Infinite Science | Publishing

Lattice structures with stiffness gradient for loads transfer at bone-prosthesis interface

G. De Pasquale

Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Italy.
Email: giorgio.depasquale@polito.it

Abstract. The fabrication of prostheses for orthopedic implants exploits additive technologies based on powder micromelting. The shape modularity, the biocompatibility of materials and the qualification procedures required by normative motivated the application of additive manufacturing since several years. The bone-prosthesis interface has great importance in implant integration, preventing prosthesis rejection and limiting time-scheduled prosthesis replacements. The load transfer between metal structures and bone requires precise modulation to stimulate the strength of new tissues. The design of lattice structures based on modular 3D stiffness variation is described in this paper, with special focus on the modeling methods based on homogenization approach.

I. Introduction

The performances of additive manufacturing (AM) processes support the inclusion of bulk and cellular (or lattice) regions on the same component. This peculiarity is well known in fabrication of orthopedic endoprosthetics where the main structure is connected to functional surfaces based on small features [1]. The functional coating is applied to the bone-prosthesis interface to facilitate the tissue growth and to improve the connection strength. The load transfer from the prosthesis to the bone may cause small localized displacements and wearing of the biological tissues, leading to time-scheduled replacements of the implant. The interface design requires the strong metal-bone integration and the controlled loading of the bone tissue. The second requirement can be obtained with the proper modulation of the interface structural stiffness, in order to move the loads towards the bone tissue. The spatial variation of the prosthesis structural strength must be evaluated in order to prevent the overload of the bone and to stimulate the load-driven tissue growth.

This paper introduces the application of homogenization design methods to the functional prosthesis surfaces. The parametric variation of the lattice cell topology is controlled across the interface region [2-5]. Preliminary experimental characterization is also reported with reference to SLM (selective laser melting) lattice structures made with Ti6Al4V alloy [6, 7].

II. Homogenization method

The main limitations in modeling cellular or lattice structures are caused by their geometrical complexity. The analytic formulation of lattice cells based on the equivalency with Euler-Bernoully-Timoshenko beam theories is applicable only for the simplest cell shapes. The finite elements method (FEM) is theoretically suitable for the prediction of structural properties of lattice structures, but simplified 1D models provide limited accuracy and full 3D models suffer the extreme computational heaviness.

Homogenization methods instead are effective in reducing the complexity of calculation and preserving high accuracy of results. They are based on the conversion of each lattice cell (or RVE, representative volume element) with equivalent elements. The equivalent homogeneous anisotropic continuum is described by elements with imposed stiffness matrix, which are able to represent the structural behavior of the original cells. The stiffness matrix is defined from the FE model results of single lattice cell in different loadings and constraints conditions. The equivalence of the two models can be computed by following different schemes, as the volume average stress-based method and the strain energy method. The periodic distribution of cells is used to impose the boundary conditions of single RVE.

The governing equation of the equivalent homogeneous material is

$$\{\sigma\} = [K]\{\varepsilon\} \tag{1}$$

where $\{\sigma\}$ and $\{\varepsilon\}$ are the stresses and strains of the equivalent homogeneous continuum. The stiffness matrix components are computed, column by column, by solving six linear static analyses. Here, the boundary conditions are imposed to provide only one non-zero component of the RVE average strain field. The non-zero average component is imposed equal to the unit and the stiffness matrix components are estimated as

$$K_{\alpha i} = \sigma_\alpha = \frac{1}{V}\int_V \sigma_{\alpha i}(x_1, x_2, x_3)dV \tag{2}$$

where V is the volume and $\alpha = 1, \dots, 6$ and $\mathrm{i} = 1, \dots, 6$ correspond to the actual static case. Finally, the Young's module of the homogenized material is obtained from the compliance matrix

$$[B] = [K]^{-1} \tag{3}$$

as

$$E_1 = \frac{1}{B_{11}}, E_2 = \frac{1}{B_{22}}, E_3 = \frac{1}{B_{33}} \tag{4}$$

DOI: 10.18416/AMMM.2019.1909S10T04

III. Design of the interface

The cellular structure of the prosthesis interface has the typical trabecular shape reported in Fig. 1. The lattice design starts with the definition of the cell shape and geometrical parameters. Figure 2 reports some examples: octahedral and cubic. Figure 3 reports the interface transition composition.

Figure 1: Hip prosthesis and trabecular lattice surface in titanium alloy [1].

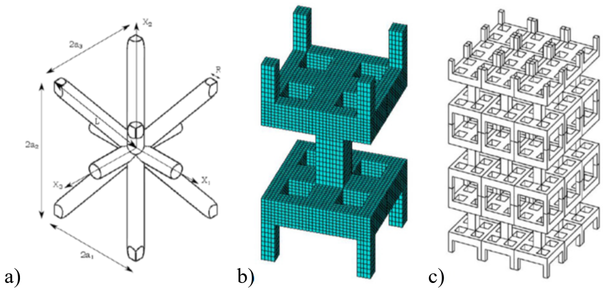

Figure 2: Octahedral cell shape (a), cubic cell shape (b), and cubic cells lattice (c).

The homogenization method is implemented on the selected cell shape by using numerical simulation tools [2]. The progressive modulation of equivalent stiffness is then imposed in order to distribute properly the interface load between metal and bone tissue.

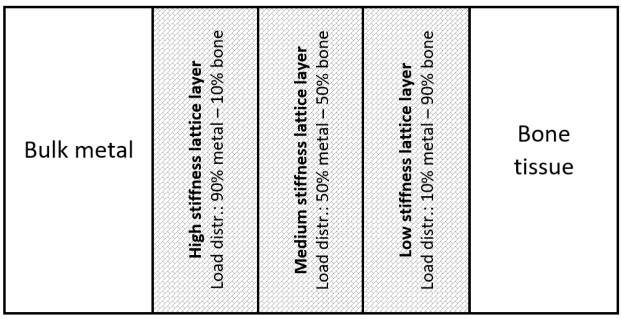

Figure 3: Composition of metal-bone interface based on lattice layers with modulated structural stiffness.

The complete procedure for calculating the lattice geometry and related structural properties is reported in Fig. 4. The relations defined during this procedure between the equivalent stiffness value and the geometrical parameters allow imposing the dimensions of lattice struts. Then, the desired load percentage is transferred to the bone tissue layer by layer. By considering the total elastic energy absorbed at the metal-bone interface under static loads, the portion of energy associated to the bone is directly proportional to the stress of the bone tissue and inversely proportional to the stress of metal lattice.

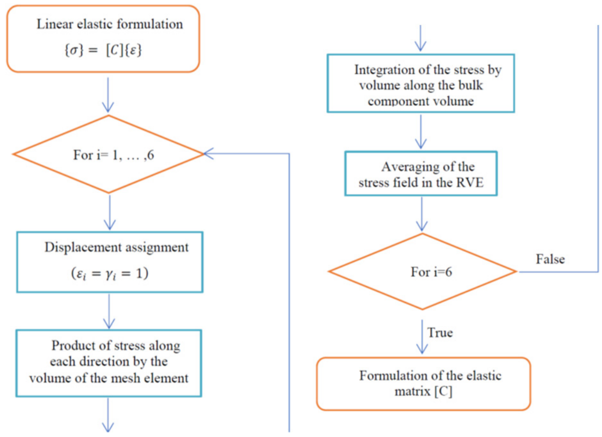

Figure 4: Homogenization process applied to the design of lattice interface with stiffness gradient.

IV. Results and discussion

Some preliminary experimental results have been achieved on SLM samples to validate the predictions of the homogenization method with cubic lattice structures (strut thickness 0.4mm, struts length 1.5mm, 20x20x30 cells). Here, the experimental equivalent Young's modules E_{exp}=1812.5MPa and E_{exp}=1810.0MPa are obtained over two measurements. The homogenized Young's module estimation is E_h=1865.0MPa, with 2.89% and 3.04% errors respectively.

V. Conclusions

The application of reduced order design modeling strategies to metal-bone interfaces is promising in the field of orthopedic prosthesis. The characteristics of AM technologies associated to dedicated design methods have the potential to improve the effectiveness and reliability of prosthesis implants with the modulation of structural behavior of the lattice.

Author's Statement

Research funding: The author state no funding involved. Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

References

[1] F. De Meo, G. Cacciola, F. Cavaliere, P. Cavaliere, *Acetabular revision in case of severe bone loss using trabecular titanium cups* Acta Orthopaedica Italica, pp.5-14, vol. 40, 2017.

[2] E. J. Barbero, *Finite element analysis of composite materials using Ansys*, CRC Press, 2014.

[3] V.S. Deshpande, N.A. Fleck, M.F. Ashby, *Effective properties of the octet-truss lattice material*. J Mech Phys Solids pp. 1747-1769, vol. 49, 2001.

[4] G. Dong, Y. Tang, Y.F. Zhao, *A survey of modeling of lattice structures fabricated by additive manufacturing*. J Mech Des 100906, vol. 139, 2017.

[5] L.J. Gibson, M.F. Ashby, *Cellular solids: structure and properties*. Cambridge University Press, 1999.

[6] G. De Pasquale, F. Luceri, M. Riccio, *Experimental characterization of SLM and EBM cubic lattice structures for lightweight applications*, Experimental Mechanics, pp. 469-482, vol. 59, 2019.

[7] G. De Pasquale, F. Luceri, M. Riccio, *Experimental evaluation of selective laser melting process for optimized lattice structures*, Proc IMechE Part E: J Process Mechanical Engineering, 2019.