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The Optimal CAD Design of a 3D Hexagonal Toroid with Regular Hexagonal Cross-Section Used in Manufacturing of LPG Storage Tanks

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Abstract: *The objective in this paper is to optimal CAD design of a 3D hexagonal toroid with regular hexagonal cross-section used in manufacturing of LPG storage tanks used in automotive industry based on the finite element analysis (FEA) approaches. A design strategy to define specific key performance indicators according to manufacturing objectives was developed to determine the optimal form of the 3D hexagonal toroidal LPG fuel tank with lower values of the stress state and linear deformation. Numerical simulations are carried out using a 3D model done in the AutoCAD Autodesk 2017 software, which was imported for analysis to SolidWorks 2017 software. The results will allow the improvement of design strategies of toroidal LPG fuel tanks, which create the relationships between work items and product components in the proposed 3D CAD objects.*

Keywords: *Automotive industry, industrial engineering design, optimization methods, 3D hexagonal toroidal LPG fuel tank*

1. Introduction

The developing of new manufacturing strategies is a complex task due to many factors (expensive equipment, expensive tests, and safety constraints) that imply virtual computer aided engineering tools in developing innovative ways in 3D CAD modelling of prototypes of storage fuel tanks used in automotive industry [1-6].

During the last few decades in manufacturing of storage fuel tanks in automotive industry various models were proposed with a wide range of adaptations in response to changing productivity, prices, and the materials use [7-13].

The most companies apply a differentiated approach in 3D CAD design and manufacturing process for new models, based on storage fuel tanks weight to satisfy the demands of the competitive market [14-19].

In order to ensure high degree of stability and safety in recent 3D models, stress analysis using both computational and experimental approaches, including finite element modeling and the design and execution of custom mechanical tests were carried out to satisfy the general structural design and certification rules [20-24].

The automotive industry has implemented improvements in the design procedure of the storage fuel tanks that involves reduce project risk, gain better control of model variants, reduce testing time and cost, effectively use data from tests and also to get better products in terms of structure, service life and durability [25-35].

The results of the optimization process provide a new insight into the behavior of the non-linear aspects of storage fuel tanks with complex geometries and gain better control on various model variants, while improving storage efficiencies with a high structural performance [36-44].

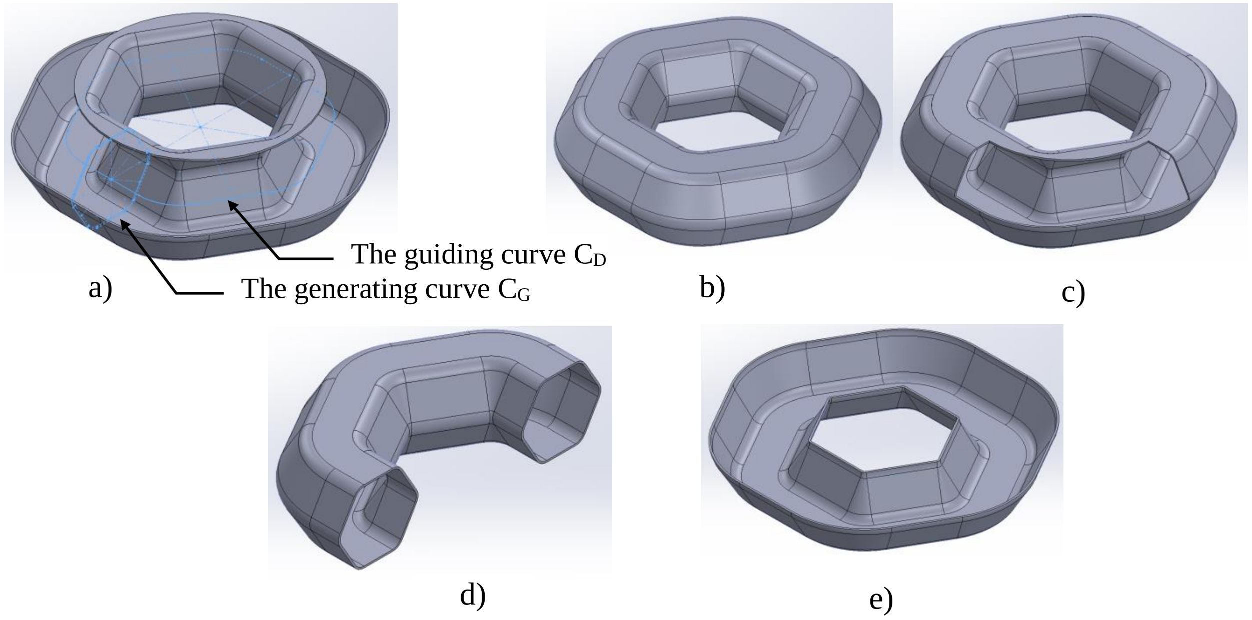
In our research, a finite element analysis was made to a 3D hexagonal toroid with regular hexagonal cross-section used for LPG storage tanks in the automotive industry to meet safety standards considering the particular geometry and the structure parameters.

2. Design methodology

In our study, optimal design of a 3D hexagonal toroid with regular hexagonal cross-section in order to reduce stress non-uniformity is performed.

2.1 Basic geometry of the parametric 3D model

Let's consider the parametric 3D model generated by revolving of a closed generating curve C_G (a hexagon with rounded corners) along a closed guiding curve C_D (a hexagon with rounded corners) as shown in figure 1.

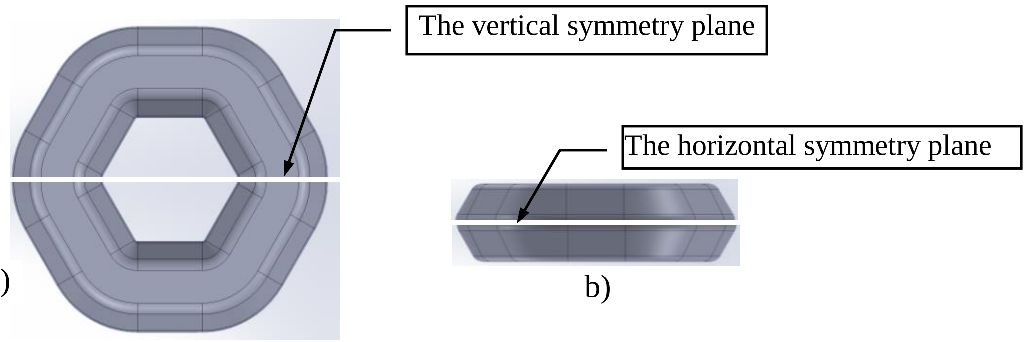


a) b) c)

d) e)

Fig. 1. The axonometric representation of the parametric 3D solid model

These parametric 3D models have two symmetry planes: one horizontal and one vertical, to define the locations of important geometrical features, as shown in figure 2.



a) b)

Fig. 2. a) and b) The orthogonal views with the symmetry planes of 3D solid model

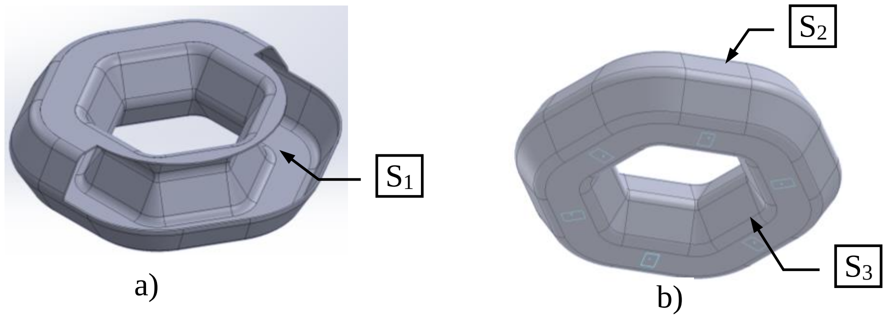
The following parameters were applied as input parameters to the 3D parametric model (figure 3): a) a closed generating curve C_G (a hexagon with a side value L = 175 mm, with rounded corners, radius R = 50 mm), and b) the guiding curve C_D (a hexagon with a side value L = 430 mm, with rounded corners, radius R = 180 mm).

2.2 Numerical analysis of the parametric 3D model

Based on the physical model, the modeling was done in the AutoCAD Autodesk 2017 software [45] and the numerical analysis was performed with SolidWorks 2017 software [46] with the Static, Thermal and Design Study modules. The design data used were:

- the tank material is AISI 4340 steel;
- the maximum hydraulic test pressure: p_{max} = 30 bar, applied on surface S_1;
- the working temperature between the limits: T = -30 ^{0}C up to T = 60 ^{0}C, applied on surface S_2;
- supporting surfaces located on the inferior side (applied on surface S_3);
- the duration of the tank exploitation: n_a = 16 years;
- the corrosion rate of the material: v_c = 0.07 mm/years.

The applied optimization function is intended to achieve a minimum mass. For the numerical computations were applied and specified the loads and restrictions to the parametric 3D model (fig. 3).



a) b)

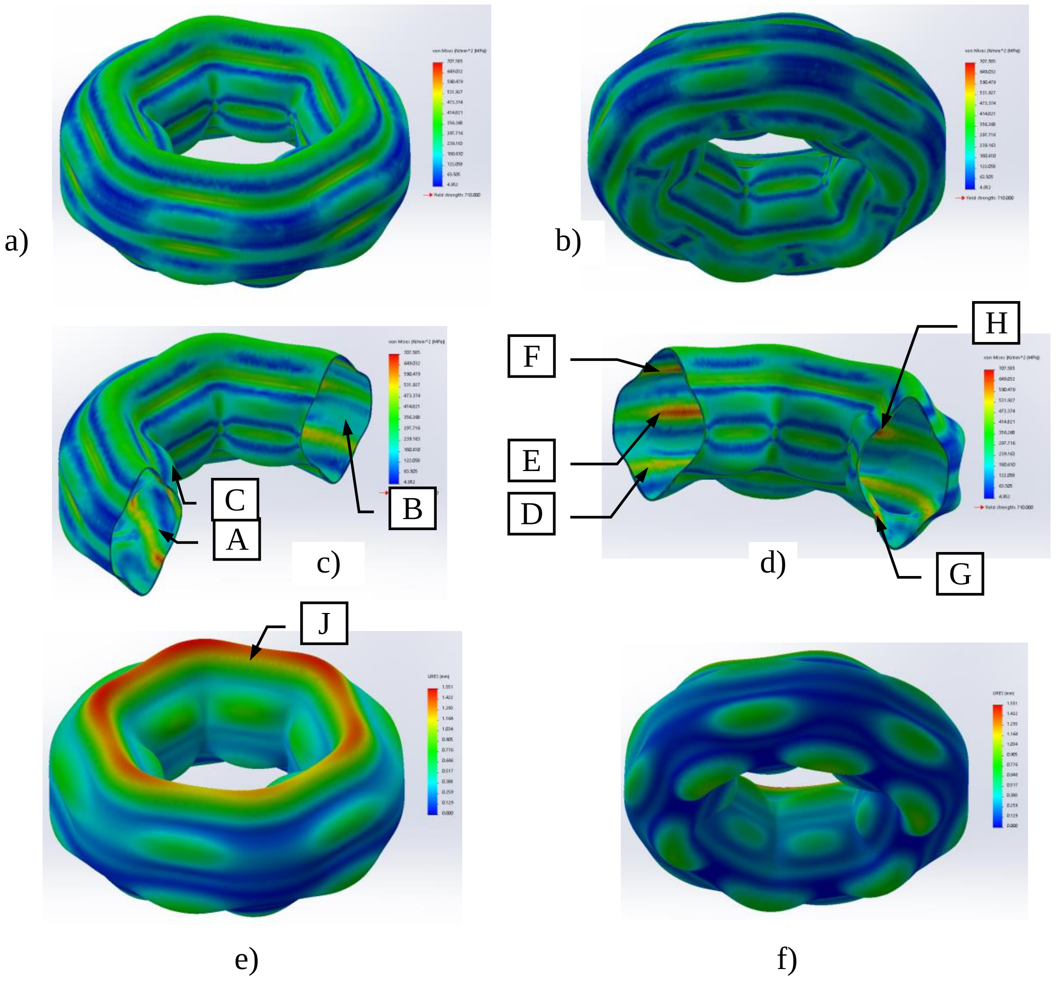
Fig. 3. Different isometric views of the parametric 3D model with the corresponding loads and restrictions

Numerical calculations were performed for: a mesh standard type, solid mesh with high quality, automatic transition, Jacobian in 16 points, maximum element size 20 mm, tolerance 1 mm, number of nodes 101959, number of elements 51617, maximum aspect ratio 31.89, number of degrees freedom 302958.

In numerical analysis the restriction of constraint was that the value of Von Mises effort $\sigma_{rez} \leq \sigma_a$ = 710 N/mm^2 (σ_a – the admissible value of the traction stress of the material).

Applying the proposed optimization procedure, the obtained values are: the thickness s = 7.35 mm for T = -30 ^{0}C with the stress value of the $\sigma_{rez.\ max}$= 707.585 N/mm^2 and a linear deformation value u_{max} = 1.551 mm.

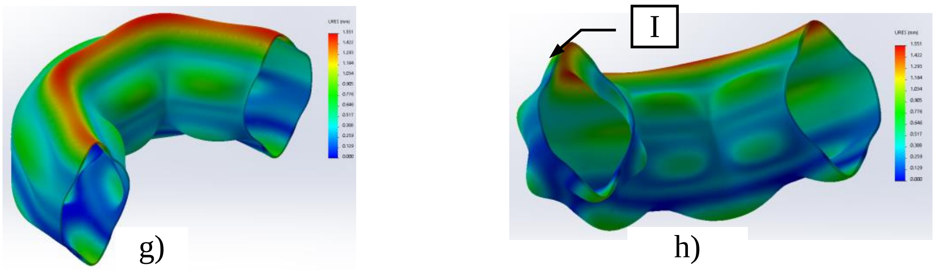
Distributions of the state of stress (fig. 4, a-d) and of linear deformations (fig. 4, e-h) are graphically represented in fig. 4.



a) b)

c) d)

e) f)



g) h)

Fig. 4. The distributions of the state of stress and of linear deformations of the parametric 3D model: a, b, e, f) non-sectioned model; c, d, g, h) half-section model

It can be noted that the highest values of efforts in the 3D model occur in the connection zones: A, B, C, .., H (fig. 4). The state of maximum deformation appears on the surfaces (J and I) (fig. 4).
The formula for calculating the thickness is the following:

$$s_{real} = s_{opt} + v_c \cdot n_a + abs(A_i) + \Delta s_a \qquad (1)$$

where: - v_c, corrosion rate of the cover, v_c = 0.07 mm/years;

- n_a, number of years of exploitation, n_a = 16 years;
- A_i, the lower deviation of the laminate sheet, A_i = - 0.6 mm, for s = 2…5 mm;
- Δs_a = 0.1 s = 0.735 mm, thinning of the sheet caused by the head cover embossing.

Finally, the minimum thickness of the sheet laminate is determined as:

$$s_{real\ min} = 7.35 + 0.07 \cdot 16 + abs(-0.6) + 0.1 \cdot 7.35 = 9.805 \text{ mm} \qquad (2)$$

A laminate sheet of AISI 4340 steel with a thickness of $s = 10^{+0.25}_{-0.6}$ mm is chosen for analysis. The numerical values of state of stress and linear deformation distribution are given in Table 1, for n_a = 16 years which corresponds to a minimal cover thickness s ≅ 7.55 mm.

Table 1: The Von Mises stress and linear deformation of geometrical 3D solid model

T [^{0}C]	-30 ^{0}C	-20 ^{0}C	-10 ^{0}C	0 ^{0}C	10 ^{0}C	20 ^{0}C	30 ^{0}C	40 ^{0}C	50 ^{0}C	60 ^{0}C
σ [N/mm^2]	681.0	648.67	616.55	584.72	562.44	543.82	525.73	508.09	526.84	549.96
u [mm]	1.423	1.424	1.425	1.427	1.428	1.430	1.432	1.433	1.435	1.437

The graph and law of variation of the Von Mises stress as a function of temperature are given in figure 5.

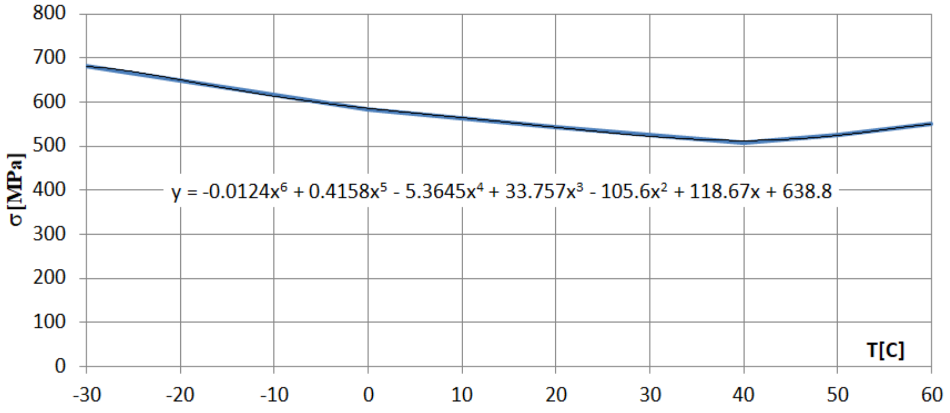


Fig. 5. The graph of Von Mises stress variation as a function of temperature

Distributions of the state of stress for different temperatures: a1 & b1) T = -30 ^{0}C, a2 & b2) T = 0 ^{0}C, a3 & b3) T = 30 ^{0}C and a4 & b4) T = 60 ^{0}C) are shown in figure 6.

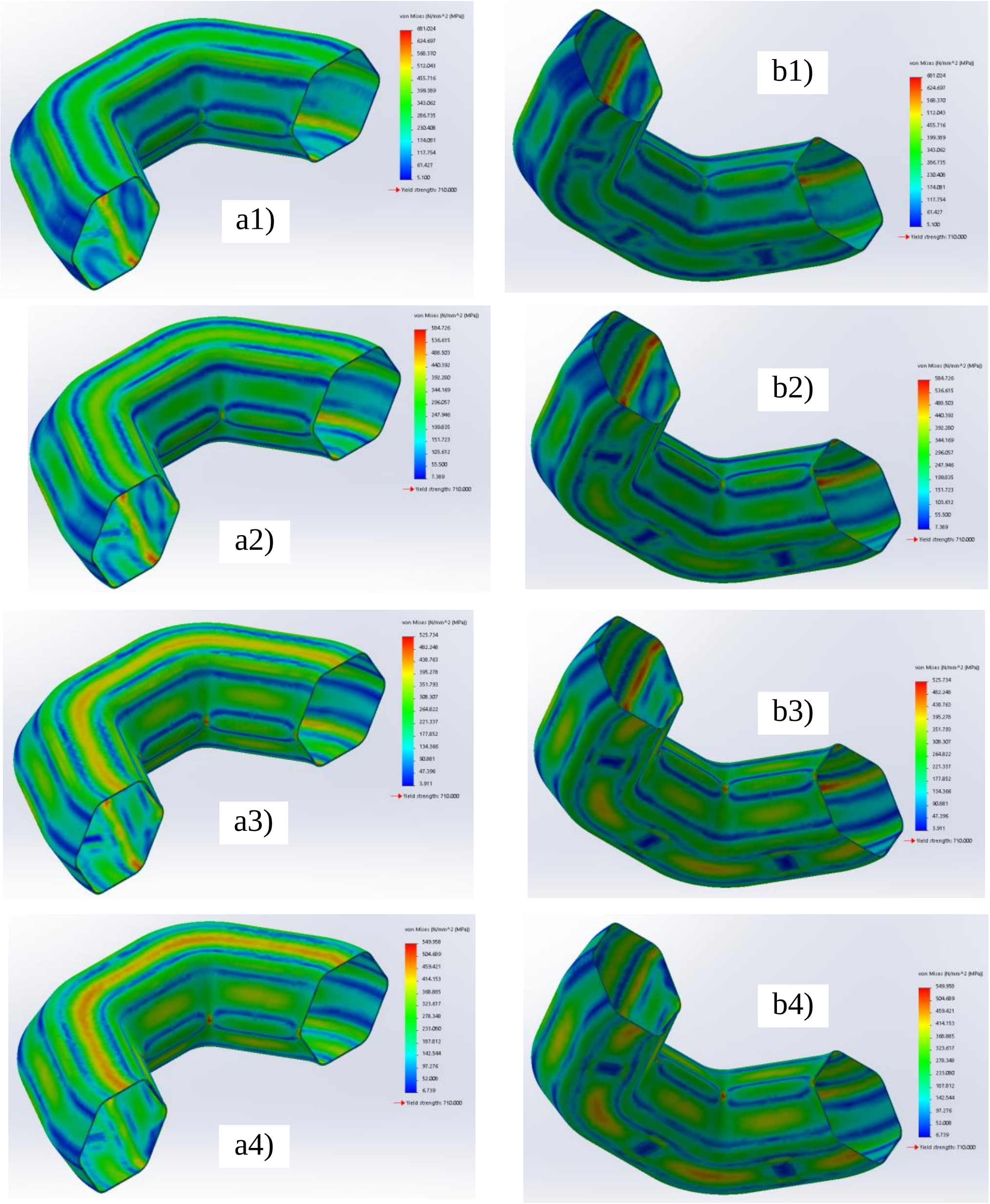


Fig. 6. Distributions of the state of stress for different temperatures:
a1 & b1) T = -30 ^{0}C, a2 & b2) T = 0 ^{0}C, a3 & b3) T = 30 ^{0}C and a4 & b4) T = 60 ^{0}C.

The graph and law of variation of the resulting linear deformations as a function of temperature are given in figure 7.

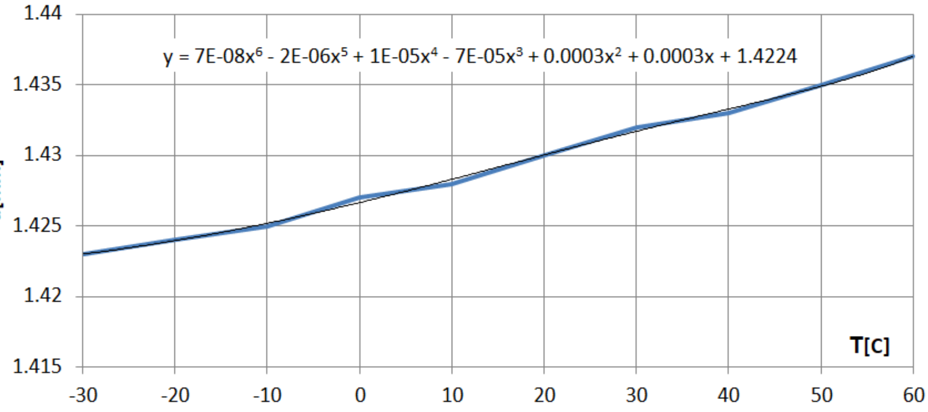


Fig. 7. The graph of the resulting linear deformations variation as a function of temperature

Distributions of the linear deformations for different temperatures: a1 & b1) T = -30 ^{0}C, a2 & b2) T = 0 ^{0}C, a3 & b3) T = 30 ^{0}C and a4 & b4) T = 60 ^{0}C) are shown in figure 8.

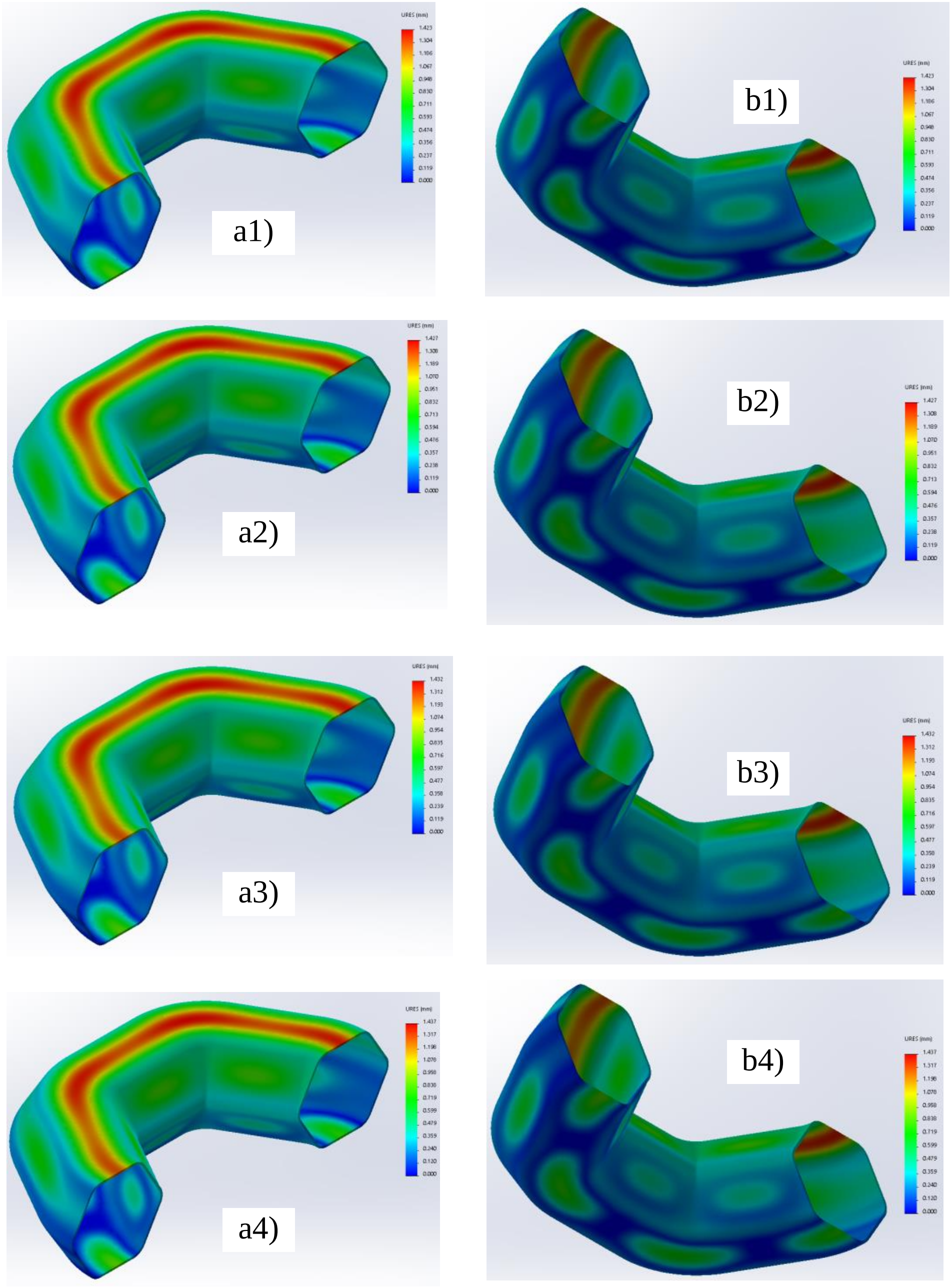


Fig. 8. Distributions of the resulting linear deformations for different temperatures:
a1 & b1) T = -30 ^{0}C, a2 & b2) T = 0 ^{0}C, a3 & b3) T = 30 ^{0}C and a4 & b4) T = 60 ^{0}C.

3. Discussion

Following the analysis of Von Mises stress and the resulting linear deformations in the parametric 3D model structure through the method of finite elements it has been found that:

- the values of Von Mises stress have a minimum value for T = 40 ^{0}C and a maximum value for T = -30 ^{0}C.
- for T = 60 ^{0}C the values of Von Mises stress have values of about 81 % from the maximum effort value (according Table 1).
- the resulting linear deformations increases with the increase of the temperature.
- the laws of variation of the Von Mises stress and the resulting linear deformations as a function of temperature are computed by polynomial interpolation.

4. Conclusions

The proposed 3D parametric modelling method allows designers in making optimal design choices of the geometric variants of the 3D hexagonal toroids with regular hexagonal cross-section used for LPG storage tanks in the automotive industry for a feasible solution within a prescribed tolerance.

Conflict of Interest: The authors declare that they have no conflict of interest.

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