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Procedia Structural Integrity 42 (2022) 356–361

Structural Integrity Procedia

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23 European Conference on Fracture - ECF23

Effects of Over-Loading on Pressure Vessel Integrity

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Abstract

The effect of proof over-pressure on pressure vessels structural integrity is analysed. Risk based approach is applied using Failure Analysis Diagramme to assess likelihood of failure. Special attention is paid to crack-like defects detected by NDT regular testing which are unacceptable by standards, but difficult to be repaired. It was show, using two examples, that such defects can remain if some strict conditions are fulfilled. In any case, with or without crack-like defects, it was shown that testing of pressure vessels with significant over-pressure can cause much more problems than it has benefits, because it acts more like the first step in eventual failure, than being proof to anything.

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Peer-review under responsibility of the scientific committee of the 23 European Conference on Fracture – ECF23

Keywords: turbine shaft; fatigue crack growth; xFEM; integrity

1. Introduction

Pressure vessels structural integrity assessment is of utmost importance for their safe and reliable operation, especially in the case of high potential consequences, as shown in [1-5]. This is especially important when it comes to the proof testing, since it has been shown that overpressure can cause significant damage and brings no benefit, [5, 6]. Therefore, the basic aim of this paper is to make risk based analysis of pressure vessels structural integrity with focus of over-pressure effect. Toward this aim, a simple engineering tool will be used to estimate likelihood, [7-12], and simple reasoning will be used to estimate consequence, [4, 8], so that risk will be evaluated as the product of these two. This approach is also adopted in the scope of ESIS TC12 activities, [13]. The main concern is the initiation of crack-like defects due to over-pressure, which was a typical consequence of over-pressure after repair welding of HSLA steel welded joints in spherical pressure vessels back in seventies and eighties, [5]. Therefore, here we will apply a simple engineering tool to evaluate the effect of over-loading in two cases, one being the spherical storage tank for VCM, [3, 5, 11], and the other one, storage tanks for compressed air in the Reversable Hydro Power Plant Bajina Basta in Serbia, [1, 6, 7].

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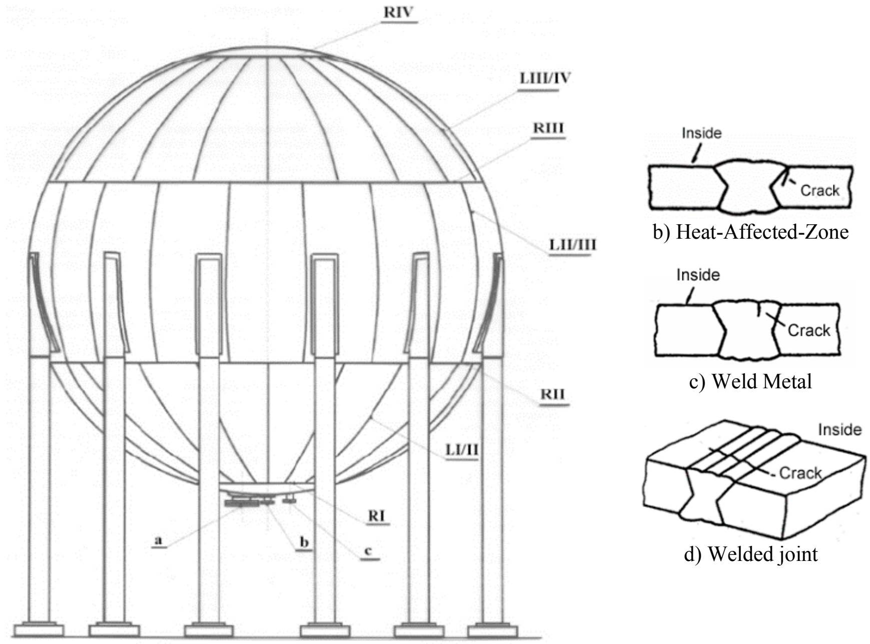
10.1016/j.prostr.2022.12.044

2. Structural integrity assessment

2.1. Spherical tank for vinyl-chloride monomer (VCM)

As the first case study, the large spherical tank, Fig. 1a, was considered, to analyse over-pressure effect on its integrity, which was jeopardized after leakage caused by undetected micro-cracks in welded joint, grown through the thickness during proof testing (pressure up to 50% above the design pressure), Fig. 1b-d, [11].



a)

Fig. 1. a) Spherical storage tank, b-d) Cracks on inner wall side of spherical tank, [11]

Here we analyse the large sphere for VCM, volume 2,000 m^3, diameter 15.6 m, made of fine grain, micro-alloyed steel TTSt E-47, Steelworks Jesenice. Design pressure was 0.5 MPa, creating membrane stress σ=pR/2t=97.6 MPa. Residual stress was taken into account since no record of post weld heat treatment (PWHT) was available, σ_R=196 MPa - maximum value transverse to the weld (40% of the Yield Stress, R_{eh}) and σ_R=480 MPa - maximum value in the longitudinal direction, (100% of the Yield Stress, R_{eh}), [11].

During NDT inspection, many crack-like defects were detected in welded joints, mostly in radial welded joints (RIII, Fig. 1a), at the border of liquid and gaseous phases, [11]. Typically, crack location was in the heat-affected-zone (HAZ), not uncommon for the steel TTSt E-47, as also indicated by the data for fracture toughness: K_{Ic} (BM)=4420 MPa√mm, K_{Ic} (WM)=2750 MPa√mm, K_{Ic} (HAZ)=1580 MPa√mm, [11].

All detected cracks were three-dimensional (3D), surface cracks, with different lengths (100-200 mm) and depth approximately 5 mm**.** For cracks of such shape, it has been shown that they would grow into depth [11], i.e. leakage would precede catastrophic failure. In the scope of conservative and at the same time simplified approach, cracks are represented as being 2D edge crack, with length 5 mm, as they are schematically shown in Fig. 1b-c. The stress intensity factor (SIF) is calculated for longitudinal cracks (HAZ and WM, Figs. 1b and 1c, respectively), and for the transverse crack (BM, Fig. 1d) as follows:

$K_I = 1.12 \cdot (pR/2t + \sigma_R)\sqrt{\pi a} = 1302.5 MPa\sqrt{mm}$ (WM and HAZ),

$K_I = 1.12 \cdot (pR/2t + \sigma_R)\sqrt{\pi a} = 2562.8 MPa\sqrt{mm}$ (BM),

providing the following ratios $K_R = K_I/K_{Ic}$:

$K_R = K_I/K_{Ic} = 1302.5/2750 = 0.47$ (WM),

$K_R = K_I/K_{Ic} = 1302.5/1580 = 0.82$ (HAZ),

$K_R = K_I/K_{Ic} = 2562.8/4420 = 0.58$ (BM).

The net stress, σ_n, is taken for all zones in welded joint as $\sigma_n = 1.33 \cdot pR/2t$ (coefficient 1.33=20/15 due to reduced cross-section), whereas the flow stress, σ_F, is estimated to $\sigma_F = (R_{eH} + R_M)/2 = 580\ MPa$ for BM, 610 MPa for HAZ and 510 MPa for WM, according to data provided in [11]. Now, one can calculate $S_R = (1.33 \cdot 97.5)/580 = 0.22$, for BM, 0.21 for HAZ and 0.24 for WM.

The coordinates (K_R, S_R) for design pressure are as follows: WM (0.24, 0.47), HAZ (0.21, 0.82), BM (0.22, 0.58), respectively, as shown in Fig. 2, with failure likelihoods 0.49 (WM), 0.85 (HAZ) and 0.61 (BM). Now for the 30% of over-pressure, the net stress is proportionally increased, whereas stress intensity factors get the following values:

$K_I = 1.12 \cdot \left(\frac{pR}{2t} + \sigma_R\right)\sqrt{\pi a} = 1520\ MPa\sqrt{mm}$ (WM and HAZ),

$K_I = 1.12 \cdot \left(\frac{pR}{2t} + \sigma_R\right)\sqrt{\pi a} = 2781\ MPa\sqrt{mm}$ (BM),

providing the following ratios $K_R = K_I/K_{Ic}$:

$K_R = K_I/K_{Ic} = 1520/2750 = 0.53$ (WM),

$K_R = K_I/K_{Ic} = 1520/1580 = 0.96$ (HAZ),

$K_R = K_I/K_{Ic} = 2781/4420 = 0.63$ (BM).

The coordinates (K_R, S_R) for over-pressure are as follows: WM (0.31, 0.53), HAZ (0.27, 0.96), BM (0.29, 0.63), respectively, also shown in Fig. 2, with failure likelihoods 0.56 (WM), 0.99 (HAZ) and 0.66 (BM). Based on the results shown here, one can notice that the over-pressure brings HAZ practically on the limit line, providing a simple explanation why new cracks are produced.

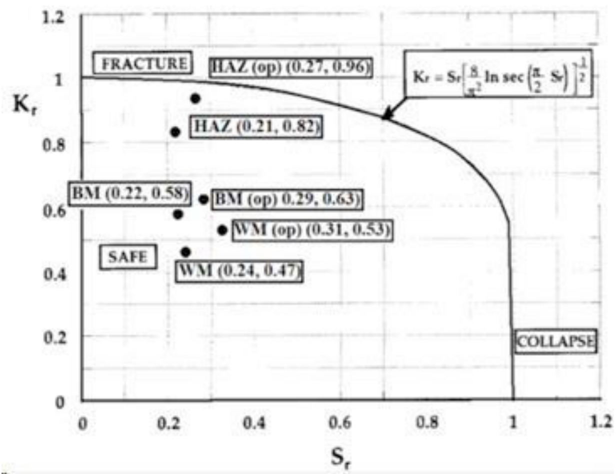


Fig. 2. The FAD for VCM storage tank with cracks in WM, HAZ and BM, design and over-pressure

Corresponding risk levels are defined in Table 1, with a consequence taken as very high, [11]. indicating the medium, high and very high risk level for WM, BM and HAZ, respectively, both under design and over-pressure. Anyhow, detrimental effect of over-pressure is clearly shown by increased value of HAZ failure likelihood up to 0.99.

Table 1. Risk matrix for spherical storage tank for VCM

Probablity category	Consequence category					
	1 – very low	2 - low	3 - medium	4 - high	5 - very high	**Risk legend**
≤0.2 very low						**Very low**
0.2-0.4 low						**Low**
0.4-0.6 medium					***p*=0.5/0.75 MPa 0.49/0.56, WM**	**Medium**
0.6-0.8 high					***p*=0.5/0.75 MPa 0.61,0.66, BM**	**High**
0.8-1.0 very high					***p*=0.5/0.75 MPa 0.85/0.99, HAZ**	**Very High**

2.2. Storage tanks for compressed air

Eight cylindrical storage tanks for compressed air in Reversible Hydro Power Plant Bajina Basta were originally used to establish the risk based procedure, [4, 6]. They have been working more than 20 years before the regular NDT (radiography) revealed non-acceptable defects, according to standards. Having in mind the fact that no mechanisms for crack growth is acting, it was decided to leave these defects and follow closely behaviour of storage tanks. Later on, since 2019, radiography was replaced with conventional ultrasonic testing (UT), providing somewhat different results, as shown in [14] and discussed here.

Consequence in this case is the highest possible, because eventual failure could cause disaster, [4]. Probability of failure is now calculated for the most critical defect, according to recent UT results. Following data is used in this analysis:

- Storage tank geometry: thickness t=50 mm, diameter D=2075 mm.
- Material (HSLA steel): R_{eh}=500 MPa, R_M=650 MPa; K_{Ic}=1580 MPa√mm.
- Crack geometry: length 2c=180 mm, depth c= 32 mm (circumferential weld – lack of fusion, from 18-50 mm).
- Longitudinal stress pR/2t=87 MPa.

Now, one can calculate the stress intensity factor $K_I=Y(a/W,a/c)(pR/2t)\sqrt{\pi a}=1{,}25(87)\sqrt{32\pi}=1090$ MPa√mm, where Y(a/W,a/c) is obtained following the procedure described elsewhere, [15]. Taking into account the fracture toughness, one gets $K_I/K_{Ic}=0.69$.

Plastic collapse ratio is calculated as follows: $S_R=\sigma_n/\sigma_F=87\cdot 2.78/575=0.42$. Thus, the coordinates in FAD are (0.42, 0.69), as shown in Fig. 3, and the probability is 0.72, making risk level high. In the case of 43% over-pressure (proof test), probability is 1.02, which is unreasonable and beyond discussion. Therefore, the recommendation was to limit over-pressure to 10%, which would correspond to high risk level, but not extremely high (probability 0.79).

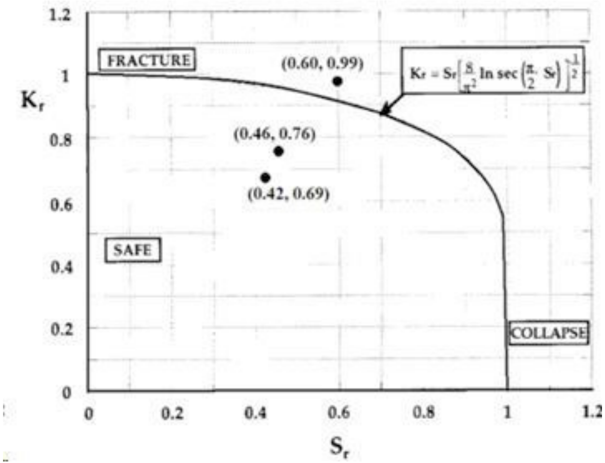


Fig. 3. FAD for design pressure (0.42,0.69), over-pressure 10% (0.46,0.76) and over-pressure 43% (0.60,0.99)

Table 2. Risk matrix for Storage tanks for compressed air in RHPP

	Consequence category					
Probablity category	1 – very low	2 - low	3 - medium	4 - high	5 - very high	**Risk legend**
≤0.2 very low						**Very low**
0.2-0.4 low						**Low**
0.4-0.6 medium						**Medium**
0.6-0.8 high					**p=8.1 MPa, 0.72 p=8.8 MPa, 0.79**	**High**
0.8-1.0 very high					**p=11.5 MPa, 1.02**	**Very High**

Discussion and conclusions

Simple engineering tools are used to assess structural integrity of pressure vessels containing crack-like defects, classified as unacceptable according to standards. Successful application of this approach is based on the fact that the geometry, including crack-like defects, considered in presented cases, are simple, so that analytical expressions can be used. In the case of more complex geometries, requiring 3D analysis, numerical methods are inevitable, as shown in [16-18].

Both here and in previous research on this topic detrimental role of proof testing was illustrated and explained, [3, 7, 11, 15], more or less proportionally to the level of over-pressure. Not only that nothing is really proved by this unnecessary procedure, but also damage in form of plastic strain and consequent cracking can appear. Especially if a crack-like defect already exists, one should not even consider proof testing. Therefore, the following conclusion is obvious:

- Effect of over-pressure on pressure vessels is detrimental from the point of view of structural integrity since it can cause unnecessary damage of welded joints, as the most crack sensitive regions. Both simple engineering method, as presented here, and previously performed more complex computational fracture mechanics analysis, lead to that conclusion.

Acknowledgements

This work is supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Contract No. 451-03-68/2022-14/200135 and. 451-03-68/2022-14/200213).

References

[1] Sedmak, S., Sedmak, A. Integrity of Penstock of Hydroelectric Power plant, Structural Integrity and Life, 5, 2005, pp. 59-70

[2] Sedmak, S., Sedmak, A., Experimental investigation into the operational safety of a welded penstock by a fracture mechanics approach, Fatigue and Fracture of Engineering Materials and Structures Vol. 18 (1995), pp. 527-538

[3] Sedmak A.; Algool, M.; Kirin, S.; Rakicevic, B.; Bakic, R.; Industrial safety of pressure vessels - Structural integrity point of view, Hemijska industrija 70 (6) 2016, pp .685-694

[4] Vučetić, I., Kirin, S., Vučetić, T., Golubović, T., Sedmak, A., Risk Analysis in the Case of Air Storage Tank Failure at RHPP Bajina Bašta, Structural Integrity and Life, Vol. 18 (1), p. 3-6

[5] Zaidi, R., Sedmak, A., Kirin, S., Martić, I., Šarkočević, Z., Structural integrity and life assessment of oil drilling rig pipes using analytical method Structural Integrity and Life, 22(1), 2022, 63–68

[6] Golubović, T.; Sedmak, A.; Spasojević Brkić, V.; Kirin, S.; Rakonjac, I.; Novel risk based assessment of pressure vessels integrity. Technical Gazette 25 (2018) No. 3, pp. 803-807

[7] Jeremić, L., Sedmak, A., Milovanović, N., Milošević, N., Sedmak, S., Assessment of integrity of pressure vessels for compressed air, Structural Integrity and Life, Vol. 21, No.1, 2021, 3–6

[8] Martić, I., Sedmak, A., Mitrović, N., Sedmak, S., Vučetić, I., Effect of over-pressure on pipeline structural integrity, Technical Gazette, 2019, Vol. 26, No. 3, p. 852-855

[9] Pilić, V., Mihajlović, V., Stanojević, P., Anđelković, A., Baloš, D., Application of innovative risk assessment methodology for damage mechanisms identification on part of amine regeneration unit, Structural Integrity and Life, Vol.19, No.1, 2019, pp.29–35

[10] Pilić, V., Stanojević, P., Mihajlović, V., Baloš, D., Damage mechanism and barrier identification on hydrogen production unit using innovative methodology for risk assessment, Structural Integrity and Life, Vol.19, No.2, 2019, pp.131–137

[11] T. Golubović, A. Sedmak, V. Spasojević Brkić, S. Kirin, E. Veg, Welded joints as critical regions in pressure vessels – case study of vinyl-chloride monomer storage tank, Hemijska Industrija, 2018, Volume 72, Issue 4, 177-182

[12] Vučetić, I., Kirin, S., Sedmak, A., Golubović, T., Lazic, M., Risk management of a hydro power plant – fracture mechanics approach, Technical Gazette 2019, 26, 428-432

[13] Correia, J.A.F.O., De Jesus, A.M.P., Muniz-Calvente, M., Sedmak, A., Moskvichev, V., Calçada, R. The renewed TC12/ESIS technical committee - Risk analysis and safety of large structures and components (Editorial), Engineering Failure Analysis, Volume 105, November 2019, Pages 798-802

[14] Sedmak, A., Jeremić, L., Milovanović, N., Sedmak, S., Milošević, N., How to deal with cracked welded structure – Application of Fracture Mechanics parameters to Structural Integrity Assessment, ASR International Conference ”Welding 2021”, online invited lecture

[15] Kirin, S., Jeremic, L., Sedmak, A., Martić, I., Sedmak, S., Vučetić, I., Golubović, T., Risk based analysis of RHPP penstock structural integrity, Frattura ed Integrita Strutturale, 14(53), 345–352, 2020

[16] Milovanović, A., Mijatović, T., Diković, Lj., Trumbulović, Lj., Drndarević, B., Structural integrity analysis of a cracked pressure vessel, Structural Integrity and Life, 21(3), 2021, 285–289

[17] Zaidi, R., Sedmak, A., Kirin, S., Grbovic, A., Li, W., Lazic Vulicevic, L., Sarkocevic, Z., Risk assessment of oil drilling rig welded pipe based on structural integrity and life estimation, Engineering Failure Analysis, Volume 112, May 2020, Article number 104508
[18] Medjo, B., Arsić, M., Mladenović, M., Savić, Z., Grabulov, V., Radosavljević, Z., Rakin, M., Influence of defects on limit loads and integrity of the pipeline at hydropower plant 'Pirot', Structural Integrity and Life, Vol.20, No.1, 2020, pp.82–86