Design of Optimized Conformal Lattice Structures

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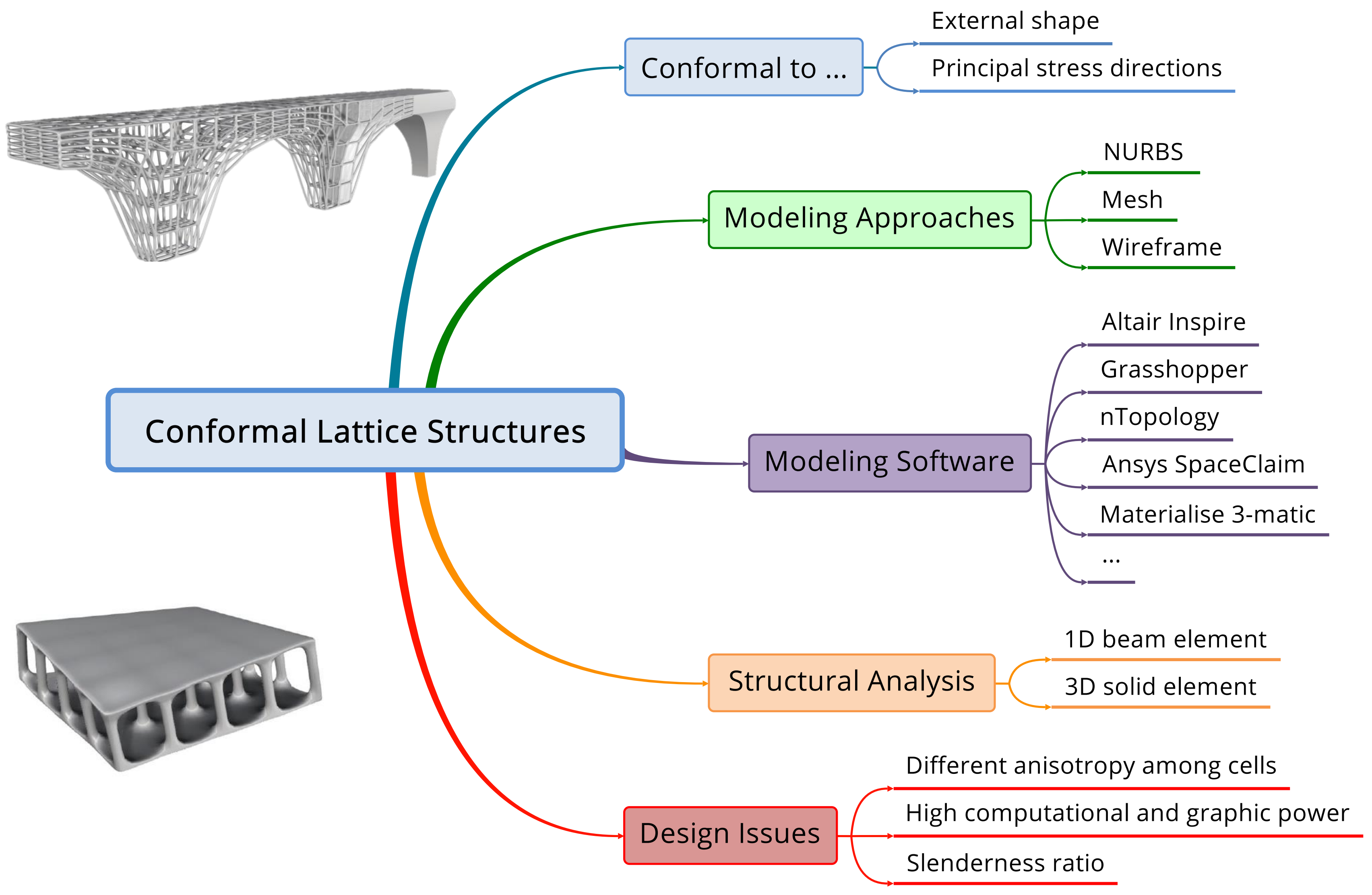
Nowadays the commercial software proposes different solutions for designing lattice structures, but still, there are no flexible tools for geometric modeling and validating conformal lattices. A conformal lattice structure can conform to the external shape of the part or to the principal stress direction taking the information from a Finite Element Analysis (FEA). This allows increasing the performance of the structures with respect to the regular ones. The available geometric modeling approaches for lattice structures are based on Non-Uniform Rational Bicubic-Splines (NURBS) or mesh. They require Boolean, offsetting, and filleting operations demanding high computational resources and time, and, even worse, they often fail; furthermore, lattice structures with a high number of elements are difficult to manage and visualize. Also, the prediction of mechanical properties is an open challenge due to the different anisotropic behavior of different cells inside the structure; this different behavior leads to the impossibility of applying the asymptotic homogenization (AH) method, widely used in composite materials and uniform lattice structures to avoid discretizing the lattices into solid models with a huge number of elements.

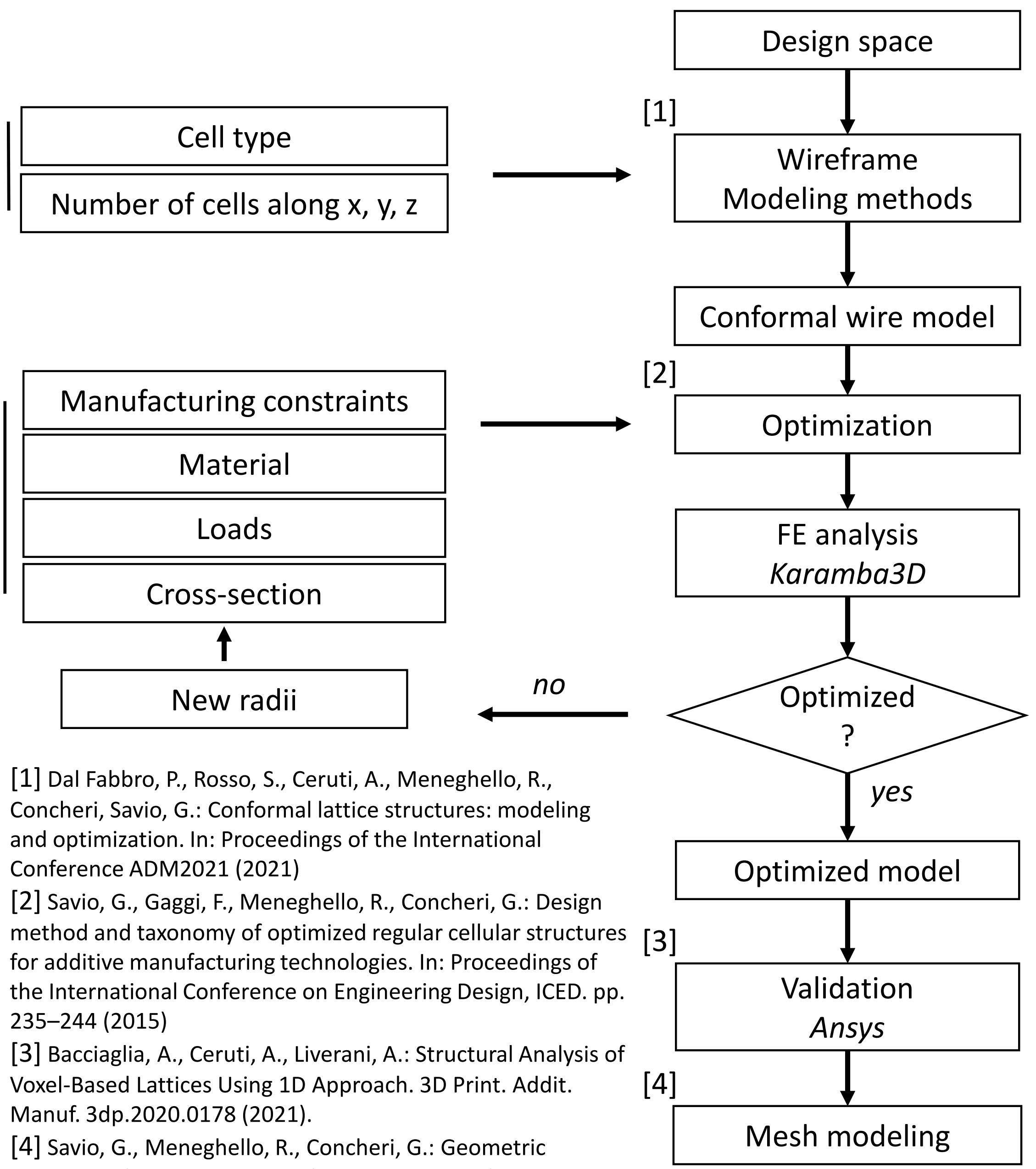
To overcome these limits, the work aims at proposing a workflow for the design and size optimization of beam-based conformal lattice structures, involving mono-dimensional elements in the structural analyses. First, four approaches for modeling the wireframe of a simple cubic conformal lattice structure are presented, then an iterative variable size optimization method is performed, and finally, two linear structural analyses based on mono-dimensional elements are performed and compared. These methods are automated in IronPhyton programming language scripts inside Grasshopper (Rhinoceros 7 software) and ANSYS 2020 R1 software through Mechanical APDL scripts. Applying the beam theory in the numerical analyses reduces the computational time and costs and allows for the computation of the behavior of the conformal structures almost in real time. Finally, a mesh modeling method is adopted together with the Catmull-Clark subdivision surface algorithm to obtain a lattice structure model with smooth surfaces, especially at the nodal zones where no further filleting operations are required. The results show that the analysis methods give reliable results and that, among the wireframe creation methods, the one based on the NURBS Free-Form deformation shows the most flexible solution being able to easily conform to boundaries of various shapes.



Conformal Lattice Structures

- Conformal to ...
  - External shape
  - Principal stress directions
- Modeling Approaches
  - NURBS
  - Mesh
  - Wireframe
- Modeling Software
  - Altair Inspire
  - Grasshopper
  - nTopology
  - Ansys SpaceClaim
  - Materialise 3-matic
  - ...
- Structural Analysis
  - 1D beam element
  - 3D solid element
- Design Issues
  - Different anisotropy among cells
  - High computational and graphic power
  - Slenderness ratio

Workflow



Design space

[1]

Wireframe Modeling methods

Cell type

Number of cells along x, y, z

Conformal wire model

[2]

Optimization

Manufacturing constraints

Material

Loads

Cross-section

FE analysis *Karamba3D*

Optimized ?

no

New radii

yes

Optimized model

[3]

Validation *Ansys*

[4]

Mesh modeling

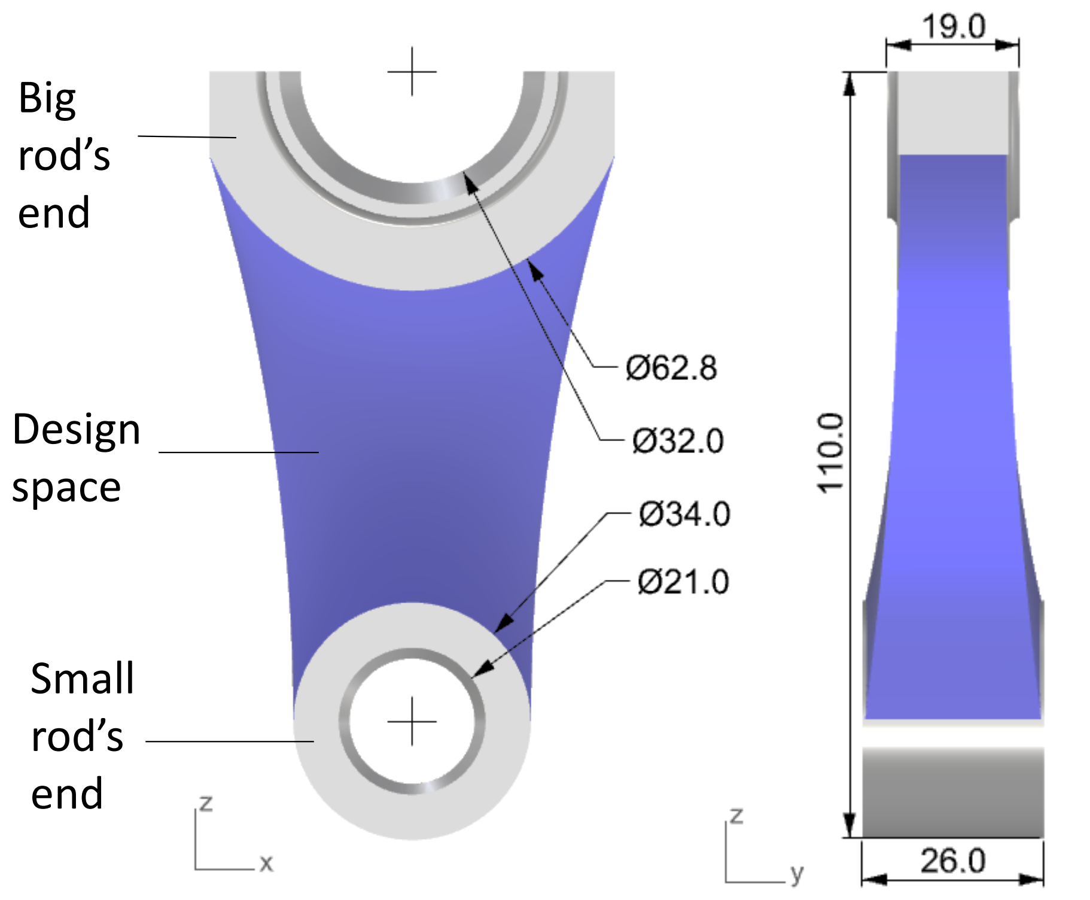
[1] Dal Fabbro, P., Rosso, S., Ceruti, A., Meneghello, R., Concheri, Savio, G.: Conformal lattice structures: modeling and optimization. In: Proceedings of the International Conference ADM2021 (2021)

[2] Savio, G., Gaggi, F., Meneghello, R., Concheri, G.: Design method and taxonomy of optimized regular cellular structures for additive manufacturing technologies. In: Proceedings of the International Conference on Engineering Design, ICED. pp. 235–244 (2015)

[3] Bacciaglia, A., Ceruti, A., Liverani, A.: Structural Analysis of Voxel-Based Lattices Using 1D Approach. 3D Print. Addit. Manuf. 3dp.2020.0178 (2021).

[4] Savio, G., Meneghello, R., Concheri, G.: Geometric modeling of lattice structures for additive manufacturing. Rapid Prototyp. J. 24, 351–360 (2018)

Case study



Optimization input

Nodal boundary conditions

Small rod's end:

- ✓ Locking all the rotations and displacements.

Big rod's end:

- ✓ Locking the displacements along x- y- directions;
- ✓ Load Z direction: -10 [kN].

Properties of AlSi10Mg (by Renishaw)

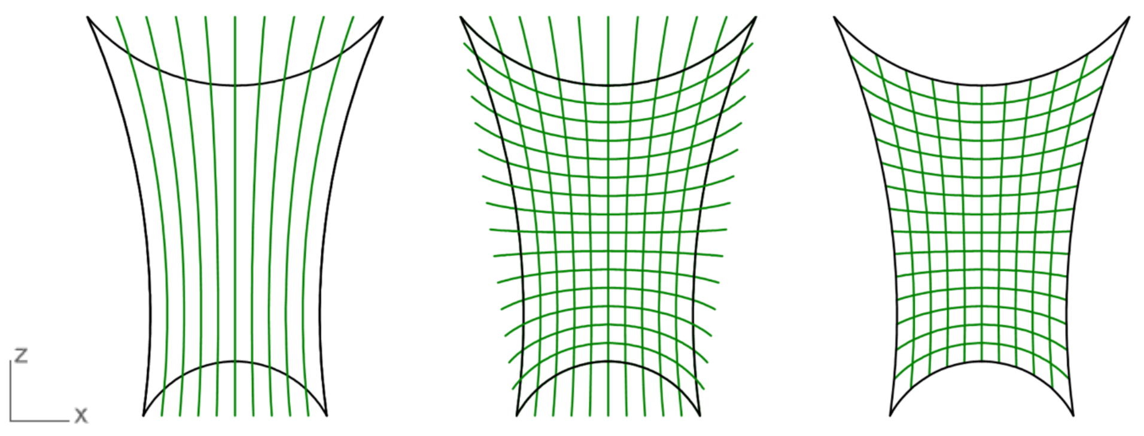
Density [kg/m³]	Young modulus [GPa]	Tensile strength [MPa]	Yield Strength [MPa]	Poisson ratio
2700	68	336.5	192	0.3

Manufacturing technology

- ✓ Selective laser melting manufacturing;
- ✓ Minimum diameter: 0.5 mm;
- ✓ Maxiumum diameter: 1.5 mm.

Wireframe modeling methods

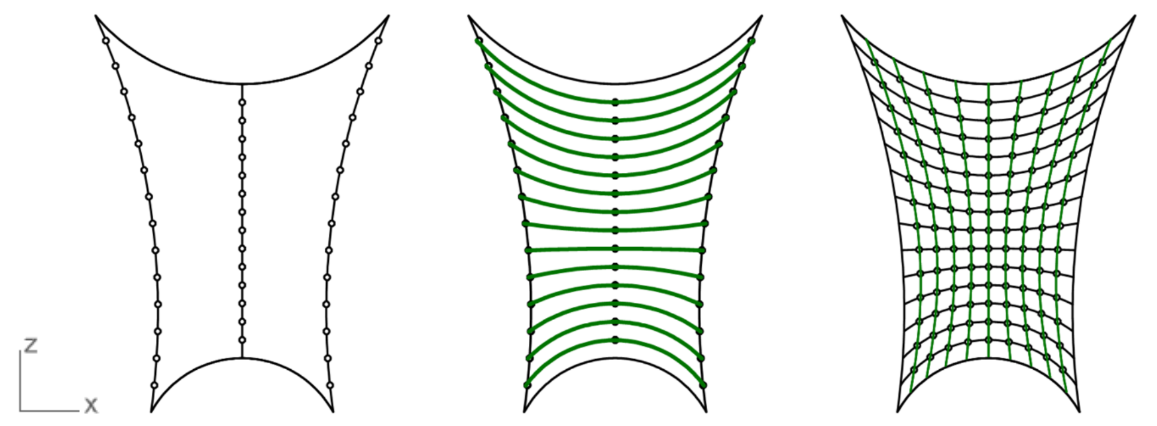
▨ Tween curve division method (TCD)



Starting from 2 opposite edges of the design domain:

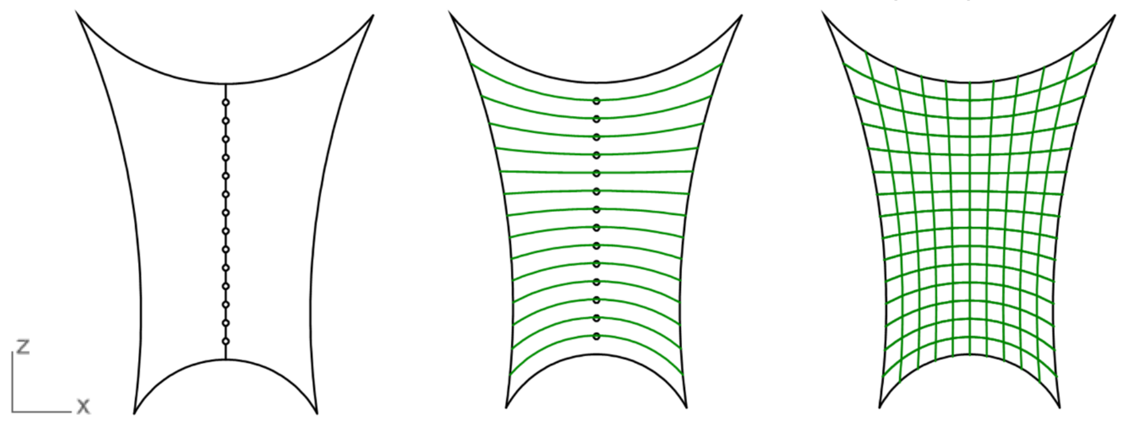
- ✓ A set of intermediate curves according to the number of the cells along x- and z- directions is created;
- ✓ A net of mutually intersecting curves is obtained;
- ✓ By splitting the curves, a list of points is obtained, which is used to construct the wireframe model.

🟩 Arc division method (AD)



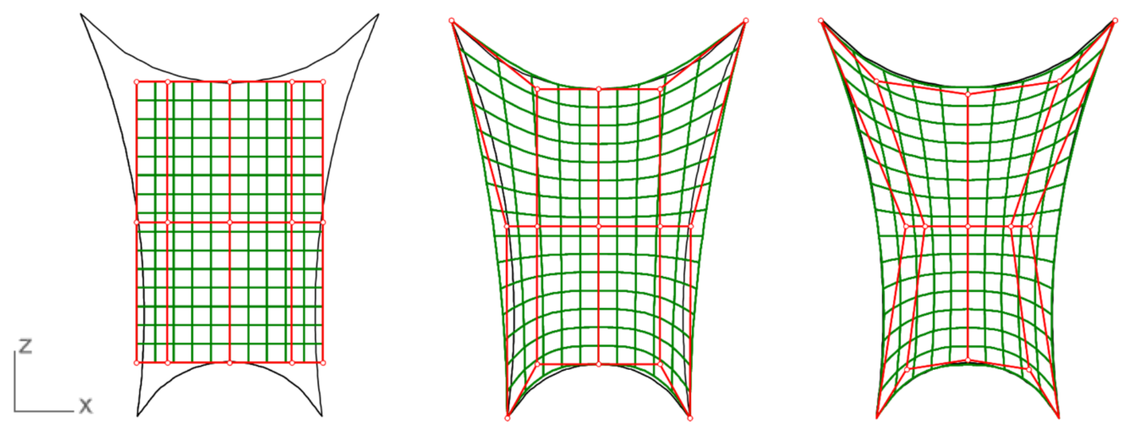
- ✓ The vertical centerline and the side curves are subdivided by the desired instances along z-direction;
- ✓ Arcs are drawn through the 3 points at each subdivision level;
- ✓ Those arcs are subdivided along the x-direction, obtaining the points for the wireframe definition.

🟥 Curvature division method (CD)



- ✓ A list of *n* curvatures (according to the instances along the z-direction) is created by linearly interpolating the curvature of the upper and lower arc;
- ✓ The vertical centerline is created and divided into *n* points;
- ✓ An arc through each point, centered along the vertical centerline, is drawn;
- ✓ The same procedure is repeated considering the arcs of the left and right profiles;
- ✓ The intersections of the arcs are used for the wireframe modeling.

🟦 Nurbs Free-Form Deformation Method (NFFD)

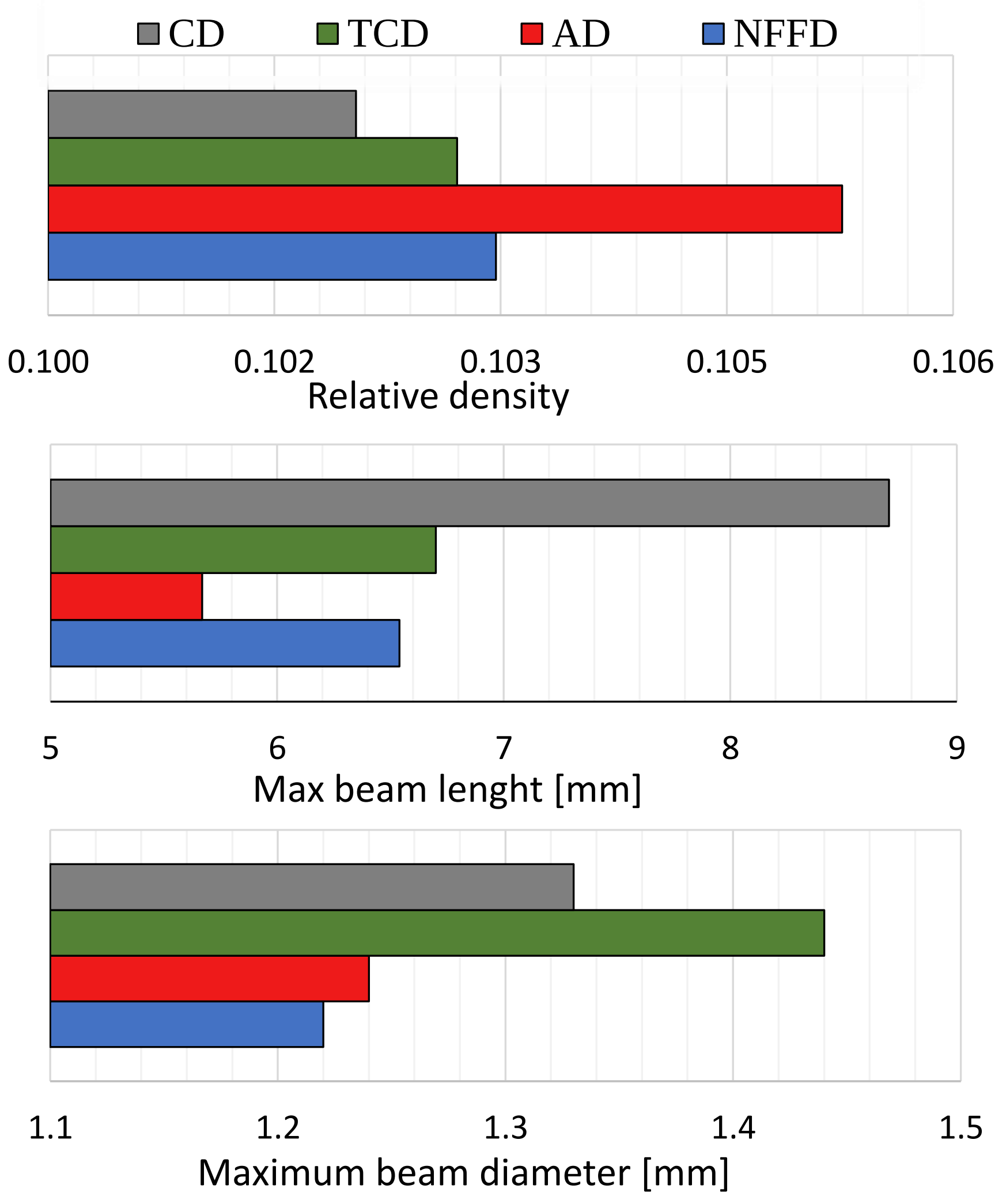


- ✓ A regular wireframe based on the repetition of a simple cubic cell along the x-, y- and z-axis is generated;
- ✓ A 3D NURBS cage is built around the wireframe;
- ✓ The cage is adapted to the design space by moving the cage's control points;
- ✓ The control points allows for warping transformations when cell densification is needed.

Optimized model

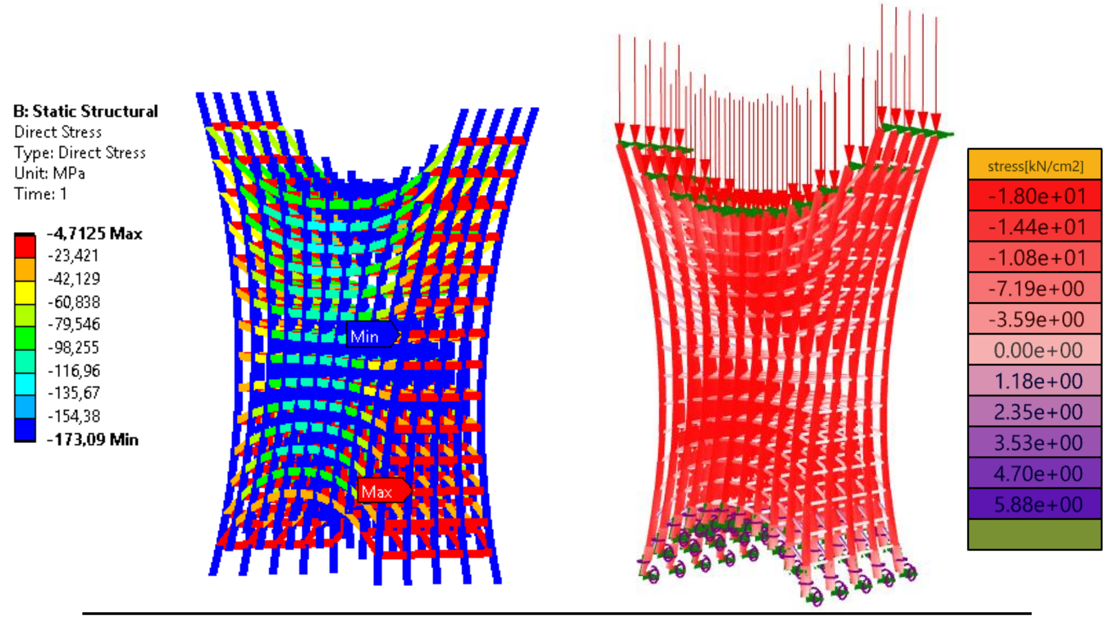
Size optimization results:

- ✓ Similar relative density for the 4 methods;
- ✓ Different sizes in maximum diameters;
- ✓ Different sizes in maximum beam-length.



Validation

Validation of NFFD conformal wireframe



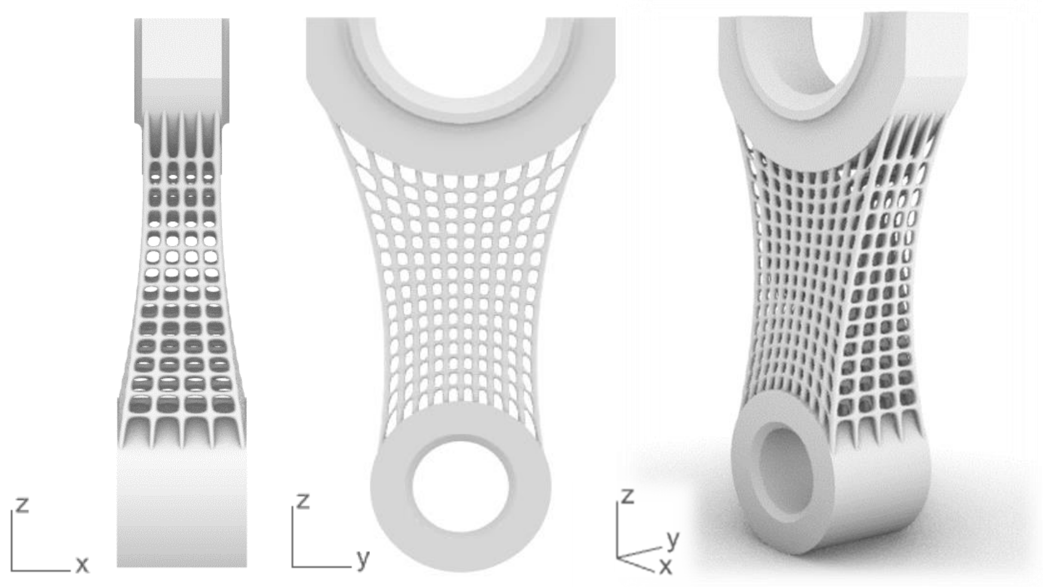
	Ansys 2020 R1	Karamba 3D
Displacement [mm]	0.175	0.174
Max Direct Stress [MPa]	-173.09	-172.80

- ✓ The two software provide similar results.

Mesh modeling

Modeling procedure:

- ✓ Costruction of the mesh model from the conformal wireframe and the optimized diameters of the beams;
- ✓ Application of the subdivision surface alghortim;
- ✓ Connection with the rod's ends.



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