Numerical modeling of the compressive behavior of 316L body-centered cubic lattice structures

Mini-Symposium : MS-01

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Introduction - Lattice structures

Advantages

- innovative designs,
- optimized functionalities,
- lightweight structures.

Applications

- aerospace, automotive,
- marine
- medical industries.

Global mechanical response

- the topology
- geometry parameters:
  - relative density,
  - cell topology,
  - cell size.

Lattice strucutres on 3D printed implants. Source: all3dp.comLattice strucures on 3D printed engine brackert. Source: https://www.3dsculplab.xyz

Introduction - Mechanical behavior

Bending-dominated or stretch-dominated

Lattice structures:

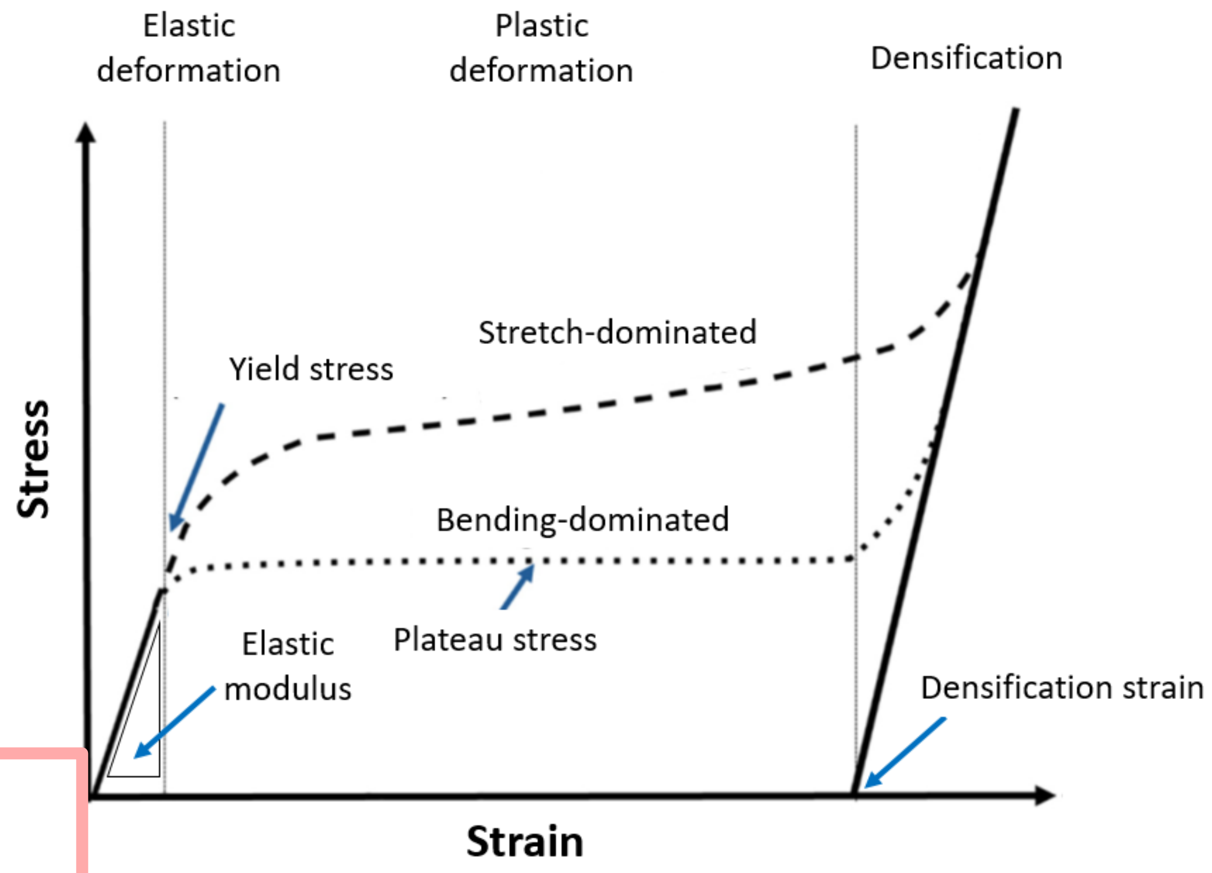
- body-centered cubic (BCC),
- face-centered cubic (FCC) + variants.

Compression: linear elastic region,

plastic deformation

densification.

FE simulations to decrease experimental campaigns.



: Köhnen P, Haase C, Bültmann J, et al (2018). Mater Des 145:205–217

STUDY : size effect on elastoplastic behavior of BCC lattice,

Different boundary conditions

Different relative densities (different strut diameters)

316L material

Introduction - Lattice structure model

The Gibson-Ashby model → Young modulus E and yield stress σ_y as function of relative density $\left(\frac{\rho}{\rho_0}\right)$

$$\frac{E}{E_0} = C\left(\frac{\rho}{\rho_0}\right)^n \qquad \frac{\sigma_y}{\sigma_{y0}} = C\left(\frac{\rho}{\rho_0}\right)^n$$

C, n determined from experimental stress-strain curves results.

Exponent $n = 0$ for full dense material

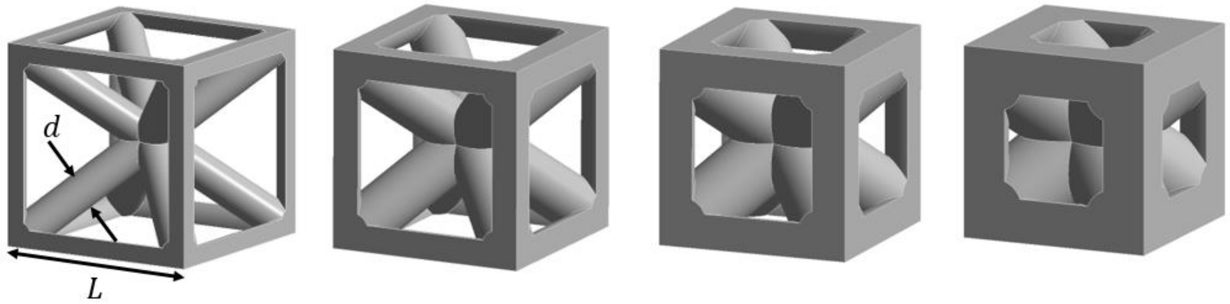
Experimental campaign - density variation

- BCC lattice cells with strut reinforcements on the x, y and z axes.
- Different relative densities: 20%, 40%, 60% and 80%.
- Material: bilinear elastic-plastic model 1st assumption based on literature, not accurate value according out tests

E_0 = 150 GPa

E_{t0} = 0.95 GPa

σ_{y0}= 225 MPa



$\rho_r = 20\%$	$\rho_r = 40\%$	$\rho_r = 60\%$	$\rho_r = 80\%$
$d = 0.54\ mm$	$d = 0.81\ mm$	$d = 1.07\ mm$	$d = 1.37\ mm$
$L = 3\ mm$	$L = 3\ mm$	$L = 3\ mm$	$L = 3\ mm$

Lattice cell deisgn at different relative densities ρ_r. Design paramters: strut diameter d and cell size L.

FE simulation: boundary conditions

4 FE models

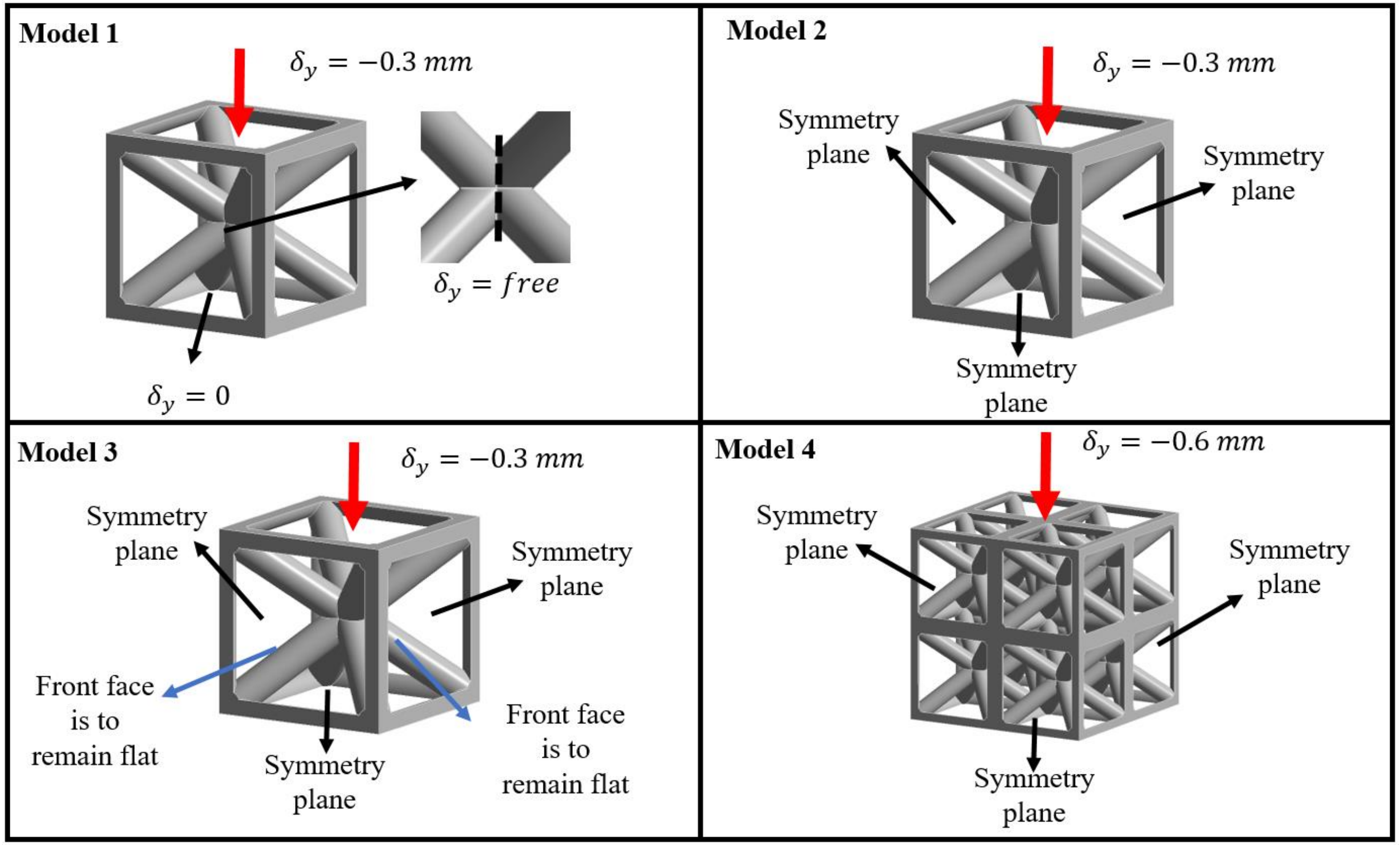
Model 1: **single cell** structure.

Lateral displacements allowed in lateral faces.

Model 3: single cell structure with planar imposition.

Lateral faces are imposed to remain flat.

"**a single cell in a large lattice structure**"



Model 2: single cell structure with three symmetry planes:

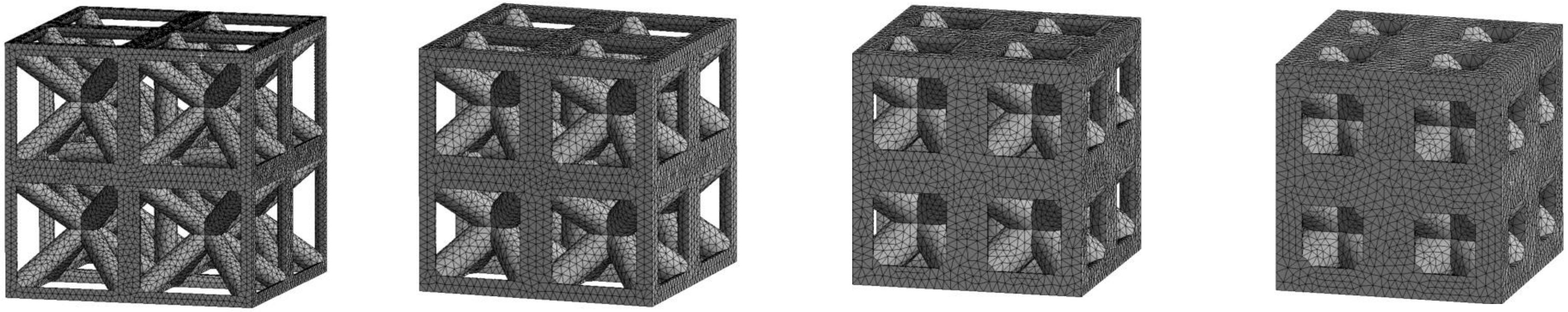
8 cells structure

Model 4: eight cells structure with three symmetry planes:

64 cell structure

FE mesh

- Meshing and simulations performed in ANSYS Mechanical – Static structural solver (implicit analysis)
- Solid tetrahedral elements SOLID187 of size between 0.13 and 0.2 mm



	$\rho_r = 20\%$	$\rho_r = 40\%$	$\rho_r = 60\%$	$\rho_r = 80\%$
Element size	0.15	0.19	0.22	0.24
Number of elements	104486	104804	102238	110898

- 6.64 hours simulation time for model 4 with 20% relative density (larger simulation time)
- Total number of cores requested: 2
- Simulation running on personal computer ACER NITRO 5, inter core I5 9th gen CPU 2.40 GHz, 16.0 GB Ram memories, NVIDIA GeForce GTX 1650 GPU.

Simulated compression results

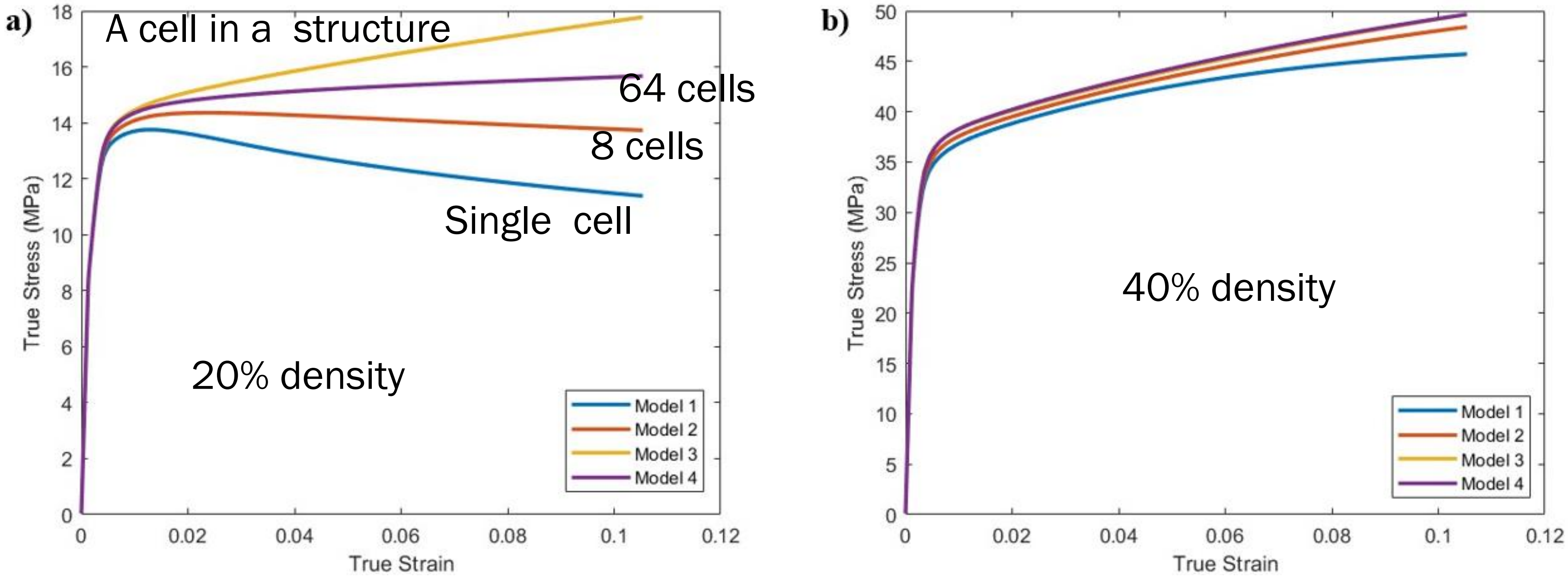
Main effect of relative density on hardening behavior E_t

Model 1 single cell weakest

Model 2 (8-cell) and 4 (64-cell) strength increases

Model 3 (ideal case of a lattice structure portion that is inside a larger arrays)

Difference is exacerbated for lower relative density (slenderness of the struts tends to increase buckling tendency)



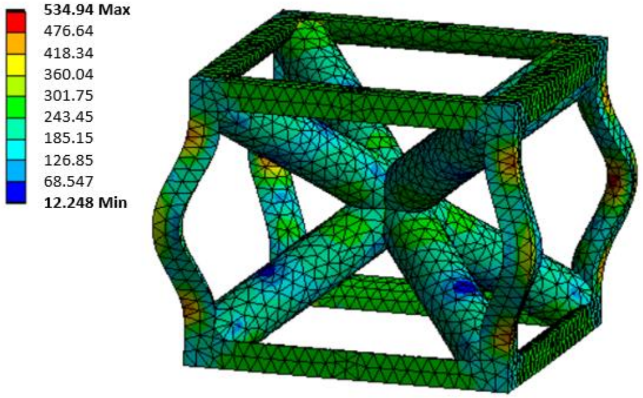
A cell in a structure = 64 cells for medium high density

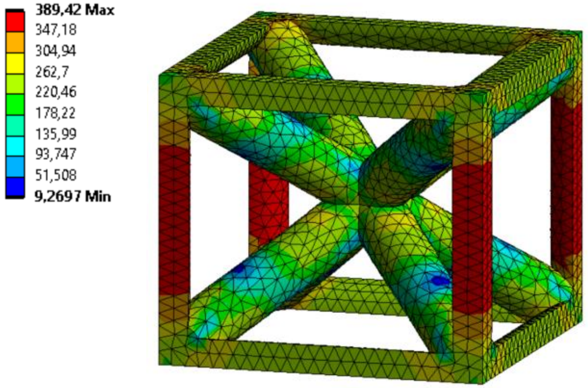
Deformation state at 10 %

Model 1: single cell structure

Model 3: single cell in a large lattice structure

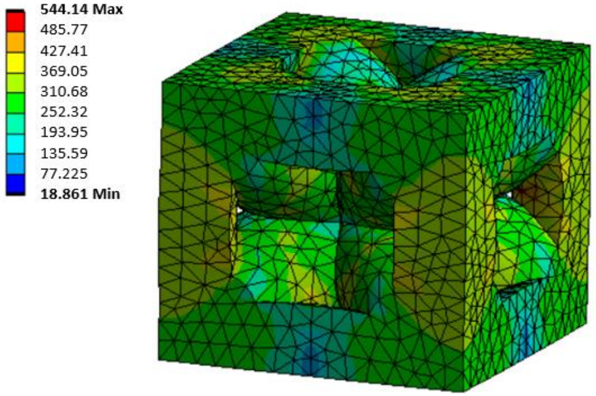
$\rho_r = 20\%$

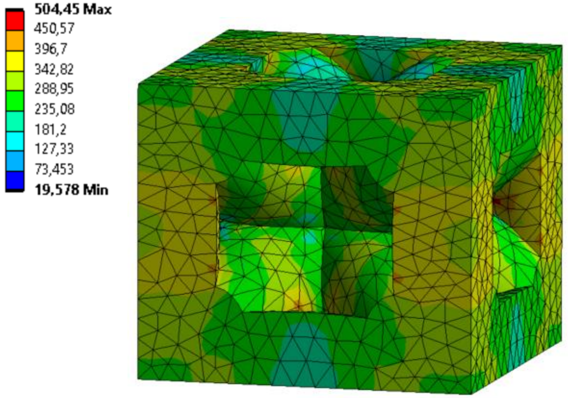




→ Buckling effect of exterior vertical struts.

$\rho_r = 80\%$





→ Buckling effect is less relevant in higher density structures due to the robustness of the struts.

Gibson-Ashby fit for each parameter

Gibson-Ashby power function

with $C = 1$ predicts → good precision

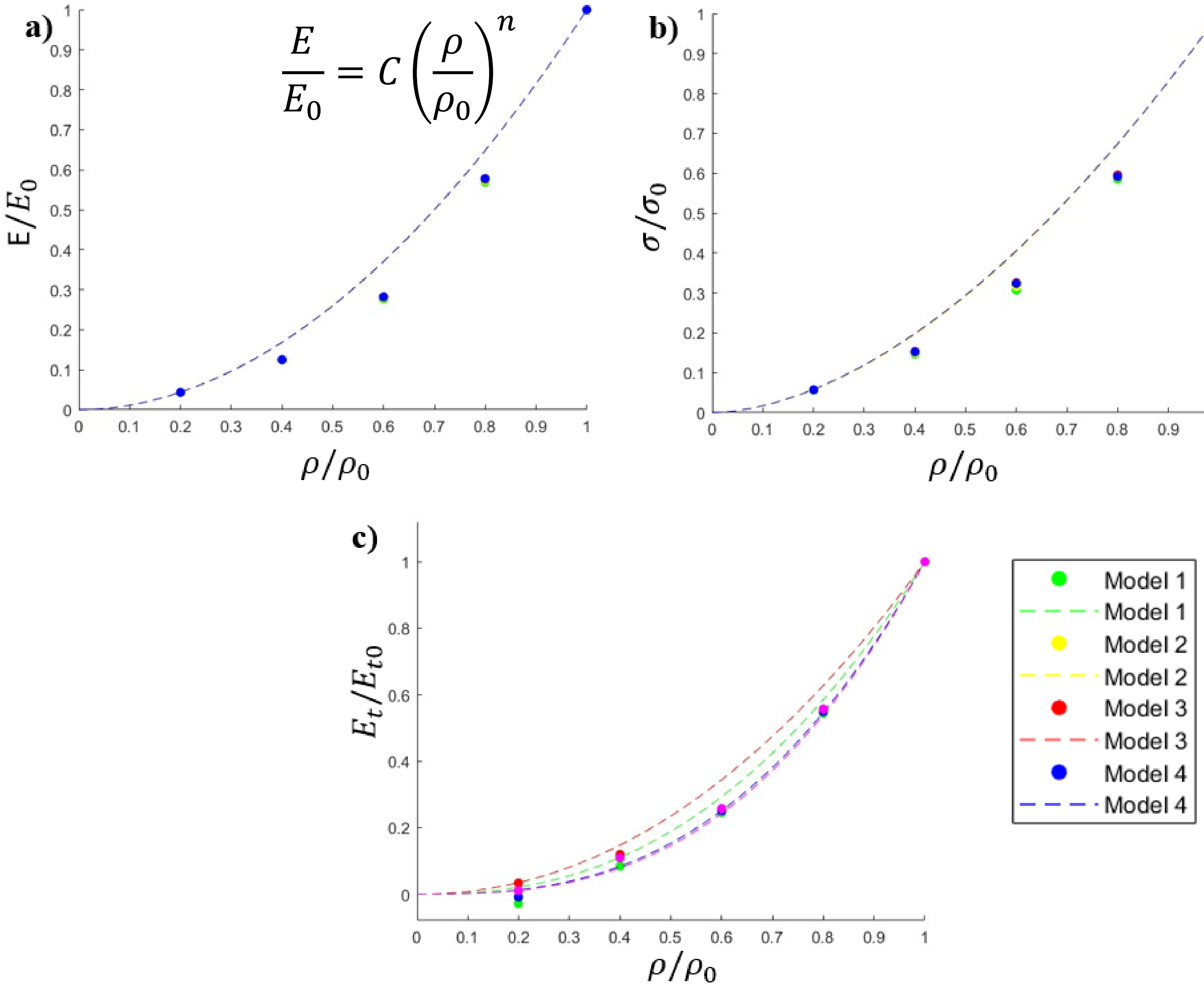
Boundary effects in FE simulation:

✓ E and σ_y overlap each other,

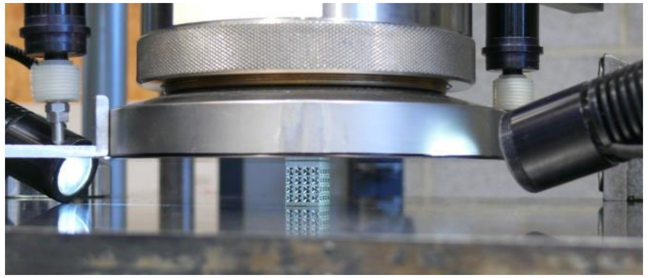
whatever model is us

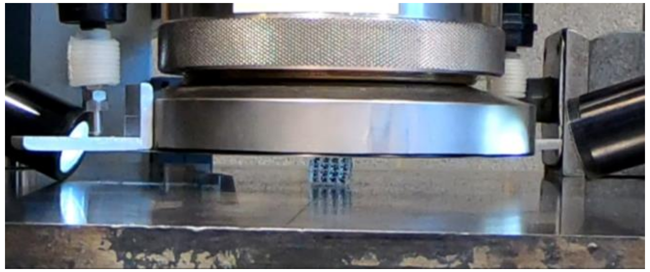
✓ Hardening E_t is strongly affected

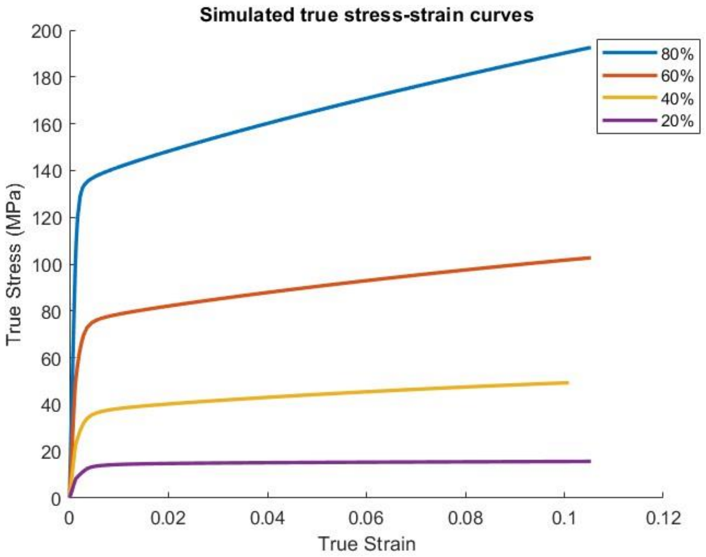
by the model used

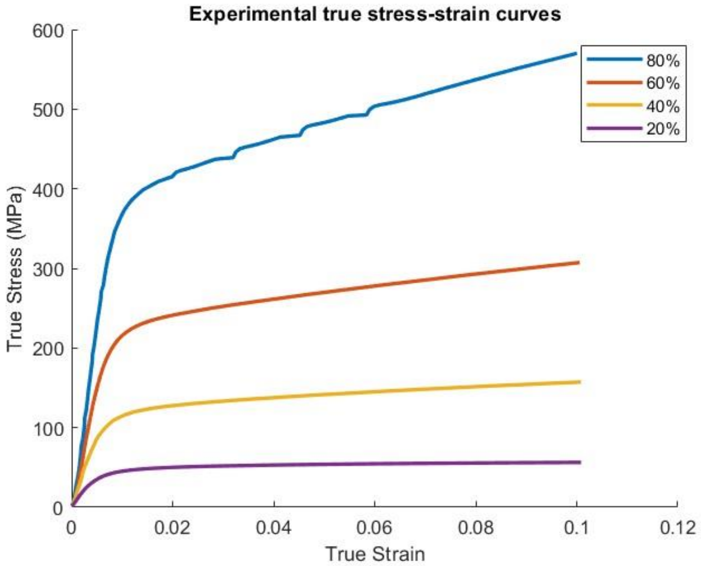


Experimental results



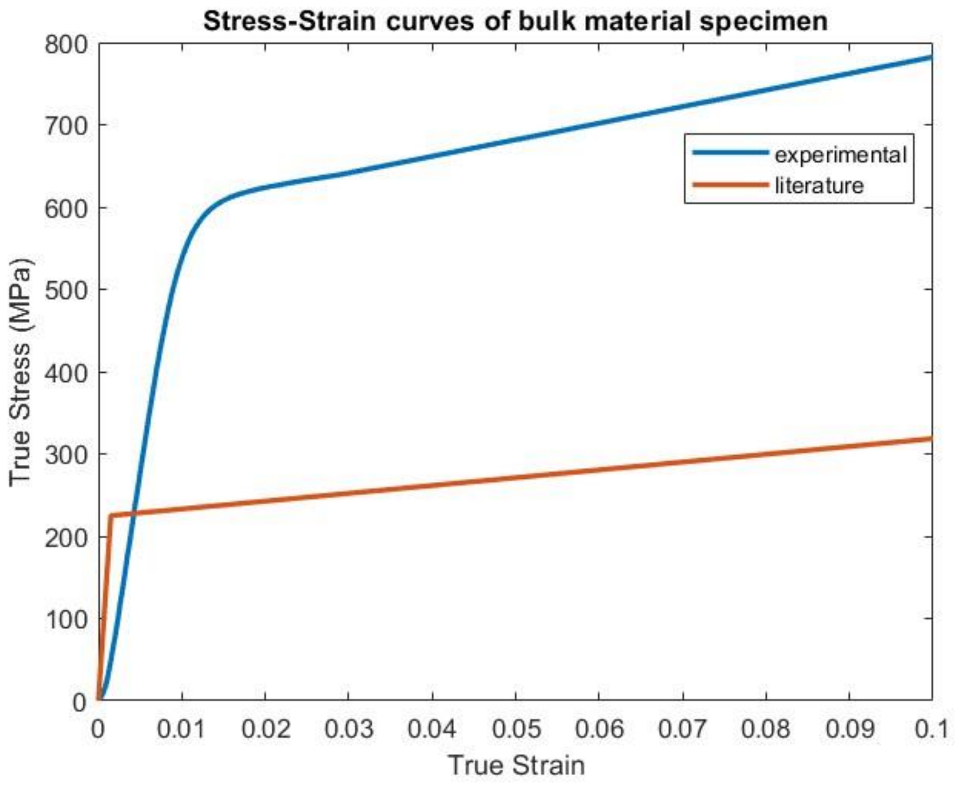






- ✓ Same shape and tendency
- ✓ Different values due to different parent material properties

Experimental results



	Experimental compression test	Literature
Young Modulus	65.1 GPa	150 GPa
Yield Stress	549.7 MPa	225 MPa
Tangent Modulus	2.01 GPa	0.95 GPa

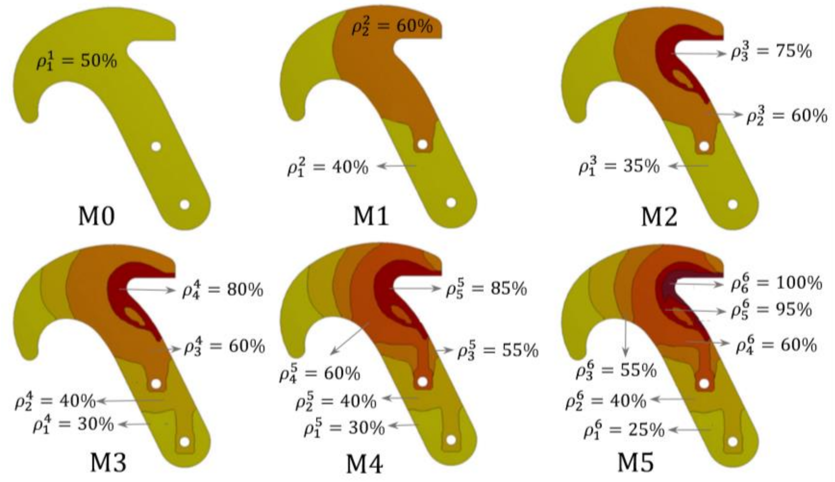
Reference: Wang Z, Zhou Y, Wang X, Wei K (2021) International Journal of Mechanical Sciences Compression behavior of strut-reinforced hierarchical lattice — Experiment and simulation. Int J Mech Sci 210:106749

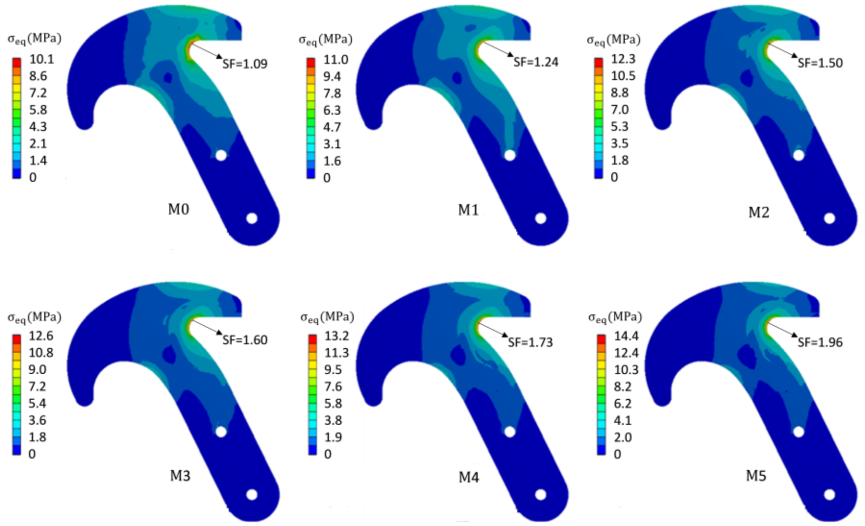
→ Lattice structures fabricated by SLM technique. 316L stainless steel used as matrix material

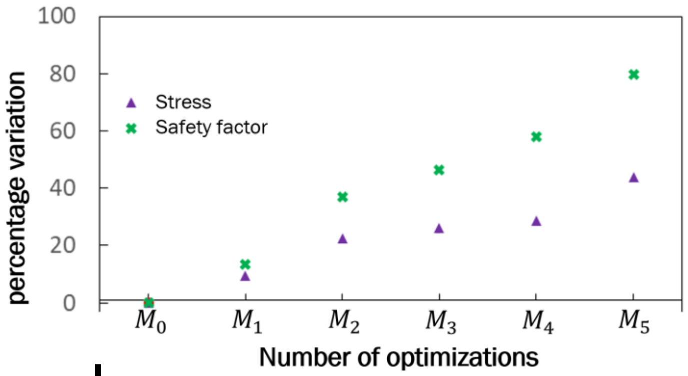
→They did not test a solid specimen, only lattice struture and the results have good agreement with simulations.

Long term goal

- applying a topological optimization methodology to improve the mechanical response of mechanical components.



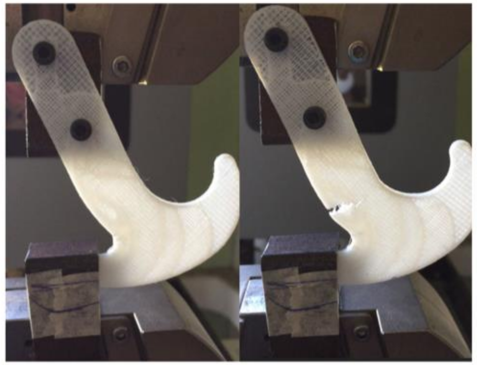


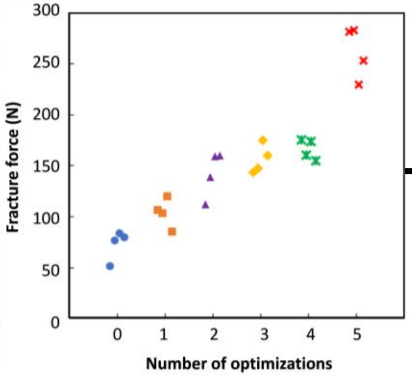


simulación de validación: incremento en el factor de seguridad

Regions with different relative density

Rilling S, Ríos I, Gómez Á, et al (2023) Int J Adv Manuf Technol.





Already proved in polymers, experiencing a considerable increase in fracture force

Conclusions and perspective

- Numerical simulations BCC lattice with $\neq$ densities, boundary conditions → elastoplastic effect response.
- Buckling is important for lower density changing global hardening .
- The Gibson-Ashby model for E and σ_y : OK single exponent n

  for hardening :

  variable n, clear effect of simulation boundary assumptions

- Ongoing : tensile experiments and simulations, effect of building strategy
- Use of constitutive laws for part optimization by changing locally the density
- Impact and energy absorption applications

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ESAFORM TOULOUSE

Thanks for your attention.

Questions ?

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