

Porosity Dependence of the Effective Modulus of PCL Gyroid Scaffolds

ABSTRACT

This study quantified the effect of geometric porosity on the axial effective modulus of poly(ϵ -caprolactone) (PCL) sheet Gyroid scaffolds. Five finite element models with target porosities of 50%, 60%, 65%, 70%, and 75% were generated from a periodic implicit surface and compressed in Abaqus Standard 2024. The PCL was modeled as isotropic and linearly elastic, with a Young's modulus of 350 MPa and a Poisson's ratio of 0.30. The effective modulus decreased from 72.96 to 23.28 MPa across the porosity range, a reduction of 68.1%. A power law fitted the five computed values with $R^2 = 0.998$ in logarithmic space. Mesh refinement altered the final modulus by less than 2.5% for the cases checked at their finest resolution. These results provide a geometry-specific interpolation for idealized finite specimens; experimental validation remains necessary before predicting the behavior of printed scaffolds.

Keywords: Gyroid; polycaprolactone; porosity; effective modulus; finite element analysis

RESUMO

Este estudo quantificou o efeito da porosidade geométrica no módulo efetivo axial de scaffolds Gyroid de poli(ϵ -caprolactona) (PCL). Cinco modelos de elementos finitos, com porosidades nominais de 50%, 60%, 65%, 70% e 75%, foram gerados a partir de uma superfície implícita periódica e comprimidos no Abaqus Standard 2024. O PCL foi representado como material isotrópico e linearmente elástico, com módulo de Young de 350 MPa e coeficiente de Poisson de 0,30. O módulo efetivo diminuiu de 72,96 para 23,28 MPa, redução de 68,1%. Uma lei de potência descreveu os cinco resultados calculados com coeficiente de determinação de 0,998 no espaço logarítmico. O refinamento da malha alterou o módulo final em menos de 2,5% nos casos verificados em sua resolução mais fina. Os resultados fornecem uma interpolação específica para a geometria e as hipóteses adotadas; é necessária validação experimental para prever o comportamento de scaffolds impressos.

Palavras-chave: Gyroid; poli(ϵ -caprolactona); porosidade; módulo efetivo; análise por elementos finitos

1 Introduction

Triply periodic minimal surfaces divide space into continuous, interpenetrating domains, a feature that has motivated their use in cellular structures. The Gyroid belongs to this family and can be represented by a periodic trigonometric isosurface suitable for computational parameterization (Maskery et al., 2018; Schoen, 1970).

In scaffolds, porosity provides space for tissue and transport pathways but also decreases the amount of load-bearing material. Numerical Gyroid studies and recent tests on printed PCL have found lower stiffness at higher porosity, although the slope depends on architecture and manufacturing conditions (Ali & Sen, 2017; González et al., 2026).

Polycaprolactone (PCL) is used to fabricate scaffolds because it is processable and can form porous polymer structures. Reported moduli for solid or nearly dense PCL range from approximately 300 to 700 MPa, reflecting differences in processing, orientation, and testing (Eshraghi & Das, 2010; Popescu et al., 2023).

Nominal porosity does not necessarily match the printed part. Defects, roughness, nozzle diameter, and wall-thickness deviations change the realized porosity and help explain differences between ideal models and experiments on both metallic and PCL Gyroids (González et al., 2026; Ma et al., 2020).

Finite element models can isolate the contribution of geometry when the constitutive law is held constant. However, cell count, mesh density, and boundary conditions affect the computed stiffness; convergence and domain definition must therefore be reported (Maskery et al., 2018; Tian et al., 2019).

This study determined the relation between geometric porosity and axial effective modulus for a family of PCL sheet Gyroids. We hypothesized that relative stiffness would decrease monotonically as the solid fraction decreased and that a power law could describe the simulated range (Ali & Sen, 2017; Guarino et al., 2007).

2 Background

The Gyroid scalar field is given by equation (1), where X , Y , and Z denote spatial phases. This periodic representation is analogous to level-set parameterizations used for other triply periodic minimal surfaces (Ma et al., 2020; Maskery et al., 2018).

(1)

The solid phase follows equation (2). Changing the threshold τ changes the sheet thickness and solid fraction.

(2)

A scaffold modulus reflects more than polymer properties: connectivity, thickness, tortuosity, and deformation mechanisms also contribute. Results on Gyroids, orthogonal lattices, and porous PCL show that architecture changes both the magnitude and the shape of the porosity–stiffness relation (Ali & Sen, 2017; Guarino et al., 2007).

Eshraghi and Das (2010) reported compressive moduli of 297.8–317.1 MPa for solid material produced by selective laser sintering. Together with results from other processing routes, these data support using 350 MPa as a reference assumption rather than a universal PCL constant (Popescu et al., 2023).

Periodic homogenization is appropriate when the objective is the constitutive matrix of a representative volume element (RVE), whereas prescribed displacements better describe the finite specimen compressed here. Linear constraint equations can impose periodicity in Abaqus but require careful pairing of nodes and treatment of degrees of freedom (Dassault Systèmes, 2025b; Tian et al., 2019).

3 Materials and methods

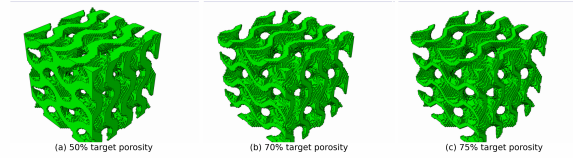
3.1 Geometry generation

A cubic $12 \times 12 \times 12$ mm domain contained two Gyroid cells along each axis. Spatial coordinates were converted to phases with a 6 mm period. Fixed phase shifts reduced artificial alignment between the Cartesian mesh and zero crossings of the scalar field (Ma et al., 2020; Maskery et al., 2018). Figure 1 shows three representative geometries.

Thresholds were calibrated with one million uniformly sampled points and a fixed random seed, independently of the finite element mesh. Each voxel was classified at its center. Realized porosity was calculated using equation (3), where N is the number of voxels per edge and N_e is the number of solid elements. This distinguishes realized porosity from its target (González et al., 2026; Xu et al., 2021).

(3)

Figure 1 – Voxelized Gyroid geometries at three target porosities: (a) 50%, (b) 70%, and (c) 75%. Source: author's simulations.



3.2 Material and discretization

PCL was modeled as homogeneous, isotropic, and linearly elastic, with $E = 350$ MPa and $\nu = 0.30$. The prescribed axial strain was 0.1%, within the small-strain regime. This idealization omits viscoelasticity, anisotropy, and processing effects (Dassault Systèmes, 2025a; Popescu et al., 2023).

The primary mesh used 64 voxels per edge (element size 0.1875 mm) and C3D8R reduced-integration hexahedra. Depending on porosity, the models contained 65,312–130,752 elements. Mesh density was selected after comparing successive discretizations (Abueidda et al., 2019; Maskery et al., 2018).

3.3 Boundary conditions and postprocessing

Nodes on the bottom face had $U^z = 0$, and two nodes were restrained laterally to eliminate rigid-body motion. All top-face nodes received $U^z = -0.012$ mm, while the side faces remained free. This represents uniform axial displacement of a finite specimen (Ma et al., 2020; Xu et al., 2021).

The axial effective modulus was calculated with equation (4), where the absolute sum of top-face reaction forces is multiplied by specimen height $L = 12$ mm and divided by cross-sectional area $A = 144$ mm² and imposed displacement $\Delta = 0.012$ mm. Reaction forces were extracted from the final output-database increment (Eshraghi & Das, 2010; Maskery et al., 2018).

(4)

All analyses used a static, linear step in Abaqus Standard 2024. The result is the apparent effective modulus along z for the specified finite specimen, not a complete periodic homogenized constitutive matrix or an experimentally validated measurement (Dassault Systèmes, 2025b; Tian et al., 2019).

3.4 Mesh refinement and curve fit

Mesheres with 48 and 64 voxels per edge were compared at target porosities of 50%, 70%, and 75%; the 75% case was also analyzed at 80 voxels per edge. This tests both representation of thin walls and the resulting reaction force (Maskery et al., 2018; Tian et al., 2019).

Relative modulus versus solid fraction was fitted in logarithmic space using equation (5), where C and n are empirical coefficients. The fit describes this modeled family and does not replace the finite element solutions (Ali & Sen, 2017; Guarino et al., 2007).

(5)

4 Results

4.1 Porosity and effective modulus

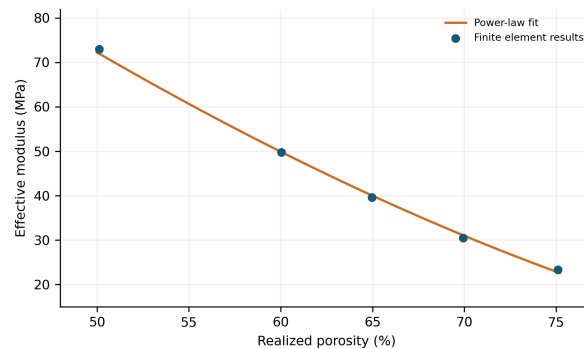
Realized porosity differed from its target by at most 0.122 percentage points. Element count declined with solid fraction while the base material, external specimen volume, and imposed displacement remained unchanged. Table 1 reports the primary series.

Table 1 – Primary results for meshes with 64 voxels per edge.

Target porosity (%)	Realized porosity (%)	Elements	E_{eff} (MPa)	E_{eff}/E
50	50.122	130,752	72.96	0.2085
60	60.034	104,768	49.77	0.1422
65	64.966	91,840	39.61	0.1132
70	69.928	78,832	30.46	0.0870
75	75.085	65,312	23.28	0.0665

The effective modulus decreased monotonically from 72.96 MPa at approximately 50% porosity to 23.28 MPa at approximately 75%, a reduction of 68.1%. This nonlinear trend is consistent with published observations on porous Gyroids, without constituting direct validation (Ali & Sen, 2017; González et al., 2026). Figure 2 shows the data and fit.

Figure 2 – Effective modulus versus realized porosity; orange line shows the fitted power law. Source: author’s simulation results.



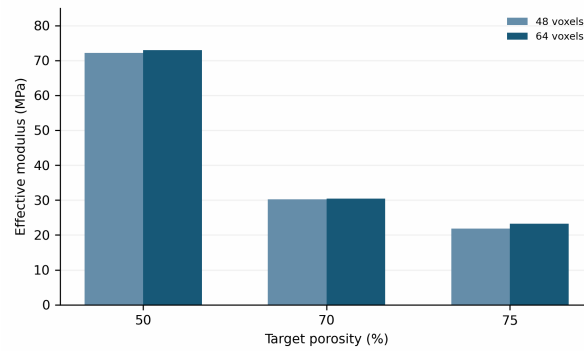
The fitted relation is shown in equation (6), with $R^2 = 0.998$ in logarithmic space. The exponent summarizes this series and should not be transferred to other Gyroid variants, fabrication processes, or boundary conditions without recalibration (Guarino et al., 2007; Hill, 1963).

(6)

4.2 Mesh refinement

The modulus changed by 1.1% between 48 and 64 voxels at 50% target porosity and by 0.8% at 70%. At 75%, the change was 6.8%; additional refinement from 64 to 80 voxels changed the result by 2.4% relative to the finer model. Figure 3 shows the 48- and 64-voxel comparison.

Figure 3 – Effective modulus computed with 48 and 64 voxels per edge. Source: author’s simulation results.

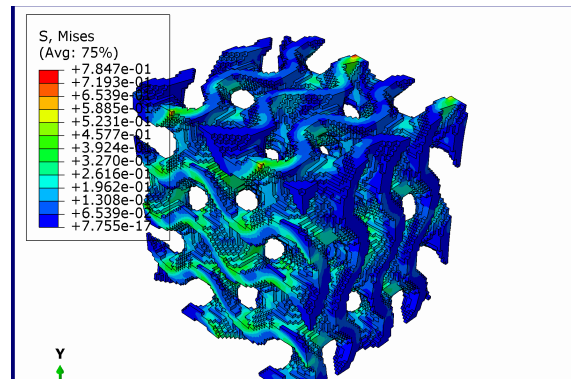


The greater sensitivity at high porosity reflects thinner walls represented by fewer voxels. An exploratory 80% case was excluded from the primary regression because its coarse meshes showed stronger discretization dependence (Ma et al., 2020; Maskery et al., 2018).

4.3 Stress field

The von Mises field at 70% porosity showed continuous load paths and concentrations near curved regions and the loading faces (Figure 4). The field is interpreted qualitatively because local peaks on voxelized boundaries are sensitive to mesh resolution and idealized loading (Abueidda et al., 2019; Ma et al., 2020).

Figure 4 – Cropped view of von Mises stress in the scaffold at 70% porosity after compression (MPa).
Source: author’s Abaqus Standard 2024 simulation.



4.4 Sensitivity to the PCL modulus

In this linear-elastic displacement-controlled model, effective stiffness scales directly with the base-material modulus when ν remains fixed. Alternative assumed values of E can thus be estimated without rerunning the solver, although printed PCL still requires characterization (Dassault Systèmes, 2025a; Popescu et al., 2023). Table 2 shows this sensitivity.

Table 2 – Linear sensitivity of the effective modulus to the assumed PCL modulus (MPa).

Realized porosity (%)	$E = 300$ MPa	$E = 350$ MPa	$E = 500$ MPa	$E = 700$ MPa
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50.122	62.54	72.96	104.23	145.93
60.034	42.66	49.77	71.10	99.54
64.966	33.95	39.61	56.58	79.21
69.928	26.11	30.46	43.52	60.93
75.085	19.96	23.28	33.26	46.57

Table 2 isolates the effect of E in the selected material model; its four columns are not measurements of four tested materials. Changes in process can also alter ν , anisotropy, viscoelasticity, and printed geometry (Eshraghi & Das, 2010; Xu et al., 2021).

The normalized ratio E_{eff}/E is therefore more transferable than an absolute modulus but still depends on architecture and boundary conditions. For a real batch, the calculated ratio should be combined with a dense-specimen modulus measured using matching manufacturing parameters (González et al., 2026; Popescu et al., 2023).

4.5 Computational reproducibility

Geometry generation uses a fixed seed and records τ , realized porosity, and node and element counts in JSON. The input files (INP) specify the material, node sets, displacement, and output requests, allowing the models to be reproduced and mesh differences audited.

Postprocessing sums RF^z over the top face and retains the ODB files, limiting manual transcription. Numerical reproducibility does not establish experimental reproducibility, which also depends on printer, nozzle, material batch, and measured porosity (González et al., 2026; Ma et al., 2020).

5 Discussion

The 68.1% decrease indicates that porosity strongly controls stiffness within this family. A smaller solid fraction decreases load-bearing area and increases susceptibility of the sheets to bending, consistent with earlier polymer Gyroid studies (Abueidda et al., 2019; Maskery et al., 2018).

The calculated 23–73 MPa range is broadly comparable in order of magnitude to other PCL scaffolds, but this is not a validation against matched specimens. Eshraghi and Das (2010) reported compressive values of 12.1–14.9 MPa for orthogonal scaffold architectures; their geometry and processing differed from those studied here.

The assumed E of 350 MPa scales all results in the adopted model. If dense PCL instead had $E = 700$ MPa with identical ν and geometry, the predicted moduli would double. This sensitivity matters because processing routes produce different PCL properties (Eshraghi & Das, 2010; Popescu et al., 2023).

A high goodness of fit does not establish a universal material law. The exponent depends on sheet topology, porosity interval, cell count, and loading conditions; different architectures can produce different curves at the same porosity (Ali & Sen, 2017; Guarino et al., 2007).

The model contains ideal geometry and omits internal voids, roughness, wall-thickness variation, and measured printed porosity. Experimental studies show that realized and nominal porosity may differ and that defects contribute to discrepancies among CAD models, finite element analysis, and tests (González et al., 2026; Ma et al., 2020).

The applied boundary conditions describe a finite specimen with free side faces, not a strictly periodic RVE. A future extension could impose periodic constraints and solve six independent load cases to obtain the full elastic matrix while checking compatibility and equilibrium (Dassault Systèmes, 2025b; Tian et al., 2019).

5.1 Limitations

The main limitation is the absence of validation on specimens made from the same PCL, process, and geometry. Published properties offer only reference ranges because molecular weight, crystallinity, orientation, and printing settings influence polymer behavior (Eshraghi & Das, 2010; Popescu et al., 2023).

Voxelization creates stepped surfaces and demands finer resolution as walls become thinner. Global-modulus refinement was adequate up to 75% for the checked cases, but local stresses and higher porosities require a conforming mesh or greater resolution (Abueidda et al., 2019; Maskery et al., 2018).

6 Conclusions

For the modeled geometry and assumptions, increasing realized porosity from 50.122% to 75.085% decreased the effective modulus from 72.96 to 23.28 MPa. The monotonic trend agrees qualitatively with numerical and experimental literature, but the absolute values are model-specific (Ali & Sen, 2017; González et al., 2026).

A power law described the five simulated cases with $R^2 = 0.998$ and exponent 1.659. It provides interpolation within this range for the same linear-elastic PCL assumption, two cells per axis, and finite-specimen boundary conditions (Guarino et al., 2007; Hill, 1963).

The final mesh refinements considered for target porosities of 50%, 70%, and 75% changed global modulus by less than 2.5%. Future work should fabricate matched specimens, measure realized porosity, and calibrate printed-material properties before comparing predictions and experiments (Ma et al., 2020; Xu et al., 2021).

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