STRUCTURAL OPTIMIZATION OF A SPECIMEN FOR TENSILE AXIAL LOADING FOR A LATTICE MATERIAL

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INTRODUCTION

Lattice structures are 2.5D or 3D porous structures, with a periodic geometry generated by the repetition in space of one or more unit cells. Unit cells are defined by the dimensions and connectivity of their strut elements, connected at specific nodes and with dimensions in the order of millimetres [8,13].

Lattice materials can adapt the mechanical and thermal properties to the needs of a specific application by acting on the bulk material and on the microarchitecture of the cell (porosity, cell geometry). This capability makes lattice materials interesting for different fields such as: biomedical, automotive, and aerospace. The biomedical field is an important application, where the lattice has to meet some additional requirements such as biocompatibility, bone ingrowth and attractive surface morphology [4].

There are still no international standards for tensile and fatigue mechanical tests.

ISO standard 13314:2011 is available for static compression tests on metal foams with porosity greater than 50% [9]. This standard is also generally adopted for compression-compression fatigue tests. For tensile test, the main issue is the design of mechanical interfaces able to clamp the specimen [1].

At the University of Trento a new type of specimen for tensile and fatigue tests was designed [2]. The specimen has a circular cross-section and 8 cells along the diameter. The solution adopted for the clamping problem is a flanged bolted joint, for the following reasons:

- The need of small axial overall dimensions for the specimen.
- Manufacturing reasons: possibility of rectifying the flanges after 3D printing, obtaining coaxial ends for the specimen and therefore mitigating spurious bending strains in the lattice.
- The need to host specimens with relatively large unit cells.

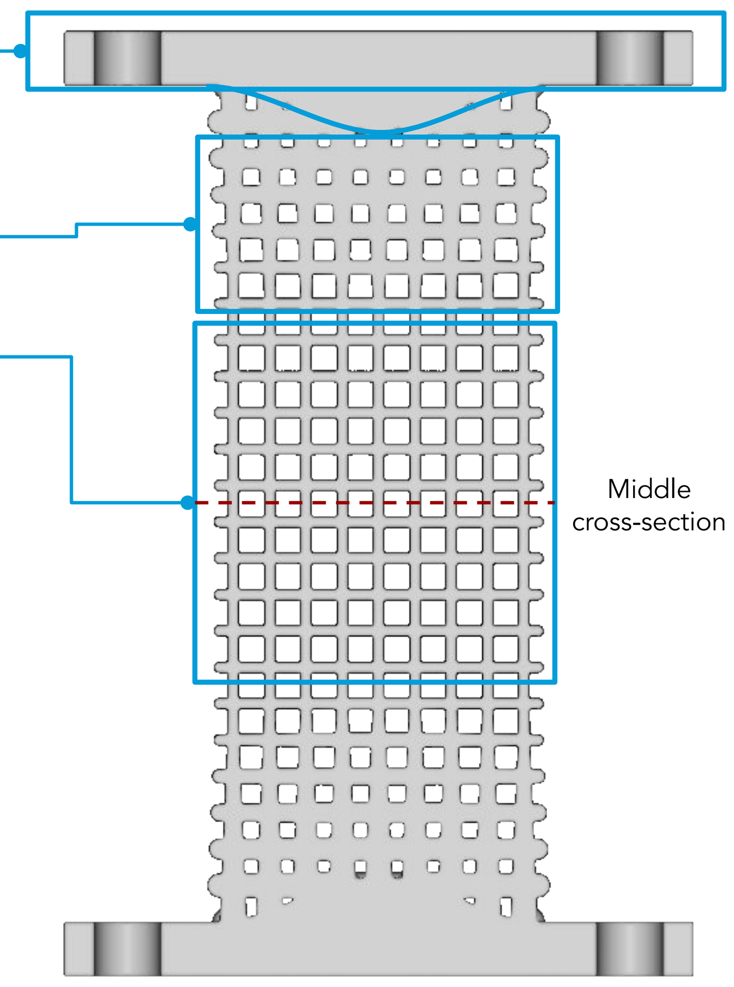
The specimen, fabricated through 3D printing, consists in 3 parts:

1. A circular flange with a bell-shaped thickening in the central part.
2. A transition zone with a linear gradient of relative density in the axial direction, up to a maximum of 75 %.
3. A uniform cellular zone, with a uniform lattice filled by cells of the same shape.

The transition zone was introduced to avoid failure at the interface with the flange. Furthermore, the flange hosts the holes for 8 bolts.

Different types of lattices were tested. A search field with three parameters of interest has been defined:

- Cell topology: simple cubic.
- Cell porosity: [50, 60, 70 ,80, 90, 95] %
- Cell side: [1, 2, 3, 4] mm



The aim of the research project is to optimize the specimen's geometry in order to get:

1. Uniform internal loads within a specimen cross-section
2. Uniform internal loads among different cross-sections of the gauge length.

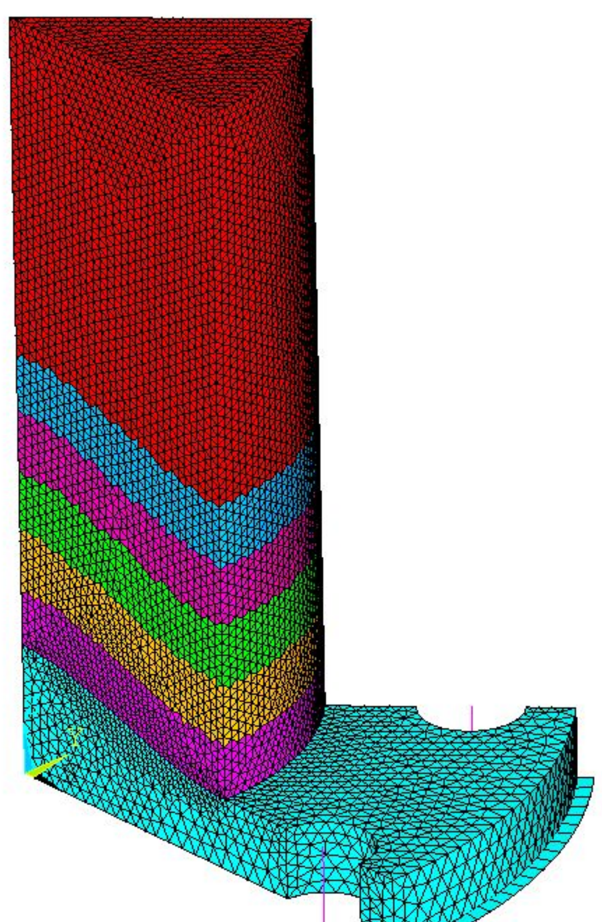
The first requirement was achieved solving an optimization problem having as variables two geometrical parameters: the flange thickness and the "bell" height. The objective function 'Δσ' is computed as the maximum percentage difference between normalized internal loads on the middle cross-section.

SIMULATION STRATEGIES

A finite element model of the specimen was created in '*ANSYS Mechanical APDL*' in order to simulate the tensile mechanical response. The homogenization technique was adopted to keep the model computationally efficient. The homogenized model was created including five layers for the transition zone, each corresponding to a cell with an average strut diameter, plus the central layer of the uniform lattice part. The layers follow the spline geometry of the "bell".

Mirror symmetry constraints and radial symmetry constraints were applied in order to simplify the model. A displacement was applied to the nodes of the middle cross-section completing implicitly the symmetry constraint.

The homogenization technique determines the effective properties of the lattice material as function of the bulk material and the morphology of the unit cell.



The effective elastic properties of the lattice material were associated to an equivalent homogeneous solid that replaces the lattice domain. These orthotropic properties were obtained from the structural analysis of a single representative volume element: the unit cell.

A homogenization tool from the *nTopology Platform* software was used to obtain the stiffness matrix of the generalized Hooke's law for the cubic cell. The elastic constants, associated to the homogeneous volume in *Ansys*, were computed from the stiffness matrix.

The homogenization method has some limitations due to the hypotheses that it is based on: (i) the 'existence of a length-scale separation between the microstructure and the domain of interest' and (ii) 'the spatial periodicity in the lattice' [1,11,12].

The 'Gibson-Ashby formula' was used to conduct a preliminary evaluation of the elastic constants. This is a power law function linking the relative density of the lattice to the relative elastic modulus of the same [6,7].

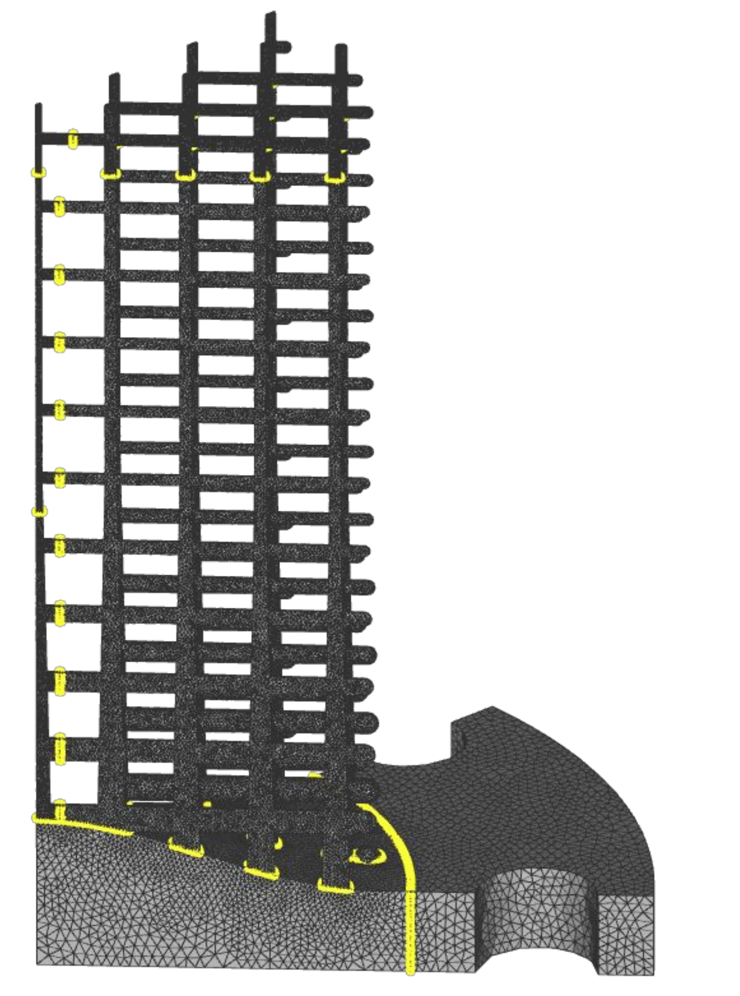
The simple cubic cell is classified as a bending-dominated cell according to Maxwell's M index, so n will be equal to 2 [10]. C1 is a constant obtained from the fit of experimental curves.

The fully detailed model was meshed via *nTopology* and imported into *ANSYS Mechanical APDL*. The creation of the mesh in *nTopology* is not trivial and it requires the splitting specimen into different parts. These are meshed separately and then connected.

The behavior of the structure was simulated in a fully elastic regime by applying a displacement on the middle cross section of the model. It considers also the bolt connection with an initial preload and the rigid-flexible contact with a counter flange.

$$\{\sigma\} = [C]\{\varepsilon\}$$

$$\frac{E}{E_0} = C_1\left(\frac{\rho}{\rho_0}\right)^n$$



OPTIMIZATION STRATEGIES

An optimization problem was set in order to define the values of the "bell" height and the flange thickness able to generate the most uniform stress distribution in the sample. These two parameters were collected inside a vector α which is the design variable vector.

The cost function 'g_0' is the metric that has to be **minimized** in the optimization process. This is a measure of the stress uniformity in the sample. The function is described by the parameter $\Delta\sigma$, computed as the maximum percentage difference between normalized stresses within the middle cross-section of the specimen. A **5%** threshold was set as the stopping condition for Δσ.

$$\begin{cases} \min_{\alpha} g_0(\alpha) = \Delta\sigma = \dfrac{(\sigma_{max} - \sigma_{min})}{\sigma_{mean}} * 100 \\ \text{s.t.}\ \alpha \in S \end{cases}$$

$$\alpha = \{h_{bell},\ h_{flange}\}$$

$$S = \{h_{bell} \in [0;\ 2.5L]\} \cup \{h_{flange} \in [0;\ 3.5L]\}$$

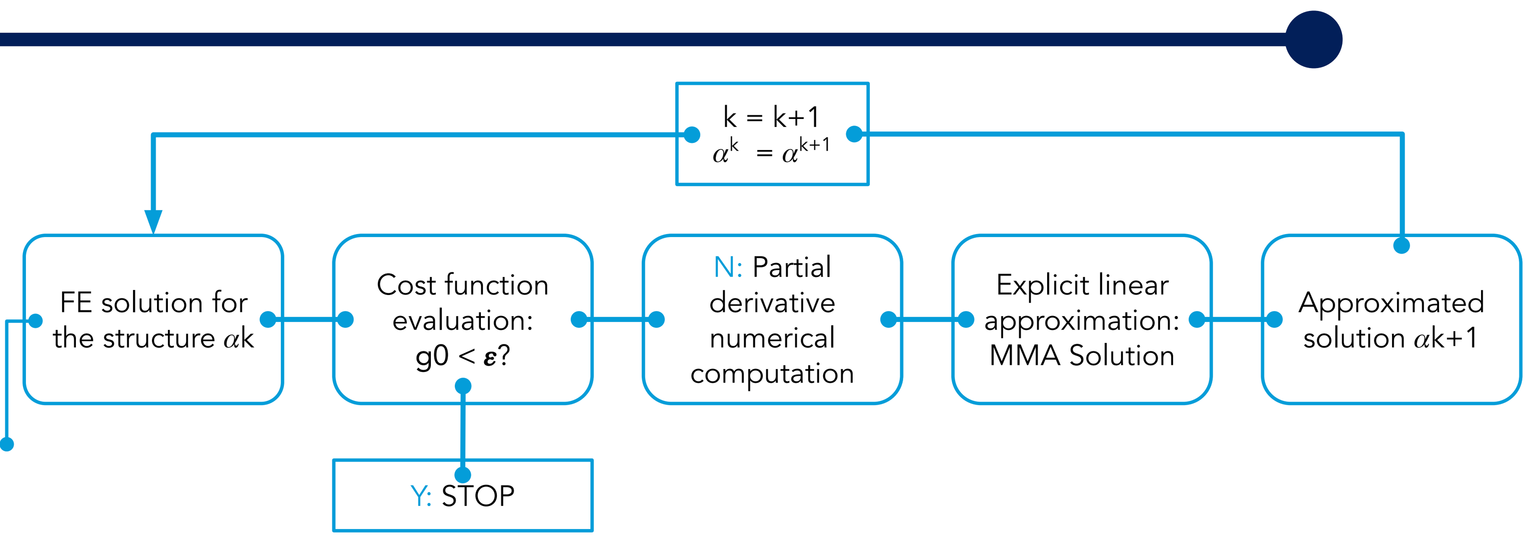
$$\text{IC: } h_{bell} = 1.25\text{L} \quad h_{flange} = 1.5\text{L}$$

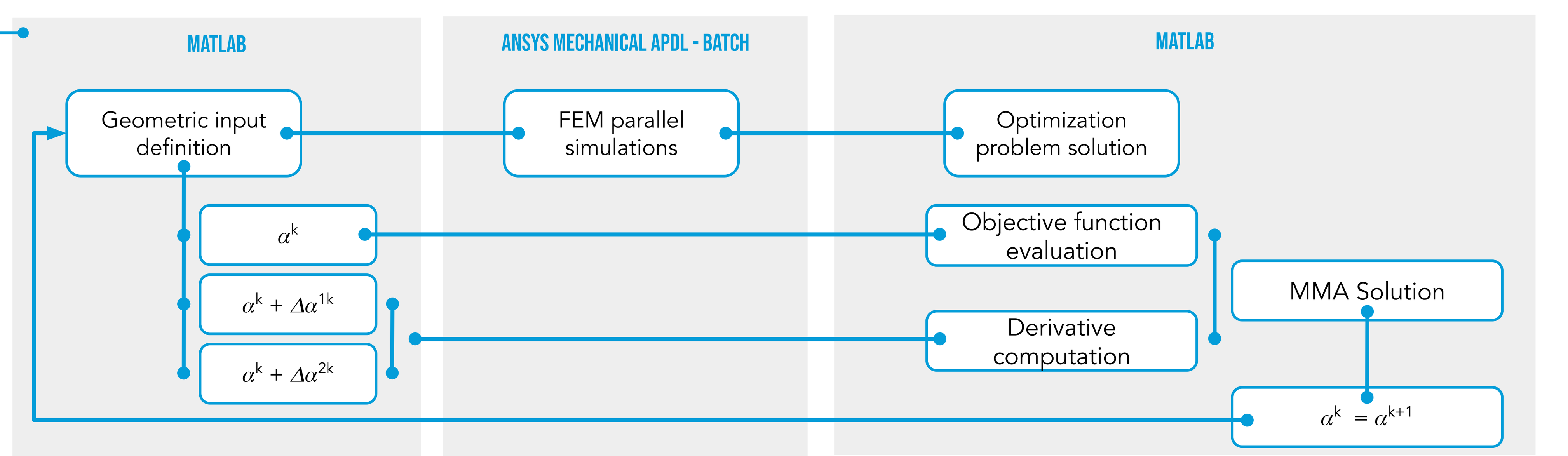
The set 'S' represents the only boundary condition applied to the optimization problem. It sets a range in which the optimum point of the design variables could be found. These boundaries are defined after manufacturing considerations and they are linked to the parameter L, the cell size.

Once the formulation of the optimization problem is completed, a **sensitivity analysis** is necessary. A numerical approach was proposed: the partial derivative of the cost function is approximated as a finite difference. The increment h was applied to the proper variable by the vector e_j.

$$\frac{\partial g_0(\alpha)}{\partial \alpha_j} = \frac{g_0(\alpha + he_j) - g_0(\alpha)}{h}$$

The proposed optimization problem could be solved iteratively by the **Method of the Moving Asymptotes** (MMA). This technique has the advantage of generating convex linear subproblems around a FE solution. Using the information given by the sensitivity analysis, the next iteration was computed till the stopping condition is satisfied. A formal scheme of the approach is proposed side by side with a flowchart describing the implementation.





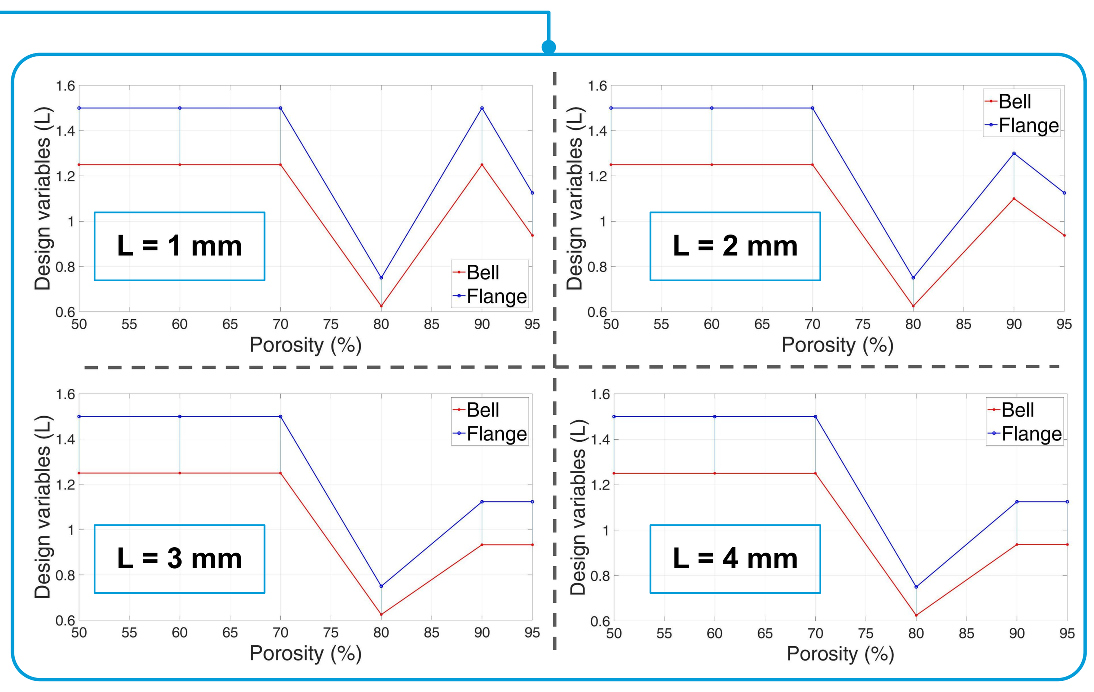
RESULTS

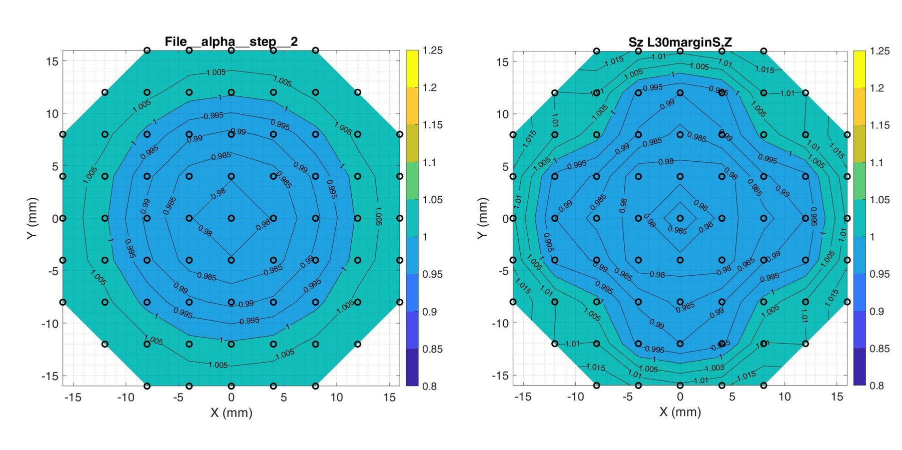
The optimization process was performed on the simple cubic cell for different porosity and different cell sizes (L). The obtained results are presented in charts where the optima "bell" height and the flange thickness, normalized with respect to L, are plotted against the lattice porosity.

There is a good agreement among the optimal values for different cell sizes. it could be stated that the porosity is the main parameter determining the design values for the simple cubic cell.

The optimization results, obtained via the homogenization process, are validated comparing the optimum configuration with the results obtained by an equivalent fully detailed FE model. Numerous comparisons have been produced for different configurations but for the sake of brevity only the following is presented:

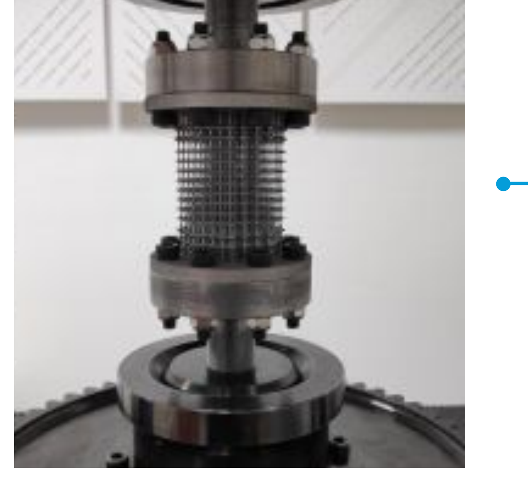
- L = 4 mm
- Porosity = 80 %





It is evident in these validations the similarity in the two stress distributions and in the Δσ values: 3.2 % for the homogeneous model and 3.4 % for the cellular model.

The initial aim of the authors can be considered reached for this unit cell, since an optimal definition of the design variables is found and verified via FE cellular simulations. An experimental campaign will be carried out in the near future in order to verify experimentally the obtained results. In addition, more cell topologies will be included in the parametric definition of the sample geometry.



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