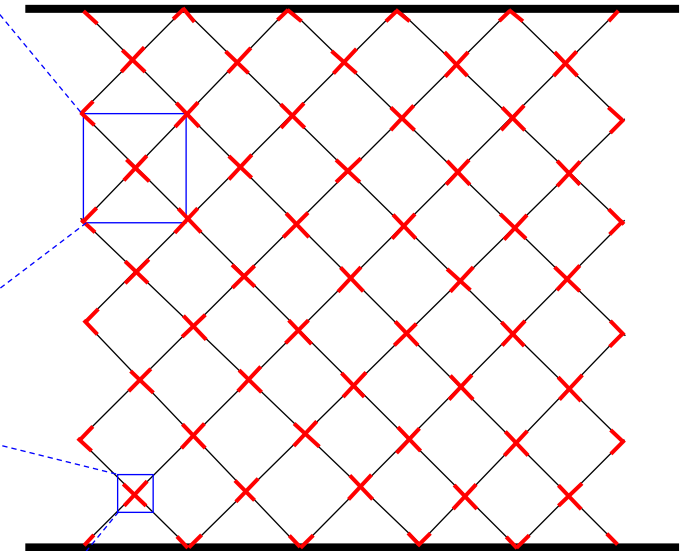
Geometry simplification

API implementation

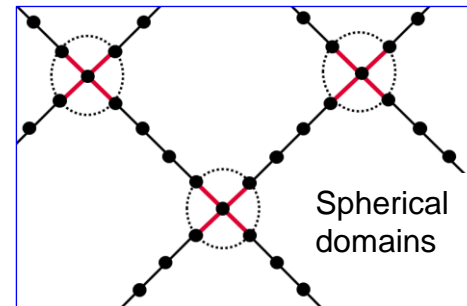
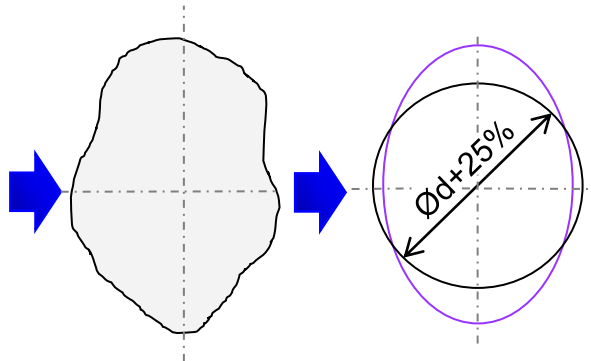
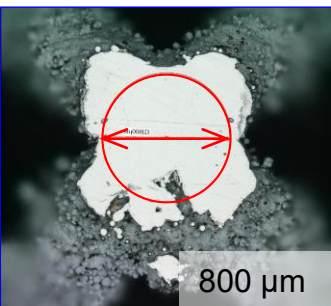
FEM representation



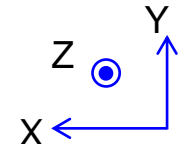
Loading direction $[0, -Y, 0]$  QUAD 4



Displacement $[0, 0, 0]$ QUAD 4

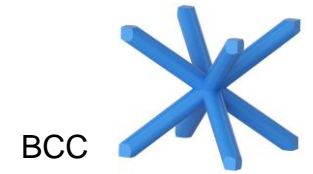


4 mm



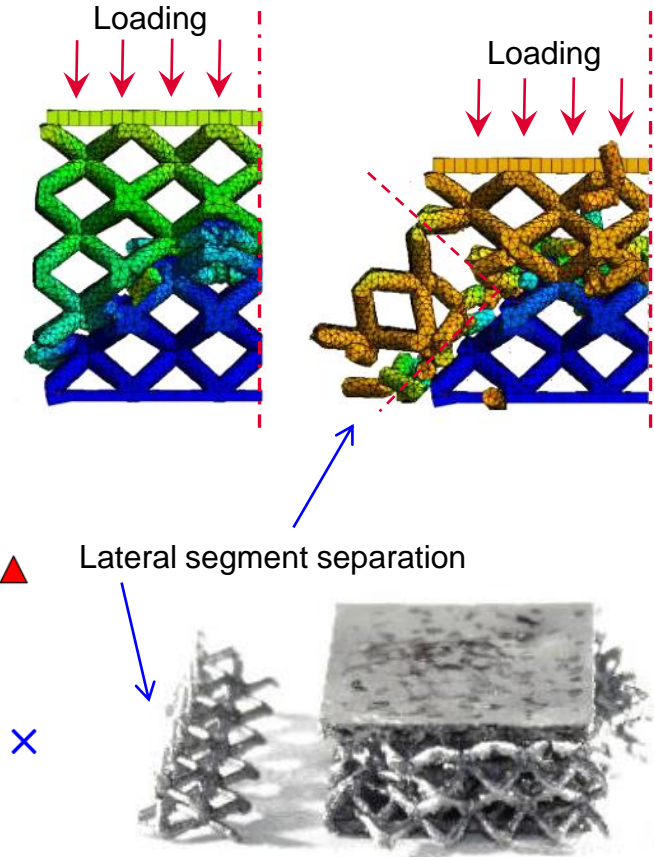
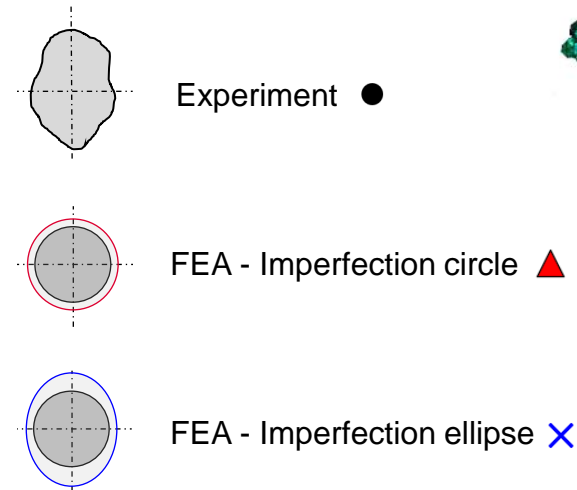
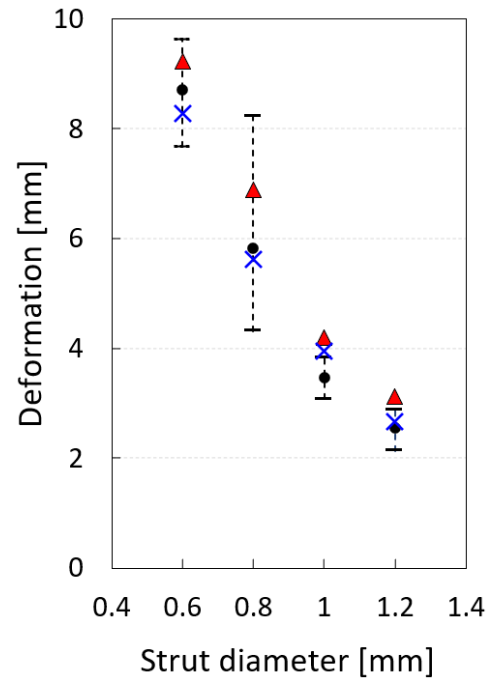
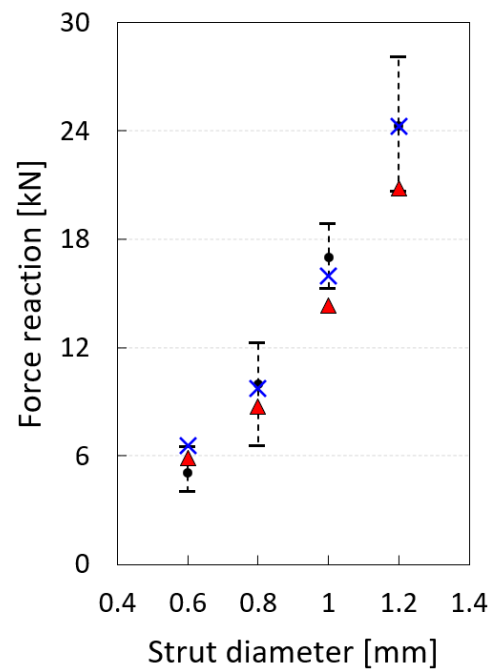
Results and discussion

Tested prediction 1 – quasi-static loading 10^{-3} s^{-1}

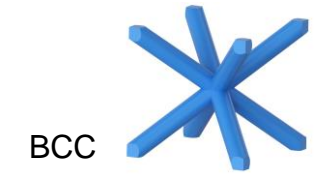


Influence of imperfections in FEA

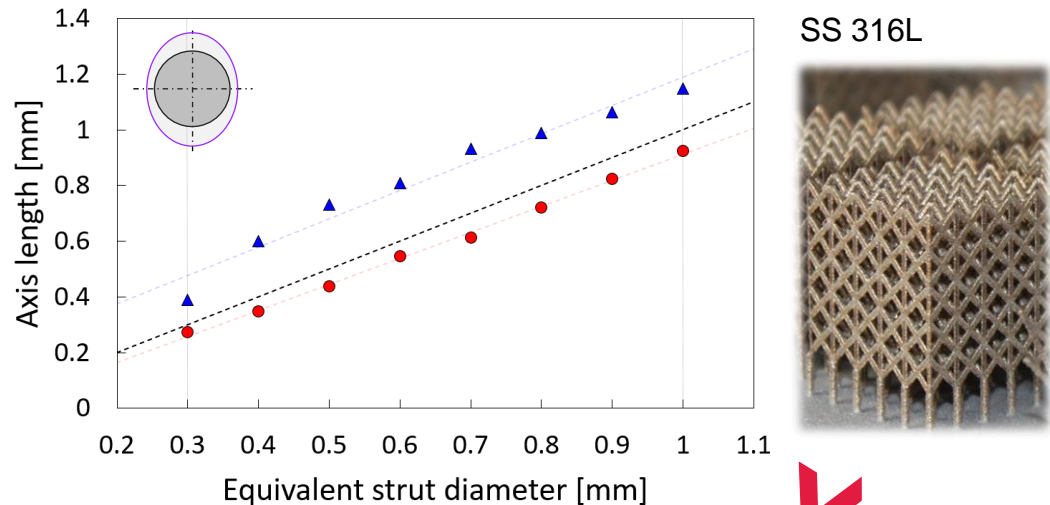
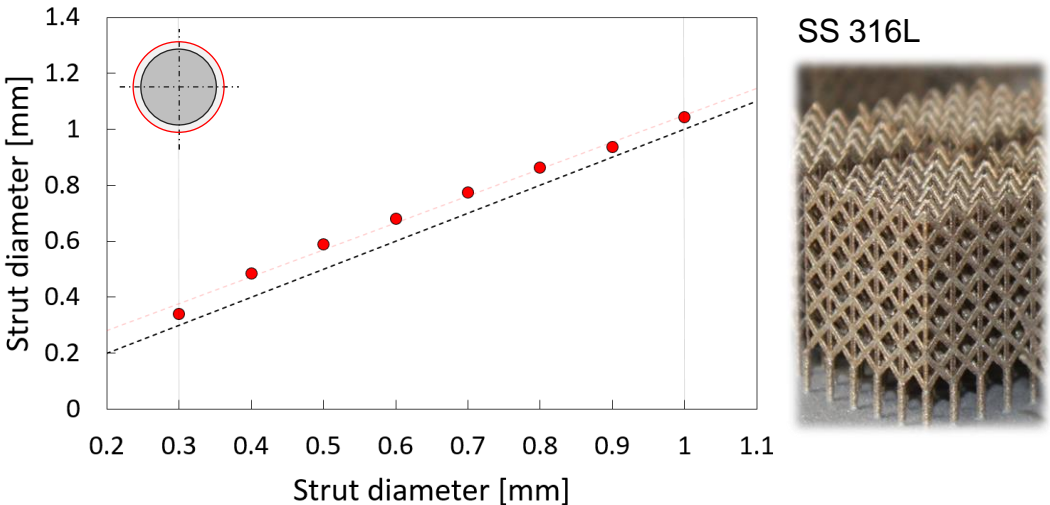
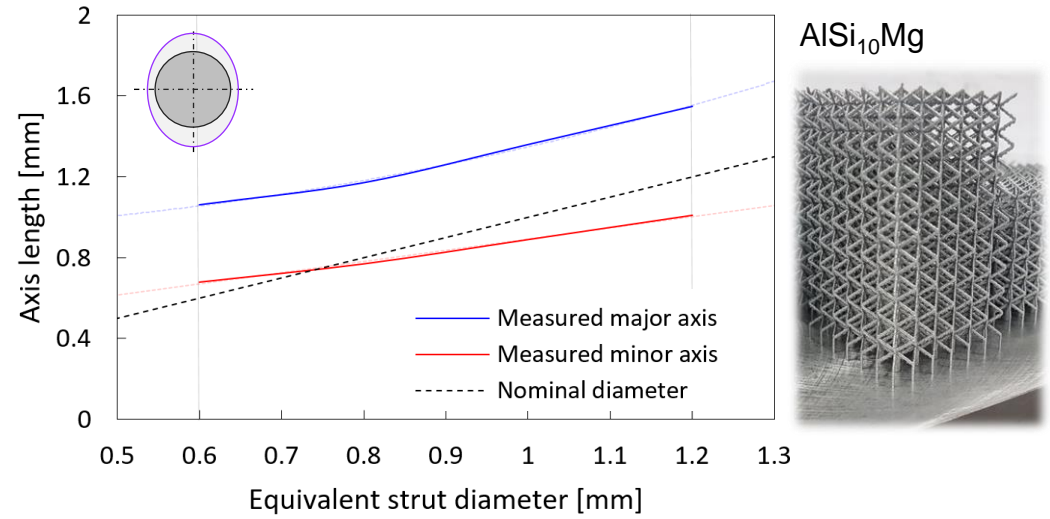
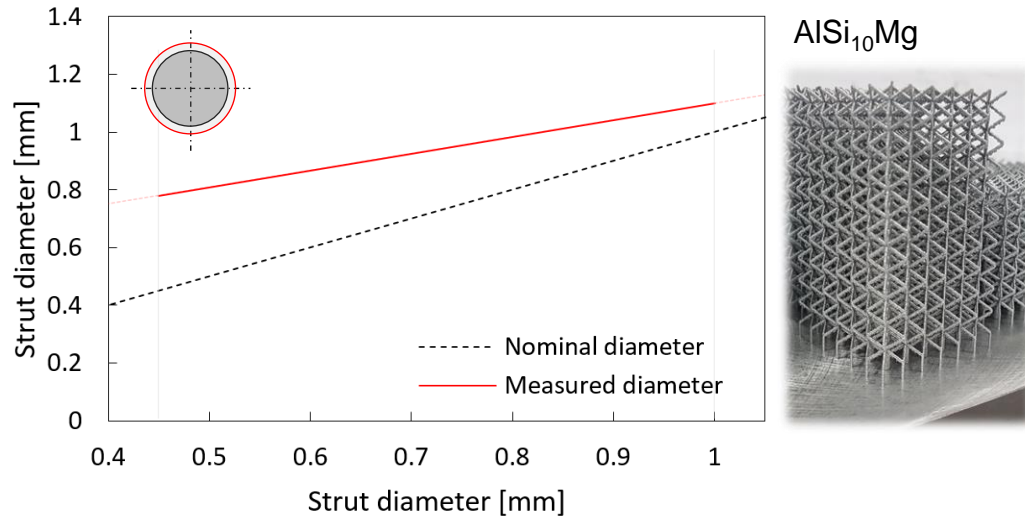
- Material model based on tensile testing on thin strut samples
- 8-noded tetrahedral elements for struts and 4-noded shells for plates



Results and discussion



Tested prediction 1 – quasi-static loading 10^{-3} s^{-1}



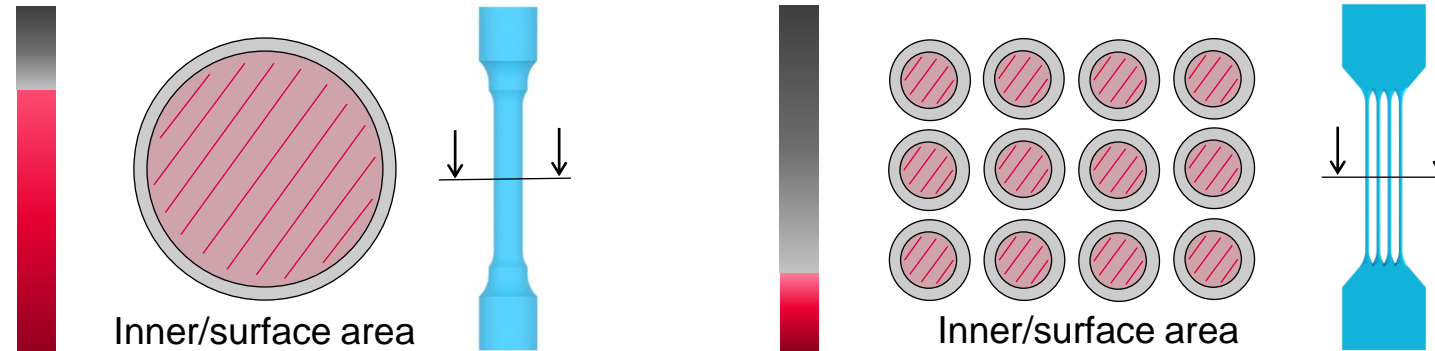
Scientific question and hypothesis

Scientific question

Q2: How does the non-linear material model based on thin strut samples influence the structure deformation?

Hypothesis

H2: DIN sample scanning strategy layout → Multi-strut sample scanning strategy layout



Tested prediction

P2: The accuracy of the material model based on the test of thin strut samples is limited to certain range of nominal strut diameters.

Results and discussion

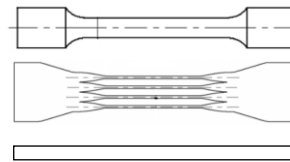


Tested prediction 2 – quasi-static loading 10^{-3} s^{-1}

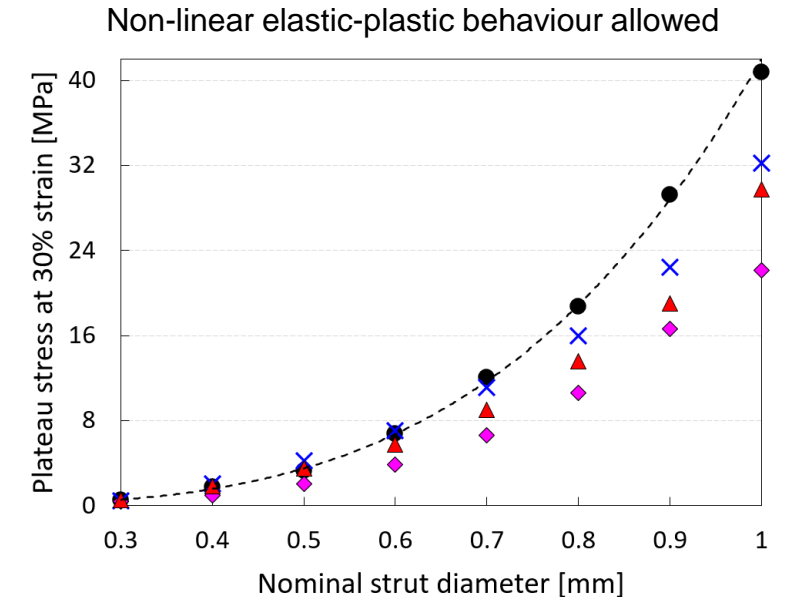
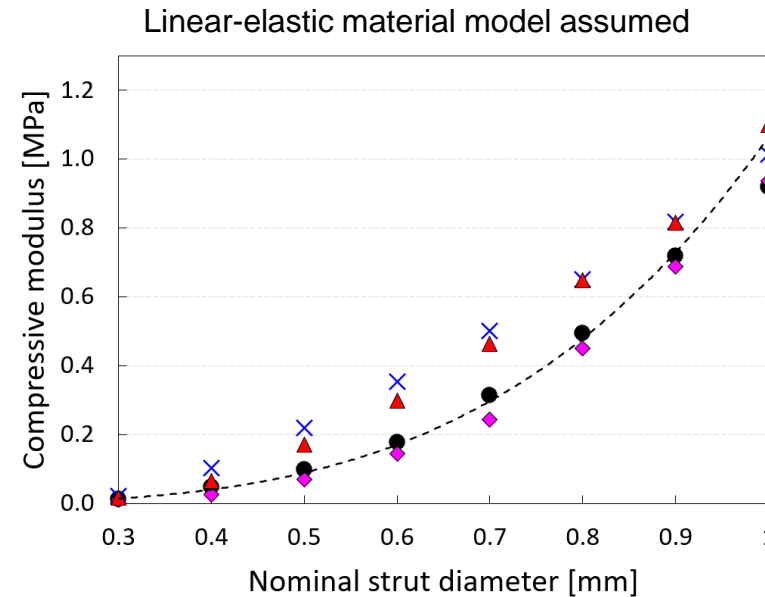
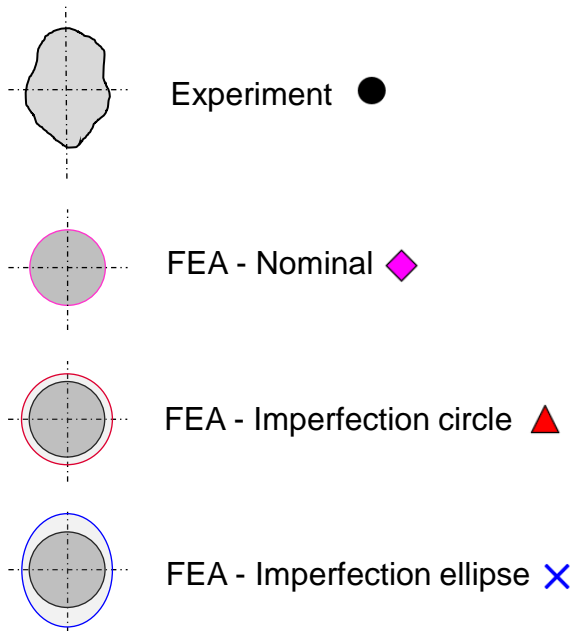
BCC

Influence of material model definition

- 2-noded Timoshenko beam elements
- Properties based on multi-strut samples



	E	Ys	Et	UTS
	GPa	MPa	MPa	MPa
Conventional sample	166 ± 15	450 ± 5	89	541
Multi-strut sample	94 ± 10	338 ± 20	787	397
Strut sample (Gümrük)	97 ± 10	325		



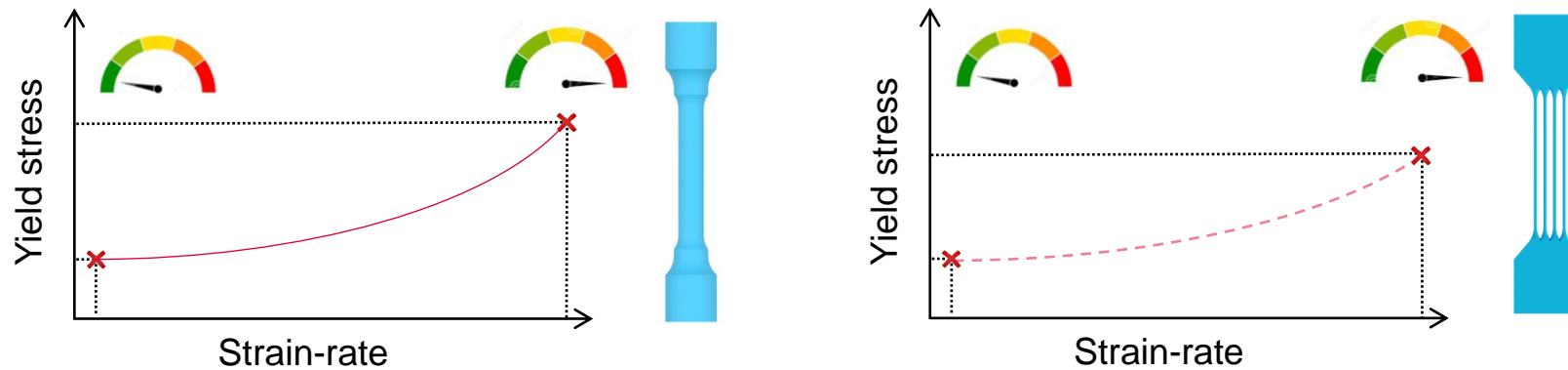
Scientific question and hypothesis

Scientific question

Q3: How does the strain-rate sensitivity influence the dynamic behavior of structure?

Hypothesis

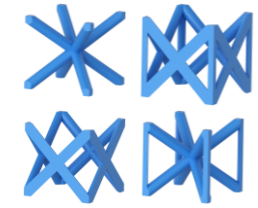
H3: Working diagram of strain-dependent 316L → Expectation of 316L strut sample sensitivity



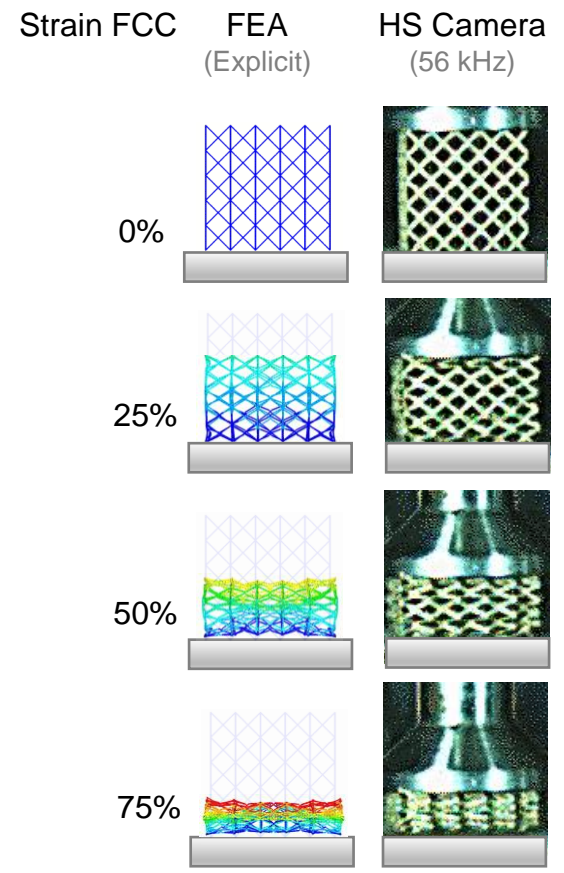
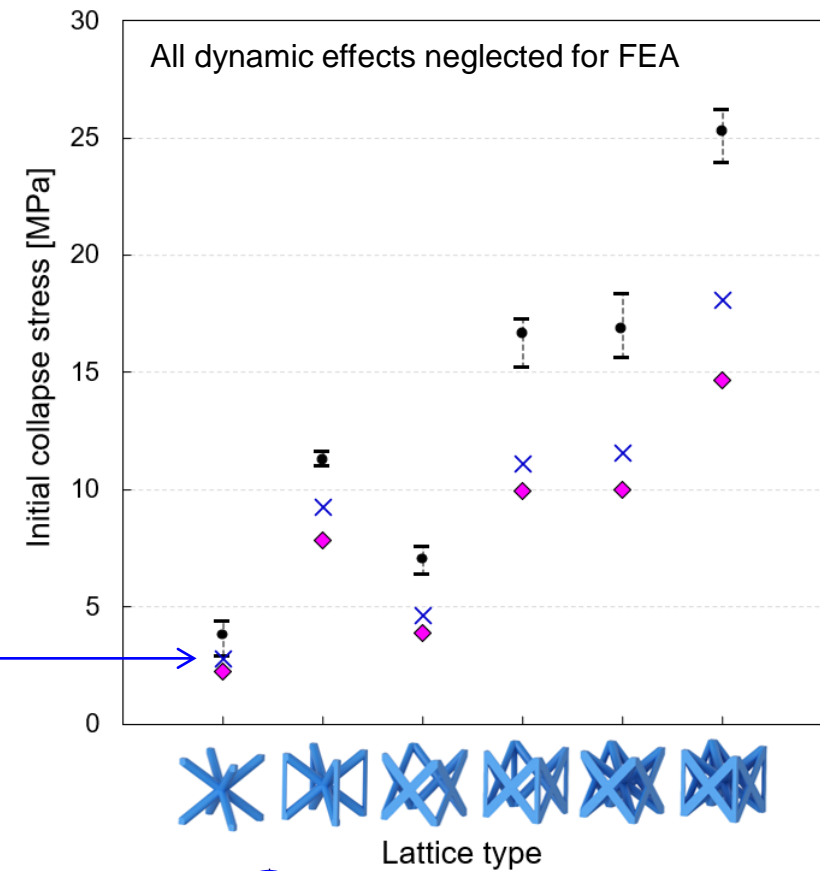
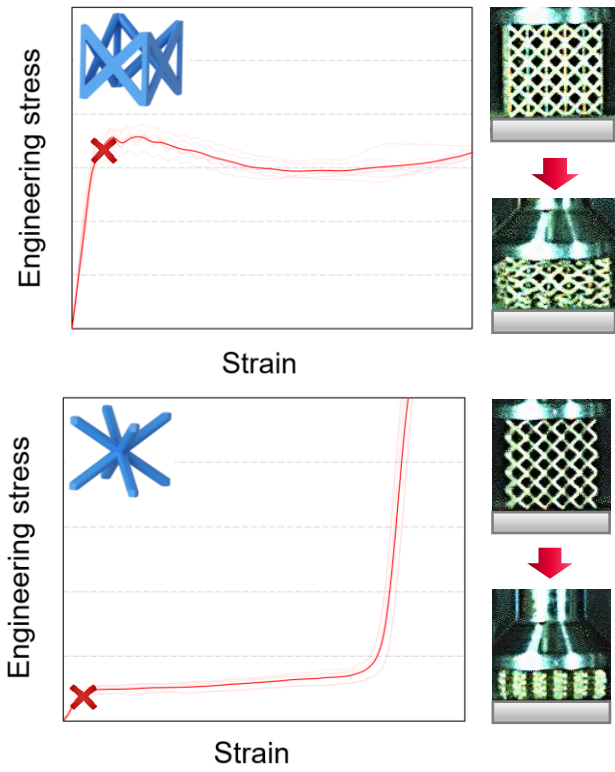
Tested prediction

P3: The sensitivity of the parent material on strain-rate cannot be neglected in simulation even for lower loading velocities.

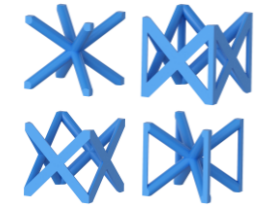
Results and discussion



Tested prediction 2 – dynamic loading 10^2 s^{-1} (intermediate velocities)

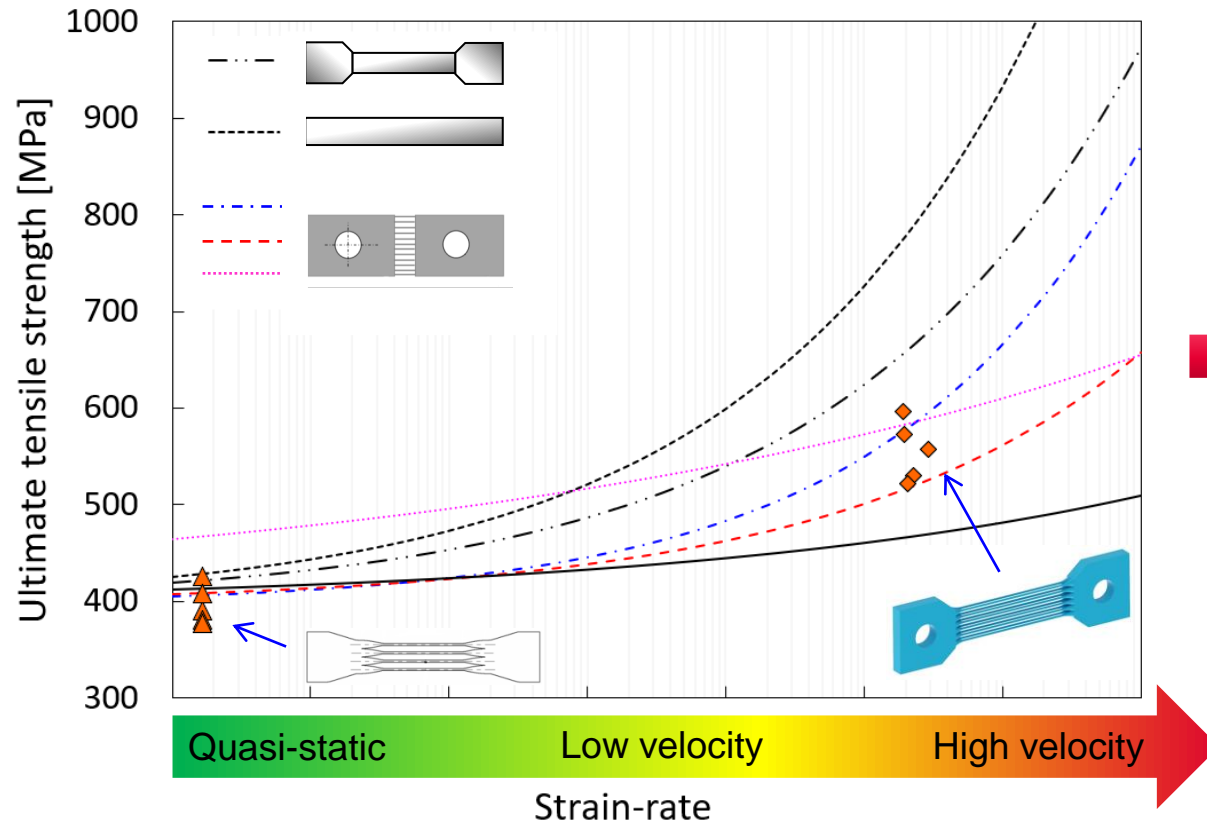


Results and discussion

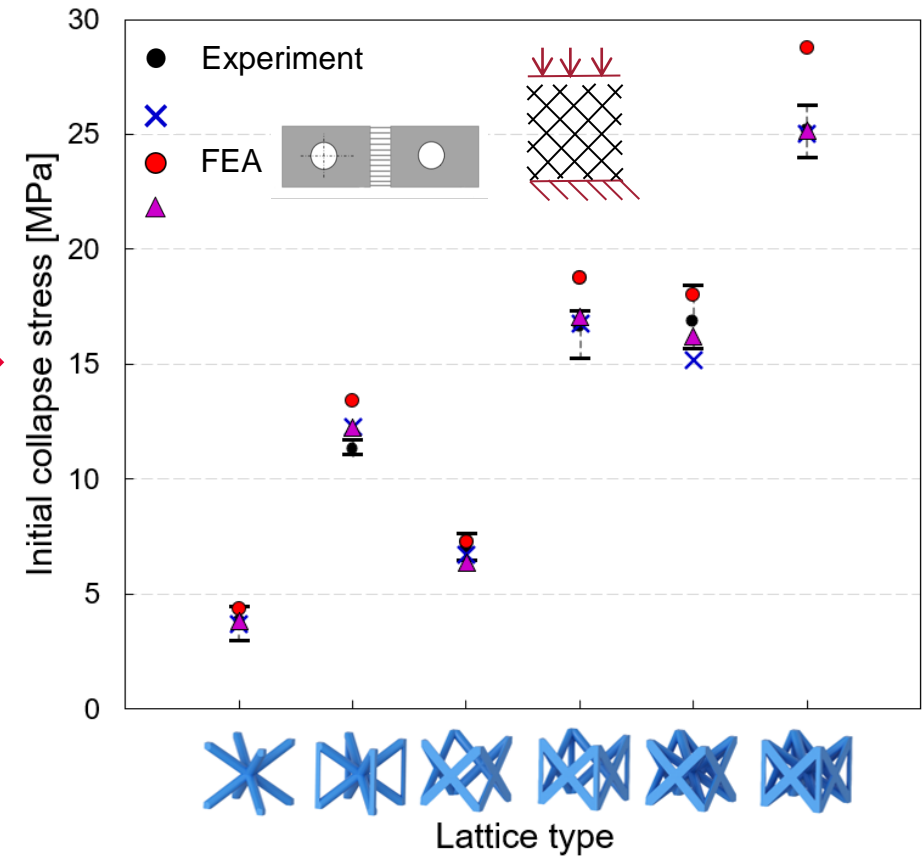


Tested prediction 3 – dynamic loading $10^2 - 10^3 \text{ s}^{-1}$

Influence of Cowper-Symonds parameters

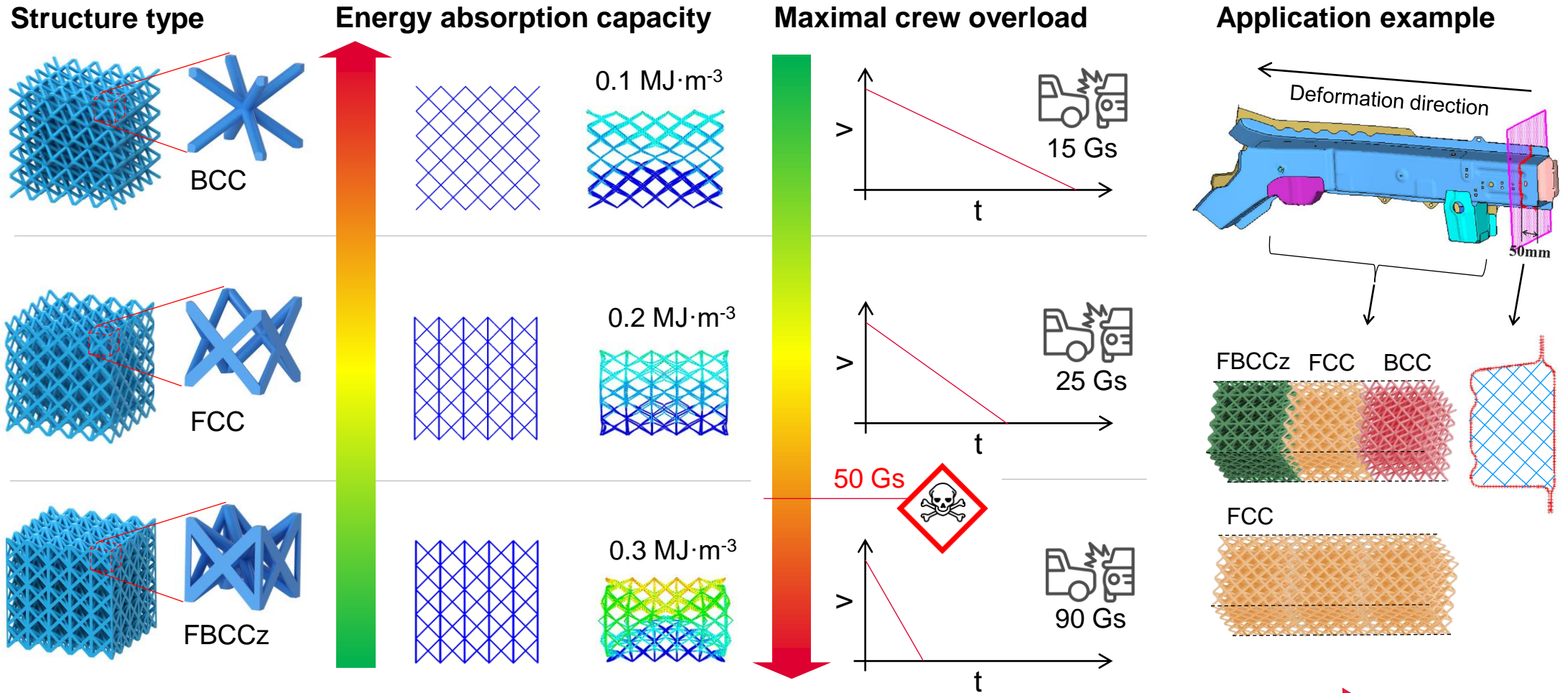


Dynamic compression of lattice structures



Conclusion

Application potential



List of publications

Journals with impact factor

- VRÁNA, R.; ČERVINEK, O.; MAŇAS, P.; KOUTNÝ, D.; PALOUŠEK, D. Dynamic Loading of Lattice Structure Made by Selective Laser Melting- Numerical Model with Substitution of Geometrical Imperfections, 2018, vol. 11, no. 11, p. 1-22. ISSN 1996-1944
- ČERVINEK, O.; WERNER, B.; KOUTNÝ, D.; VAVERKA, O.; PANTĚLEJEV, L.; PALOUŠEK, D. Computational Approaches of Quasi-Static Compression Loading of SS316L Lattice Structures Made by Selective Laser Melting. Materials, 2021, vol. 14, no. 9, p. 1-24. ISSN: 1996-1944.
- WERNER, B.; ČERVINEK, O.; KOUTNÝ, D.; REISINGER, A.; PETTERMANN, H.E.; TODT, M. Numerical and experimental study on the collapse of a triangular cell under. International Journal of Solids and Structures, 2021, vol. 236, no. 76, p. 1-12. ISSN: 0020-7683.
- ČERVINEK, O.; PETTERMANN, H.; TODT, M.; KOUTNÝ, D.; VAVERKA, O. Non-linear dynamic finite element analysis of micro-strut lattice structures made by laser powder bed fusion. Journal of Materials Research and Technology, 2022, vol. 18, no. 1-16, p. 3684-3699. ISSN: 2238-7854.
- VRÁNA, R.; KOUTECKÝ, T.; ČERVINEK, O.; ZIKMUND, T.; PANTĚLEJEV, L.; KAISER, J.; KOUTNÝ, D. Deviations of the SLM produced Lattice Structures and Their Influence on Mechanical properties. Materials, 2022, vol. 15, no. 9, p. 1-20. ISSN: 1996-1944.
- NOPOVÁ, K.; JAROŠ, J.; ČERVINEK, O.; PANTĚLEJEV, L.; GNEIGER, S.; SENCK, S.; KOUTNÝ, D. Processing of AZ91D Magnesium Alloy by Laser Powder Bed Fusion. Appl. Sci. 2023,13, 1377. <https://doi.org/10.3390/app13031377>

Conference proceedings

- VRÁNA, R.; VAVERKA, O.; ČERVINEK, O.; PANTĚLEJEV, L.; HURNÍK, J.; KOUTNÝ, D.; PALOUŠEK, D. Heat Treatment of the SLM Processed Lattice Structure Made of AlSi10Mg and Its Effect on the Impact Energy Absorption
- ČERVINEK, O.; VRÁNA, R. KOUTNÝ, D.; PALOUŠEK, D. Static and Dynamic Compression Performance of Lattice Structures Made by Selective Laser Melting.

Other results

- Functional specimen (RIV-G/B) – Protective element based on energy absorption

THANK YOU FOR YOUR ATTENTION

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