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- Dr Katarina Monkova
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Preliminary structural assessment of Bézier-based lattice cells

Emanuele Vincenzo Arcieri^{a,*}, Sergio Baragetti^a

^aDepartment of Management, Information and Production Engineering, University of Bergamo, Viale Marconi 5, Dalmine 24044, Italy

Abstract

This study presents a preliminary assessment of the structural behavior of a Bézier-based lattice elementary cell, focusing on the influence of ligament thickness and position of control points of the base curve. Only nine finite element analyses were conducted in Abaqus to evaluate the effects of the geometric parameters on stress distribution, displacement, strain energy and cell volume. Results reveal that ligament thickness exhibits a strong linear correlation with cell volume and a moderate correlation with stress, displacement and strain energy. The position of the intermediate control points in the direction perpendicular to the segment connecting the base curve endpoints shows moderate correlations with structural response. These findings offer preliminary design guidance for tailoring Bézier-based lattice cells for lightweight structures with minimal computational effort.

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Keywords: Lattice structures; Bézier curves; finite element analysis

1. Introduction

The rapid evolution of additive manufacturing has played a pivotal role in the diffusion of lattice structures, since it enables the fabrication of architectures which are difficult or even impossible to obtain with traditional manufacturing technologies. Lattice structures offer many advantageous properties, such as high strength-to-mass ratios which make them very attractive for aerospace engineering (Borikar et al., 2023; Liu et al., 2024).

The structural response of lattice structures is significantly influenced by their inner structure and a broad spectrum of properties, such as stiffness and bulk modulus, can be tailored to specific performance requirements by modifying the geometry of the elementary cell (Lebeas et al., 2010; Hashemian et al., 2011; Bai et al., 2022; Almalki et al., 2023).

* Corresponding author. Tel.: +39-035-205-2382.

E-mail address: emanuelevincenzo.arcieri@unibg.it

The adoption of curved elements in place of straight ligaments has emerged as a promising strategy to enhance energy absorption capabilities of lattice structures. In this scenario, Bézier curves are particularly attractive thanks to their favorable balance between the wide range of achievable geometries and the reduced number of defining parameters. The shapes of Bézier curves are defined by a limited number of control points and this enables the creation of a broad design space by varying only a few geometric factors (Álvarez-Trejo et al., 2021, 2023).

Given the broad spectrum of achievable mechanical properties, identifying architectures that provide targeted structural responses remains a significant challenge. Understanding how geometric parameters influence the mechanical behavior of lattice structures is therefore essential for guiding design decisions. Following the studies of Álvarez-Trejo et al. (2021, 2023), this work investigates the influence of geometric parameters on the structural response of a Bézier-based lattice structure in a fast way, using finite element modeling in Abaqus and Taguchi design of experiments approach in modeFRONTIER software. The objective is to provide designers with preliminary guidance for generating Bézier-based lattice structures with tailored mechanical properties with minimal computational effort, supporting accelerated exploration of lightweight structures. In contrast to Fanelli et al. (2025), where numerous finite element simulations were conducted, the present work employs only nine simulation runs to roughly assess the influence of control point positions of the base Bézier curve and ligament thickness on the structural response of a single lattice cell. The ligament thickness linearly influences cell volume and has moderate correlation with stresses, displacement and strain energy. The position of the intermediate control points in the direction perpendicular to the segment connecting the base curve ends has moderate correlations with structural response.

Nomenclature

P_0	first control point of the base Bézier curve
P_1	second control point of the base Bézier curve
P_2	third control point of the base Bézier curve
P_3	fourth control point of the base Bézier curve
s	ligament thickness
u	parameter for the definition of the base Bézier curve
$U1$	maximum lateral displacement
$U2$	maximum vertical displacement (in magnitude)
x_1, y_1	coordinates of P_1 in the local coordinate system
λ	distance between the endpoints of the base Bézier curve

2. Materials and methods

The 21 mm × 25 mm × 25 mm elementary cell of a sandwich panel was analyzed (Fanelli et al., 2025). The two skins are 2 mm thick and the core presents a pattern of 4 × 4 anti-symmetric cubic Bézier curves extruded along the out-of-plane direction (Fig. 1a). Such curves have four control points, P_0 , P_1 , P_2 and P_3 (Fig. 1b), and follow the parametric formulation reported in Equation 1:

$$C(u) = (1 - u)^3 P_0 + 3u(1 - u)^2 P_1 + 3u^2(1 - u) P_2 + u^3 P_3 \quad (1)$$

with $u \in [0,1]$.

Considering a single antisymmetric Bézier curve defined in a local coordinate system, with P_0 positioned in (0,0) and P_3 in ($\lambda,0$), the intermediate control points are in $P_1(x_1, y_1)$ and $P_2(\lambda - x_1, -y_1)$, where $\lambda = 5.25$ mm is the distance between the endpoints of the curve.

The lattice structure was modeled using 2D plane strain elements and a mesh size of 0.05 mm. The cell material was assumed to be homogeneous, isotropic and linear elastic PLA. A Young's modulus of 3500 MPa and a Poisson coefficient of 0.36 were defined. A general static analysis was conducted, accounting for geometric nonlinearity. The bottom skin of the cell was fixed and a pressure of 0.1 MPa was uniformly applied on the top skin.

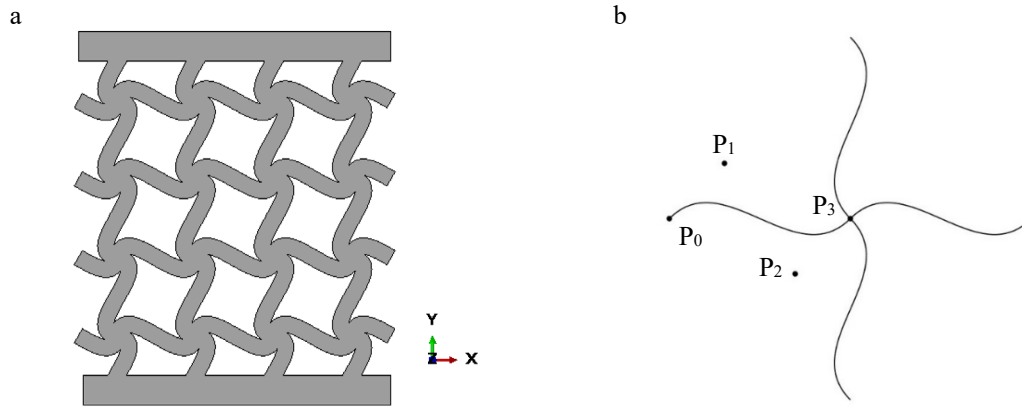


Fig. 1. (a) geometry of the elementary cell; (b) scheme for Bézier curve and repetition pattern (Fanelli et al., 2025).

Table 1. Parameter combinations used in the study.

Run	s (mm)	x_1 (mm)	y_1 (mm)
1	0.5	0.5	0.5
2	0.5	1.6	1.6
3	0.5	2.7	2.7
4	0.8	0.5	1.6
5	0.8	1.6	2.7
6	0.8	2.7	0.5
7	1.1	0.5	2.7
8	1.1	1.6	0.5
9	1.1	2.7	1.6

This work preliminarily investigates the influence of the ligament thickness s and position of P_1 with respect to P_0 . Design of experiments analysis based on the Taguchi method was conducted by interfacing modeFRONTIER with Abaqus in order to have automated generation and evaluation of design variants. The geometric parameters were varied according to a Taguchi L9(3^4) orthogonal array, as reported in Table 1. In this way, only nine finite element simulations were run to investigate the effects of three factors, each at three levels. The values for s were selected so that the ratio s/λ is always below 0.3, preserving topological integrity (Álvarez-Trejo et al., 2023).

3. Results and discussion

To investigate the structural behavior of the elementary cell of the lattice structure, the maximum von Mises stress, the maximum lateral displacement U_1 , the maximum vertical displacement in magnitude U_2 , the strain energy and the cell volume were considered. Due to the antisymmetric configuration of the base curve, lateral displacement occurs for the studied loading case of a uniform pressure applied on the top skin. Both displacement components were analyzed, as they provide a measure of the cell energy absorption capabilities. The cell volume was also examined, given its relevance to strength-to-mass optimization.

To explore correlations among input and output parameters, a scatter matrix analysis was performed, Fig. 2. The distribution of each parameter is reported in the diagonal plots, while the scatter plots are shown in the upper part. The lower triangle indicates the correlation coefficients. Coefficient values close to 1 denote strong positive linear relationships and values near -1 indicate strong negative correlations. A pronounced linear correlation was found between cell volume and thickness s , as the correlation coefficient is 0.956. In contrast, the position of the control point P_1 exhibits weak correlations with volume, since coefficients are -0.083 for x_1 and 0.269 for y_1 . The parameter

x_1 has negligible correlation with the structural behavior, with coefficients ranging from -0.369 to 0.373 . Conversely, y_1 demonstrates a moderate correlation with structural performance, as it influences the curvature of the Bézier ligament. Increments in y_1 lead to increased von Mises stresses, with a coefficient of 0.677 , and higher vertical displacement U_2 (in magnitude), with a correlation coefficient of -0.555 . It should be noted that U_2 is negative due to the direction of the applied load according to the adopted coordinate system (see Fig. 1a). The relationship between y_1 and U_1 is defined by a correlation coefficient of 0.489 . An increase in thickness s results in reduced stresses in the lattice structure and smaller lateral and vertical (in magnitude) displacements. The obtained correlation coefficients are -0.634 , -0.720 and 0.605 , respectively. The correlation between s and strain energy is described by a coefficient of -0.599 , while y_1 shows a moderate positive correlation with energy (0.553), further supporting its role in influencing the mechanical response.

4. Conclusions

This study provides a preliminary evaluation of the mechanical behavior of Bézier-based lattice structures, highlighting the influence of geometric parameters on stress distribution, displacement, strain energy and volume. The design space was investigated using only nine finite element analyses. The results show that ligament thickness presents a strong linear correlation with cell volume and moderate correlations with stress, displacement and strain energy. Moderate correlations were also observed with the position of the intermediate control points in the direction perpendicular to the segment connecting the base curve ends, since higher y_1 values lead to increased ligament curvature.

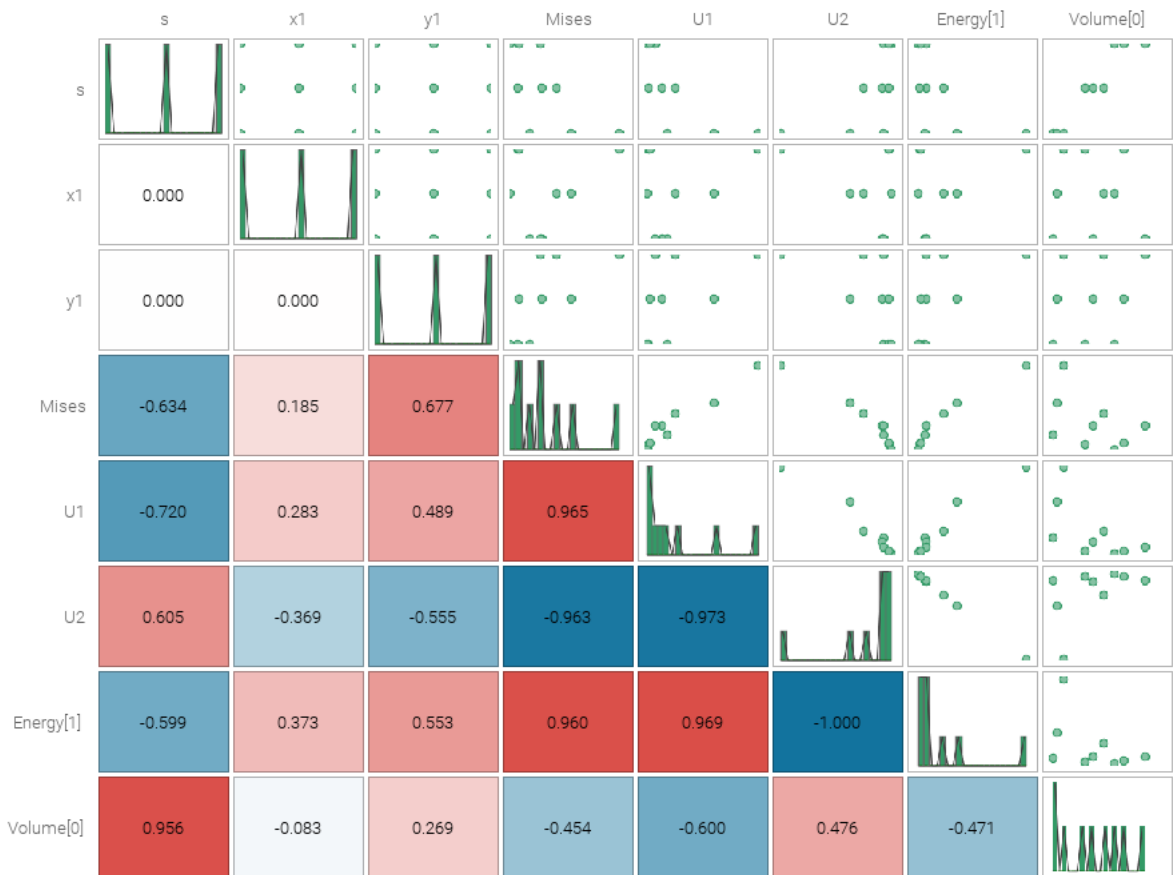


Fig. 2. Results of the analysis in modeFRONTIER.

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