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Elastic and Plastic Properties of Gyroid Sheet Foams †

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Abstract: Gyroid foams have significant potential for biomedical applications. Their highly porous configuration is beneficial for biological cell growth and proliferation, and thus, they are a valid alternative to design scaffolds for biomedical applications, such as bone tissue growth. The modification of the cell density allows for the mechanical properties of the implant to be adjusted and avoiding unwanted phenomena, such as stress shielding occurring when the stiffness of the implant is much higher than the stiffness of the replaced tissue. Thus, this work consisted of the analysis of the gyroid unit cells through numerical homogenization. The obtained results allowed to correlate the apparent density of the gyroid foam with the relative Young's modulus and relative yield stress.

Keywords: gyroid sheet foams; numerical homogenization

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1. Introduction

In comparison to other scaffold shapes, gyroid-based scaffolds present higher permeability than other triply periodic minimal surfaces (TPMSs). Additionally, TPMS-based foams built using additive manufacturing technology have been shown to be able to achieve the necessary mechanical properties to replace human bone [1,2]. Finally, gyroid cellular materials can also be used in order to obtain structures with a higher stiffness-to-weight ratio [3] for structural applications.

In this work, the gyroid foam used was sheet-like instead of solid. Sheet-based networks tend to present higher stiffness and strength than solid networks [4]. The difference between gyroid sheet networks and gyroid solid networks lies in how the surface is converted to a solid. The gyroid surface divides the space into two parts, and if the space enclosed by one of the sides of the surface is chosen, a solid network is obtained. If the surface is "thickened", a sheet network is obtained. Figure 1 highlights the difference between both foam typologies.

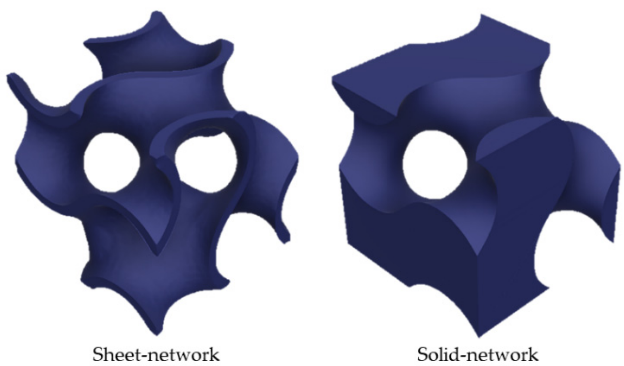


Figure 1. Gyroid foam topologies.

2. Materials and Methods

Gyroid unit cells models, corresponding to density variations, were developed by computing the gyroid surface in MATLAB and exporting the STL files. The different density values were achieved by attributing to the surface different thickness values. The corresponding representative volume element (RVE) was a cube with an edge length of 20 mm, and the different thicknesses were 1 mm, 3 mm and 5 mm. In order to reduce the computational cost of the analysis, the RVE was chosen for one period of the gyroid, equivalent to one cell. The meshed models and employed boundary conditions are shown in Figure 2. Each model was discretized using 10-node tetrahedral elements, using as a seed mesh the surface mesh exported from MATLAB.

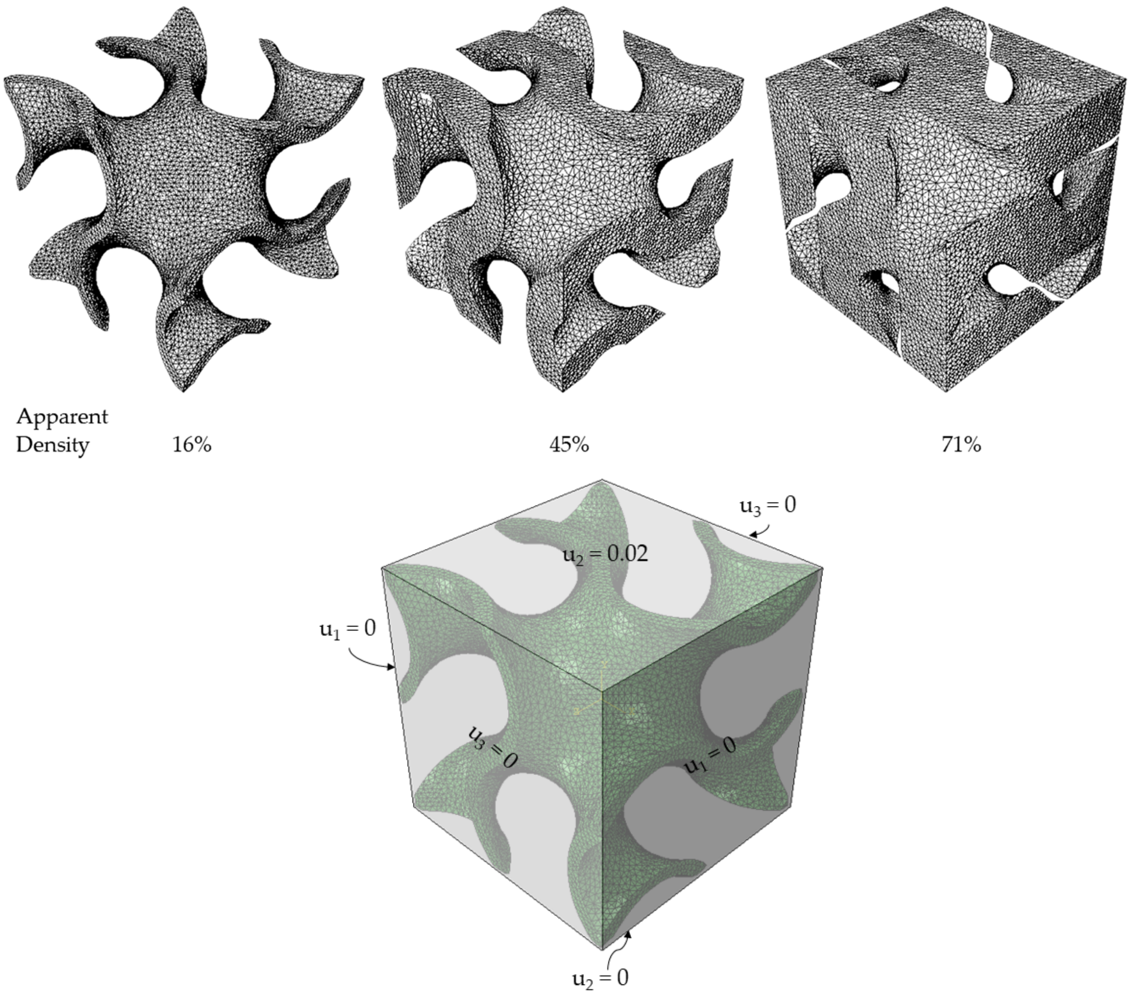


Figure 2. Gyroid models and boundary conditions.

The constituent material of the gyroid unit cell was defined as an isotropic material with E = 3000 MPa and υ = 0.3. The plastic properties of the building material, necessary for the second stage of the study, consisted of considering a material with perfectly plastic behavior. Three different values of yield stress were tested, namely 10 MPa, 30 MPa and 50 MPa.

The equivalent elastic properties were calculated using a homogenization approach where a unit strain, in this case $\varepsilon = 0.1\%$, was applied through $u_2 = 0.02$ at the top face of the RVE [3]. Thus, through Hooke's law it is possible to calculate the Young's modulus from the average apparent stress. The average apparent stress was the volume average of the stress in the model.

The second stage of the study was meant to determine the plastic properties of the cells. Implant design involves both the stiffness of the material as well as its capacity to carry the loads in the human body, i.e., it must have reasonable stiffness and high strength. The equivalent yield stress, σ_y^e, was determined according to Equation (1).

$$\sigma_{equiv}^{yield} = \frac{\sum F_{y=l_{RVE}}}{A_{RVE}} \tag{1}$$

3. Results

The relation between the foam volume fraction and its elastic properties are shown in Figure 3. Additionally, an adjusted trend curve is included. The relative Young's modulus mentioned in Figure 3 corresponded to the ratio between the apparent Young's modulus and the Young's modulus of the bulk material. The adjustment of data corresponds to a third-order polynomial. The results which were obtained are in agreement with the literature [5].

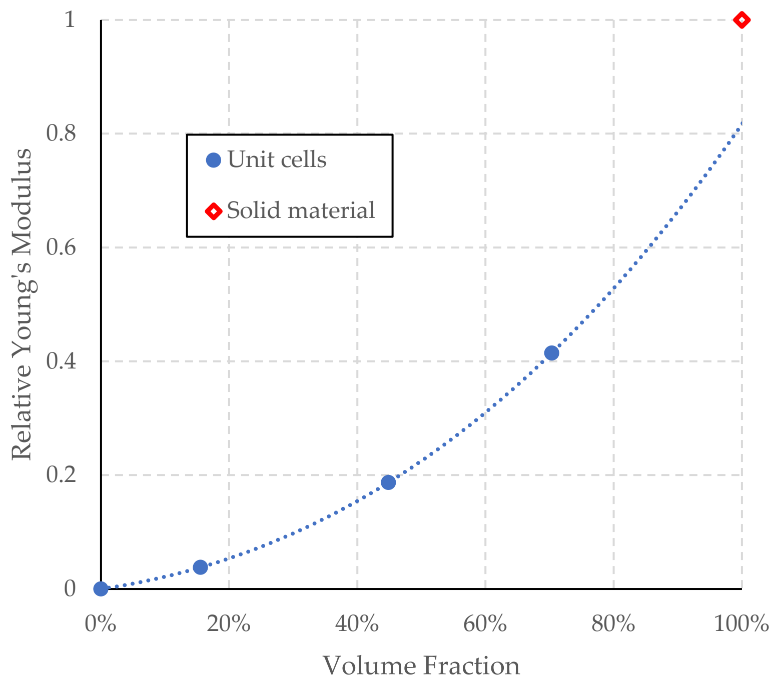
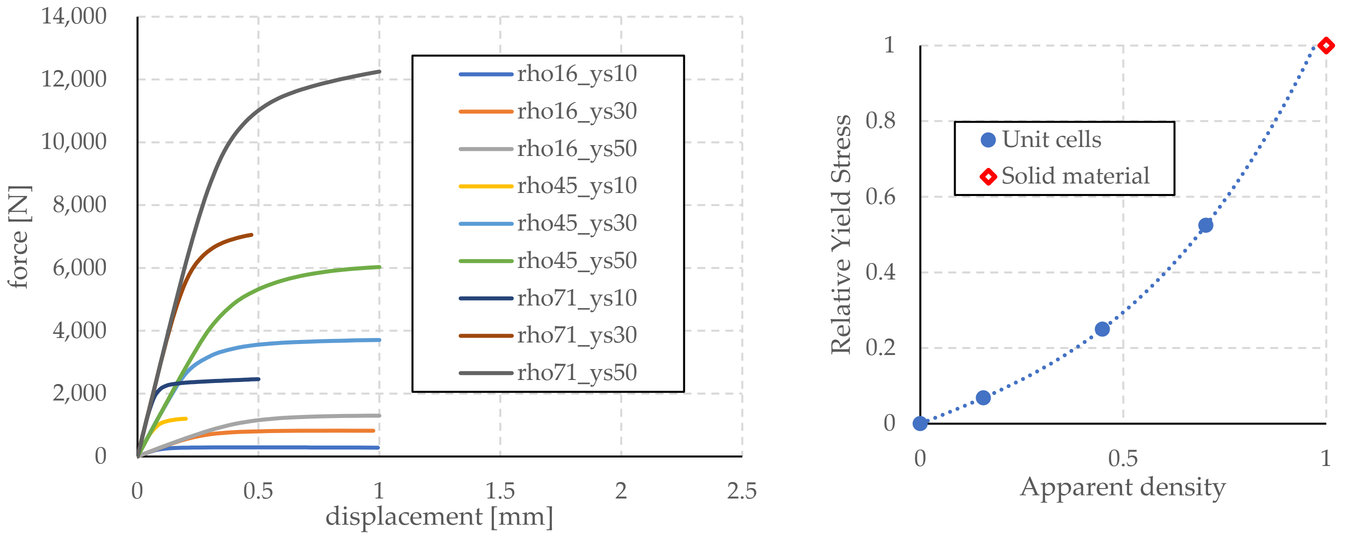


Figure 3. Young's modulus ratio and comparisson to the solid material.

The results of the FE simulations to determine the yield stress of the cells are shown in Figure 4a. In order to have a more accurate fit of the data, corresponding to the relative yield stress, several values of yield stress of the bulk material were tested. The relative yield stress is given by the ratio of the equivalent yield stress in the cell and the yield stress of the bulk material. Similarly to the relative Young's modulus, the relative yield stress was also plotted against the relative density, as shown in Figure 4b.



(**a**) (**b**)

Figure 4. Determination of the relative yield stress of the unit cells (**a**) Force displacement plot and (**b**) obtained scaling law.

4. Conclusions

In conclusion, the results of this work contribute to the mechanical characterization of gyroid foams. However, these data should be further improved with experimental results. Structurally, it is important that the stiffness and strength of the implant are correctly predicted. Stiffness must not be greater than the stiffness of the surrounding bone to avoid stress shielding, while the implant must still be able to support weight and have enough strength. The obtained results can also be used in the design of functionally graded implants through the combination of structural optimization techniques. Thus, the implant properties can further be adjusted to decrease the possibility of stress shielding and improve cell growth.

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