Welded joints as critical regions in pressure vessels – case study of vinyl-chloride monomer storage tank

Tamara Golubovic[1], Aleksandar Sedmak[1,*], Vesna Spasojevic Brkic[1], Snezana Kirin[2], Emil Veg[1]

[1]Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, 11000 Belgrade, Serbia
[2]Innovation Center of the Faculty of Mechanical Engineering, Kraljice Marije 16, 11000 Belgrade, Serbia[3]

Abstract
Welded joints are analysed as critical regions in a pressure vessel in respect to structural failure due to the elastic-plastic fracture/crack growth. To assess structural integrity of pressure vessels used in chemical industry the risk based procedure has been introduced and applied in the case of a large spherical pressure vessel used as a vinyl ¬chloride monomer (VCM) storage tank in HIP Azotara Pančevo. The risk matrix has been used, taking into account the basic definition of risk, being the product of the probability and consequence, and applied to different regions of welded joints, having different mechanical properties, *i.e.* crack resistance. To estimate probability, the failure assessment diagram (FAD) has been used, as an engineering tool, defined according to the position of the operating point for different regions of the welded joint, relative to the critical point on the limit curve. Generally speaking, consequence is estimated based on pressure vessel parameters, or by detailed analysis of health, safety, business and security issues, but in the analysed case, the worst case scenario is assumed, with the highest consequence due to potential disaster for environment and fatalities.

Keywords: *welded joint; heterogeneous material; risk matrix; structural integrity*.

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1. INTRODUCTION

Crack-like defects are the biggest risk in operating large pressure vessels, *i.e.* storage tanks in chemical industry, as explained and described in [1]. These defects are likely to appear in welded joints because of complex microstructure in different regions (Base Metal – BM, Weld Metal – WM, Heat Affected Zone – HAZ), being more or less sensitive to cracking. Therefore, disregarding their potentially disastrous effect is not an option. So, if these defects are detected in so-called unaccepted form and size, according to ISO 5817 standard, the careful consideration is certainly required and decision to be made by top management. To overcome the gap between engineers and managers, there is a need to provide simple, *e.g.* risk based structural integrity assessment of all cases involving crack-like defects, especially if toxic and/or flammable storage medium is used such as vinyl chloride monomer (VCM).

Structural integrity point of view has been explained and applied for pressure vessels used in chemical industry [1], based on fracture mechanics parameters, but also introducing quality assurance [2], and risk based approaches, as two specific, additional aspects. Risk based approach, in one of its simplest form, uses the risk matrix (Fig. 1) with one axis representing probability and the other one, representing consequence. This approach has been analysed in number of recent publications [3-6].

According to the ISO 31010 standard [7], three general approaches are commonly employed to estimate probability:

a) The use of relevant historical data to identify events or situations, which have occurred in the past and hence be able to extrapolate the probability of their occurrence in the future.

b) Probability forecasts using predictive techniques such as fault tree analysis and event tree analysis. Simulation techniques may be required to generate probability of equipment and structural failures due to ageing and other degradation processes, by calculating the effects of uncertainties.

c) Expert opinion can be used in a systematic and structured process to estimate probability. There are a number of formal methods for eliciting expert judgement, which provide an aid to the formulation of appropriate questions.

Correspondence: Aleksandar Sedmak, Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, 11000 Belgrade, Serbia
e-mail: asedmak@mas.bg.ac.rs
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Risk		Consequence category				
		A	B	C	D	E
Probability category	5	Medium	Medium high	Medium high	High	Very high
	4	Medium	Medium	Medium high	High	High
	3	Low	Medium	Medium	Medium high	Medium High
	2	Low	Low	Medium	Medium	Medium high
	1	Very low	Low	Medium	Medium	Medium

Figure 1. Risk matrix

Obviously, the first option is obsolete for any serious consideration, especially since it has little or no relevance to any specific case. The second one is based on survey or similar activities, not aimed here, because of its complexity. The third one is actually used in this research, focused on the original, simple methodology, based on risk matrix. The more complicated methods for risk assessment (*e.g.* API procedure [8], or its European competitor, RIMAP [9], both based on empirical rules) are not considered here.

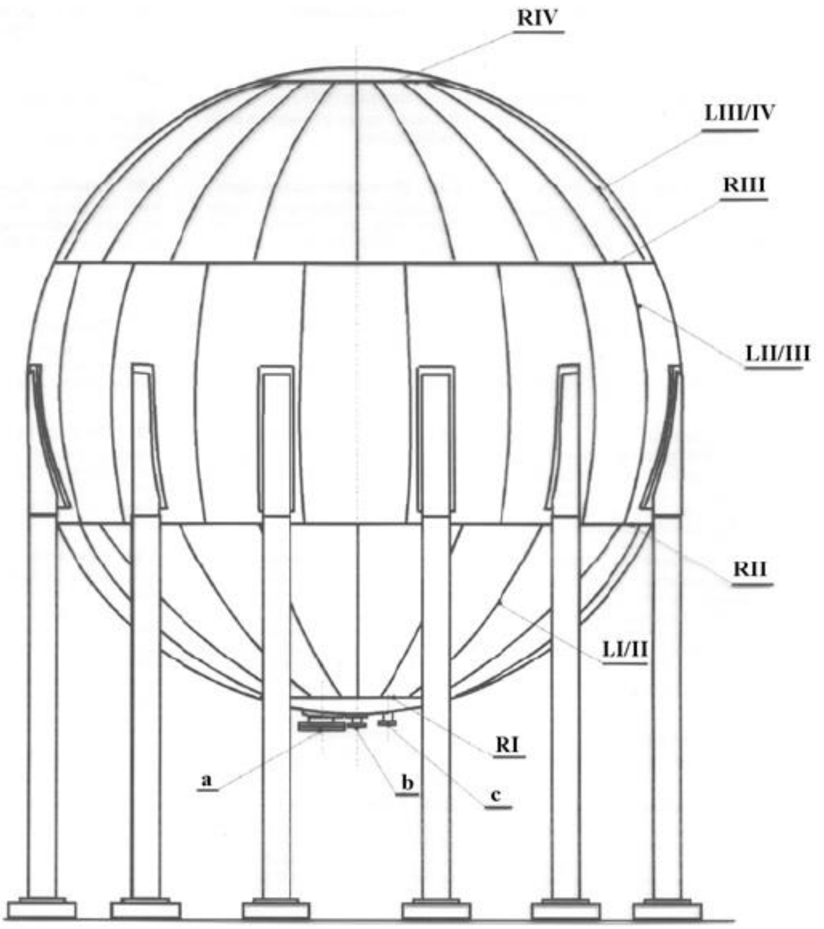
As for the consequence, a simple and efficient approach is to use pressure vessel (PV) classification, according to Pressure Equipment Directive PED 97 [10], based on contained medium, product of pressure and volume, p×V, plus temperature and environmental effects. There are 5 classes in this approach, similar to 6 classes presented in Figure 1, or 4 classes, as given in [8]. One should notice that these classifications are arbitrary, emphasizing more consequences (like in [8]) or probabilities, like here. Anyhow, a more complicated option is to categorize consequences, based on several parameters: health, safety, environment, business and security. In the case analysed here, consequence is fixed to the highest one, being the only reasonable option for a VCM storage tank, located near residential area.

In the risk matrix shown in Figure 1, consequences are categorized as A to E; A indicates the lowest, almost negligible consequence, whereas E refers to fatal and serious consequences. Probability categories are 1 to 5, starting with a very unlikely event, ending with a highly probable event (Fig. 1). Combination (product) of consequence and probability is then defined as the risk, ranging from the very low to very high, including also low, medium, medium high and high risk (Fig. 1). Such a classification is more precise than the one introduced in [8], but in any case, it is arbitrary and custom made. This is obviously a simplified approach, as opposed to the complex ones, defined *e.g.* in the RIMAP document [9]. Anyhow, the concept of using risk matrix can be useful in combination with fracture mechanics approach and structural integrity assessment, as shown in the following text using a large spherical storage tank for VCM as the case study.

One simple option to estimate probability of failure is to use the Failure Assessment Diagram (FAD), which provides analysis for a cracked component, in the scope of its structural integrity assessment. The basic concept is to evaluate ratios between the stress intensity factor and fracture toughness (Y coordinate, K_r), which can be interpreted as the probability of brittle fracture, and between the local stress and its critical value (X coordinate, S_r), which can be interpreted as the probability of plastic collapse (Fig. 2). The point defined by these two coordinates is either in the safe or in the unsafe region, which are separated by the limit curve obtained by applying Dugdale's plastic zone concept [11]. Probability of failure can be estimated in the same way, as the ratio between the distance from the calculated point to the zero point and the distance from to the corresponding point at the limit curve and the zero point, as shown in the following text.

2. CASE STUDY – WELDED JOINTS IN A LARGE SPHERICAL STORAGE TANK FOR VCM

As the case study, a possibility of leakage from a large spherical tank (Fig. 2) is briefly analysed. Leakage was actually caused by undetected micro-cracks in a welded joint, which have grown through the thickness during proof testing (cold-water test with pressures up to 50 % above the operating pressure, Fig. 3) [12]. More detailed analysis, based on structural integrity assessment, is given in [12]. Generally speaking, large spherical tanks (Fig. 4), 150 to 5000 m^3 in volume, up to 20 m in diameter, are used for storage of liquefied natural gases (LNG), ammonia, carbon dioxide or VCM. In the case analysed here, it is a large sphere for VCM, 2000 m^3 in volume, 15.6 m in diameter, made of fine grain, micro-alloyed steel TTSt E-47 (Steelworks Jesenice, Slovenia).



Legend:
R – radial
L – longitudinal
I, II, III, IV – No. of horizontal welded joint
a, b, c - connections

Figure 2. Spherical storage tank, reprinted with permission from [12]

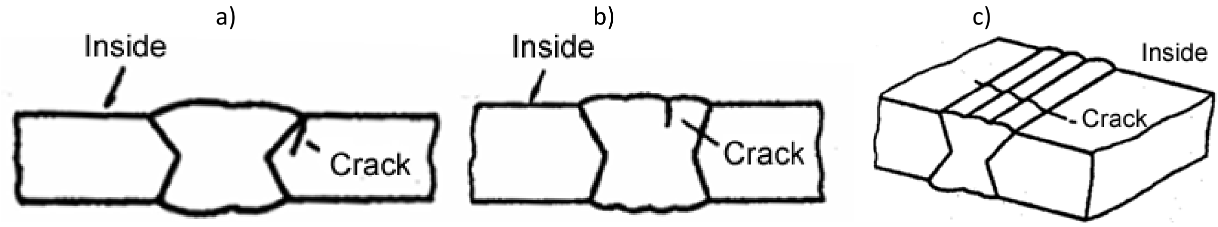
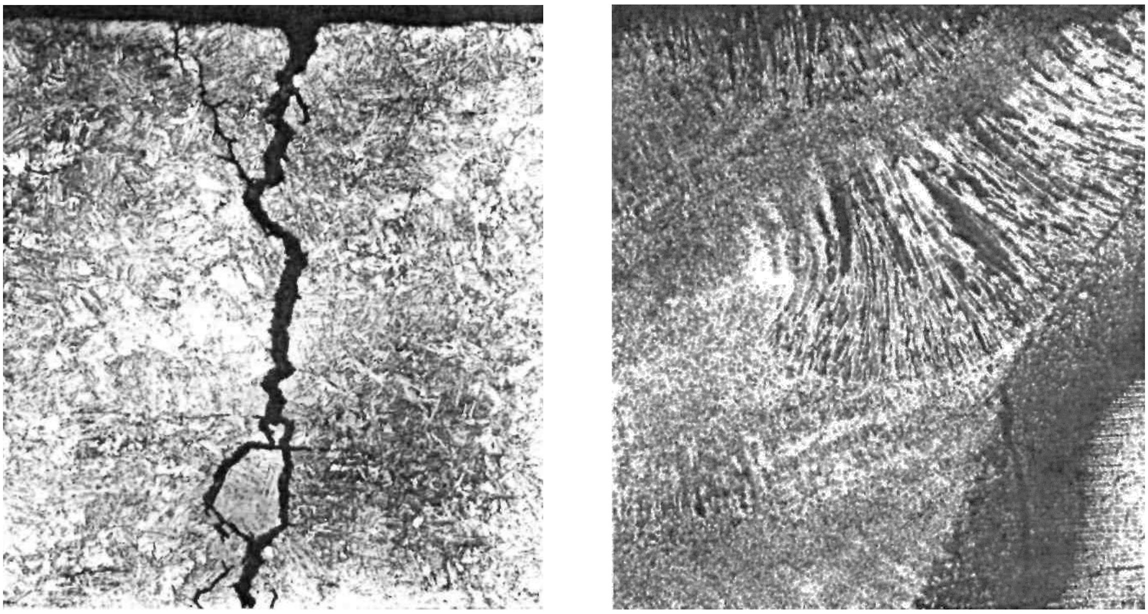


Figure 3. Cracks on the inner wall side of the spherical tank, a) HAZ, b) WM, c) complete welded joint, reprinted with permission from [12]

Several spherical tanks are also in service in the company HIP-AZOTARA (Pančevo, Serbia). In regular in-service inspection, many defects, mostly cracks, had been detected in welded joints from the inner side of the sphere. The cracks mostly developed in radial welded joints (RIII, Fig. 2), in its upper part, at the border of liquid and gaseous phases [12]. The occurrence of cracks was mostly detected in the heat-affected-zone (HAZ), being typical for the micro-alloyed steel TTSt E-47 [12]. Namely, microstructure of TTSt E-47 welded joints is complex one (Fig. 4) with some regions in HAZ being sensitive to cracking. This is also clear from the data for fracture toughness [12]: K_{Ic} (BM)=4420 MPa √mm, K_{Ic} (WM)=2750 MPa √mm, K_{Ic} (HAZ)=1580 MPa √mm.

Location, number and direction of cracks in a tank, repaired by grinding, are given in [12]. Here we focus on risk assessment for the cracks shown in Figure 3. The following data are used:

- Geometry: thickness t = 20 mm, volume 2000 m^3, diameter D = 15.6 m; curvature effect negligible (t / R = 20 / 7800)
- Material, TTSt.E/47 steel: R_{eh} = 480 MPa, R_M = 680 MPa; $K_{I\,c}$= 2750 MPa √mm for the weld metal, K_{Ic} = 1580 MPa √mm for HAZ, K_{Ic} = 4420 MPa √mm for the base metal [12].



a) Fusion zone b) Heat-affected-zone

Figure 4. Micrographs of cracks in TTSt E-47 welded joints, magnification 10:1, reprinted with permission from [12]

- Loading: max. pressure p = 0.5 MPa (taken at ≈40 °C, since it depends on temperature - no isolation [12]), stress $\sigma = pR / 2t$ = 97.5 MPa.
- Residual stress σ_R = 196 MPa - max. value transverse to the weld, taken to be 40 % of the Yield Stress, R_{eh}, or σ_R = 480 MPa - max. value in longitudinal direction, taken to be 100 % of the Yield Stress, R_{eh}, since no measurements available, and no record of post weld heat treatment (PWHT) exists [12]);

All cracks are three-dimensional (3D), *i.e.* so-called surface cracks, with different lengths (100-200 mm) and depth approximately 5 mm**.** For cracks of such shape (much longer than deep), it has been shown that they would grow into depth [13], *i.e.* leakage would precede catastrophic failure. Therefore, the cracks are represented as being a 2D edge crack, with length 5 mm (as if they are running all over the circumference, *i.e.* as they are schematically shown in Fig. 3a-b), enabling conservative and simplified approach to solve the problem.

The stress intensity factor (SIF) is then calculated for two cases, one for longitudinal cracks (HAZ, Fig. 3a, and WM, Fig. 3b), and the other one for a transverse crack (BM, Fig. 3c):

$K_I = 1.12\ (pR/2t + \sigma_R)\ \sqrt{\pi a} = 1.12\ (97.5 + 169)\sqrt{\pi 5} = 1302.5\ \sqrt{mm}$

for WM and HAZ,

$K_I = 1.12\ (pR/2t + \sigma_R)\ \sqrt{\pi a} = 1.12\ (97.5 + 480)\sqrt{\pi 5} = 2532.8\ \sqrt{mm}$

for BM.

Now, one can calculate ratios $K_r = K_I / K_{IC}$:

$K_r = K_I / K_{IC} = 1302.5 / 2750 = 0.47$ for WM,

$K_r = K_I / K_{IC} = 1302.5 / 1580 = 0.82$ for HAZ,

$K_r = K_I / K_{IC} = 2562.8 / 4420 = 0.58$ for BM.

The net stress, σ_n, and the flow stress, σ_F, are taken as the same for all zones in the welded joint:

$\sigma_n = 1.33\ pR /2t$ (coefficient 1.33=20/15 due to reduced cross-section),

$\sigma_F = (R_{eH} + R_m) / 2 = 580$ MPa

$S_R = (1.33 \times 97.5) / 580 = 0.22$

The coordinates (K_R, S_R) for WM, HAZ and BM are as follows: (0.22, 0.47), (0.22, 0.82), (0.22, 0.58), respectively, as shown in Figure 5. If one takes the ratio of distance from zero point to these three points and distance between the zero point and the cross-section point on the limit curve, the result is 0.48 (WM), 0.84 (HAZ) and 0.59 (BM). Taking these values as probabilities, one can see that the crack in WM and BM produces a medium high risk, whereas the crack in HAZ produces a very high risk (cat. E & 1, upper right field, marked in red in Fig. 1).

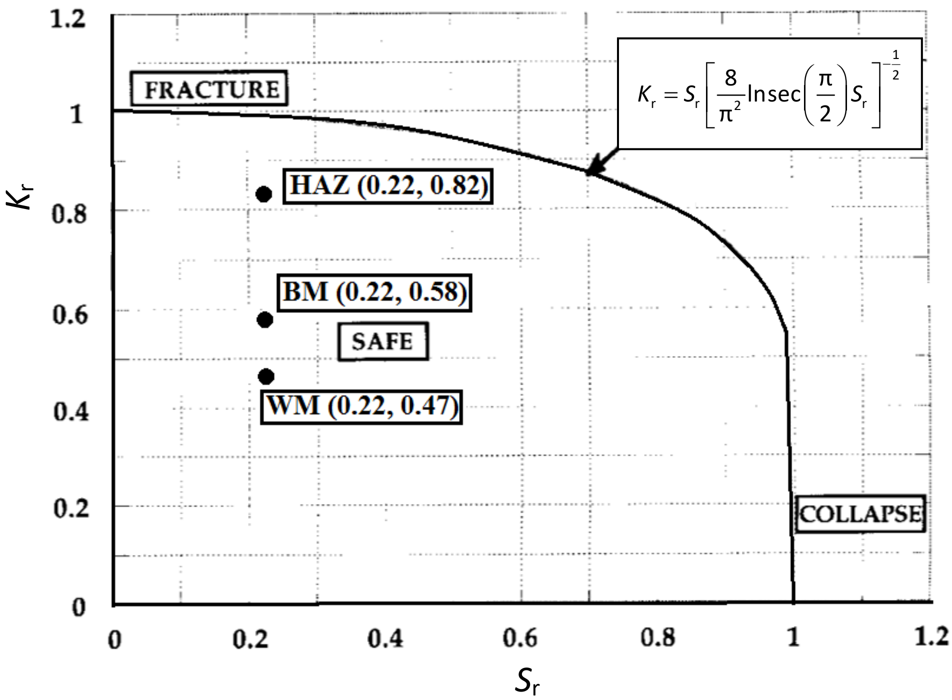


Figure 5. The FAD for VCM storage tank with cracks in WM HAZ and BM

3. DISCUSSION

The case study presented in this paper has proved that the HAZ is the most critical region in the welded joint, with very high risk of causing failure due to crack presence, whereas cracks in WM and BM produce medium high risk. Anyhow, one should keep in mind high level of conservatism used in this analysis, just to mention the assumption of crack length running all over the circumference. Also, residual stresses are taken as being the maximum possible, which is not realistic even for the simple reason that welding was performed as multipass one, with subsequent passes acting similar as a post welding heat treatment would do. Finally, the assumption of residual stresses being as high as 100 % of Yield Strength for the transverse crack, is overconservative, because even if this would be the case, it only applies for the weld metal (*i.e.* centre of a welded joint). One can also argue that in this case fracture toughness of WM should apply, but that also would be overconservative assumption.

One should also notice that only so-called leakage has been analysed in this paper. Anyhow, since cracks have been taken as already running all over the circumference, leakage in this case means catastrophic failure.

4. CONCLUSIONS

Based on the results shown here, one can state the following:

Risk based approach is an engineering tool for assessment of structural integrity, based on the risk matrix presentation as the most suitable for managers to make decisions, even difficult ones.

Welded joint is a critical region in PV and any welded construction, with either WM or HAZ being the most critical, depending on a combining effect of microstructure (K_{Ic}) and residual stress. In the case study presented here the HAZ is the most critical region.

Further development of the presented methodology is recommended, *e.g.* reducing its conservatism by using the finite element method to calculate the stress intensity factors, and/or by measuring residual stresses, if possible.

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SAŽETAK

Zavareni spojevi kao kritična mesta u posudama pod pritiskom – studija slučaja rezervoara za vinil-hlorid monomere

Tamara Golubovic[1], Aleksandar Sedmak[1,*], Vesna Spasojevic Brkic[1], Snezana Kirin[2], Emil Veg[1]

[1]Mašinski Fakultet, Univerzitet u Beogradu, Kraljice Marije 16, 11000 Beograd, Srbija
[2]Inovacioni Centar Mašinskog Fakulteta, Kraljice Marije 16, 11000 Beograd, Srbija

(Naučni rad)

U ovom radu su analizirani su zavareni spojevi, kao kritična mesta posuda pod pritiskom u smislu integriteta konstrukcije usled elasto-plastičnog loma/rasta prsline. U cilju procene integriteta posuda pod pritiskom u hemijskoj industriji uvedena je i primenjena procedura procene rizika na primeru velike sferične posude koja se koristi kao rezervoar za skladištenje vinil-hlorid monomera (VCM) u okviru kompanije HIP Azotara Pančevo. Korišćena je matrica rizika, pri čemu je rizik definisan kao proizvod verovatnoće i posledice, što je primenjeno na različite oblasti zavaranog spoja, sa različitim otpornostima na rast prslina. Dijagram procene otkaza (*Failure assessment diagram* – FAD) je primenjen u svrhu procene verovatnoće. Ovaj dijagram prestavlja jednostavan inženjerski alat za procenu verovatnoće otkaza, koja se definiše na osnovu položaja radne tačke, u odnosu na kritičnu tačku na graničnoj krivi. Uopšteno govoreći, posledica se procenjuje na osnovu parametara posude pod pritiskom, ili detaljnom analizom zdravstvenih, bezbedonosnih, poslovnih i sigurnosnih problema, ali u ovom slučaju treba pretpostaviti najgori mogući scenario, koji bi predstavljao potencijalnu katastrofu za okolinu i doveo do velikog broja smrtnih slučajeva.

Ključne reči: zavareni spoj, heterogeni materijal, matrica rizika, Integritet konstrukcije