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Prediction of the elastic response of TPMS cellular lattice structures using finite element method

M.R. Karamooz-Ravari*, M. Taheri Andani†

*Department of Mechanical Engineering, Graduate University of Advanced Technology, Kerman, Iran, email: m.karamooz@kgut.ac.ir
†S.M. Wu Manufacturing Research Center, College of Engineering, Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA, 48109

Abstract

Cellular lattice structures are a group of porous materials in which the cells are regularly distributed. Since the morphology of the cells is complicated, the fabrication of them is challenging using conventional methods. However, with the advent of additive manufacturing technology, more attention is focused on these classes of materials because the regular geometry makes it possible to tailor the mechanical response of the structure. Among all kinds of cellular lattice structures, those based on triply periodic minimal surfaces are of great importance due to mechanical and biological properties. Since the fabrication of such structures is challenging and expensive, it is desirable to predict their mechanical response before fabrication. In this paper, finite element approach is employed to predict the elastic response of two well-known Schwarz minimal surfaces named P-Type and G-Type. To do so, first, the cloud points of the surfaces are generated using the implicit equation of the surface and are converted into solid finite element models. The results show that at the same value of porosity, the P-Type specimen provides a higher value of elastic modulus than G-Type one.

Introduction:

Nowadays, a lot of patients suffer from organ loss and defects which might be arisen in some clinical situations. Tissue engineering is a multi-disciplinary science which employs engineering and life science in order to regenerate organs and tissues using scaffolds, cells and growth factors. A scaffold is a porous structure which provides a substitute for cells to proliferate and differentiate. A suitable scaffold must have several requirements which are necessary for suitable cell functions. It is previously shown that porous materials based on triply periodic minimal surfaces (TPMS) are might be a good candidate for being used scaffolds [1]. With the advent of additive manufacturing technology, several attempts have been made to use TPMS for designing and fabricating tissue engineering scaffolds [2]. The regular microstructure of the cellular lattice structures, such TPMS ones, allows the designer to adjust the mechanical properties of the scaffold to be similar to the neighbor tissue [3].

In bone regeneration, the bone formation might be triggered by mechanical signals of the osteocytes. If the elastic modulus of the scaffold mismatch with that of surrounding bone, the work of osteoclasts may resorb the bones and cause osteoporosis. Accordingly, it is necessary to adjust the mechanical response of the scaffold to that of the surrounding bone. Since the fabrication and characterization of the scaffolds might be time-consuming and expensive [4-6], it is desirable to develop numerical models for the prediction of the mechanical response before fabrication. Several analytical [7-10] and numerical [1, 3, 11-13] models have been developed for the prediction of the mechanical response of cellular lattice structures. However, such kind of models can rarely be found for TPMS ones. Kadkhodapour et al. [14] studied the failure mechanisms of additively manufactured diamond-like and simple cubic cellular lattice structures using finite element method. Montazerian et al. [15] studied the compressive response of some different TPMS cellular lattice structures using numerical models. Kadkhodapour et al. [16] investigated the mechanical response of P-type and D-type cellular lattices utilizing finite element approach.

In this paper, the elastic response of P-type and G-type TPMS cellular lattice structures are investigated through unit cell model in combination with finite element method. To do so, first, the geometric model of the unit cell is generated using their corresponding point clouds. These point clouds are obtained by the implicit equation of the surface of the lattice. Then, by attributing the bulk material parameters, the finite element simulations are performed for a range of porosities. The obtained results demonstrate that at the same value of porosity, the elastic modulus of the P-type architecture is greater than that of G-type one.

Materials and Methods

For the sake of modeling purposes, two main steps must be followed. First, the geometric model of the porous material must be constructed. Then, suitable material parameters for the bulk material, from which that porous material is built, must be attributed. In this sections, these two steps are followed.

Geometrical Modeling

There are several types of TPMS architectures in the literature such as P-Type, G-Type, and D-Type. In this study, just P- and G-Type structures are investigated. The main property of TPMSs is that the curvature of such surfaces is zero everywhere. It is possible to develop implicit equations for some of the TPMSs. Fortunately, P- and G-Type surfaces can be described using implicit equations as follows [1, 2]:

$$\begin{aligned} P-Type:&\quad \cos(x)+\cos(y)+\cos(z)-a=0 \\ G-Type:&\quad \cos(\mathrm{x})\sin(\mathrm{y})+\cos(\mathrm{y})\sin(\mathrm{z})+\cos(\mathrm{z})\sin(\mathrm{x})-a=0 \end{aligned} \tag{1}$$

in this equations, x, y, z are the coordinates in Cartesian coordinate system, and a is parameter between 0 and1. To model the geometry of the porous structures, first the cloud points of each type is produced and a triangular mesh passes through. Then the provided mesh is exported as OBJ file which is a combination of vertexes and their connection. This OBJ file is then used to construct a set of surfaces which defines the surface of TPMS architecture. Since there are several holes in the obtained surfaces, a MATLAB program is developed to fill the holes by constructing a surface with the shape of the hole. After producing a closed surface of the geometry of the repeating unit cell of the structure, the three-dimensional model is extracted as the intersection of surfaces. Figure 1 (a) and (b) show the repeating unit cell of P-Type and G-Type pores respectively.

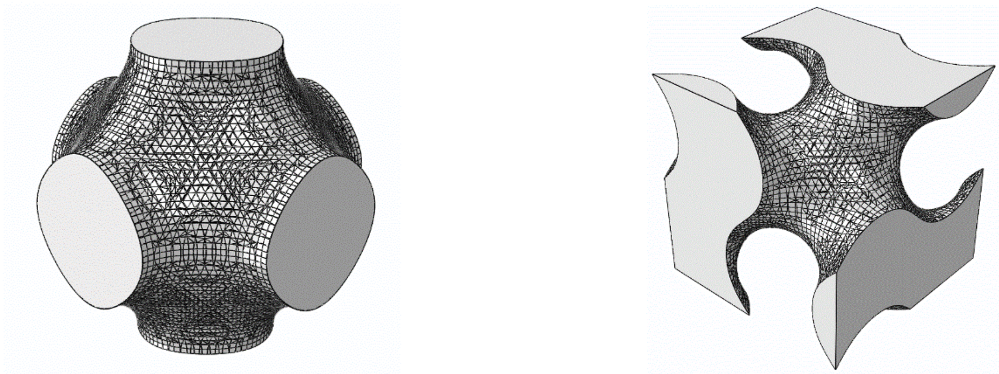
(a) (b)

Figure 1: The repeating unit cell of a) P-Type porosity b) G-Type porosity

To achieve a specific value of porosity the value of "a" should be adjusted. Figure 2 shows the change in the value of porosity with the parameter "a".

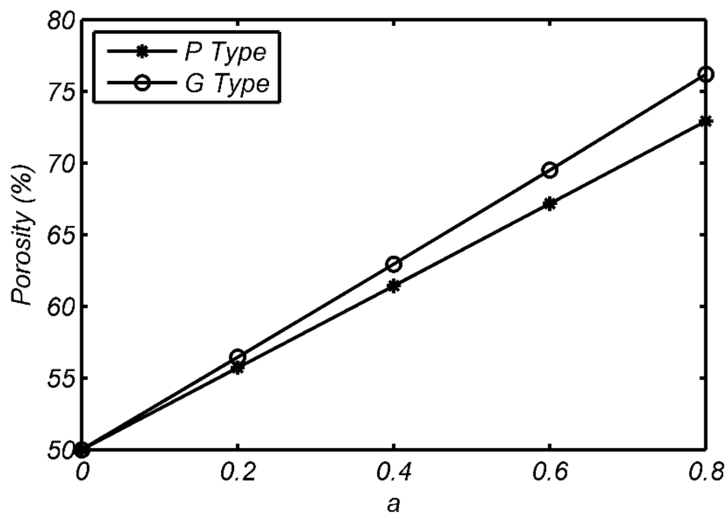

Figure 2: The change of porosity with "a"

Loading and Boundary conditions

Since the unit cell model is used to simulate the elastic modulus of the structure, the periodic boundary conditions should be applied to. In this study, the boundary conditions similar to ones used by Panico and Brinson [17] are used. Figure 3 shows these applied boundary conditions.

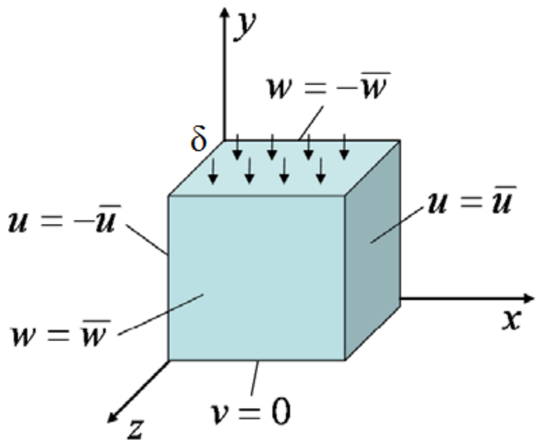

Figure 3: Applied boundary conditions [17]

If the required force to apply a displacement of δ is F, the elastic modulus of the cellular lattice can be calculated using Eq. 2:

$$E^* = \frac{\frac{F}{A}}{\frac{\delta}{L}} = \frac{F}{\delta \cdot L} \qquad (2)$$

<u>*Bulk material*</u>

As the mechanical properties of the lattice in the elastic region are of importance, the bulk material is considered to be elastic. Consequently, only two material parameters, E_s and ν_s, are needed for modeling purposes. Since the non-dimensional elastic modulus of the lattice (E^*/E_s) is going to be reported, in this report, E_s=1.0 and ν=0.3 are used in modeling procedure.

<u>*Finite element simulations*</u>

The models are generated through ABAQUS 6.11-1 and meshed using 10-node quadratic tetrahedron elements (denoted by C3D10 in ABAQUS) and a mesh study analysis is performed to ensure the results. To do so, the mesh size is reduced until the change in the results would be smaller than 5 percent. All the simulations are performed on 2 Intel Xeon X5670 (12 core), 2.93 GHz processors with 24 cores and 24 GB RAM.

<u>Results</u>

Figure 4 shows the change of elastic modulus of P-Type and G-Type specimens with the value of porosities. As demonstrated in this figure, the elastic modulus of both P-Type and G-Type structures decrease almost linearly by increasing the value of porosity. The most important finding of this study is at the same value of porosity the elastic modulus of the P-Type structure is higher than that of the G-Type structure by a factor of 1.4.

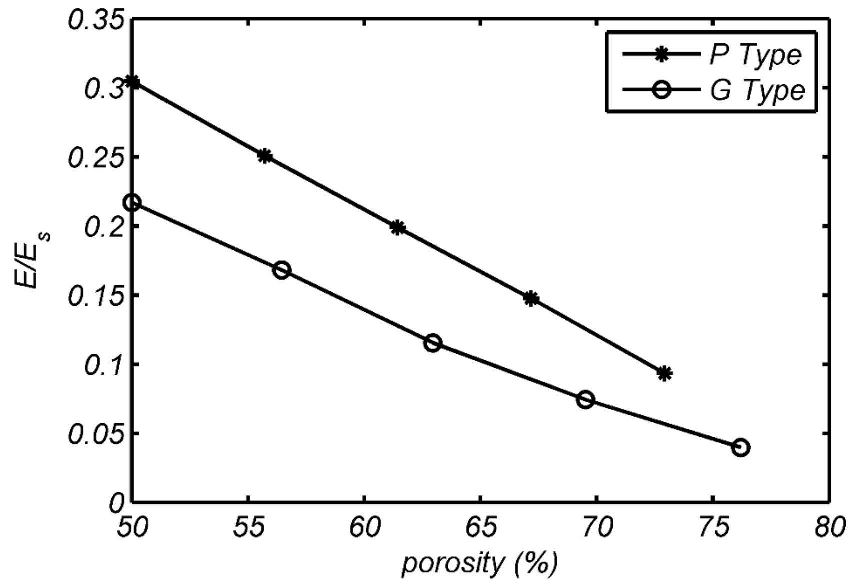

Figure 4: Non-dimensional elastic modulus versus porosity

References

1. Rajagopalan, S. and R.A. Robb, *Schwarz meets Schwann: design and fabrication of biomorphic and durataxic tissue engineering scaffolds.* Medical image analysis, 2006. **10**(5): p. 693-712.
2. Melchels, F.P., et al., *Mathematically defined tissue engineering scaffold architectures prepared by stereolithography.* Biomaterials, 2010. **31**(27): p. 6909-6916.
3. Karamooz Ravari, M. and M. Kadkhodaei, *A computationally efficient modeling approach for predicting mechanical behavior of cellular lattice structures.* Journal of Materials Engineering and Performance, 2015. **24**(1): p. 245-252.
4. Esfahani, S.N., et al., *Independent tuning of stiffness and toughness of additively manufactured titanium-polymer composites: Simulation, fabrication, and experimental studies.* Journal of Materials Processing Technology, 2016. **238**: p. 22-29.
5. Rahmanian, R., et al. *Modeling and validation of additively manufactured porous nitinol implants*. in *ASME 2014 conference on smart materials, adaptive structures and intelligent systems*. 2014. American Society of Mechanical Engineers.
6. Taheri Andani, M., et al., *Achieving biocompatible stiffness in NiTi through additive manufacturing.* Journal of Intelligent Material Systems and Structures, 2016. **27**(19): p. 2661-2671.
7. Ushijima, K., W. Cantwell, and D. Chen, *Prediction of the mechanical properties of micro-lattice structures subjected to multi-axial loading.* International Journal of Mechanical Sciences, 2013. **68**: p. 47-55.
8. Gümrük, R. and R. Mines, *Compressive behaviour of stainless steel micro-lattice structures.* International Journal of Mechanical Sciences, 2013. **68**: p. 125-139.
9. Ptochos, E. and G. Labeas, *Elastic modulus and Poisson's ratio determination of micro-lattice cellular structures by analytical, numerical and homogenisation methods.* Journal of Sandwich Structures & Materials, 2012. **14**(5): p. 597-626.
10. Ravari, M.K., et al., *On the effects of geometry, defects, and material asymmetry on the mechanical response of shape memory alloy cellular lattice structures.* Smart Materials and Structures, 2016. **25**(2): p. 025008.
11. Karamooz Ravari, M., M. Kadkhodaei, and A. Ghaei, *A unit cell model for simulating the stress-strain response of porous shape memory alloys.* Journal of Materials Engineering and Performance, 2015. **24**(10): p. 4096-4105.
12. Karamooz Ravari, M., et al., *Numerical investigation on mechanical properties of cellular lattice structures fabricated by fused deposition modeling.* International Journal of Mechanical Sciences, 2014. **88**: p. 154-161.
13. Naghieh, S., et al., *Numerical investigation of the mechanical properties of the additive manufactured bone scaffolds fabricated by FDM: The effect of layer penetration and post-heating.* Journal of the mechanical behavior of biomedical materials, 2016. **59**: p. 241-250.

14. Kadkhodapour, J., et al., *Failure mechanisms of additively manufactured porous biomaterials: Effects of porosity and type of unit cell.* Journal of the mechanical behavior of biomedical materials, 2015. **50**: p. 180-191.
15. Montazerian, H., et al., *Porous scaffold internal architecture design based on minimal surfaces: A compromise between permeability and elastic properties.* Materials & Design, 2017. **126**: p. 98-114.
16. Kadkhodapour, J., H. Montazerian, and S. Raeisi, *Investigating internal architecture effect in plastic deformation and failure for TPMS-based scaffolds using simulation methods and experimental procedure.* Materials Science and Engineering: C, 2014. **43**: p. 587-597.
17. Panico, M. and L. Brinson, *Computational modeling of porous shape memory alloys.* International Journal of Solids and Structures, 2008. **45**(21): p. 5613-5626.