The Influence of Corrosion and Temperature Variation on the Minimum Safety Factor of a 3D Hexagonal Toroid with Regular Hexagonal Cross-Section Used in Manufacturing of LPG Storage Tanks

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Abstract: *In this paper we investigate the minimum safety factor (SF) values of a three-dimensional (3D) hexagonal toroid with regular hexagonal cross-section used in manufacturing of LPG storage tanks from the automotive industry. A design strategy was proposed to determine SF according to manufacturing objectives due to the influence of corrosion and temperature variation. Numerical simulations were carried out to determine the surfaces or curves for which the SF has the minimum values and the corresponding variation laws were computed by polynomial interpolation. We coupled numerical simulations of a 3D model (done in the AutoCAD Autodesk 2017 software, which was imported for analysis to SolidWorks 2017 software) with numerical limit analysis to calculate confidence intervals of the safety factor. The results of analyzed cases advocate the need for implementing a reliability improvement program of toroidal LPG fuel tanks.*

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

1. Introduction

The dynamics of storage fuel tanks markets, technology, and competition have brought changes in design driven innovation strategy that have potential to create a competitive advantage [1-6].
During the last few decades the evolution of the storage fuel tanks industry can be characterized by the convergence of technologies and designs to create new products in terms of adaptations, differentiation and quality [7-11].
Numerous contributions to the storage fuel tanks literature have investigated various models (based on material, capacity, and vehicle type) with different prices to satisfy the demands of the competitive market [12-15].
The manufacturers of storage fuel tanks, make use of new materials, to keep costs low, while bolstering safety, and increasing reliability in various environmental conditions [16-19].
3D CAD modelling of prototypes of storage fuel tanks used in automotive industry is a strategic resource to get better products in terms of structure, service life and durability and to avoid expensive tests equipment and expensive tests [21-32].
There are various softwares with virtual computer aided engineering tools specialized for storage fuel tank design, analysis, and evaluation, which performs calculations in accordance with national standards [33-40].
In the manufacturing of fuel tank various materials such as plastic, steel, and aluminum are used to satisfy the general structural design and certification rules [41].
Current storage fuel tanks industry trends show that the basic methods of protection of materials (like use of corrosion-resistant materials and application of surface coatings) have largely remained the same, the advanced approaches and techniques adopted can create appropriate protection systems with high reliability and performance [42, 43].
Many different methods have been developed in the technical literature to compute the safety factor (or factor of safety) (SF or FOS), ranging from simplified approaches to more sophisticated methods and advanced numerical procedures. These methods are based on several considerations, such as the accuracy of predictions on the imposed loads, strength, wear estimates and rigor in results interpretive research. Such methods allow us to calculate confidence

intervals of the SF due to uncertainty and exploitation conditions, data errors, and model structural inadequacies [43].
In our research, the minimum safety factor (SF) of a three-dimensional (3D) hexagonal toroid with regular hexagonal cross-section used in manufacturing of LPG storage tanks was determined due to the influence of corrosion and temperature variation. The obtained results provide a new insight into the design decisions are made during the early design stages in the storage fuel tanks development process.

2. Design methodology

In our previous studies [14, 44, 45], an optimal design of a 3D hexagonal toroid with regular hexagonal cross-section was 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 [14].

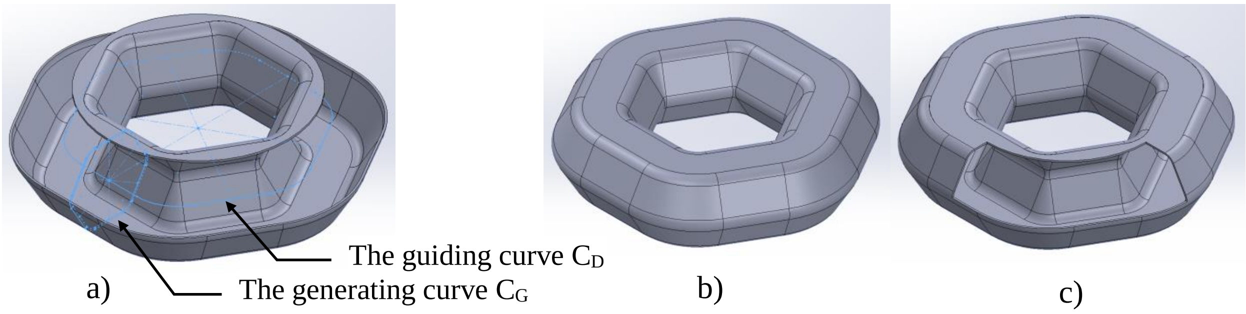


Fig. 1. The axonometric representation of the parametric 3D solid model

The following parameters were applied as input parameters to the 3D parametric model (figure 1): 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 [39] and the numerical analysis was performed with SolidWorks 2017 software [40] 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;
- the working temperature between the limits: T = -30 ^{0}C up to T = 60 ^{0}C;
- supporting surfaces located on the inferior side;
- the duration of the tank exploitation: n_a = 16 years;
- the corrosion rate of the material: v_c = 0.07 mm/years.

Let's compute for parametric 3D model the safety factor (SF) relative to a limit state of resistance using the following formula [43]:

$$SF = \sigma_k / \sigma_{max} \geq 1 \qquad (1)$$

where: - σ_k, the effort limit taken into account;
- σ_{max}, the maximum effective effort of the cover material.

In addition, the minimum value of the SF that must exceed a prescribed allowable value [43]:

$$SF_{min} \geq SF_{adm} \qquad (2)$$

In this case, the maximum effective effort of the cover material corresponds to the Von Mises effort, and the the effort limit taken into account is the admissible value of the traction stress of the material.

It can be seen that due to the geometry of the cover material, the boundary conditions, or the intensity of application or distribution of different loads occurring during exploitation, the safety factor has different values on the surface of the envelope, with values ranging from 2.1 to 273.18. Graphical representations for cases with various values of SF are given in fig. 2.

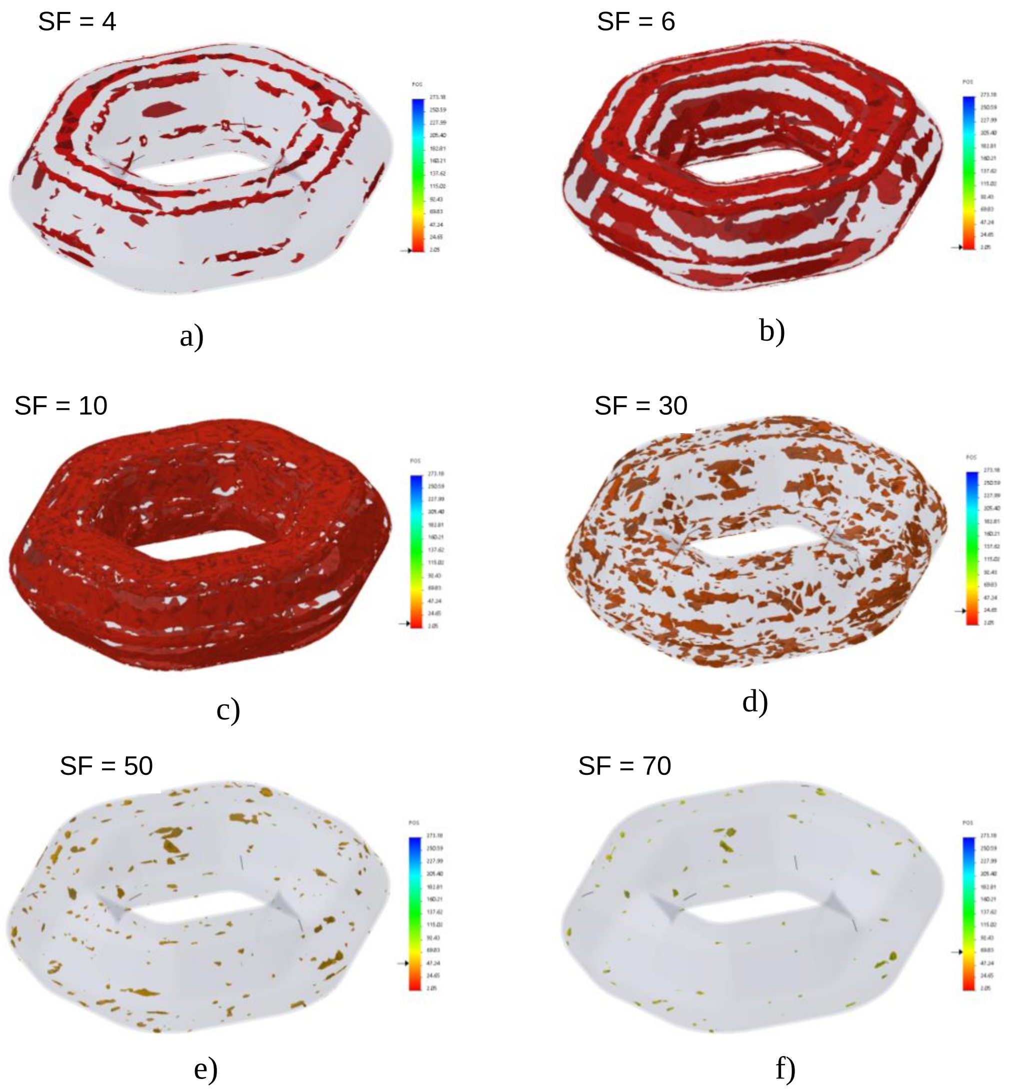


Fig. 2. Different isometric views of the parametric 3D model with the corresponding values of SF

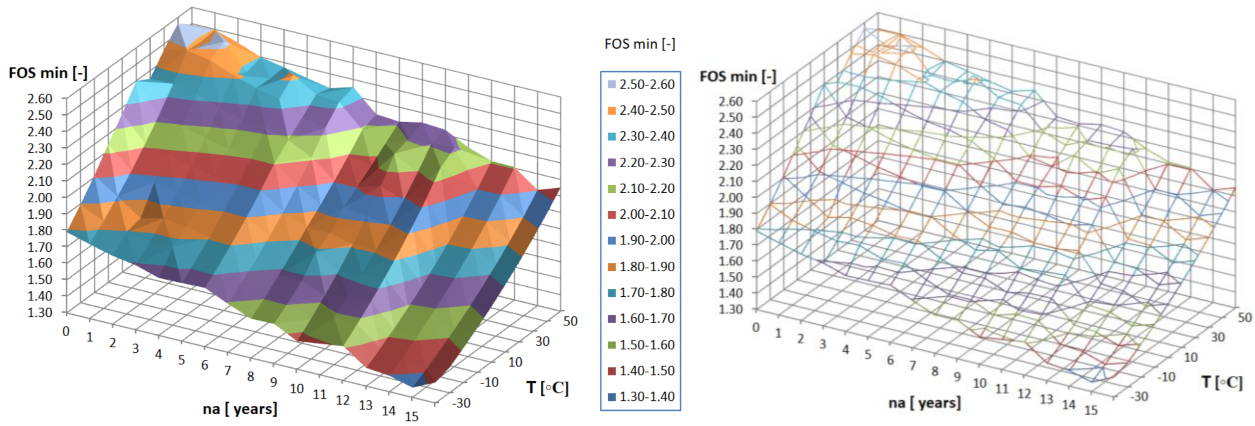
Numerical calculations were performed for: mesh standard type, solid mesh with quality high, automatic transition, Jacobian in 16 points, element size 10 mm, tolerance 1 mm, number of nodes 130215, number of elements 68415, maximum aspect ratio 26.30, number of degrees freedom 346152.

Table 1: The minimum safety factor

SF$_{min}$ [-]	**T** [^{o}C]									
n$_a$ [years]	-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
0	1.791	1.896	2.012	2.14	2.263	2.399	2.351	2.467	2.563	2.493
1	1.751	1.83	1.917	2.011	2.115	2.229	2.355	2.494	2.486	2.497
2	1.715	1.795	1.82	1.977	2.082	2.198	2.326	2.469	2.522	2.453
3	1.692	1.769	1.853	1.945	2.046	2.156	2.279	2.415	2.372	2.398
4	1.649	1.775	1.838	1.925	2.021	2.126	2.241	2.368	2.365	2.372
5	1.652	1.727	1.808	1.898	1.996	2.104	2.223	2.337	2.418	2.34

6	1.657	1.731	1.813	1.901	1.998	2.105	2.185	2.259	2.337	2.313
7	1.594	1.663	1.738	1.819	1.908	2.005	2.112	2.23	2.324	2.354
8	1.538	1.605	1.679	1.759	1.843	1.921	2.005	2.094	2.19	2.223
9	1.541	1.607	1.68	1.79	1.845	1.939	2.003	2.07	2.14	2.212
10	1.470	1.544	1.625	1.713	1.812	1.92	2.041	2.175	2.203	2.241
11	1.489	1.586	1.654	1.728	1.808	1.895	1.99	2.094	2.208	2.231
12	1.508	1.579	1.656	1.74	1.831	1.931	2.039	2.158	2.219	2.158
13	1.41	1.465	1.525	1.589	1.658	1.734	1.815	1.905	2.002	2.109
14	1.397	1.453	1.513	1.577	1.647	1.724	1.807	1.898	1.997	2.107
15	1.359	1.409	1.464	1.524	1.588	1.658	1.733	1.815	1.904	2.002
16	1.425	1.452	1.508	1.569	1.634	1.705	1.781	1.864	1.953	2.051

The graphs of 3D surfaces (by type surf and fire) corresponding to the variation of minimum SF for SF_{min} (n_a, T), taking into account the results from Table 1, are graphically shown in fig. 3.



a) b)

Fig. 3. The 3D graphs SF_{min} (n_a, T): a) surf type; b) fire type

The graphs of the isothermal coefficient variation curves, SF_{min} (n_a, T = ct), are graphically shown in fig. 4.

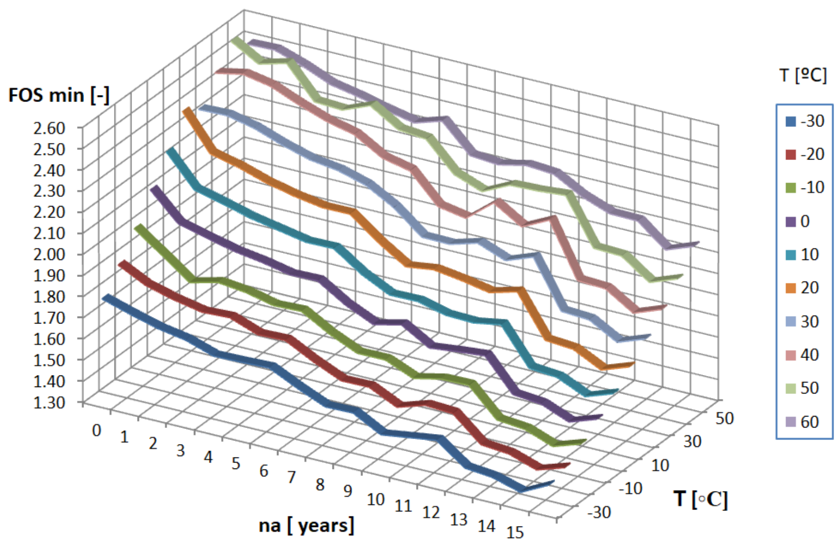
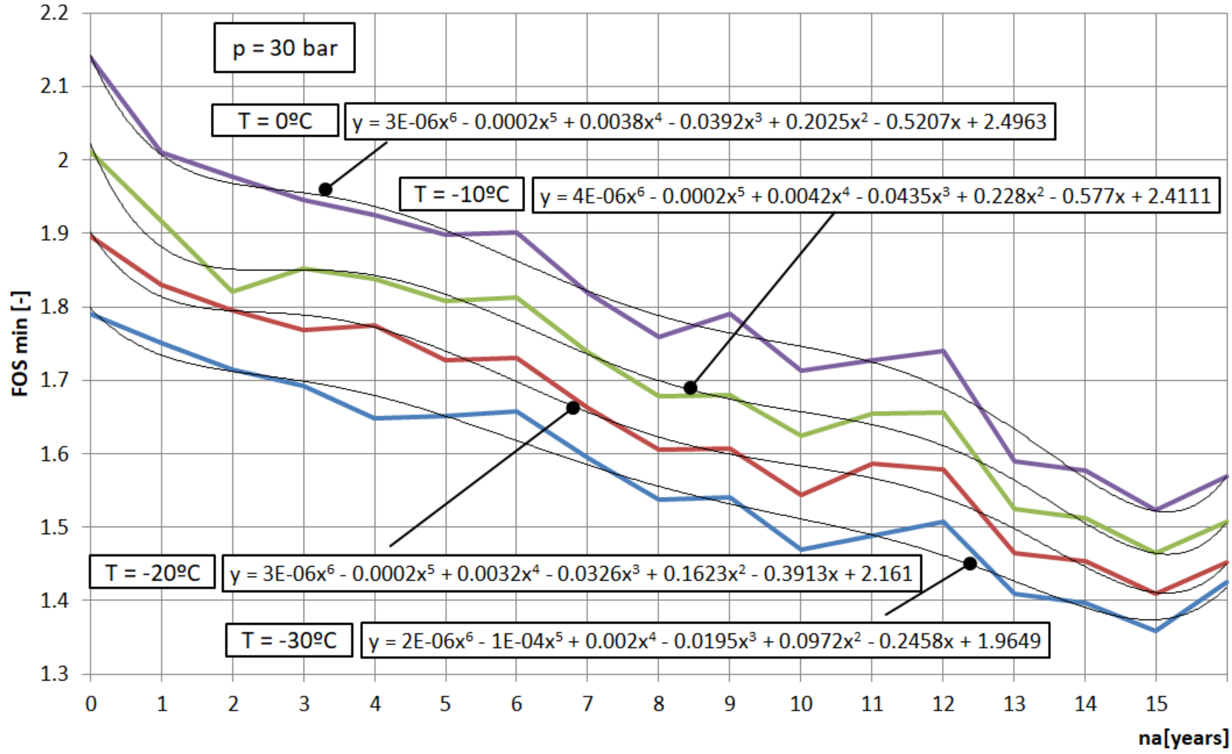
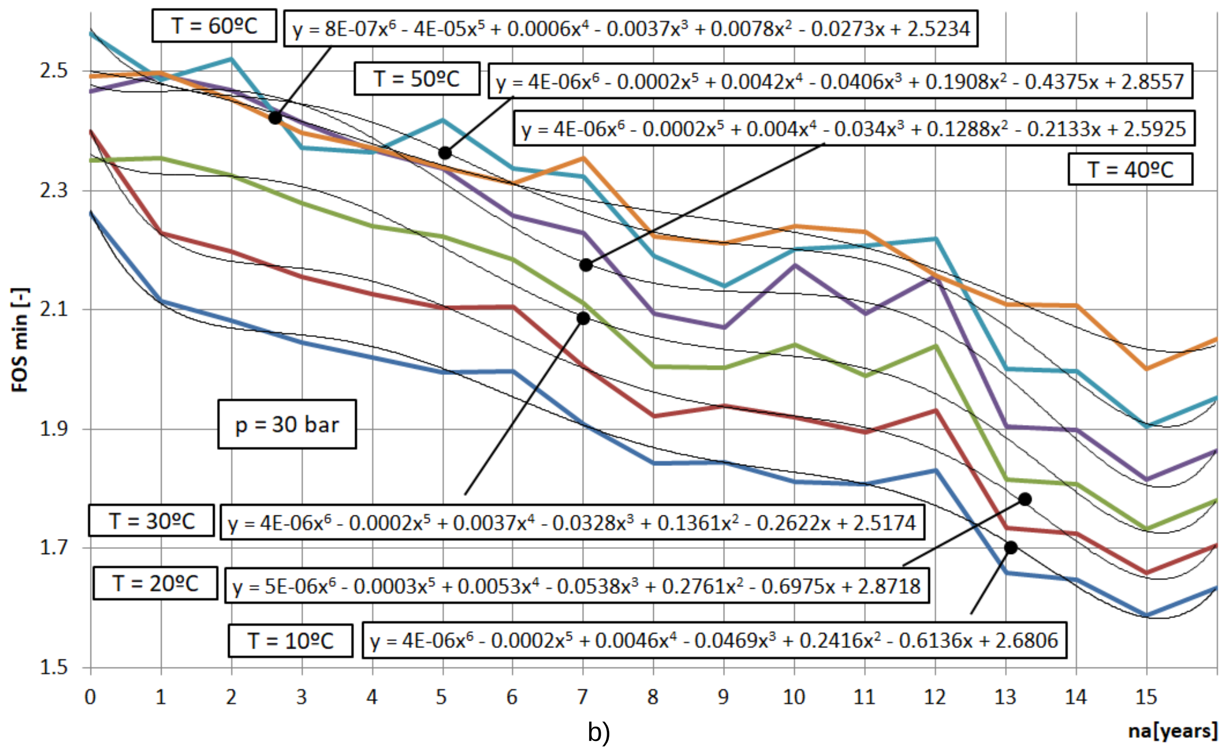


Fig. 4. The 3D graphs of the isothermal coefficient variation curves, SF_{min} (n_a, T = ct)

The graphs and laws of the variance of resulting SF_{min} (n_a, T = ct), calculated through a polynomial interpolation using Microsoft Excel 2017 are shown in fig. 5.



a)

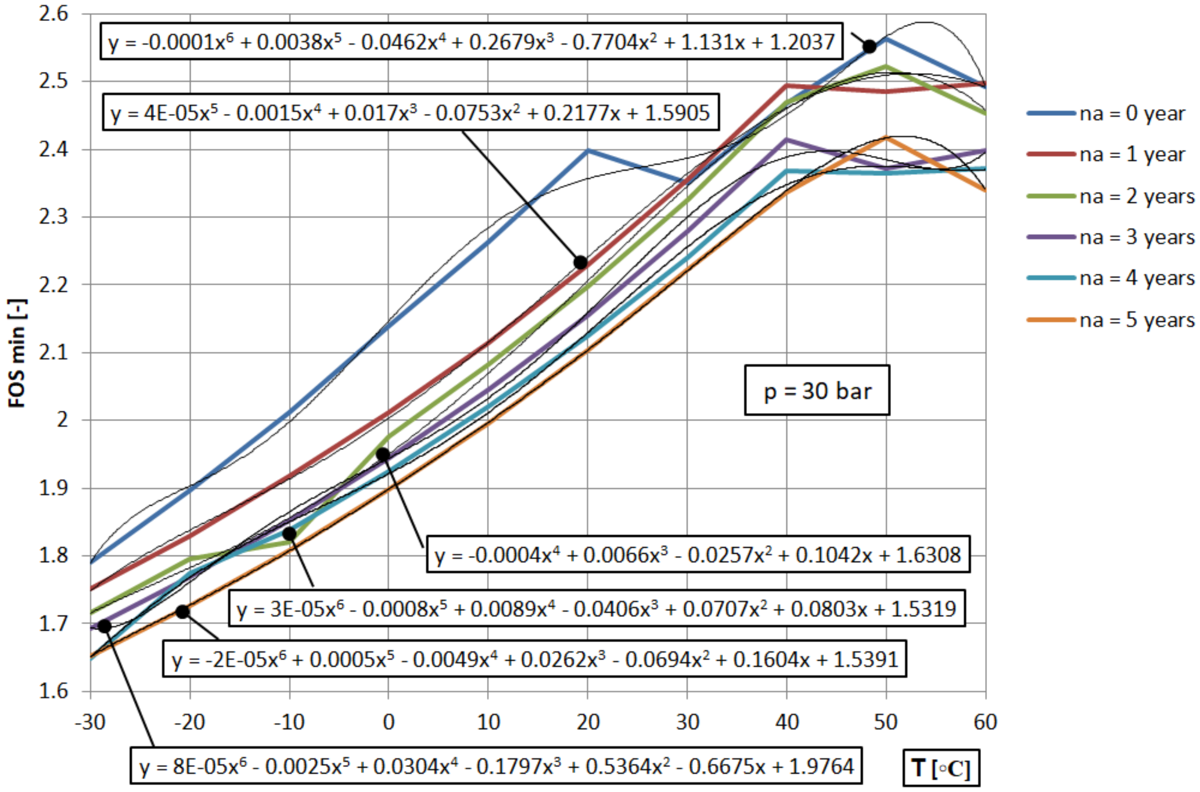


b)

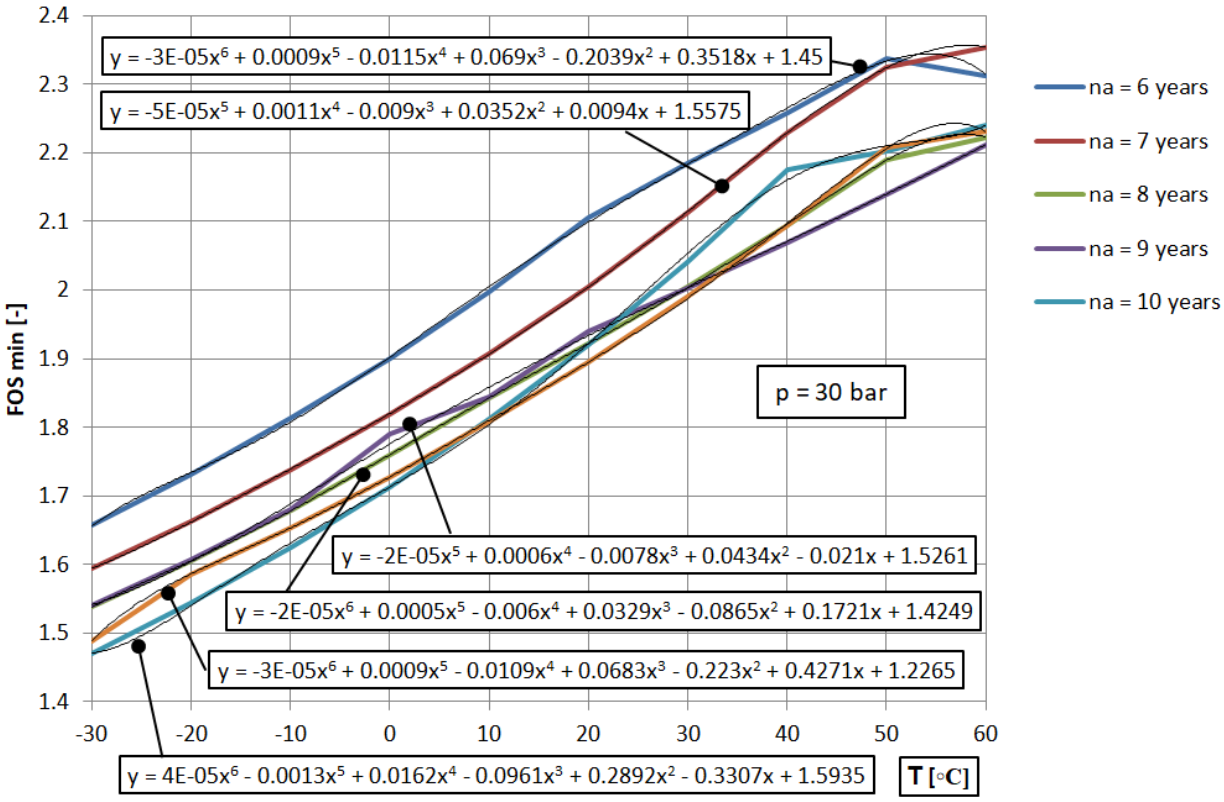
Fig. 5. The 2D graphs and laws of the variance of resulting SF_{min} (n_a, T = ct)

The graphs of the isothermal coefficient variation curves, SF_{min} (n_a = ct, T), are graphically shown in fig. 6.

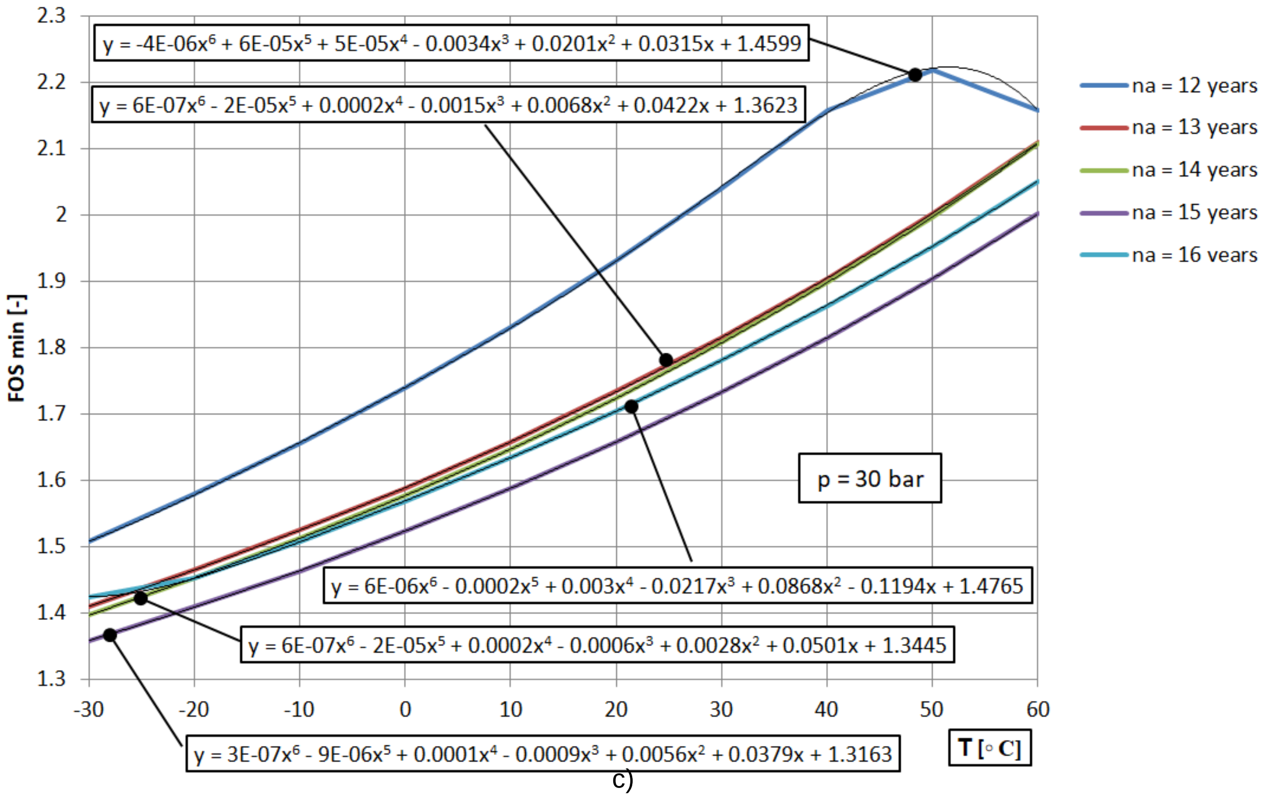
The graphs and laws of the variance of resulting SF_{min} (n_a = ct, T), calculated through a polynomial interpolation using Microsoft Excel 2017 are shown in fig. 6.



a)



b)



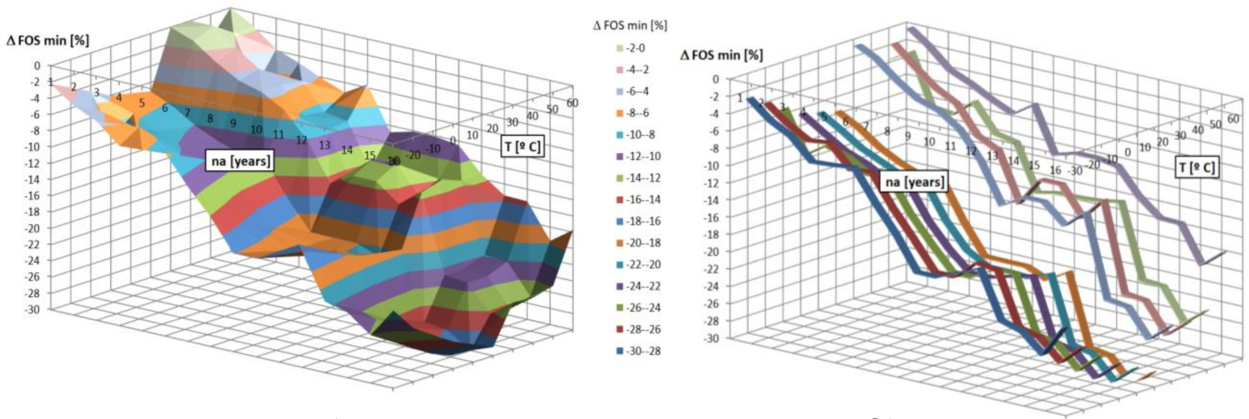
c)

Fig. 6. The 2D graphs and laws of the variance of resulting SF_{min} (n_a = ct, T)

The computed percentage decrease of minimum SF (for n_a = 0 years), considering the simultaneous influence of corrosion and temperature, is given in Table 2 and fig. 7.

Table 2: The percentage decrease of minimum safety factor

Δ SF_{min} [%]	T [⁰C]									
n_a [years]	-30 ⁰C	-20 ⁰C	-10 ⁰C	0 ⁰C	10 ⁰C	20 ⁰C	30 ⁰C	40 ⁰C	50 ⁰C	60 ⁰C
1	-2.23	-3.48	-4.72	-6.02	-6.53	-7.08	0.17	1.09	-3.00	0.16
2	-4.24	-5.32	-9.54	-7.61	-7.99	-8.37	-1.06	0.08	-1.59	-1.60
3	-5.52	-6.69	-7.90	-9.11	-9.58	-10.12	-3.06	-2.10	-7.45	-3.81
4	-7.92	-6.38	-8.64	-10.04	-10.69	-11.37	-4.67	-4.01	-7.72	-4.85
5	-7.76	-8.91	-10.13	-11.30	-11.79	-12.29	-5.44	-5.26	-5.65	-6.13
6	-7.48	-8.70	-9.89	-11.16	-11.71	-12.25	-7.06	-8.43	-8.81	-7.22
7	-10.99	-12.28	-13.61	-15.00	-15.68	-16.42	-10.16	-9.60	-9.32	-5.57
8	-14.12	-15.34	-16.55	-17.80	-18.55	-19.92	-14.71	-15.11	-14.55	-10.83
9	-17.92	-18.56	-19.23	-19.95	-19.92	-19.96	-13.18	-11.83	-14.04	-10.10
10	-17.92	-18.56	-19.23	-19.95	-19.92	-19.96	-13.18	-11.83	-14.04	-10.10
11	-16.86	-16.35	-17.79	-19.25	-20.10	-21.00	-15.35	-15.11	-13.85	-10.50
12	-15.80	-16.71	-17.69	-18.69	-19.08	-19.50	-13.27	-12.52	-13.42	-13.43
13	-21.27	-22.73	-24.20	-25.74	-26.73	-27.71	-22.79	-22.78	-21.88	-15.40
14	-21.99	-23.36	-24.80	-26.30	-27.22	-28.13	-23.13	-23.06	-22.08	-15.48
15	-24.12	-25.68	-27.23	-28.78	-29.82	-30.88	-26.28	-26.42	-25.71	-19.69
16	-20.43	-23.41	-25.04	-26.68	-27.79	-28.92	-24.24	-24.44	-23.80	-17.72



a) b)

Fig. 7. The 3D graphs of Δ SF_{min} (n_a, T): a) surf type; b) fire type

A direct determination of SF_{min} (n_a, T) is shown in fig. 8.

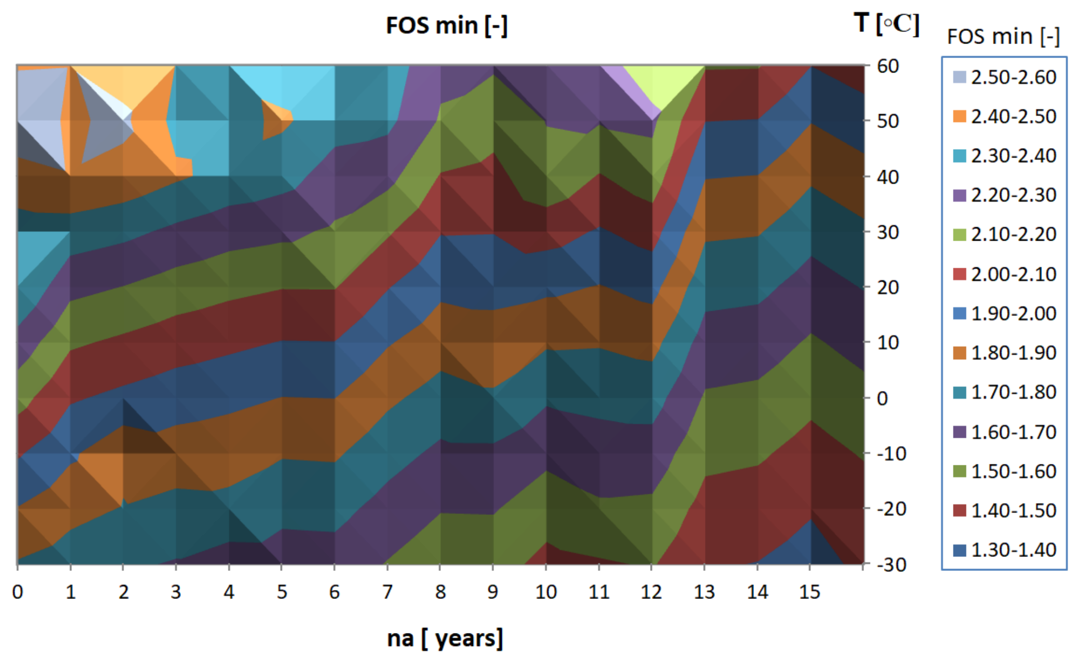


Fig. 8. The 2D graph of SF_{min} (n_a, T)

3. Discussion

Following the SF analysis and the resulting graphs for the parametric 3D model structure through the method of finite elements it has been found that:

- the graphical and analytical results of the mathematical dependencies determined by the laws of variation, allow for the determination of minimum SF considering the simultaneous influence of the corrosion and temperature;
- the laws of variation determined are important predictive tools for the minimum SF computed for a limit state of efforts;
- the percentage of decrease of the minimum SF is higher at the negative operating temperatures, increasing with the increase of the exploitation period (fig. 7).
- the graphs of the isothermal coefficient variation curves, as a result of the influence of a single parameter, keeping the constant value of the other parameter are graphically plotted: a) SF_{min} (n_a, T = ct), shown in fig. 4, and b) SF_{min} (n_a = ct, T), shown in fig. 6.

4. Conclusions

The proposed method is applicable in the design phase of a 3D hexagonal toroid with regular hexagonal cross-section used in manufacturing of LPG storage tanks from the automotive industry.

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

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