ADDITIVE 4 BIOMEDICAL

UNIVERSITÀ DEGLI STUDI FIRENZE
DIEF DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

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COST EFFECTIVE TITANIUM SPINAL PROSTHETIC FATIGUE LIFE OPTIMIZATION

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CoCo AM SC 09/A3 Additive Manufacturing · ADM Associazione Nazionale Disegno e Metodi · CoMET · aias

Lattice structures and fatigue life

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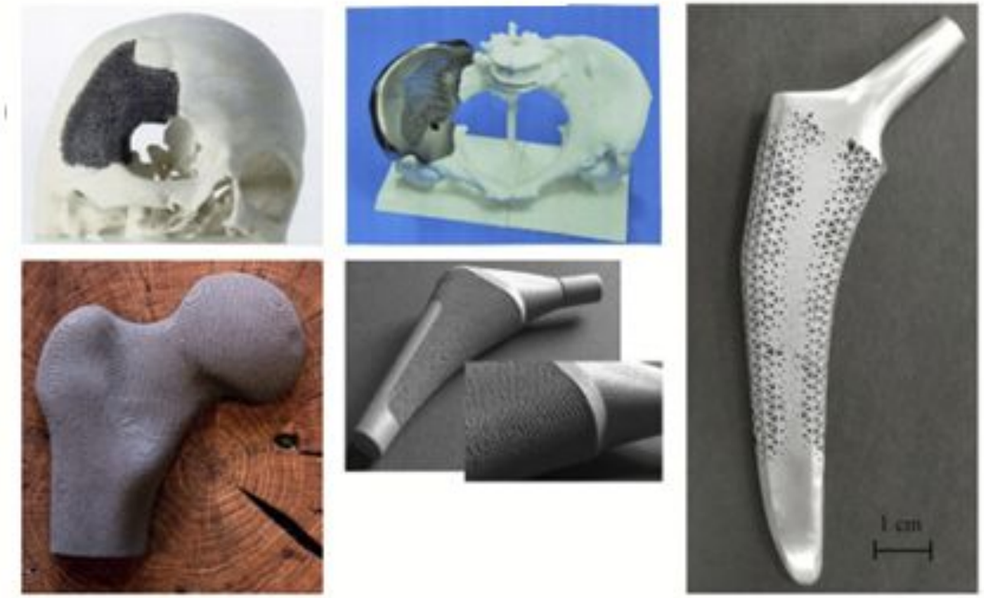
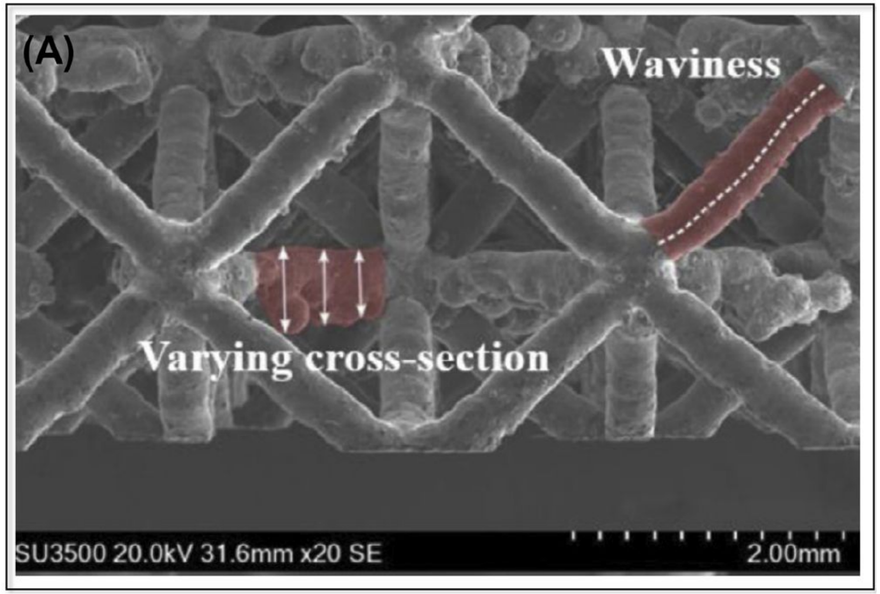
Lattice structures are based on the repetition of a unit cell. The strut-based cells are composed by struts and nodes.

These structures are implied in the production of prosthetic devices for their tunable properties.





The industrial application of these structures in critical components is yet to be implemented due to a proper understanding of the fatigue properties.

This is a localized phenomenon in which the Additive Manufacturing process plays a major role.

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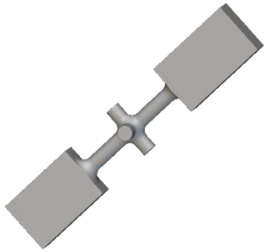
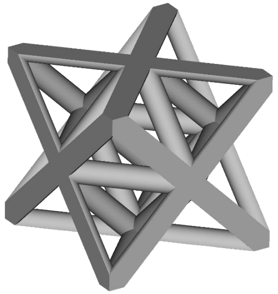
Prosthetic device optimization workflow

The proposed workflow aims to design and optimize the fatigue properties of a prosthetic device.

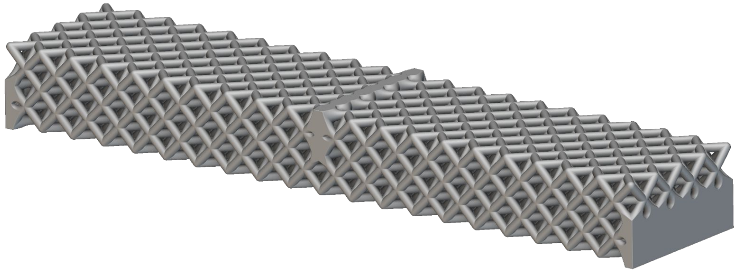
Cost effective fatigue tests are performed on micro-specimens. The results are used as inputs for an optimization algorithm which is verified experimentally. An easy to simulate Octet Truss (OT) cell topology is selected.



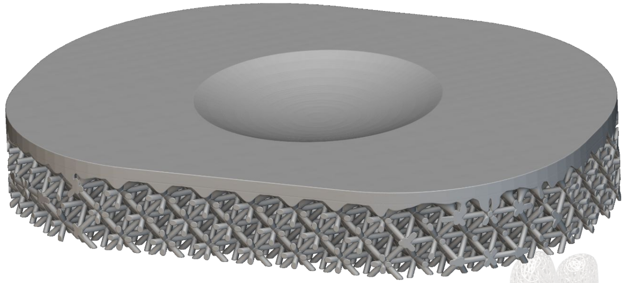
Fatigue life estimation



Stretching dominated cell



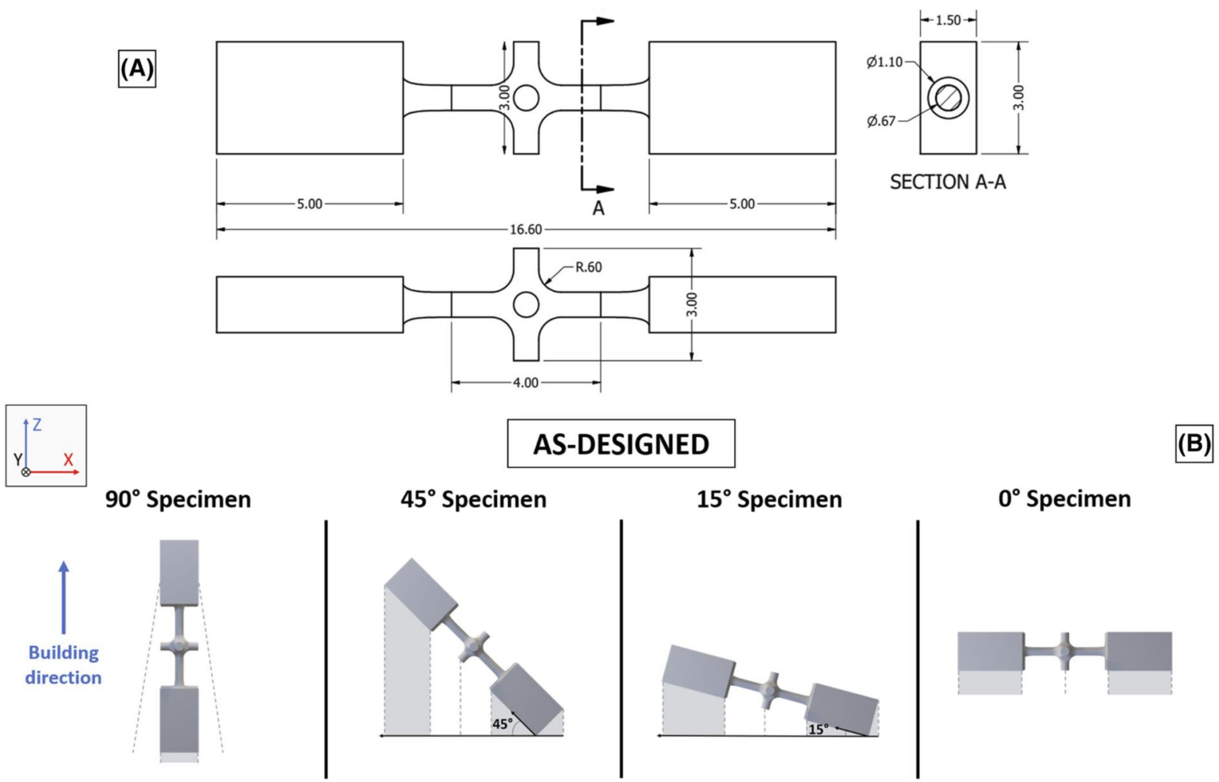
Optimization verification

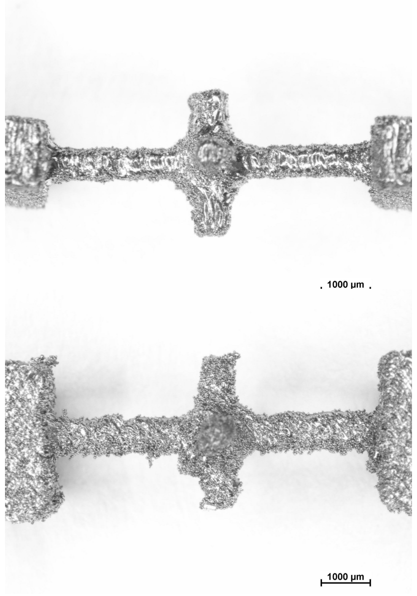


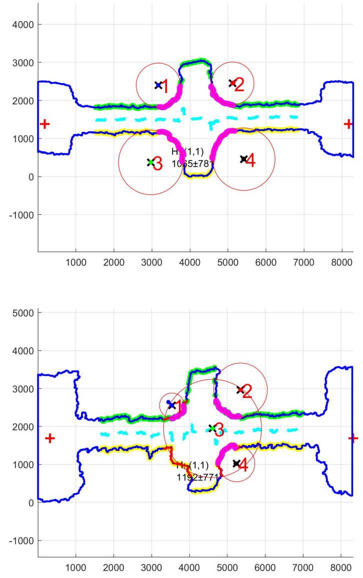
Design and optimization on a realistic prosthetic device

Micro specimens design

The lattice fatigue life is estimated using time and cost effective micro-specimens eboding the lattice constitutive elements, namely struts and nodes.







A preliminar metrological analysis is performed in order to measure the effective values of the geometrical details.

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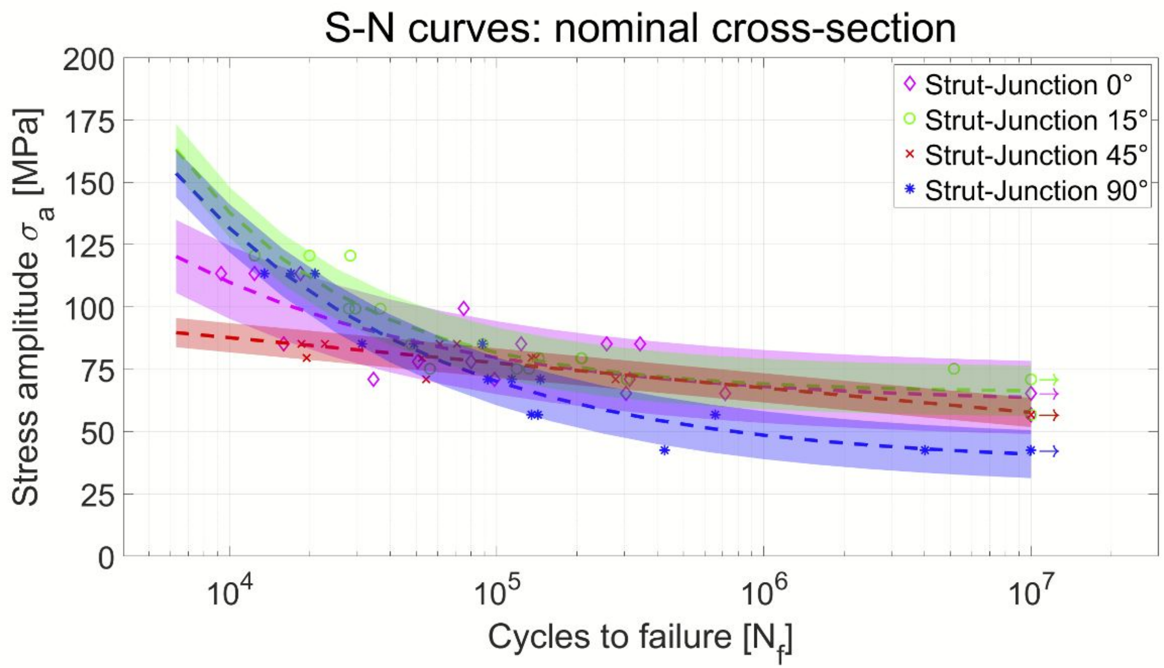
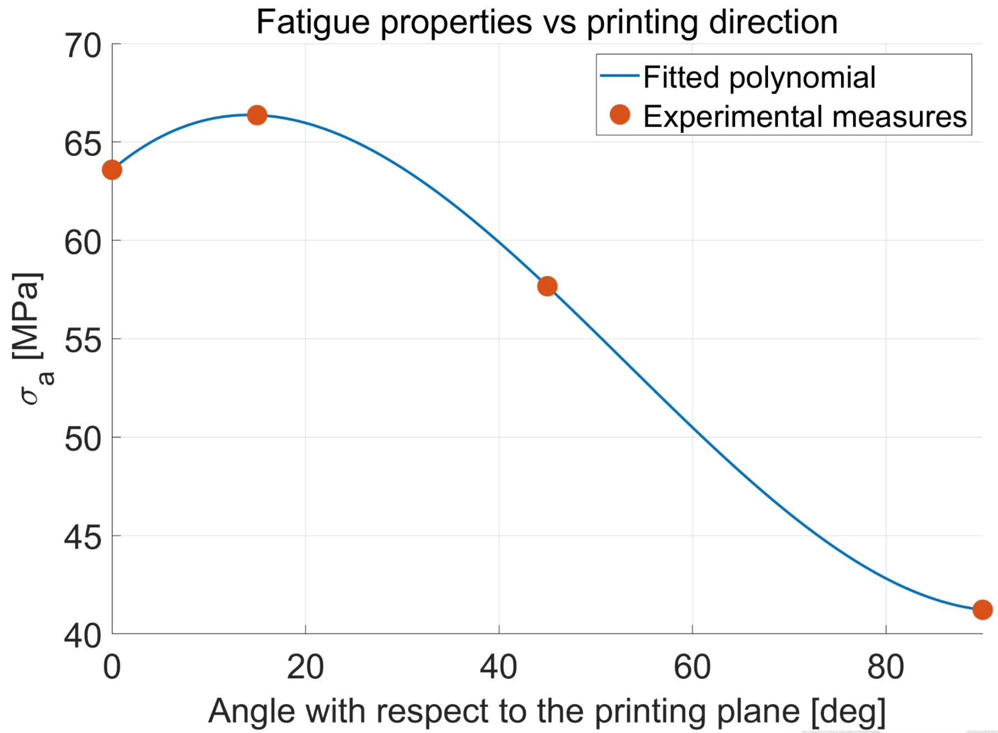
Fatigue life vs printing direction

Murchio et al. [1] found the fatigue life of each trabecula depending on the elevation angle with respect to the printing plane. This characteristic is mainly due to the surface defects and the "staircase effect".





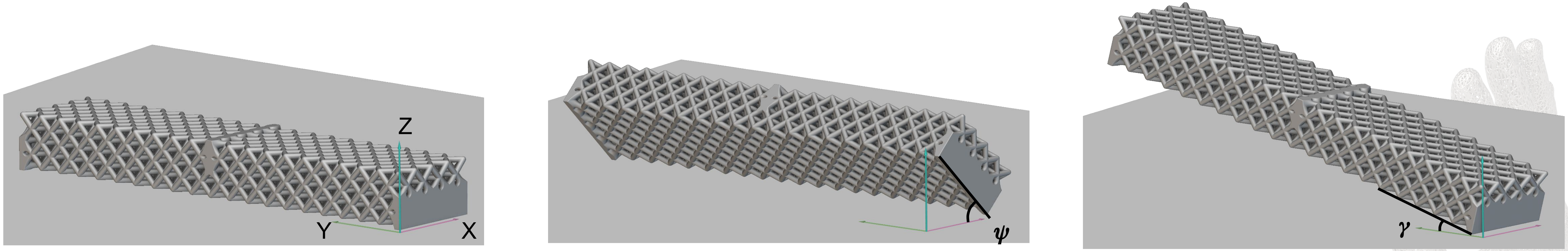
Improving fatigue life

The optimization problem aims to improve fatigue life modifying the printing direction (γ and ψ) of the sample.

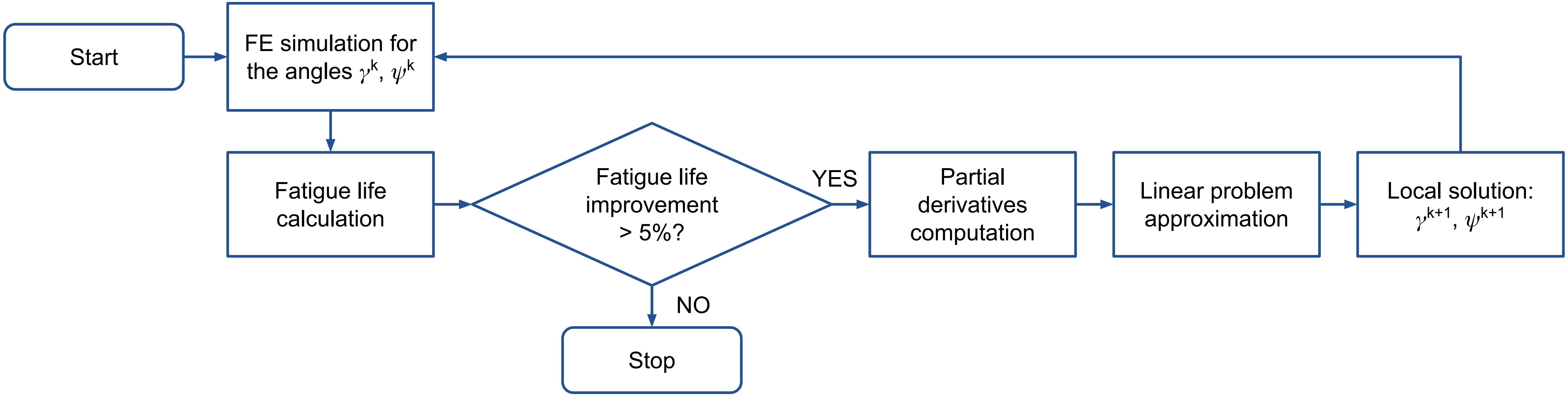
The proposed optimization problem maximizes the minimum value of the safety factor (ϕ) among the different structure trusses.

The optimization of this cost function has to take into account the presence of a constraint on a minimum value on the safety factor and an upper and a lower limit on the possible angular position of the sample.

$$\begin{cases} \max_{\gamma,\psi} g_0(\gamma,\psi) = \max_{\gamma,\psi} \min_i \phi_i(\gamma,\psi) \\ \text{s.t.} \quad \begin{cases} g_i(\gamma,\psi) = \phi_i \geq \phi^* \\ \gamma \in S \\ \psi \in S' \end{cases} \end{cases}$$



Solution approach



An initial configuration for the structure orientation is proposed. For instance the structure is thought to be printed vertically.

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

The partial derivatives were computed using a numerical approximation.

The SLP algorithm gives a convex approximation of the problem in a set around the point γ^k, ψ^k

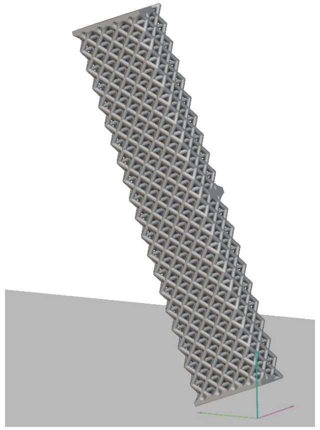
Optimization verification

The optimization routine predict a +60% in the fatigue resistance.

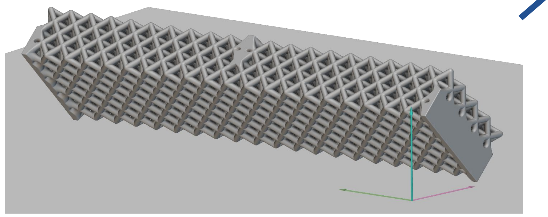
Two specimens batch are printed and tested in three-point-bending, the experimental improvement is the fatigue resistance is +20%.

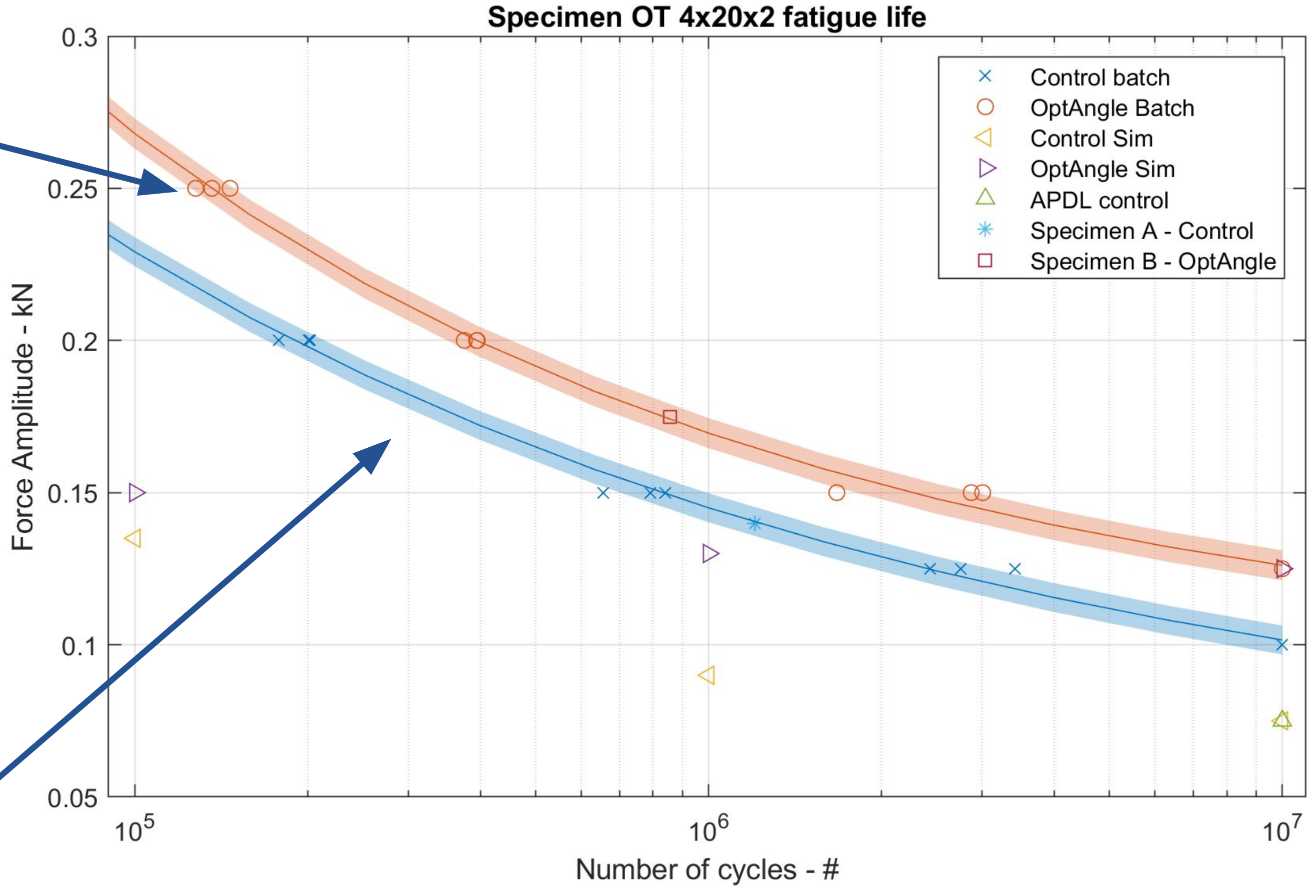
Micro-CT scan are performed in order to investigate the mismatch between the prediction and the real fatigue improvement.

Specimen optimal orientation
$\gamma = 70° - \psi = 90°$



Specimen initial orientation
$\gamma = 0° - \psi = 45°$

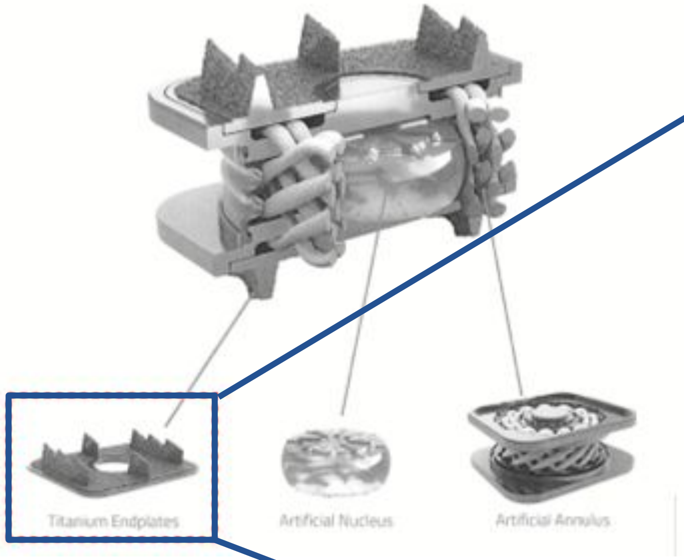


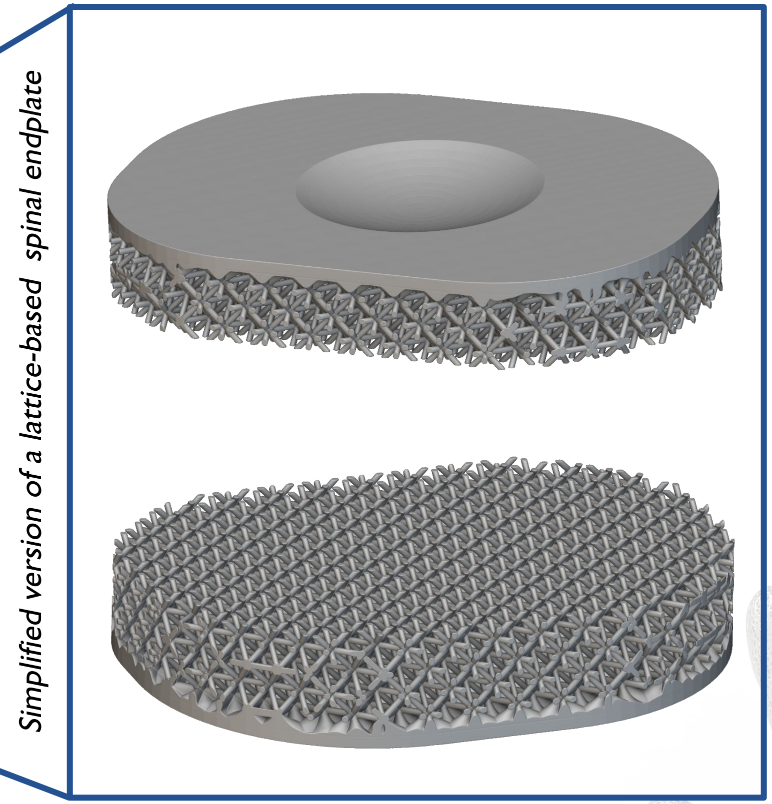


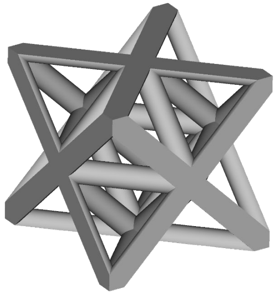
Prosthetic device design

Titanium Endplate for a Total Disc Replacement (TDR) device

[8]







In accordance with the previous analysis a Octet Truss cell is selected

[5] https://www.njspineandortho.com/m6c-disc-replacement-procedure/ (visited 08.2022)

Fatigue life estimation

The simulation of the prosthetic device takes into account the complete system: the polymeric disk representing the intervertebral disk, the titanium endplate and the lower vertebra.

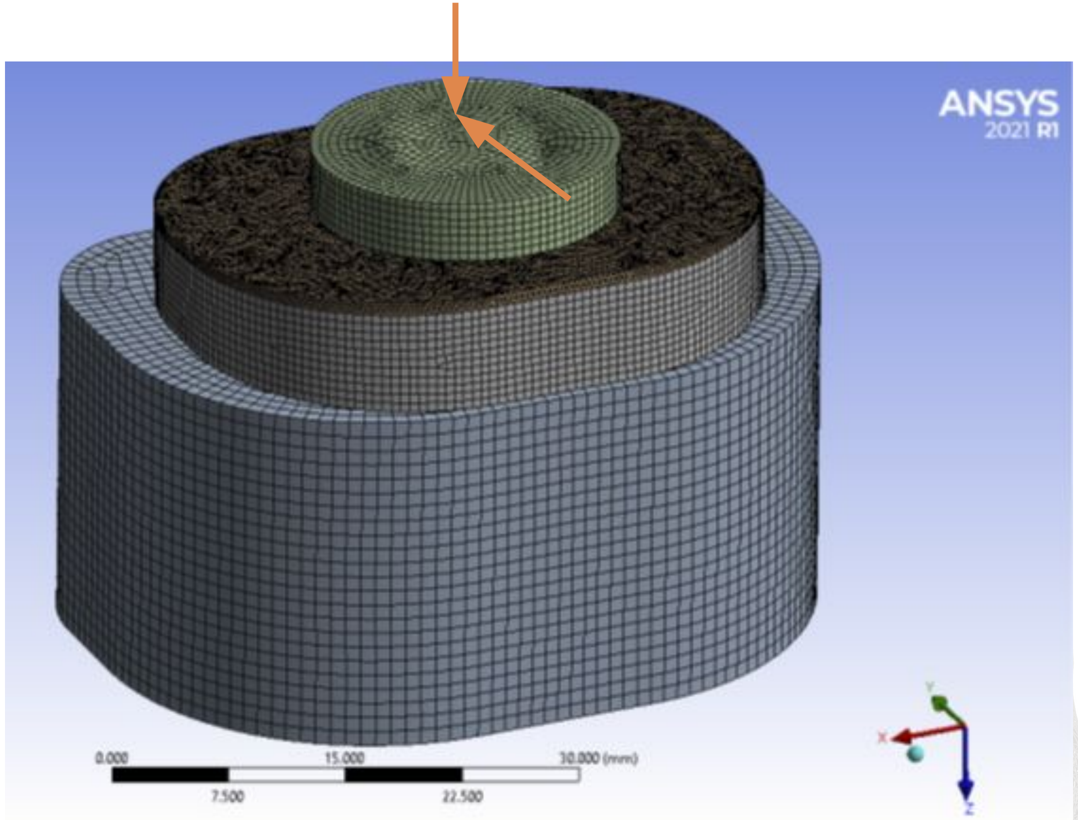
The loading conditions resemble the everyday life ones for a male.

F_z [N]	F_y [N]	$\sigma_{eq,max}$ [MPa]	ϕ_{min}
1180	118	48.8	1.2

$$\varphi = \frac{\sigma_{all}}{\sigma_{eq}}$$

Fatigue stress at **10^7 cycles** of single **strut-junction** specimen tested at R=-1. Values from 40 ÷ 70 MPa according to the orientation.

Beam elements axial stress (**FE simulation**)



Prosthetic device optimization

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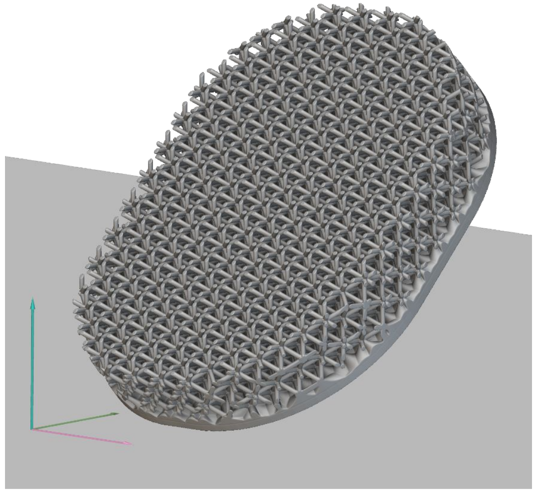
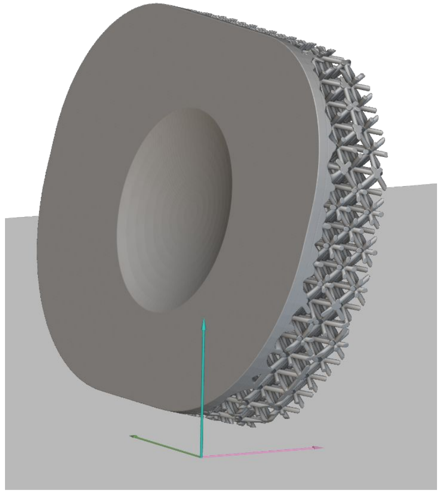


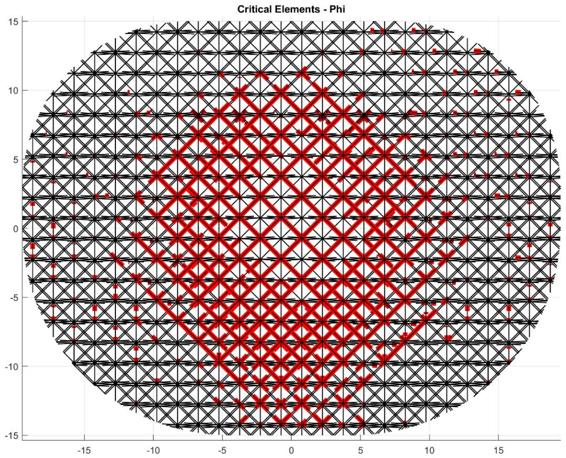
Initial printing orientation:
$\gamma = 0° - \psi = 50°$

→

Optimal printing orientation:
$\gamma = 76° - \psi = 0°$



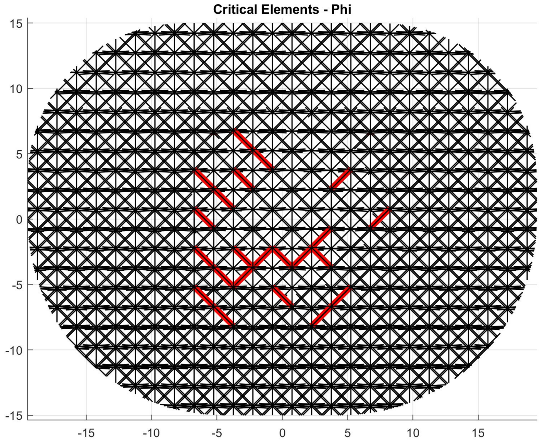
+43% fatigue life



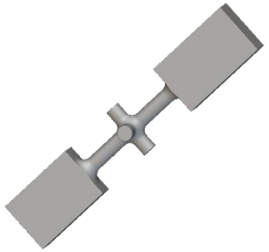
Critical elements in the initial configuration

→

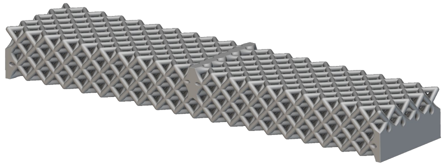
Critical elements in the optimal configuration



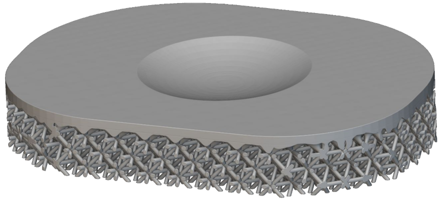
Conclusions



Cost-effective fatigue test on micro-specimen are able to predict with a reasonable accuracy the full lattice fatigue life.



The optimization algorithm is able to improve the fatigue life of a lattice component acting on its printing direction



A lattice-based prosthetic device is designed and its fatigue life can be estimated and improved by optimizing the orientation in the printing process

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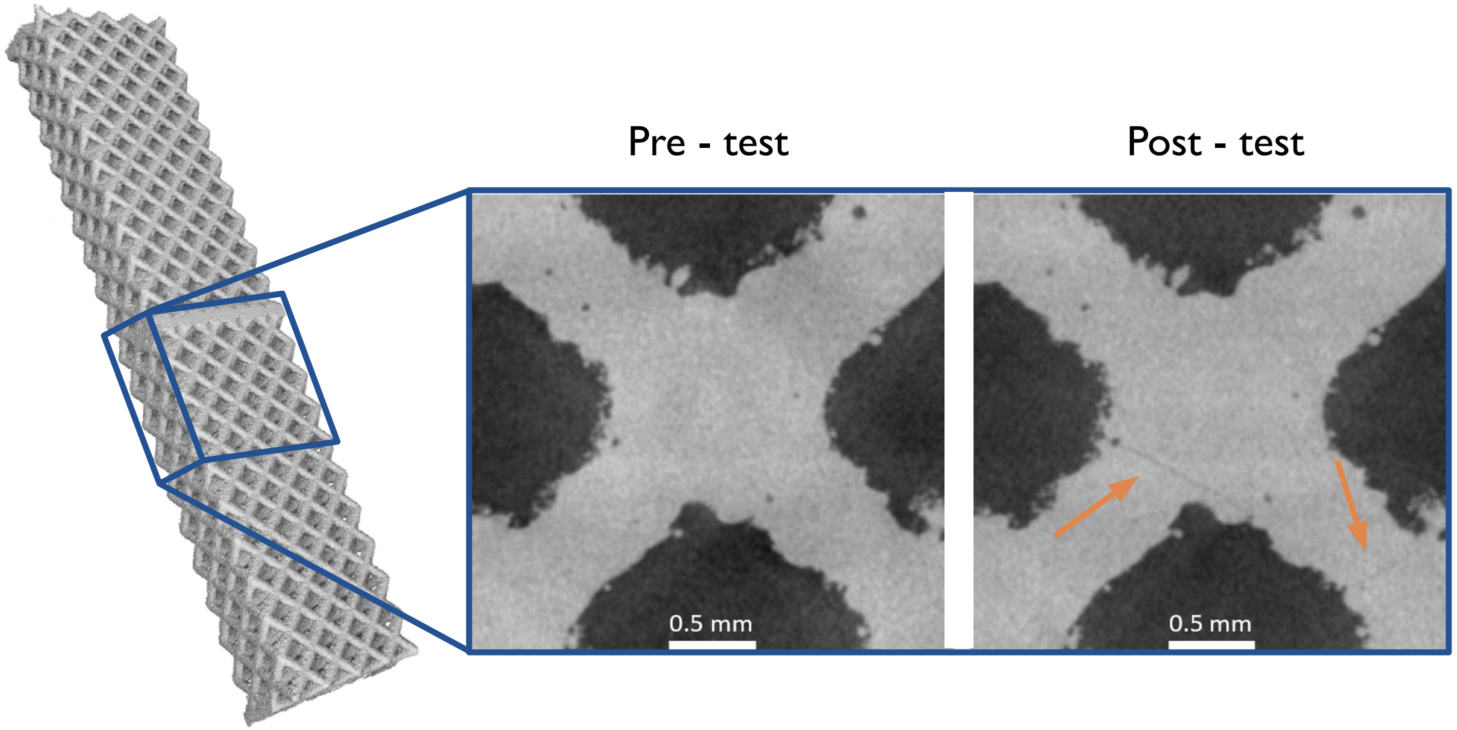
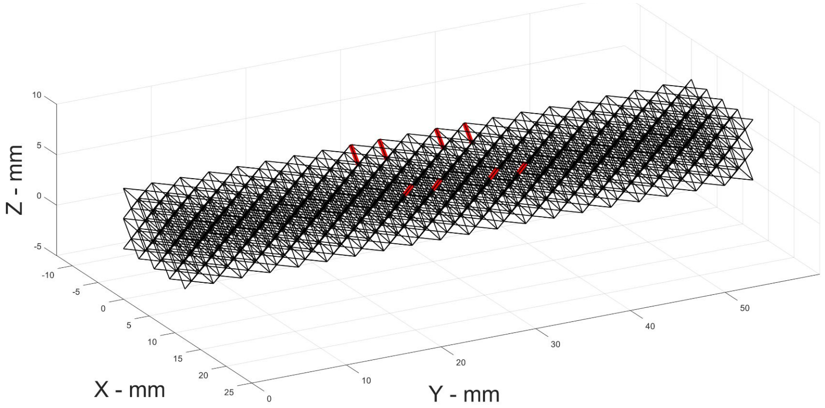
MICRO-CT ANALYSIS

One specimen for each batch is scanned before and after the fatigue test in the laboratories of the University of Padova. Cracks are found in both of the analyzed samples but in the lower part of the geometry.

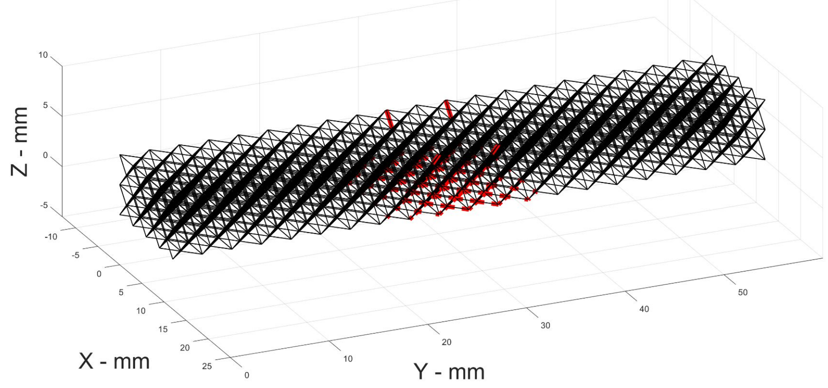
This evidence can be explained with a beam simulation in place of the truss one, showing a stress concentration near the nodes.



Truss simulation - critical elements



Beam simulation - critical elements



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