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Integrity assessment of ammonia spherical storage tank

Aleksandar Milovanović[1], Aleksandar Sedmak[2]

[1]*D.Sc.student, Faculty of Mechanical Engineering, University of Belgrade, Serbia*
[2]*Faculty of Mechanical Engineering, University of Belgrade, Serbia*

Abstract

The integrity of the ammonia spherical tank (with a volume of 1800 m3 and the outer diameter of 15120 mm, nominal wall thickness 30 mm) was analyzed due to discovered cracks on the longitudinal and transverse but joints of the segments, of different lengths and depth. The calculation according to EN 13445-3: 2014 specifies the minimum required spherical shell wall thickness. The finite element method was used to analyze the cracks and determine the hoop stress value. The stress intensity factor for the analysed cracks was analytically determined, and the obtained values were compared with the critical value of the stress intensity factor to assess the integrity of the observed structure.

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Keywords: structure integrity; stress intensity factor; spherical tank; finite element method; calculation of spherical shell wall thickness;

1. Introduction

The ammonia spherical tank (with a volume of 1800 m3, outer diameter D_s = 15120 mm and nominal wall thickness s_e = 30 mm), with maximum working pressure p = 16 bar and test pressure p_i = 20,8 bar, was tested in 2017 using non-destructive methods (NDT) by an accredited laboratory. A number of cracks were found on the longitudinal and transverse butt joints of the segments, three most critical of which no. 173, no. 203 and no. 197, shown in Figures 1.a and 1b, were analyzed in this paper. These cracks were treated with a profile milling cutter, and the tank was not remediated by welding, but the cracks were analyzed by finite element method.

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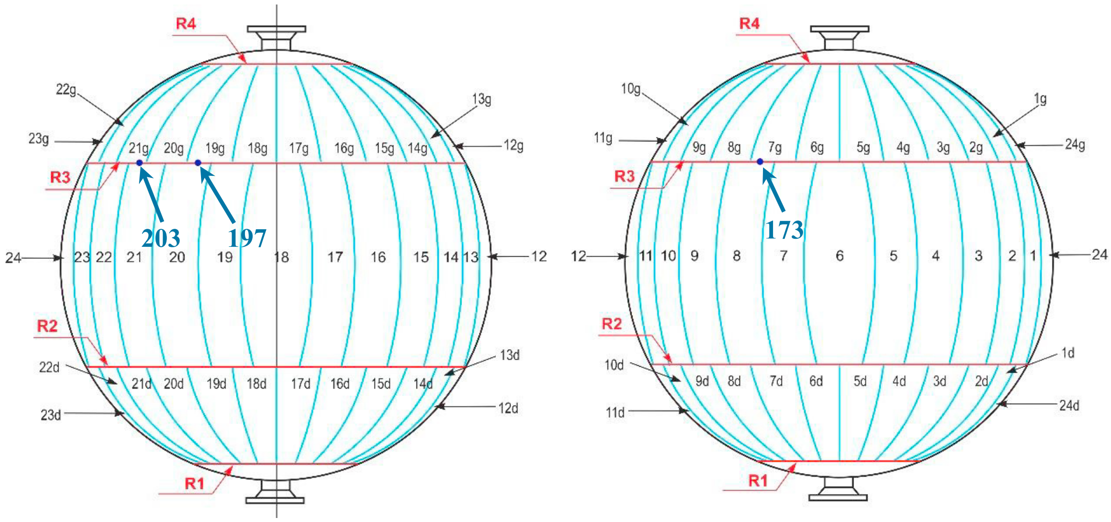

Figure 1: a) north side, inside view; b) south side, inside view

2. Spherical tank stresses according to EN 13445-3: 2014

The ammonia spherical tank is made of A36.52 [1], characterized by the following mechanical properties and chemical composition:

Table 1. Chemical composition in %.

Designation	C%	Mn%	Si	P_{max}	S_{max}	Al_{total}	N	Cr	Cu	Mo	Nb	Ni	Ti_{max}	V
A36.52	≤0.157	1.39	0.3	0.013	0.021	≥0.015	-	0.08	-	0.02	-	-	-	0.08

Table 2. Mechanical properties.

Designation	Standard	Thickness [mm]	$Rp_{0,2t}$ [MPa]	Rm [MPa]	Elongation ε [%]	Toughness KV $(J)_{min}$		
						-20°	0°	+20°
A36.52	AFNOR	≤ 50	360	520	23	47	-	-

Determination of the permitted stress for material A36.52:

$$f = min\left(\frac{Rm}{1,875}; \frac{Rp_{0,2t}}{1,5}\right), \tag{1}$$

$$f = 240\ MPa. \tag{2}$$

Determination of the permitted stress for material A36.52 for local conditions:

$$\sigma_{dl} = 1,5 \cdot f, \tag{3}$$

$$\sigma_{dl} = 360\ MPa. \tag{4}$$

Determination of the required wall thickness for a spherical shell exposed to the internal pressure according to EN 13445:3-2014 [2]:

$$e_{min} = max(e_{min1}, e_{min2}), \tag{5}$$

$$e_{min1} = \frac{p \cdot D_e}{4 \cdot f \cdot Z + p} + c + \delta_e = 26,16mm, \tag{6}$$

$$e_{min2} = \frac{p \cdot D_i}{4 \cdot f \cdot Z - p} + c + \delta_e = 26,15mm, \tag{7}$$

$$e_{min} = 26,16mm. \tag{8}$$

where:
$p = 16\ bar$ – calculation pressure,
$D_e = 15120\ mm$ – the outer diameter of the shell,
$D_i = D_e - 2 \cdot e_n = 15065{,}4\ mm$ – the inner diameter of the shell,
$e_n = 27{,}3\ mm$ – the minimum measured thickness of the shell wall,
$Z = 1$ – the weakening coefficient of welded joint,
$c = 1\ mm$ – the addition to corrosion and wear,
$\delta_e = 0\ mm$ – the absolute value of negative tolerance for the nominal wall thickness.

3. The finite element model and influence of processed cracks on the structure stress condition

In order to form the finite element model of the ammonia spherical tank structure with completely real geometric forms, it was necessary to draw a part of the sphere containing a crack in a three-dimensional form based on the original structure documentation. The maximum length of the sphere shell participating in reinforcement and required for forming the finite element model is determined according to the following equation from EN 13445: 3-2014:

$$l_{so} = \sqrt{(2 \cdot r_{is} + e_{as}) \cdot e_{as}} = 661{,}54\ mm. \tag{9}$$

where:
$r_{is} = D_e/2 - e_{as} = 7531\ mm$ – mean radius of the sphere,
$e_{as} = s_e - c - \delta_e = 30 - 1 - 0 = 29mm$ - wall thickness reduced by values c and δ_e.
Figure 2 shows the model in a three-dimensional form, with crack dimensions no. 173.

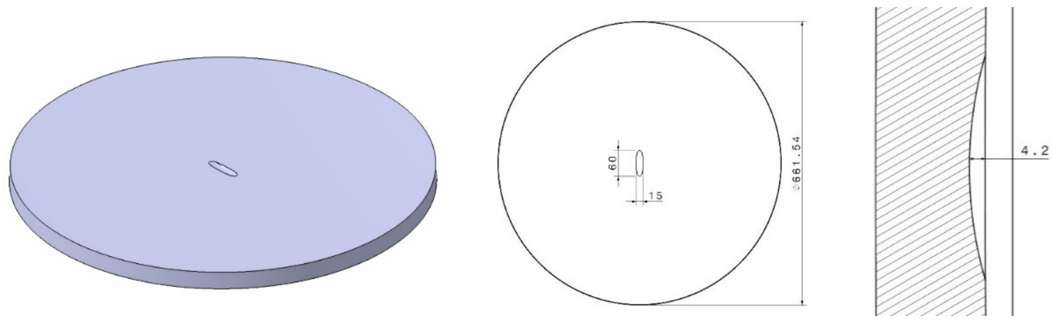

Figure 2: Formed model in the three-dimensional form

The finite element mesh consists of 2558929 tetrahedron-type elements and contains a total of 544427 knots. The size of the finite element in the local zone (crack zone) is 0.2 mm, and on the part of the spherical shell without damage in the form of a crack, it is 2 mm. The details of the finite elements mesh in the crack zone are shown in Figure 3.

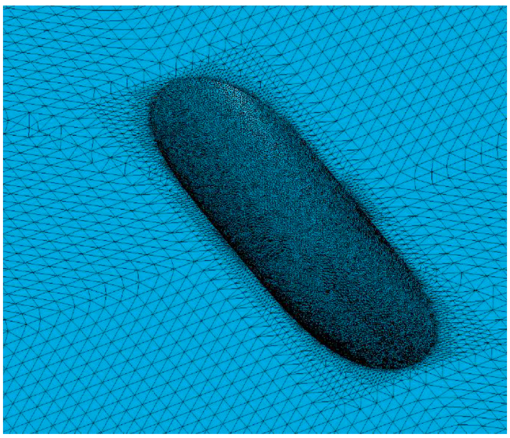

Figure 3: Details of the finite element mesh

The influence of the treated cracks on the spherical tank structure stress condition was simulated by introducing a groove on the sheath structure segment. The model is loaded by a uniform pressure field whose value was obtained by adding the calculation pressure and the maximum value of the hydrostatic pressure of the fluid. (p = 16 bar). Table 3 shows grooves dimensions and values of maximum stresses in the concentration zones.

Table 3. Dimensions of grooves and maximum stress values

Groove	Dimensions $l \times b \times a$ $[mm]$	Maximum stress MPa	Corrected dimension $l \times b \times a$ $[mm]$	Maximum stress $[MPa]$
173	60 x 15 x 4,2	391,6	60 x 25 x 4,2	331,9
203	50 x 20 x 5	373,8	50 x 25 x 5	354,7
197	45 x 30 x 6	367,5	45 x 40 x 6	358,1

Figures 4, 5 and 6 show the stress field in the zone of the analyzed grooves. Maximum hoop stress occurring on the spherical tank shell in the concentration zone - at the bottom of the groove no. 173 where the shell thickness is reduced from the projected 30 mm to 25.8 mm is $\sigma_{max,s} = 391{,}6\ MPa$, (Figure 4.a) which is greater than the permitted local stress $\sigma_{dl} = 360\ MPa$. As the stress proof is not satisfied, the dimensions of the analyzed groove need to be corrected so that the value of the maximum hoop stress is reduced. Maximum hoop stress occurring on the spherical tank shell in the concentration zone - at the bottom of the corrected groove No. 173 is $\sigma_{max,s} = 331{,}9\ MPa$, which is less than the permitted local stress. (Figure 4.b)

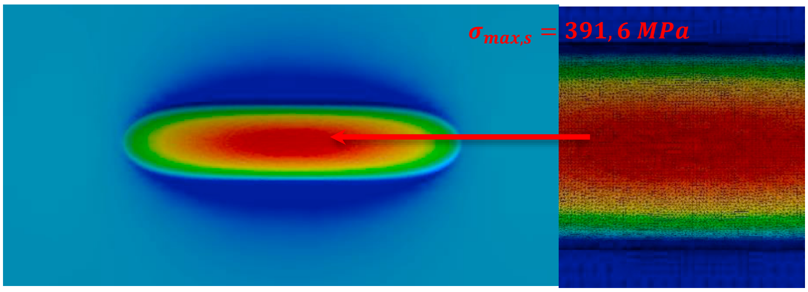

Figure 4.a: Stress field for the groove size 60 x 15 x 4.2 mm

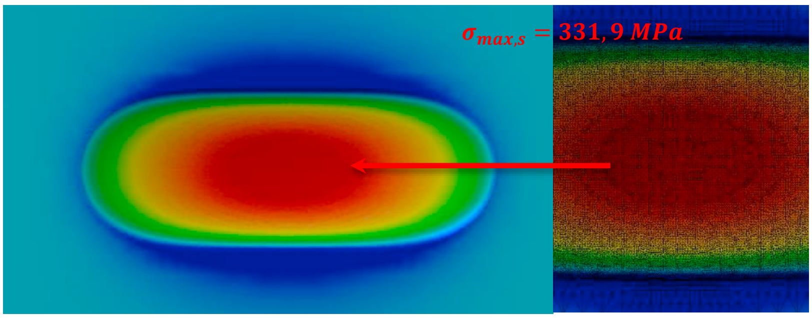

Figure 4.b: Stress field for the corrected groove size 60 x 25 x 4.2 mm

Maximum hoop stress occurring on the spherical tank shell in the concentration zone - at the bottom of the groove no. 203 where the shell thickness is reduced from the projected 30 mm to 25 mm is $\sigma_{max,s} = 373{,}8\ MPa$, which is greater than the permitted local stress $\sigma_{dl} = 360\ MPa$ (Figure 5.a). As the stress proof is not satisfied, the dimensions of the analyzed groove should be corrected so that the value of the maximum hoop stress is reduced. Maximum hoop stress occurring on the spherical tank shell in the concentration zone - at the bottom of the corrected groove no. 203 is $\sigma_{max,s} = 354{,}7\ MPa$, which is less than the permitted local stress. (Figure 5.b)

Maximum hoop stress occurring on the spherical tank shell in the concentration zone - at the bottom of the groove no. 197 where the shell thickness is reduced from 30 mm to 24 mm, is $\sigma_{max,s} = 367{,}5\ MPa$, larger than the permitted local stress $\sigma_{dl} = 360\ MPa$ (Figure 6.a). Thus, dimensions of groove need to be corrected so that the maximum hoop stress is reduced, to $\sigma_{max,s} = 358{,}1\ MPa$, which is less than the permitted local stress. (Figure 6.b)

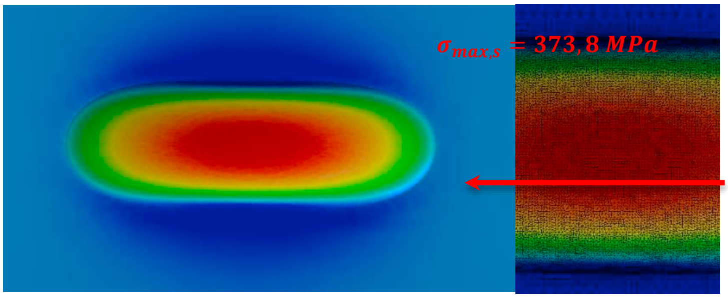

Figure 5.a: Stress field for the groove size 50 x 20 x 5 mm

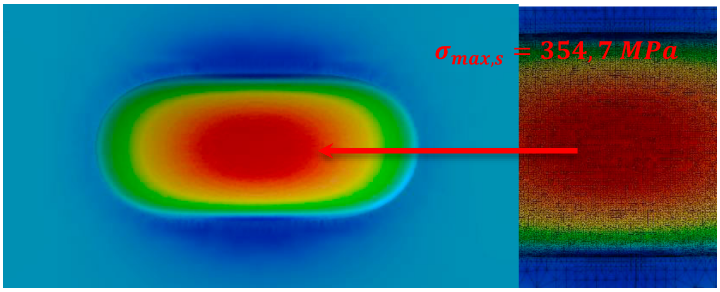

Figure 5.b: Stress field for the corrected groove size 50 x 25 x 5 mm

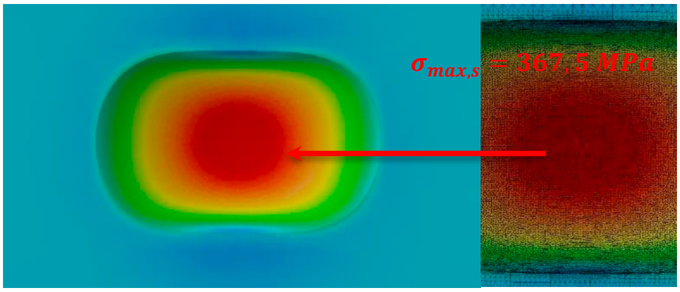

Figure 6.a: Stress field for groove size 45 x 30 x 6 mm

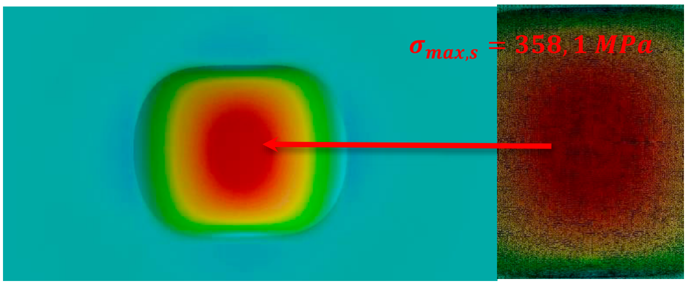

Figure 6.b: Stress field for corrected groove size 45 x 40 x 6 mm

4. Application of linear elastic fracture mechanics

Application of LEFM [3] is based on the stress intensity factor, K_I, which on the one hand represents the structure load and geometry, including the shape and size of the fracture, while on the other hand, its critical value, called fracture toughness, K_{IC}, represents the material property. On the basis of this interpretation of the LEFM parameters, simple dependencies are obtained to evaluate the structure integrity:

$K_I \leq K_{IC}$- the structure integrity is not compromised,
$K_I > K_{IC}$- the structure integrity is compromised as brittle fracture is possible.

The cracks separated as critical are analyzed by the fracture mechanics methods applying the conservative approach. In order to determine the stress intensity factors, it is necessary to know the load and geometry; the fracture toughness could not be determined, so a conservative estimate of its value was used. The possibility of corrosion and fatigue, the influence of residual stresses and the impact of terminals proximity were also taken into account. Analysis of critical cracks is given below. Data relevant to crack no. 173 analysis are:

- vessel geometry (thickness $t = 24{,}8\ mm$, mean radius $R_{sr} = 7545{,}5\ mm$),
- crack geometry (length $l = 60\ mm$, width $b = 25\ mm$, depth $a = 4{,}2\ mm$, location - on the transverse butt welded joint of the segments R3, away from the terminals),
- load (internal pressure $p = 16\ bar$, residual stress $\sigma_R = 0\ MPa$),
- fracture toughness of the weld metal $1560\ MPa\sqrt{mm}$, taken as the minimum value [4].

For stress intensity factor the following is obtained:

$$K_I = \left(\frac{p \cdot R_{sr}}{2 \cdot t} + \sigma_R\right) \cdot \sqrt{\pi \cdot a} = 884{,}15\ MPa\sqrt{mm}, \tag{10}$$

which is 56.7% of the critical value ($K_{IC} = 1560\ MPa\sqrt{mm}$) and does not bring the vessel into a dangerous state.

Data relevant for the crack no. 203 analysis are:

- vessel geometry (thickness $t = 24\ mm$, mean radius $R_{sr} = 7545{,}5\ mm$),
- crack geometry (length $l = 50\ mm$, width $b = 25\ mm$, depth $a = 5\ mm$, location - on the transverse butt welded joint of the segments R3, away from the terminals),
- load (internal pressure $p = 16\ bar$, residual stress $\sigma_R = 0\ MPa$),
- fracture toughness of the weld metal $1560\ MPa\sqrt{mm}$, taken as the minimum value.

For the stress intensity factor, the following is obtained:

$$K_I = \left(\frac{p \cdot R_{sr}}{2 \cdot t} + \sigma_R\right) \cdot \sqrt{\pi \cdot a} = 996{,}84\ MPa\sqrt{mm}\ , \tag{11}$$

which is 63.9% of the critical value ($K_{IC} = 1560\ MPa\sqrt{mm}$) and does not bring the vessel into a dangerous state.

Data relevant for the crack no. 197 analysis are:

- vessel geometry (thickness $t = 23\ mm$, mean radius $R_{sr} = 7545{,}5\ mm$),
- crack geometry (length $l = 45\ mm$, width $b = 40\ mm$, depth $a = 6\ mm$, location - on the transverse butt welded joint of the segments R3, away from the terminals),
- load (internal pressure $p = 16\ bar$, residual stress $\sigma_R = 0\ MPa$),
- fracture toughness of the weld metal $1560\ MPa\sqrt{mm}$, taken as the minimum value.

For the stress intensity factor, the following is obtained:

$$K_I = \left(\frac{p \cdot R_{sr}}{2 \cdot t} + \sigma_R\right) \cdot \sqrt{\pi \cdot a} = 1139{,}46\ MPa\sqrt{mm}, \tag{12}$$

which is 73.1% of the critical value ($K_{IC} = 1560\ MPa\sqrt{mm}$) and does not bring the vessel into a dangerous state.

5. Conclusion

The integrity of the ammonia spherical tank was checked against to discovered cracks on the longitudinal and transverse but joints. The finite element method enabled calculation of the stress intensity factors, which turned out to be smaller than the critical value, proving the integrity of the spherical tank.

References

[1] AFNOR material standard
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