

STRUCTURAL INTEGRITY OF SPHERICAL STORAGE TANKS-REVIEW PAPER IN MEMORY OF PROF. STOJAN SEDMAK AND PROF. ZVONKO LUKAČEVIĆ

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Abstract: An overview of research efforts to solve the problem of structural integrity of spherical tanks with cracks in welded joints made of high strength low alloyed steels. Structural integrity analysis was based on comparison of crack driving forces, determined analytically and numerically, with material crack resistance, defined by J-R curves, i.e. “classical” fracture mechanics approach. In addition, “modern” approaches are also presented, such as risk-based approach and application of the Finite Element Method (FEM). Three case studies are presented to illustrate different approaches. This paper is dedicated to two good friends, two great names in welding - Prof. Stojan Sedmak and Prof. Zvonko Lukačević.

1 INTRODUCTION

Spherical shape of a storage vessel is preferred for fluids under high pressure, because of smallest surface area per unit volume and the uniform distribution of stresses, what make it as ideal shape from the point of view of design thickness and total weight. Anyhow, since spheres are much more expensive to build than cylindrical vessels, they are used mostly for large volumes of stored fluids. They are made typically from fine-grained, high strength low alloyed (HSLA) steels, also in order to reduce the thickness and thus, the weight. Although weldable, these steels are also known for the history of cracking in welded joints, mostly for older generations of HSLA steels with relatively high content of Carbon, in late eighties of the last century [1]. Common cause of these phenomenon was the unproper execution of welding procedure specification (WPS), especially in combination with unnecessary high pressure during cold water testing.

Fine-grained steel, NIOVAL 47, microalloyed by V, with 460 MPa nominal yield strength, was used mostly to produce spherical storage tanks in 1970-ties. Lack of experience with new type of steel, in addition to already mentioned problems, made a big issue in their further use, and led to a controversial decision to ban this type of steel from further use in pressure vessels [2]. Anyhow, a number of spherical storage tanks are still in service, requiring strict monitoring, as is the case also in Serbia.

On the other hand, in the similar time frame, fracture mechanics parameters were applied to assess the structural integrity of a large pipeline from Alaska to USA with similar cracking problems. Once the results of a large study have been accepted by NIST, with arguments that the fracture mechanics analysis is acceptable basis for exemption from existing standards, if this analysis provides reasonable and conservative (safe) assessment of structural integrity, engineers were equipped with the tool needed to deal with so-called unacceptable defects, such as cracks, [3-5]. This approach was also used in ex Yu to establish criteria for crack acceptance out of the standard rules. The basic idea is to compare a crack driving force, expressed through stress intensity factor, J integral or crack tip opening displacement, with a materials resistance to cracking, named fracture toughness, and expressed as a critical value of these three basic fracture mechanics parameters. This approach is applied here to three case studies with additional analysis in last two case studies, one so-called risk-based approach, and the other one which includes the Finite Element Method (FEM).

2 LEAKAGE OF SPHERICAL STORAGE TANKS

Spheres, volume 150 to 5000 m³, have been used for storage of different fluids, such as liquefied natural gases (LNG), ammonia, carbon dioxide, vinyl chloride monomer (VCM), since 1977. The sphere, shown in Fig. 1, volume 2000 m³, was produced of 24 assembled segments and two lids (bottom and top), with wall thickness 20 mm, and supported by 12 legs. It was welded by longitudinal joints - L (total length 483 m), performed 50% by submerged arc welding (SAW) and 50% by SMAW, and radial joints - R (total length 120 m), performed by SMAW. Corresponding consumables were used for welding, e.g. electrodes EVB-60 (AWS E8018-G) of Steelworks Jesenice.

The HSLA steel was used (TTSt E-47) with the yield strength $R_{p0.2} = 470\text{-}506 \text{ MPa}$, tensile strength $R_m = 639\text{-}660 \text{ MPa}$, elongation = 25-27%, impact toughness 120-166 J/cm² at 0°C, and following chemical analysis: 0.18-0.19% C; 0.44-0.45% Si; 1.42-1.43% Mn; 0.08% V; 0.048-0.055% Nb; 0.012-0.015% P; 0.009-0.014% S.

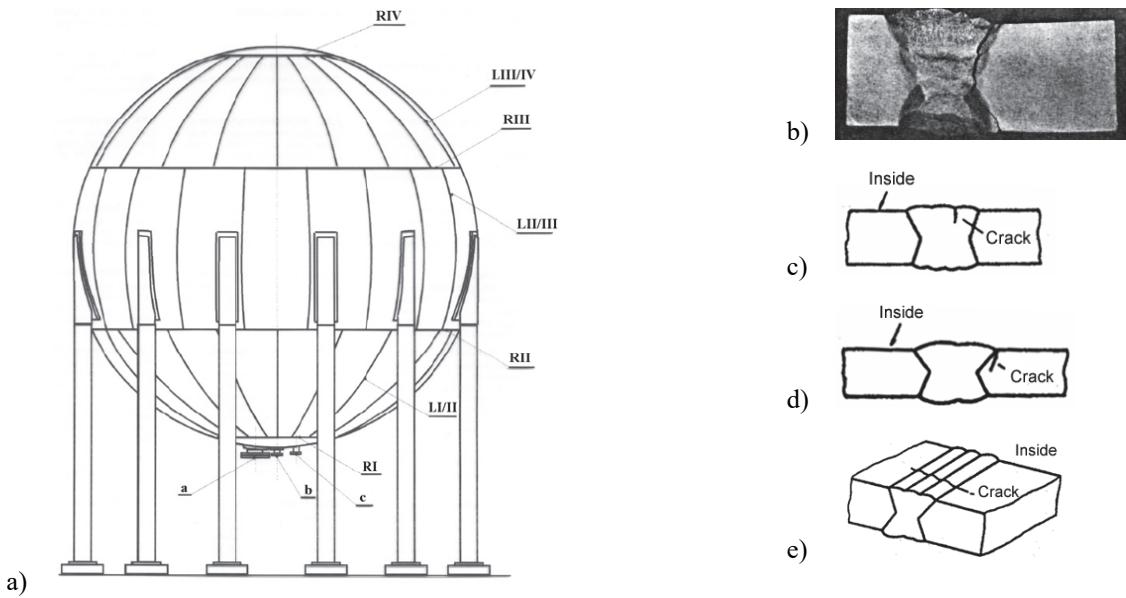


Figure 1. a) spherical pressure vessel, b) HAZ crack macrograph c-e) schematics of cracks

During regular inspection of spherical tank, a large number of cracks in welded joints have been detected after proof test under 30% of overload in 1986-90 and in 1996 on the inner wall side, as shown in Fig. 1b-e.

It is also to underline one misfit in former regulations. The sequence in production prescribed final non-destructive testing, repairing of detected defects, and pressure vessel, considered as finished was exposed to proof pressure test, which might be significantly higher than operating pressure. This means that the effect of overloading (compared to operating pressure) during proof test is neglected, although there are several locations, mostly connected with welded joints, of significant stress concentration. During high pressure proof test, very small cracks could initiate. Having this in mind, the data about sphere behaviour in elastic plastic range can help in structural integrity assessment.

3 CASE STUDY 1 - STRUCTURAL INTEGRITY ASSESSMENT BY J INTEGRAL [6]

Spherical storage tank is now analysed, with outer diameter $D_s=21250$ mm and wall thickness $h=25$ mm, designed for pressure $p_d=6$ bar and proof test pressure $p_0=10$ bar at temperature $t=15^\circ C$, also produced of fine-grained HSLA steel, TTSt E-47 class, with tested Yield Stress 480 MPa and Ultimate Tensile Strength 680 MPa.

J integral testing had been performed using standard C(T) specimen (Fig. 2a) and unloading compliance method to evaluate J_{lc} , a measure of fracture toughness, and to define J-R curve, as presented in Fig. 2b. Resistance curves are obtained for parent metal (PM), with the cracks in rolling direction (CT1, CT2) and transversal to it (CT3, CT4).

Stable crack growth behaviour is evaluated comparing J-R curve of the PM with crack driving force from King's model, [6,7], as shown in Fig. 3. Basic equations of the King's model are:

$$J_e = \frac{1-\nu^2}{E} K_I^2 \quad J_p = \frac{4\sigma_F}{E} (a + a_p) \sigma - a \sigma_{LY} - \frac{h-d}{h} a_p \sigma_Y \quad J = J_e + J_p \quad (1)$$

where ν is Poisson's ratio, E is modulus of elasticity, K_I stress intensity factor, σ_F flow stress (mean value of yield stress and tensile stress), a_p plastic correction of crack length, σ applied stress, σ_{LY} net section yielding stress, J_e elastic part of J integral and J_p its plastic part.

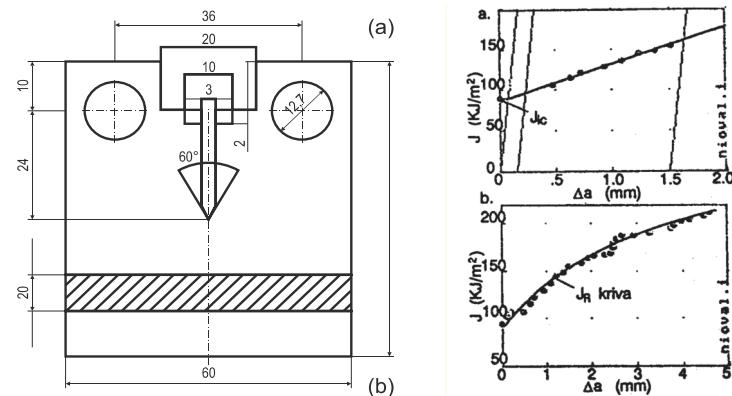


Figure 2. a) C(T) specimen for J integral testing, b) Typical J integral values

Set of CDFs, for different levels of applied stress vs. the relative crack depth, (d/h), is presented in Fig. 3, together with J-R curves, positioned at the maximum crack depth $d=5$ mm (ratio $d/h=0.2$), for the parent metal in rolling (CT1) and cross-rolling (CT4) direction. The conclusion was that stable crack growth is not critical since required CDF for detected small cracks corresponded to pressure of 22 bar ($\sigma/\sigma_Y=0.97$) and the pressure in proof test was 10 bar.

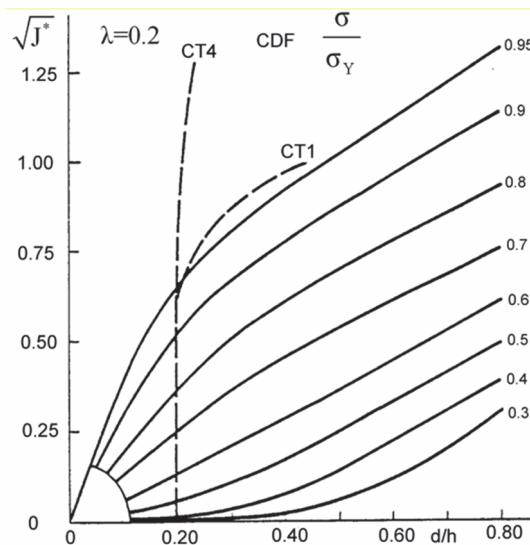


Figure 3. Crack resistance J -R curves for BM vs. J crack driving force (CDF)

4 STRUCTURAL INTEGRITY ASSESSMENT-“MODERN” RISK-BASED APPROACH

In this chapter, structural integrity assessment is described, using recently introduced risk-based approach, including fracture mechanics parameters and concepts, [8-11]. This concept goes well with activities of ESIS TC12, [12-13], especially when so-called “critical” components, such as pressure vessels, are analysed. It is well known that consequences of failure of pressure vessels can be extremely serious, even catastrophic, [14]. On the other side, frequency of pressure vessel failures is very low, and typically related to welded joints, as the most crack sensitive areas, [10].

Probability is well known mathematical term, defined as number of events divided by number of possible events. Anyhow, such a definition takes just statistics into account, while much more important factor is missing-state of the component. It is self-evident that the probability of failure of a pressure vessel with a crack is much higher than for a sound pressure vessel, and more or less proportional to defect size. Based on this reasoning, probability can be estimated according to the position of the service point in the Failure Assessment Diagram (FAD), [8-9].

4.1 Failure Assessment Diagram application

Failure Assessment Diagram, level 2, as shown in Fig. 4, is relatively simple and very efficient engineering tool to assess structural integrity of a cracked component made of elastic-plastic material, such as High Strength Low Alloyed (HSLA). Basically, FAD indicates position of a point corresponding to a given stress state for a cracked component, either in the safe and unsafe region divided by so-called limit curve:

$$K_r = S_r \left[\frac{8}{\pi^2} \ln \sec \left(\frac{\pi}{2} S_r \right) \right]^{-1/2} \quad (2)$$

where $S_r = S_n/S_c$ and $K_r = K_I/K_{Ic}$, S_n is the stress in net cross section, S_c the critical stress (Yield Strength, Tensile Strength or any value in-between), K_I for the stress intensity factor and K_{Ic} for its critical value, i.e. fracture toughness.

As already explained, probability of failure is here taken as being proportional to the defect size, so it can be defined as the ratio OA/OB, Fig. 4.

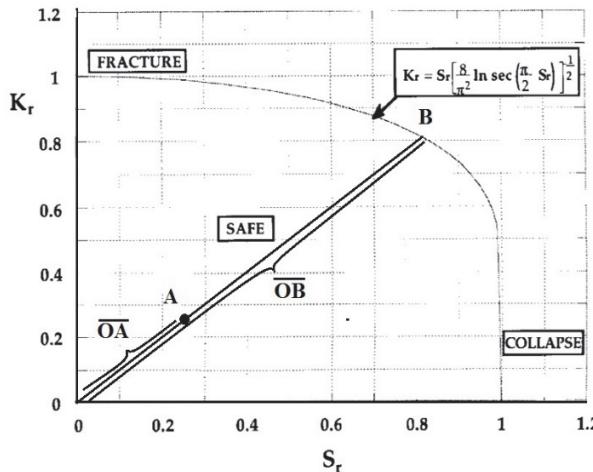


Figure 4. FAD with service point A and corresponding point on limit curve B

5 CASE STUDY 2 - SPHERICAL TANKS FOR AMMONIA STORAGE

This analysis was performed on two spherical storage tanks for ammonia storage (volume 1000 m^3 , diameter $D = 12400 \text{ mm}$ and wall thickness $t = 30 \text{ mm}$, Fig. 5a). The operating pressure was $p = 16.5 \text{ bar}$ and water proof test pressure $p = 25 \text{ bar}$ was applied in 1998 and 1999 together with Non-Destructive Testing (NDT), [2, 11, 14]. The tanks have been constructed in 1979 using micro-alloyed steel St.E460, similar to TTSt E-47, with nominal yield strength $R_{p0.2} = 460 \text{ MPa}$, ultimate tensile strength $R_m = 600 \text{ MPa}$, elongation $A_5 = 28\%$, welded by electric arc procedures with basic consumables.

Ultrasonic, dye penetrant and magnetic particle methods had been used. The last one, in combination with fluorescent light, turned out to be the most efficient for detection of surface and small subsurface cracks. A large number of transverse cracks in weld metal and longitudinal cracks in HAZ along fusion line of inner welded joints have been detected, as shown in [2, 11, 14]. The longitudinal cracks were considered as more dangerous because of size (highest length up to 300 mm, depth up to 13.5 mm) and position.

Fracture mechanics testing for determination of crack resistance in the form of J-R curves and critical J integral value, J_{lc} , was performed using three tensile, single edge notched specimens, testing by compliance method (ASTM E 813). The crack was located in HAZ, passing through fusion line region. Calculated mean value was $J_{lc} = 221 \text{ kN/m}$.

The King's model was applied for CDF calculation, taking into account the largest longitudinal crack of 300 mm in length and $c = 13.5 \text{ mm}$ deep, with the ratio $c/h = 0.45$ for thickness $h = 30 \text{ mm}$. Then CDFs are plotted against J-R curves, as shown in Fig. 5b, indicating the critical pressure for unstable crack propagation 30.8 bar, being above prescribed proof test pressure, 25 bar.

Now, at this point we shift to the risk-based approach. Using previously obtained results, [11], fracture toughness was taken as $K_{lc} = 2750 \text{ MPa}\sqrt{\text{mm}}$, the minimum value in HAZ. One typical crack was presented as an edge crack with length $a = 13.5 \text{ mm}$, as if it was along the whole circumference.

Therefore, the conservative approach has been applied, with the following data:

- PV geometry (thickness $t = 25 \text{ mm}$, diameter $D = 12500 \text{ mm}$);
- St.E460 steel: $R_{p0.2} = 480 \text{ MPa}$, $R_m = 680 \text{ MPa}$; $K_{lc} = 2750 \text{ MPa}\sqrt{\text{mm}}$, [14];
- simplified crack geometry (edge crack, length 13.5 mm, ratio length/thickness=0.45);
- loading (max. pressure $p = 0.6 \text{ MPa}$, stress $\sigma = p \cdot R/2 \cdot t = 75 \text{ MPa}$, residual stress $\sigma_R = 196 \text{ MPa}$ - max. value transverse to the weld, [14]);

The SIF is then calculated as: $K_I = 1.12 \cdot (p \cdot R/2t + \sigma_R) \sqrt{\pi a} = 1.12 \cdot (75 + 196) \sqrt{\pi} \cdot 13.5 = 1971 \text{ MPa}\sqrt{\text{mm}}$, resulting in the ratio $K_R = K_I/K_{lc} = 1971/2750 = 0.72$.

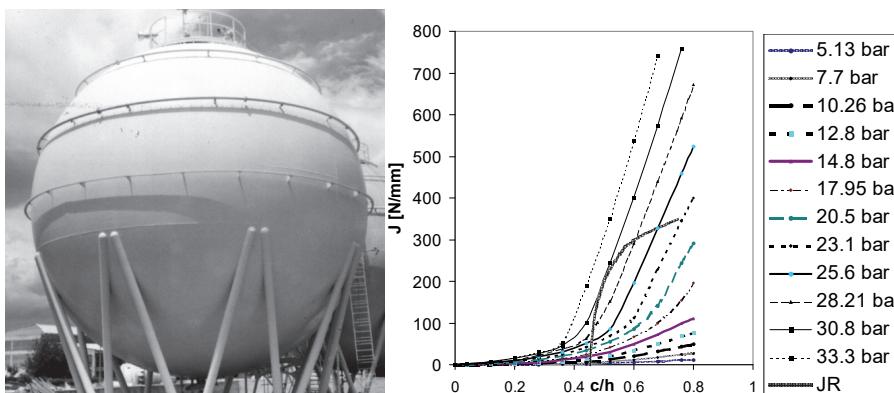


Figure 5. a) Spherical pressure vessel for VMC, b) CDFs vs. J-R curves

The net stress is $\sigma_n = 1.82 \cdot p \cdot R / 2t$, due to cross-section reduction, and critical stress is $\sigma_F = (R_{ch} + R_M) / 2 = 580$ MPa; resulting in $S_R = (1.82 \cdot 75) / 580 = 0.24$. Thus, the coordinates in FAD are (0.24, 0.72), resulting in probability of failure 0.75, Fig. 6.

The same calculation for the proof testing (pressure $p=1$ MPa) „pushes“ the stress intensity factor (SIF) over K_{Ic} value ($3285 / 2750 = 1.19 > 1$), indicating clearly that the proof test is detrimental and dangerous.

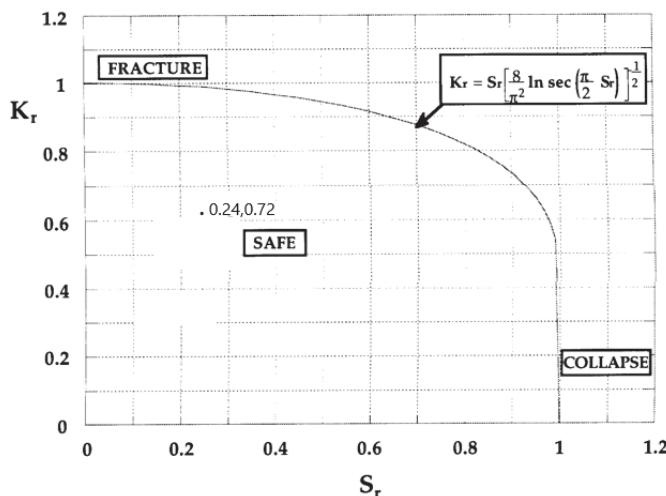


Figure 6. The FAD for the spherical tank for VMC – case study 2

6 CASE STUDY 3 - STRUCTURAL INTEGRITY ASSESSMENT OF THE SPHERICAL TANK- “CLASSICAL” FRACTURE MECHANICS APPROACH AND FINITE ELEMENT METHOD

During regular periodic inspection of transversal and longitudinal welded joints of the segments of the spherical storage tank for storing liquid ammonia (with a volume of 1800 m³, outer diameter $D_s = 15120$ mm and nominal wall thickness $s_e = 30$ mm) by NDT, 211 irregularities were detected in the form of unacceptable defects (cracks), [15-16]. Therefore, the most critical defect (No. 197, indicated by an arrow in Fig. 7) was analysed by fracture mechanics approach using a conservative approach to prove pressure vessel integrity.

Data relevant for the crack 197 are:

- vessel geometry (thickness $t = 25$ mm, mean radius $R_{sr} = 7545,5$ mm),
- crack geometry (length $l = 45$ mm, depth $a = 6$ mm, location - the transverse butt welded joint R3),
- load (internal pressure $p = 16$ bar, residual stress $\sigma_R = 0$ MPa),
- fracture toughness of the weld metal 1560 MPa/mm, taken as the minimum value for Nioval 47.

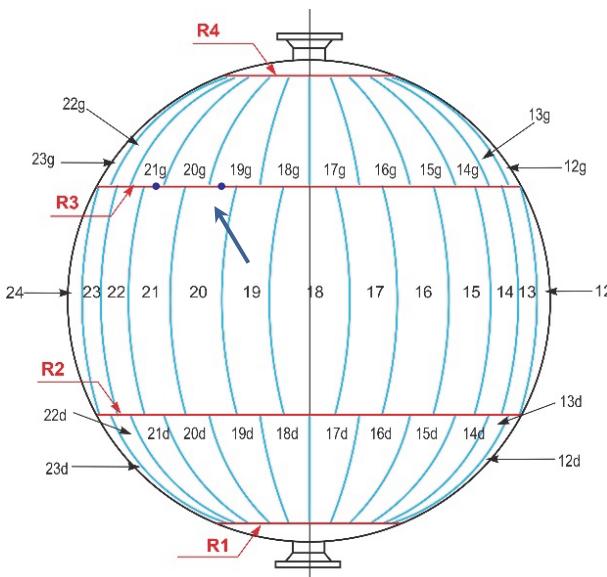


Figure 7. The spherical storage tank for liquid ammonia

For the stress intensity factor the following is obtained:

$$K_I = \left(\frac{p \cdot R_{sr}}{2 \cdot t} + \sigma_R \right) \cdot \sqrt{\pi \cdot a} = 1139 \text{ MPa}\sqrt{\text{mm}} \quad (3)$$

which is 73,1% of the critical value (1560 MPa $\sqrt{\text{mm}}$) and does not bring the vessel into a dangerous state. Parameter S_r is determined according to:

$$S_r = \frac{\sigma_n}{\sigma_F} = \frac{\frac{p \cdot R_{sr}}{2 \cdot t}}{\frac{R_{p0,2} + R_m}{2}} = 0.43. \quad (4)$$

Thus, coordinates of the defect 197 are (0.43, 0.73), Fig. 8, indicating the probability of failure 0.75.

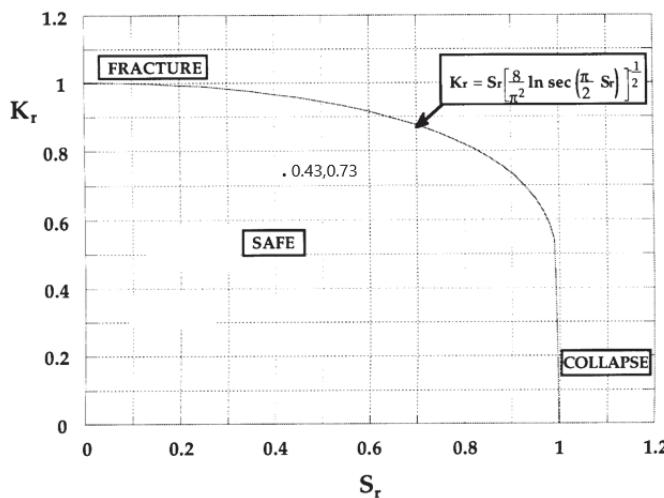


Figure 8. The FAD for the spherical tank for ammonia - case study 3

6.1 Finite element model and influence of cracks on the stress state

The 3D finite element model of the ammonia spherical tank structure was made consisting of 2558929 tetrahedron-type elements and 544427 nodes. The size of the finite element in the local crack zone was 0.2 mm, otherwise it was 2 mm. The details of the finite elements mesh generated in the crack zone are shown in Figure 9.

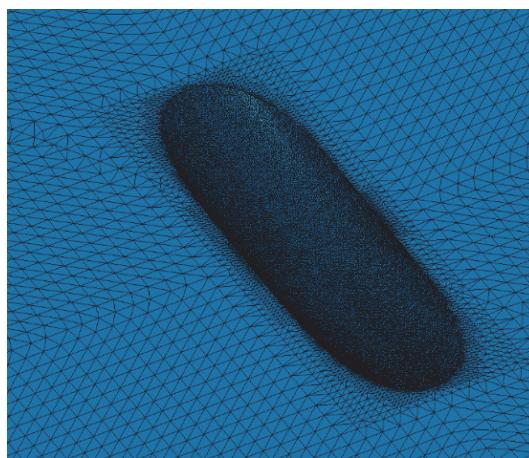


Figure 9. Details of the finite element mesh

Maximum hoop stress occurring on the spherical tank shell in the concentration zone - at the bottom of the groove No. 197 (dimensions 45 x 30 x 6), was $\sigma_{max,s}=367.5$ MPa, larger than the permitted local stress $\sigma_{dl}=360$ MPa (Fig. 10a). Thus, dimensions of groove needed to be corrected (45 x 40 x 6), so that the maximum hoop stress is reduced, to $\sigma_{max,s}=356.6$ MPa, Fig. 10b.

Table 1. Dimensions of grooves and maximum stress values

Defect	Groove dimensions $l \times b \times a / \text{mm}$	Maximum stress / MPa	Corrected dimensions $l \times b \times a / \text{mm}$	Maximum stress / MPa
197	45 x 30 x 6	367.5	45 x 40 x 6	356.6

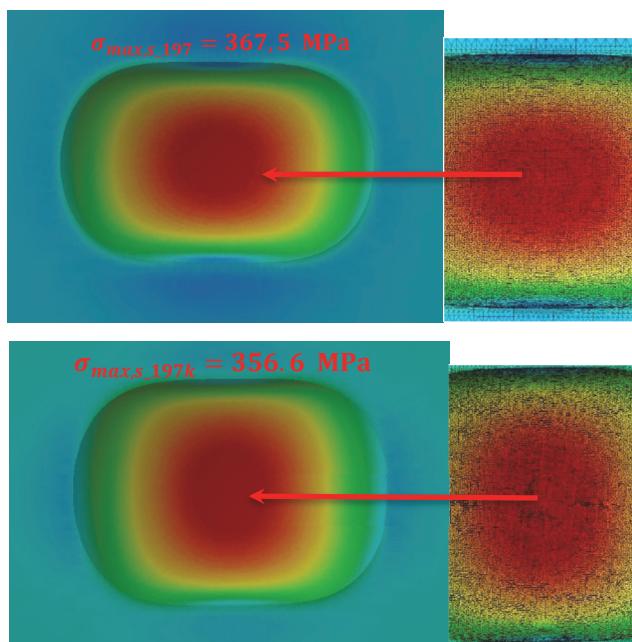


Figure 10. Stress field for groove size a) $45 \times 30 \times 6 \text{ mm}$, b) $45 \times 40 \times 6 \text{ mm}$

7 CONCLUSION

Three somewhat different, but complementary approaches to structural integrity assessment have been presented and applied to spherical tank weldment cracking problem. In each of presented case studies it was shown that fracture mechanics parameters can be successfully applied to analyse cracking problems in spherical tanks. In addition, it was demonstrated that the risk-based analysis, as well as the Finite Element Method, can be also used as additional tool to assess structural integrity of welded joints in large spherical tanks, made of HSLA steels.

ACKNOWLEDGEMENT

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