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EFFECT OF GEOMETRIC PROPERTIES AND BOUNDARY CONDITIONS ON THE STRUCTURAL BEHAVIOR OF CONCRETE HELICOID SHELL STRUCTURES

Yasmine Merah^{*1}, Ahmed Merah²

¹Department of Civil Engineering and Hydraulics ,LARGHYDE Laboratory, University of Biskra, Algeria

²University Ammar Telidji of Laghouat, Research Laboratory of Civil Engineering (LRGC), Laghouat, Algeria

¹<https://orcid.org/0009-0008-6254-0287>, ²<http://orcid.org/0000-0003-3910-7326>

Email: * yasmine.merah@univ-biskra.dz, a.merrah@lagh-univ.dz

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ABSTRACT

Helicoid shells, despite their architectural significance, remain underexplored in the existing literature. While prior research has focused on global shape optimization. This study introduces a parametric study by investigating the influence of four key geometric parameters namely the inner radius r_1 , outer radius r_2 , one-loop height H , and obliqueness angle α on the total strain energy and displacement in the axis z of two concrete helicoid shell configurations. The study is carried out using COMSOL Multiphysics. The results demonstrate that structural performance is highly sensitive to geometric parameters. For the full-turn helicoid, the outer radius r_2 governs the global performance, leading to the most efficient strain-energy reduction, while the inner radius r_1 also plays a significant role by enhancing global stiffness. In the half-turn helicoid, both inner radius r_1 and outer radius r_2 become the dominant parameters, producing the largest improvement in strain energy. The obliqueness angle α exhibits a secondary influence in the half-turn helicoid case, while the height H has a non-negligible effect in both cases.



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I. INTRODUCTION

In general, the modeling of shell structures has attracted significant attention due to their high structural efficiency and ability to span large areas with minimal material. Numerous studies have focused on the effect of geometry parameters in shell structures behavior [1] [2]. Recent advancements in computational modeling and finite-element analysis have renewed interest in the modeling of concrete shell geometries, enabling engineers to design forms that were previously difficult to analyze. Starting by a parametric study investigated the static behavior of long cylindrical concrete thin shells under self-weight using ANSYS software, examining the effects of span, central angle, and thickness in the structural performance [3]. In addition, Michiels and Adriaenssens [4] demonstrate that thin concrete roof shells can be inherently earthquake-resistant, owing to their low mass, high geometric stiffness, and elevated natural frequencies that limit seismic demand. The results show that shells with a small-to-medium span can be naturally earthquake-resistant. More recent research, Emami et al [5] present an integrated computational framework that uses parametric modelling and sensitivity analysis to simultaneously evaluate the structural and environmental performance of perforated concrete shell structures.

The study identifies the perforation ratio as the dominant design variable and recommends an optimal range of 10–20% to strike a structural efficiency and daylight performance. Prateek and Garg [6] numerically evaluate hyperbolic paraboloid shell footings using FEM, focusing on the influence of shell geometry (f/a ratio), beam cross-section, and embedment depth on structural performance. Aijaz et al [2] Investigate the feasibility of using concrete domes for housing by conducting a detailed parametric analysis of geometry, thickness, openings and reinforcement. The results identify the optimal design parameters: a rise-to-span ratio of between 0.3 and 0.35; a crown opening of 1 m for effective skylighting; and curved door and window openings that reduce stresses by up to 30%, while also enhancing the architectural aesthetic. Sheeja et al [7] present FEM-based parametric studies on conical shell foundations, examining the influence of rise-to-radius ratio and shell thickness on settlement and load capacity. Nachiar et al [8] investigate the optimization of spherical shell roofs by analyzing the influence of radius-to-thickness ratios on structural performance.

Many studies also focus on the optimization of complex shell structures such as [9] [10] and others focus on the effect of various parameters in the optimization process [11] [12]. Helicoid shell structures are one of the most important complex geometries. Paul [13] explores the geometry and classification of helicoid surfaces, identifying five distinct types of helicoid and their potential applications in architecture and civil engineering. Rynkovskaya and Ivanov [14] presents an improved analytical method for evaluating the stress-strain behavior of right helicoids. Evgeniya and Marina [15] develops analytical and numeric-analytical methods for stress-strain analysis of shallow right and oblique helicoid shell structures based on the Kirchhoff-Love thin shell theory. A comparison of multiple shape optimization solvers in COMSOL to identify the most effective approach for shape optimization of both spherical dome and helicoid concrete shells was also studied [10]. Based on the previous researches, the present study investigates the effect of geometric parameters namely the inner radius r_1 , outer radius r_2 , one-loop height H , and obliqueness angle α on the total strain energy and displacement in the axis z in both half- and full-turn concrete helicoid shells. By studying the influence of these parameters, this work provides a structured methodology to support preliminary design decisions prior to defining the final shell geometry.

II. HELICOID CONCRETE SHELL STRUCTURE

Helicoid surfaces are a class of shell structures, makes them ideal for applications such as spiral staircases and ramps in reinforced concrete structures. In parametric form, a general helicoid can be expressed as [16] [13]:

$$x = r \cos v; y = r \sin v; z = cv + kr \quad (1)$$

With $k = \cotg \alpha$

If $\alpha = \pi/2$ the surface is referred to as a straight (right) helicoid; otherwise, it is classified as an oblique helicoid. The helicoid is represented in the Eq.2 as follow:

$$\begin{aligned} x(r, v) &= r \cos(v), y(r, v) = r \sin(v), z(r, v) = cv + r \cotg \alpha \\ r_1 &\leq r \leq r_2 \\ 0 &\leq v \leq 2\pi \end{aligned} \quad (2)$$

Here, r and v represent the curvilinear coordinates of an arbitrary point on the helicoid surface. The parameter r denotes the radial distance from the helicoid axis Oz , while v is the angular coordinate measured from the Ox axis to the projection of the point onto the xOy plane. The parameter c corresponds to the vertical displacement of the generatrix per unit radian and is related to the height of one helicoid loop H by the Eq.3:

$$c = \frac{H}{2\pi} \quad (3)$$

When the angular parameter of the helicoid is limited to a half turn ($0 \leq v \leq \pi$) as in the Fig.2.a, but the structure is required to reach the full height H , the c parameter must be adjusted to be $c = \frac{H}{\pi}$. The corresponding parametric formulation ensures geometric continuity where the total elevation is completed within half a rotation.

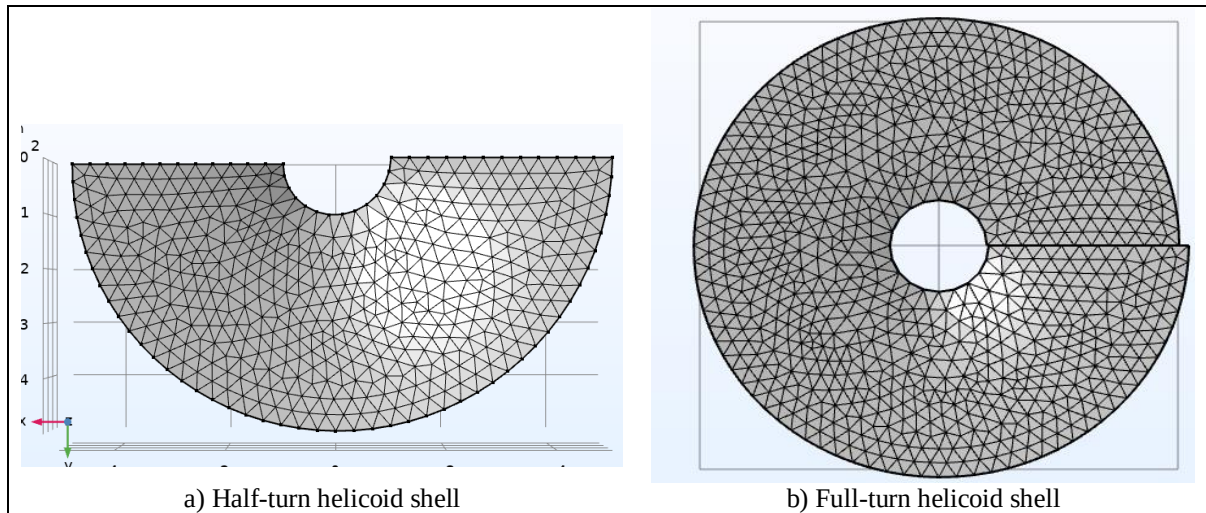


Figure1: Meshing of helicoid shell.

Source: Authors, (2026).

The shell structure in this example is made of concrete with a material density of 2300 kg/m^3 . A vertical distributed load of $10,000 \text{ N/m}^2$ is applied to the shell surface. The helicoid shell has a uniform thickness of 0.16 m . The finite element discretization was performed using COMSOL Multiphysics with an automatic meshing set to extra fine element size for both configurations as shown in the (Fig.1).

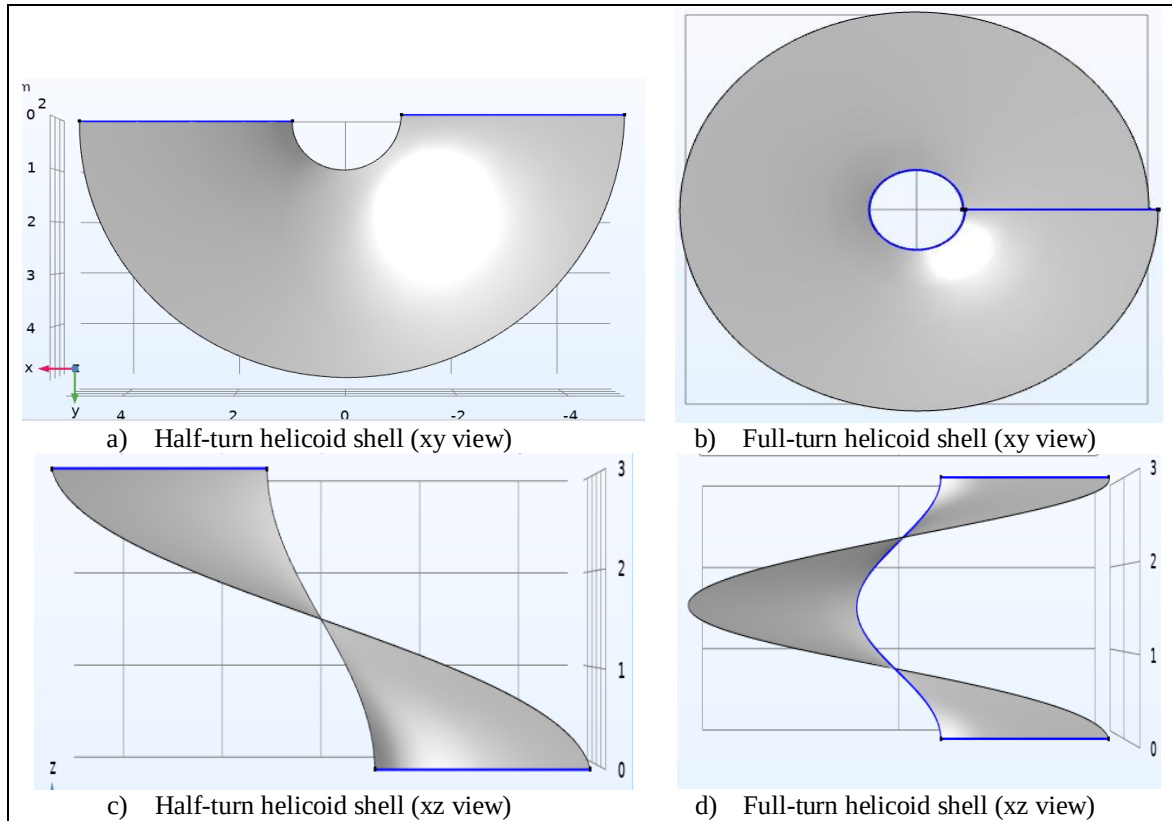


Figure 2: Boundary conditions of both helicoid shell configurations.

Source: Authors, (2026).

The Fig. 2 illustrates the boundary conditions applied to the two helicoid shell configurations considered in this study.

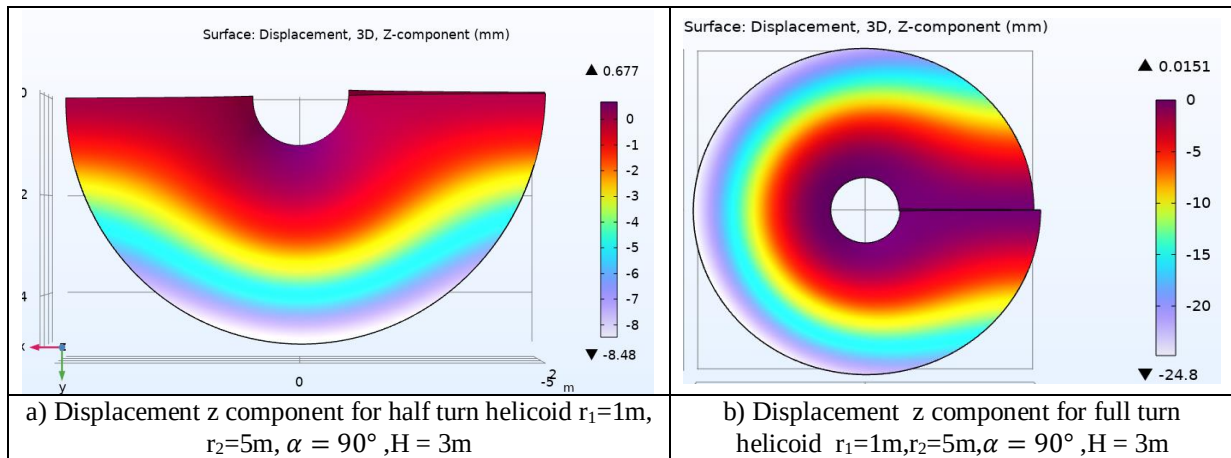


Figure 3: Displacement z component of both helicoid shell configurations.

Source: Authors, (2026).

The comparison between the full turn helicoid and the half turn helicoid (Fig. 3) highlights the significant influence of geometry and boundary conditions on structural response. In Fig. 2.b, the helicoid is constrained at both the inner edge and the extremity, providing a higher degree of restraint. In contrast, the half-turn helicoid in Fig. 2.a is fixed only at the extremity, resulting in a less constrained system. Despite these differences, the maximum displacement along the global z-axis is 24.8 mm for the full-turn helicoid (Fig.3.b) and 8.48 mm for the half-turn helicoid (Fig.3.a). The lower displacement observed in the half-turn case can be attributed to its reduced geometric extent and load path length, which limits the deformation even though fewer boundary constraints are applied.

Table 1: Geometric parameters values for helicoid shell structure

Parameters	Description of the variable parameter	Description of other parameters
Inner radius	1, 2, 3, 4, 5 m	$r_2=r_1+4\text{ m}$, $H = 3\text{ m}$, $\alpha = 90^\circ$
Outer radius	2, 3, 4, 5 m	$r_1=1\text{ m}$, $H = 3\text{ m}$, $\alpha = 90^\circ$
One loop height	2.5, 3, 3.5, 4, 4.5, 5 m	$r_1=1\text{ m}$, $r_2=5\text{ m}$, $\alpha = 90^\circ$
α	87, 88, 89, 90, 91, 92, 93 (Deg)	$r_1=1\text{ m}$, $r_2=5\text{ m}$, $H = 3\text{ m}$

Source: Authors, (2026).

The parameters of the helicoid shell are defined by the values in the Table 1.

III. PARAMETRIC STUDY RESULTS

In this section, the results of the parametric study performed on both the full-turn and half-turn helicoid shell structures. The analysis highlights the influence of key geometric parameters on the structural response, focusing on strain energy and maximum deflection as performance indicators. A comparative evaluation of the two configurations is provided to clarify their distinct mechanical behaviors and to identify the effect of each parameters in stiffness and overall structural efficiency.

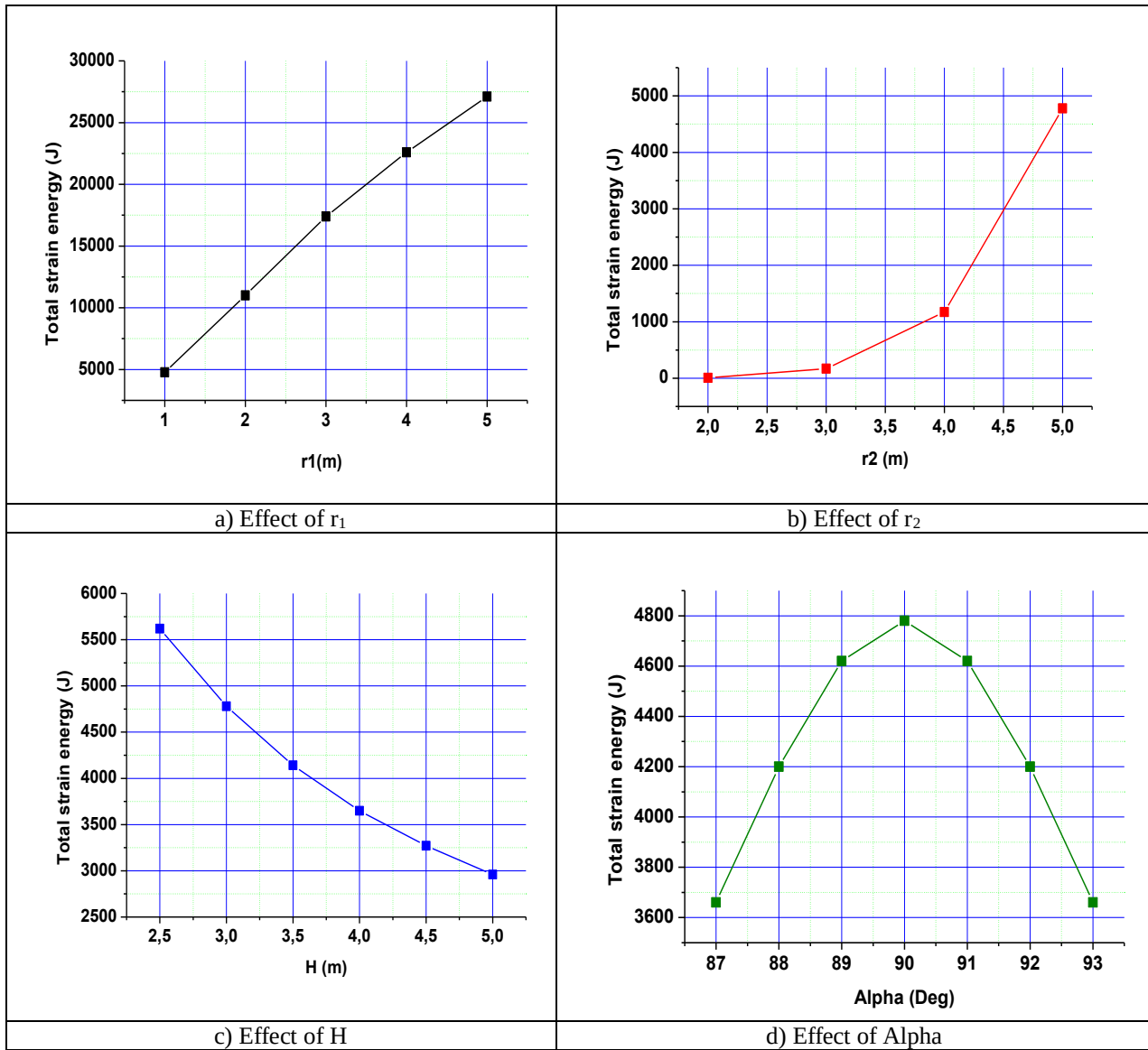
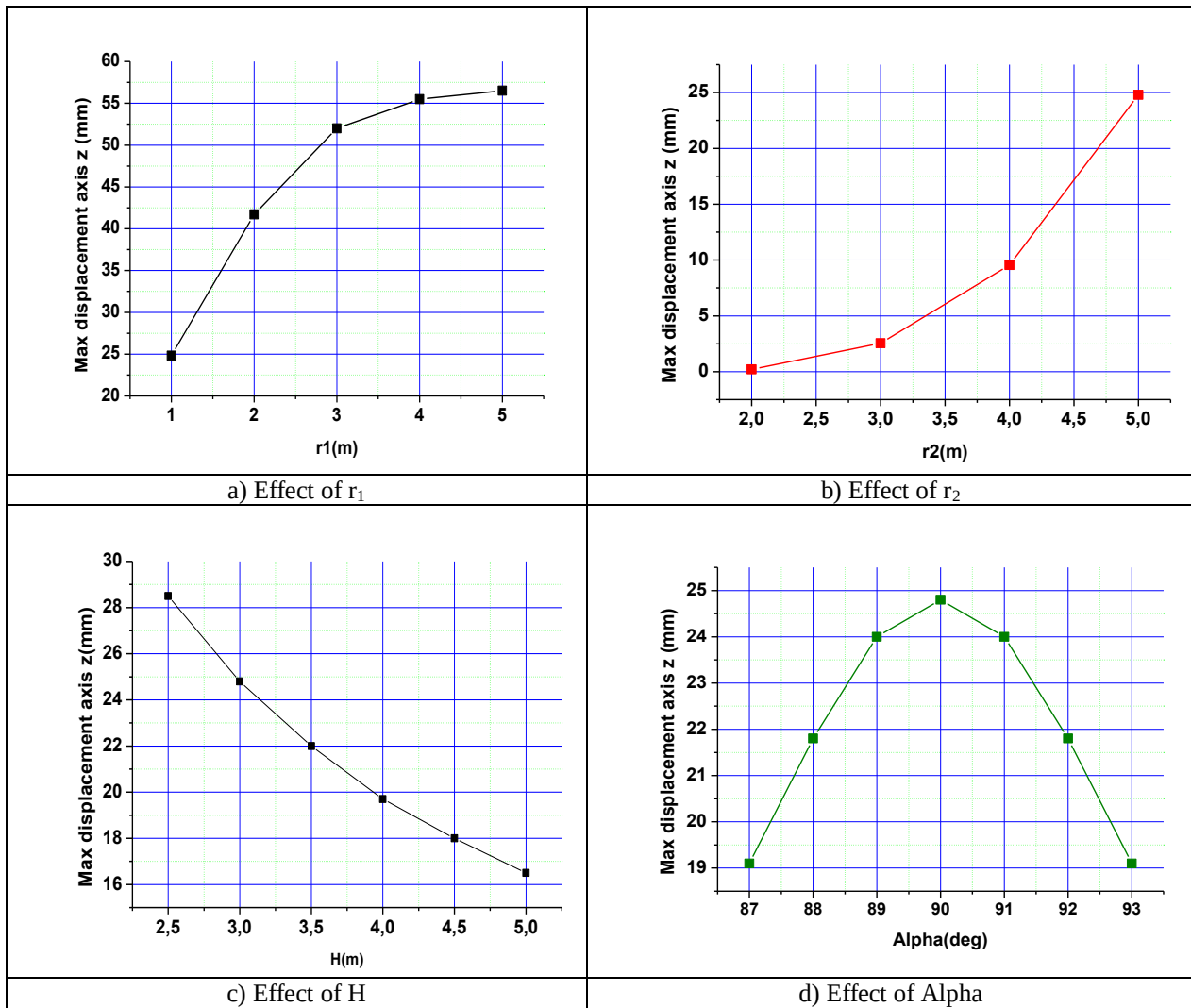


Figure 4: Effect of geometric parameters on the strain energy of full turn helicoid shell structure (case1).

Source: Authors, (2026).

The results in the Fig.4 demonstrate how changes in the key geometric parameters of the full-turn helicoid shell affect its total strain energy. A clear increase in strain energy is observed as the inner radius (r_1) increases. This behavior suggests that a larger inner radius reduces the effective load-bearing capacity of the shell, resulting in higher deformation energy under applied loads. Similarly, the outer radius (r_2) has a significant impact on strain energy, especially beyond a certain point ($r_2=3$). While moderate increases in r_2 result in limited changes, a significant increase in strain energy is observed at larger values, suggesting a loss of structural efficiency due to an increased shell span and greater bending influence. In contrast, increasing the one-loop height (H) results in a noticeable reduction in strain energy. This reflects the beneficial role of the geometric stiffness introduced by the greater vertical height. As for the obliqueness angle (α), the strain energy reaches a maximum at $\alpha = 90^\circ$, decreasing for slightly lower or higher angles. This indicates that small deviations from the orthogonal configuration can improve force redistribution and reduce strain energy.

Figure 5: Effect of geometric parameters on the displacement axis z of full turn helicoid shell structure (case1).

Source: Authors, (2026).

The results in the Fig.5 show that increasing the inner (r_1) and outer (r_2) radius leads to higher maximum displacements, indicating a reduction in global stiffness. In contrast, increasing the one-loop height (H) significantly reduces displacement, demonstrating the positive impact of geometric rise on maximum displacement. The obliqueness angle (α) has a maximum displacement occurs when $\alpha = 90^\circ$, but slight deviations from this angle minimize displacement values.

Table 2: The maximum and minimum values of strain energy for case 1.

Parameters	Max values of strain energy	Min values of strain energy	Difference (%)
r_1 (m)	27100	4780	82.4%
α (rad)	4780	3660	23.4%
r_2 (m)	4780	5.35	99.9%
H (m)	5620	2960	47.3%

Source: Authors, (2026).

The Table 2 presents the maximum and minimum values of strain energy for case 1. The results indicate that the inner radius r_1 has a pronounced influence on the strain energy. Reducing r_1 value leads to a significant decrease in strain energy corresponding to a reduction of 82.4%. This improvement highlights the sensitivity of the structural stiffness to changes in the inner radius, as a smaller r_1 enhances the efficiency of the shell structure. The change of the outer radius r_2 exhibits the most pronounced influence on strain energy minimization. Reducing r_2 value leads to a substantial decrease corresponding to a reduction of 99.9%. It is important to note that this effect is strongly dependent on the shell width ($r_2 - r_1$). Excessive radial extension, particularly for larger shell widths, significantly increases total strain energy due to amplified bending effect. In contrast, variation of the obliqueness angle α results in a more moderate improvement of 23.4%, indicating that the small inclination of the helicoid surface can contribute to structural performance, but, its effect is less dominant compared to radial parameters. Finally, the height H exhibits also moderate influence on the strain energy. Increasing H results in 47.3% reduction in the total strain energy.

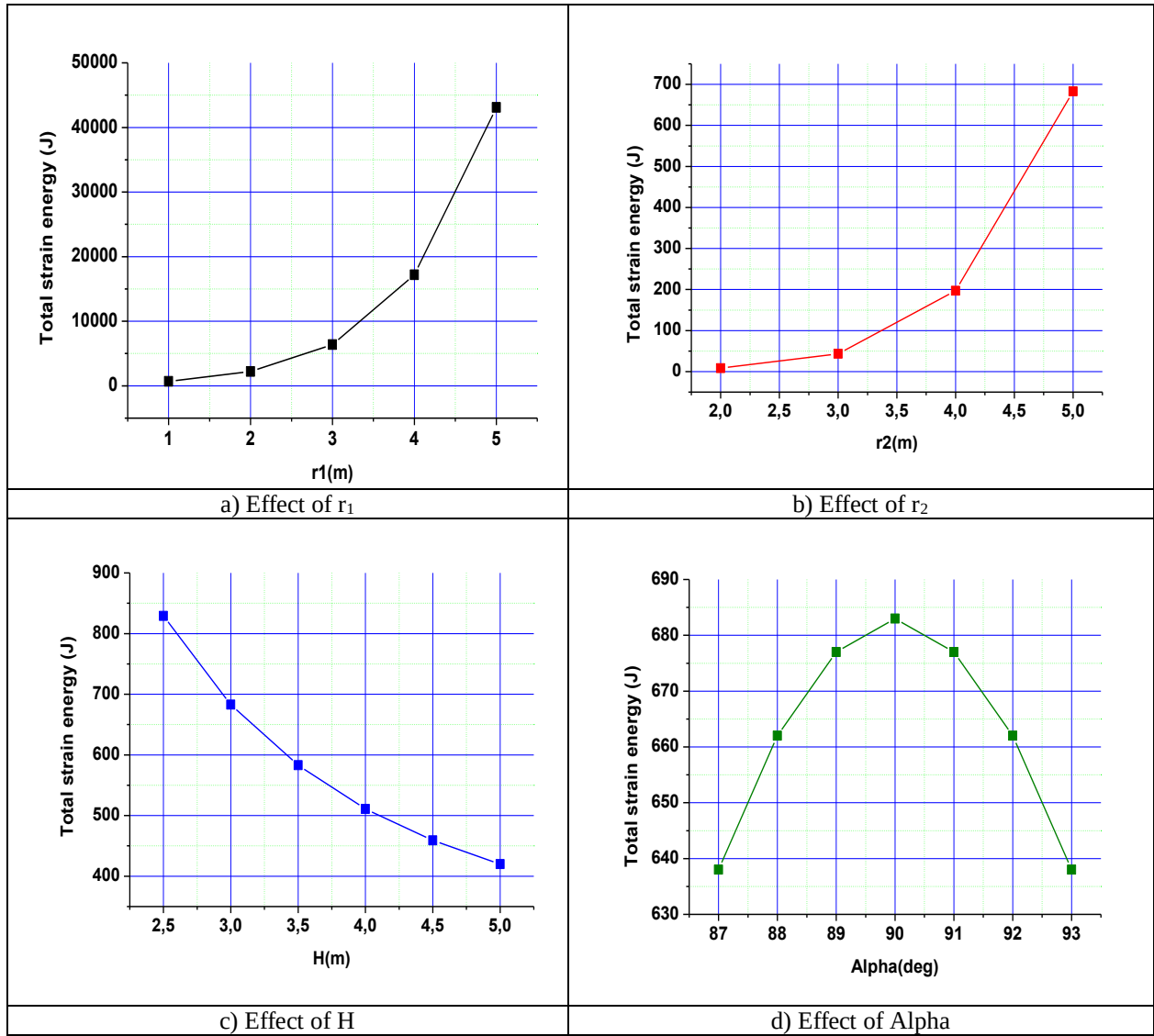
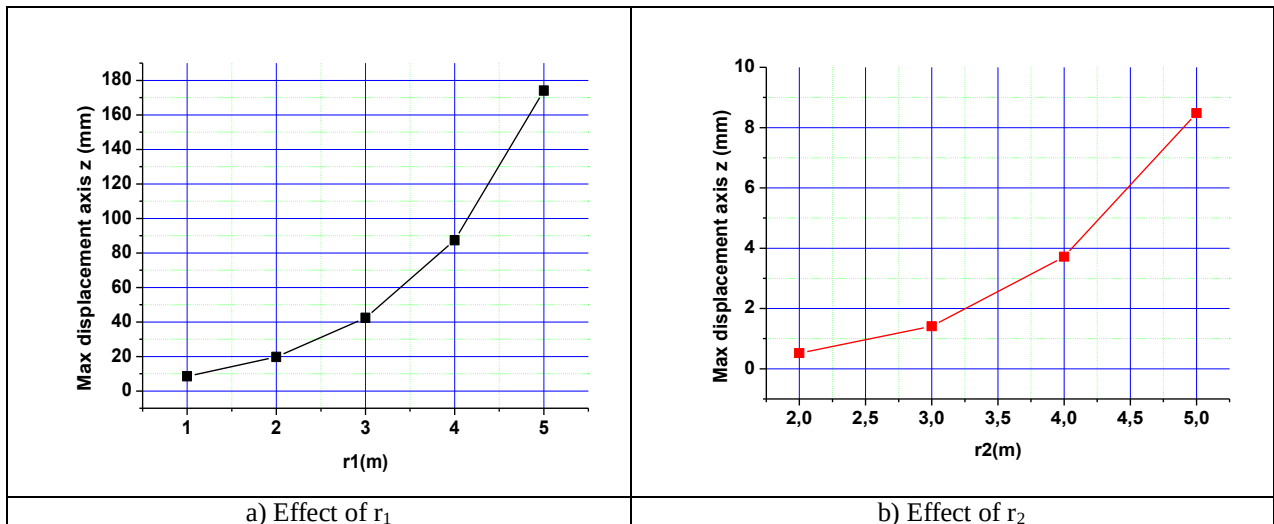


Figure 6: Effect of geometric parameters on the strain energy of half turn helicoid shell structure (case2).
Source: Authors, (2026).

As in the case 1, the total strain energy increases with the increase of the inner (r_1) and outer (r_2) radius, confirming that enlarging the shell span and central opening reduces structural stiffness. However, the full-turn helicoid shell (Case 1) in the Fig.4 consistently exhibits higher strain energy levels than the half-turn configuration (Case 2) in the Fig.6 except the situation when r_1 is very large. In contrast, increasing the one-loop height (H) reduces strain energy in both cases. The obliqueness angle (α) exhibits a similar behavior in both configurations, with peak strain energy observed when $\alpha = 90^\circ$. However, slight deviations from this angle enhance structural efficiency.



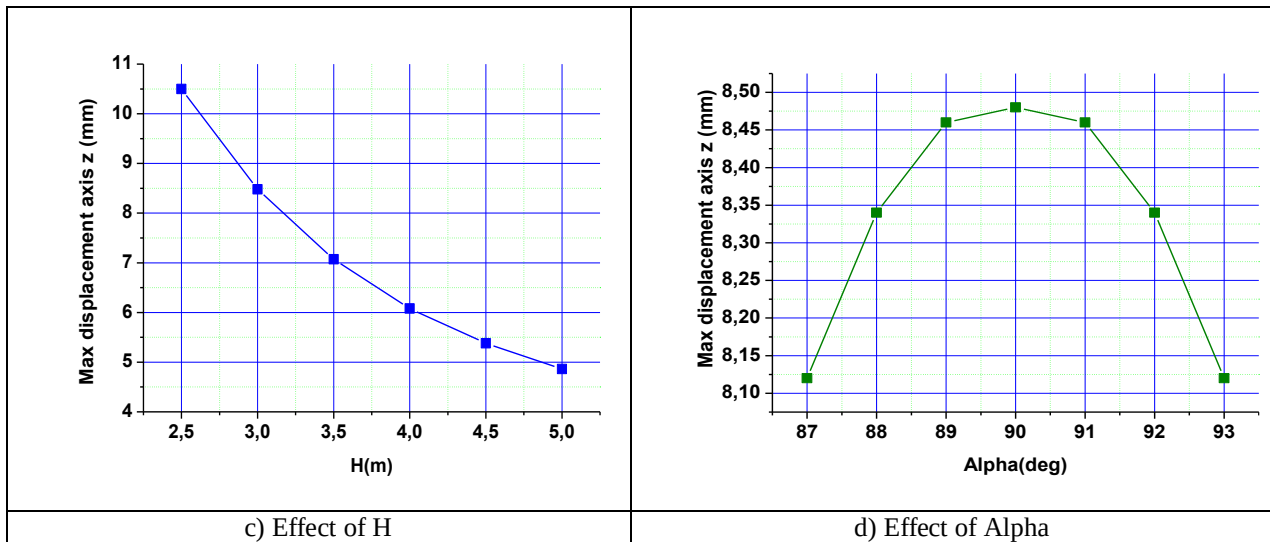


Figure 7: Effect of geometric parameters on the displacement of half turn helicoid shell structure (case2)

Source: Authors, (2026).

According to Fig. 7, the half-turn helicoid shell exhibits increased displacement with increasing inner and outer radius (r_1 and r_2), while displacement decreases as the one-loop height H increases. In addition, when the obliqueness angle reaches $\alpha = 90^\circ$, half turn helicoid shell also shows maximum displacement.

Table 3: The maximum and minimum values of strain energy for case 2.

Parameters	Max values of strain energy	Min values of strain energy	Difference (%)
r_1 (m)	43100	683	98.4%
α (rad)	683	638	6.6%
r_2 (m)	683	8.31	98.8%
H (m)	829	420	49.3%

Source: Authors, (2026).

The results in Tables 2 and 3 show that the radial dimensions r_1 and r_2 are the parameters that most influence the strain energy of the helicoid shells. In both cases, the outer radius (r_2) exhibits the strongest influence, with strain energy variation (99.9% in Case 1 and 98.8% in Case 2). However, the inner radius (r_1) is significantly more sensitive in Case 2 (98.4%) than in Case 1 (82.4%), suggesting that Case 2 is more affected by changes near the shell core, possibly due to the boundary conditions. The height (H) has a similar moderate influence in both cases, with differences of 47.3% and 49.3%, respectively, indicating that increasing the shell rise improves stiffness similarly in both configurations. A key distinction between the two cases is the influence of the obliqueness angle (α). In Case 1, α produces a noticeable variation of 23.4%, whereas in Case 2, its effect is minimal at 6.6%. This suggests that Case 2 is less sensitive to angular variations.

IV. CONCLUSION

Based on the results of strain energy and displacement results for both full and half-helicoid shell structures, the following conclusions can be drawn:

- The parametric study demonstrates that helicoid shell performance is highly sensitive to geometric parameters, with clear differences observed between full and half helicoid configurations. Overall, the half helicoid exhibits better structural efficiency in most cases.
- The inner radius r_1 is identified as one of the most influential parameters in both configurations. Its variation leads to significant reductions in strain energy and displacement, with the half helicoid showing the highest improvements, confirming the strong effect of the inner boundary on global stiffness.
- The outer radius r_2 governs the global structural behavior. Reducing r_2 results in near-complete reductions in strain energy and displacement for both configurations.
- Despite its limited variation, the obliqueness angle α acts as a sensitive parameter. Small angular adjustments lead to measurable reductions in strain energy and displacement even though its influence on half helicoid remains limited.
- The height parameter H has the moderate influence on structural performance. While increasing H improves geometric stiffness, its contribution remains secondary compared to radial parameters.

These conclusions provide practical guidance for the preliminary design of helicoid shell structures, supporting informed parameter selection to achieve efficient and structurally robust designs.

V. AUTHOR'S CONTRIBUTION

Methodology: Yasmine Merah

Writing – Original Draft Yasmine Merah

Writing – Review and Editing: Yasmine Merah, Ahmed Merah

Conceptualization: Yasmine Merah, Ahmed Merah.
Methodology: Yasmine Merah, Ahmed Merah.
Investigation: Yasmine Merah, Ahmed Merah.
Discussion of results: Yasmine Merah, Ahmed Merah.
Writing – Original Draft: Yasmine Merah, Ahmed Merah..
Writing – Review and Editing: Yasmine Merah, Ahmed Merah.
Resources: Yasmine Merah, Ahmed Merah.
Supervision: Yasmine Merah, Ahmed Merah.
Approval of the final text: Yasmine Merah, Ahmed Merah.

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