The optimal design of a 3D pentagonal toroid with circular cross-section used in manufacturing of LPG storage tanks

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Abstract. This paper presents a 3D solid modelling to generate a pentagonal toroid with circular cross-section used in manufacturing of LPG storage tanks from the automotive industry. Stress and linear deformation analysis are applied to optimize the geometrical product shape. As a result, in numerical simulation a feasible time-cost integrated project schedule was developed to formulate a construction sequence of product components based on the physical relationships between CAD objects.

1. Introduction
In manufacturing of storage fuel tanks in automotive industry various models, options and changes in trends offered by the materials were used in a wide-ranging during the last few decades to satisfy the demands of the competitive market for new models and materials [1-6].

Virtual CAE (computer aided engineering) tools play an important role in 3D designing geometrical solutions in storage fuel tanks used in automotive industry. The ability to combine advanced materials and material states allow developing new manufacturing strategies [7-9].

Various research teams have attempted to develop innovative ways in 3D CAD modelling of prototypes of storage fuel tanks, through continuous innovation into the designing process based on the cost and performance [10, 11].

Both static and dynamic conditions are combined in 3D CAD design of storage fuel tanks for selection of materials that offer advantages (high specific strength, low cost, good forming characteristics, high impact resistance and thermal stability) that give the optimum efficiency in terms of structure, service life and durability [12-17]. This information is shown to be essential in geometric pre-processing phases for finite element analysis (FEA) purposes.

In order to meet these requirements, in recent 3D models, computational analysis and mechanical tests were made to determine various related factors of design engineering to satisfy the general structural design and certification rules and decrease fabrication costs.

2. Design methodology
Let’s consider the 3D model generated by revolving of a generating circle \( C_G \) along a guiding pentagonal curve \( C_D \), with connected round corners, as shown in figure 1.
These 3D pentagonal toroids with circular cross-section have two symmetry planes: one horizontal and one vertical, to define the locations of important geometrical features, as shown in figure 2.

The following parameters were applied as input parameters to the 3D parametric model (figure 3): a) a generating circle with a radius $R = 200$ mm, and b) the guiding curve $C_D$, a pentagon with a side value $L = 400$ mm, which is connected to corners with a radius $R = 250$ mm.

Optimized CAD design of these fuel storage tanks was imported to SolidWorks 2018 software for analysis with the: Static, Thermal and Design Study modules.

The parameterized model used in the numerical simulation is shown in figure 3 and the notations are specified in the surfaces where are applied the loads and restrictions. The design data used are:

- the tank material is AISI 4340 steel;
- the maximum hydraulic test pressure: \( p_{\text{max}} = 30 \) bar, applied on surface \( S_1 \);
- the working temperature between the limits: \( t = -30 \, ^\circ \text{C} \) up to \( t = 60 \, ^\circ \text{C} \), applied on surface \( S_2 \);
- five supporting surfaces located on the inferior side (applied on surface \( S_3 \));
- the duration of the tank exploitation: \( n_a = 20 \) years;
- the corrosion rate of the material: \( \nu_c = 0.085 \) mm/years.

The applied optimization function is intended to achieve a minimum mass.

The calculation had a mesh standard type, solid mesh with high quality, automatic transition, Jacobian in 16 points, maximum element size 20 mm, tolerance 0.5 mm, number of nodes 130864, number of elements 65579, maximum aspect ratio 19.48, number of degrees freedom 344787.

The applied restriction of constraint is that the value of Von Mises effort \( \sigma_{\text{rez}} \leq \sigma_a = 710 \) N/mm\(^2\) (\( \sigma_a \) - the admissible value of the traction stress of the material). Applying the optimization procedure, the obtained values are: the thickness \( s = 2.7 \) mm for \( t = -30 \, ^\circ \text{C} \) with the stress value of the \( \sigma_{\text{rez}, \text{max}} = 707.825 \) N/mm\(^2\) and linear deformation value \( u_{\text{max}} = 1.106 \) mm.

Distributions of the state of stress and of linear deformations are shown in fig. 4.

It can be noted that the highest values of efforts in the 3D model occur in the pentagonal inner connection zones (as shown in fig. 4a), while the maximum deformations occur on the upper part of the model, where the deformation of the tank cover is not influenced by the tank support surfaces (which are considered fixed, as shown in fig. 4b).

![Figure 4. Distributions of the state of stress and of linear deformations of the parametric 3D model.](image-url)
Distributions of the state of stress and of linear deformations for different temperatures: a1 & b1) $t = -30 \, ^\circ C$, a2 & b2) $t = 0 \, ^\circ C$, a3 & b3) $t = 30 \, ^\circ C$ and a4 & b4) $t = 60 \, ^\circ C$) are shown in figure 5.

**Figure 5.** Distributions of the state of stress and of the linear deformations for different temperatures: a1 & b1) $t = -30 \, ^\circ C$, a2 & b2) $t = 0 \, ^\circ C$, a3 & b3) $t = 30 \, ^\circ C$ and a4 & b4) $t = 60 \, ^\circ C$.
The graphs of the 3D variation of: a) the Von Mises stress variation (fig. 6a), b) and the resulting linear deformations variation (fig. 6b) are given in dependency with the temperature and the evolution of corrosion wear occurring during the exploitation.

![Graph](image)

(a)

![Graph](image)

(b)

Figure 6. Distributions of: (a) the Von Mises stress variation and (b) the resulting linear deformations variation in dependency with the temperature and \( n_a \).

The formula for calculating the thickness is the following:

\[
s_{\text{real}} = s_{\text{opt}} + v_c \cdot n_a + \text{abs}(A_i) + \Delta s_a ,
\]

where:
- \( v_c \), corrosion rate of the cover, \( v_c = 0.085 \text{ mm/years} \);
- \( n_a \), number of years of exploitation, \( n_a = 20 \text{ years} \);
- \( A_i \), the lower deviation of the laminate sheet, \( A_i = -0.6 \text{ mm} \), for \( s = 2 \ldots 5 \text{ mm} \);
- \( \Delta s_a = 0.1 \text{ s} = 0.27 \text{ mm} \), thinning of the sheet caused by the head cover embossing.

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

\[
s_{\text{real min}} = 2.7 + 0.085 \cdot 20 + \text{abs}(-0.6) + 0.1 \cdot 2.7 = 5.27 \text{ mm}.
\]

A laminate sheet of AISI 4340 steel with a thickness of \( s = 5.5^{+0.25}_{-0.6} \text{ mm} \) is chosen for analysis.
The numerical simulation was made for \( n_a = 20 \) years which corresponds to the end of exploitation time when the cover thickness is minimal \( s = 2.9 \text{ mm} \). The variation of stress and of linear deformations with temperature and number of years of exploitation is shown in tables 1 & 2.

**Table 1.** The variation of stress with temperature and number of years of exploitation.

| \( n_a \)   | \( t \), °C | \(-30\) | \(-20\) | \(-10\) | \(0\) | \(10\) | \(20\) | \(30\) | \(40\) | \(50\) | \(60\) |
|------------|-------------|--------|--------|--------|-----|-----|-----|-----|-----|-----|-----|
| 0 years    | \(\sigma\), N/mm\(^2\) | 456.3  | 430.9  | 408.8  | 387.0 | 365.5 | 350.7 | 355.3 | 360.2 | 367.1 | 377.6 |
| 5 years    |             | 503.0  | 479.2  | 455.7  | 432.5 | 409.6 | 391.6 | 394.4 | 397.5 | 404.3 | 414.6 |
| 10 years   |             | 569.4  | 545.3  | 521.4  | 497.8 | 474.3 | 451.2 | 440.9 | 445.4 | 453.6 | 463.4 |
| 15 years   |             | 597.2  | 574.0  | 551.1  | 528.7 | 506.7 | 495.3 | 500.3 | 507.3 | 515.8 | 524.6 |
| 20 years   |             | 663.3  | 640.6  | 618.2  | 596.3 | 575.3 | 569.4 | 574.3 | 579.5 | 584.9 | 590.4 |

**Table 2.** The variation of linear deformations with temperature and number of years of exploitation.

| \( n_a \)   | \( t \), °C | \(-30\) | \(-20\) | \(-10\) | \(0\) | \(10\) | \(20\) | \(30\) | \(40\) | \(50\) | \(60\) |
|------------|-------------|--------|--------|--------|-----|-----|-----|-----|-----|-----|-----|
| 0 years    | \(u\), mm  | 0.557  | 0.573  | 0.589  | 0.606 | 0.623 | 0.640 | 0.658 | 0.676 | 0.694 | 0.713 |
| 5 years    |             | 0.631  | 0.647  | 0.663  | 0.680 | 0.67  | 0.715 | 0.733 | 0.752 | 0.771 | 0.79  |
| 10 years   |             | 0.726  | 0.742  | 0.759  | 0.776 | 0.794 | 0.812 | 0.830 | 0.848 | 0.867 | 0.885 |
| 15 years   |             | 0.845  | 0.863  | 0.881  | 0.90  | 0.919 | 0.938 | 0.958 | 0.978 | 0.998 | 1.02 |
| 20 years   |             | 0.990  | 1.007  | 1.024  | 1.042 | 1.059 | 1.077 | 1.095 | 1.113 | 1.132 | 1.15 |

**Figure 7.** Distributions of: (a) the Von Mises stress variation and (b) the resulting linear deformations variation for \( n_a = 0, 5, 10, 15 \) and 20 years of exploitation.
The evolution of Von Mises stress variation (fig. 7a) and of the resulting linear deformations variation (fig. 7b) during the years of exploitation for \( n_a = 0, 5, 10, 15 \) and 20 years are given in figure 7.

The graphs and the variation laws determined by a polynomial interpolation of Von Mises stress variation (fig. 8a) and of the resulting linear deformations (fig. 8b) are shown in fig. 8.

Figure 8. The graphs and the variation laws by a polynomial interpolation of: (a) the Von Mises stress variation and (b) the resulting linear deformations variation for \( n_a = 0, 5, 10, 15 \) and 20 years.

3. Conclusions
The values of Von Mises stress have minimum values between \( t = 20 ^\circ C \) and \( t = 30 ^\circ C \), for the variation curves corresponding to \( n_a \) years of exploitation: 0, 5, 10, 15 and 20 years, having the maximum values for \( t = -30 ^\circ C \). For \( t = 60 ^\circ C \) the values of Von Mises stress have values in the range of 81.38% to 89.01% from the maximum effort value (according fig. 8b and Table 1). Also, it can be seen that the resulting linear deformation increases with the temperature increase (fig. 8b). With the evolution of corrosion, the Von Mises stress and the resulting linear deformations increase.
simultaneously. The proposed parametric modelling method of the pentagonal toroid with circular cross-section of LPG fuel tanks in automotive industry allows the determination of optimal geometric rules that satisfy the general structural design and certification rules.

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