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Procedia Structural Integrity 2 (2016) 3654–3659

Structural Integrity Procedia

www.elsevier.com/locate/procedia

21st European Conference on Fracture, ECF21, 20-24 June 2016, Catania, Italy

Risk Based Approach to Integrity Assessment of a Large Spherical Pressure Vessel

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Abstract

The risk based approach has been applied, in its simplest form, i.e. by using the risk matrix to illustrate how the water proof test can shift risk from high to very high level in the case of large spherical pressure vessel (ammonia storage tank). Having in mind the basic definition of risk, being the product of the probability and consequence, and fixing the consequence at the highest level, only probability of unfavourable event (leakage and/or failure) has been evaluated. Toward this end, the failure assessment diagram (FAD) has been used here as another simple engineering tool to estimate probability of the failure, as the function of the position of the operating point, i.e. defining probability as the ratio between the distance of the operating point from the zero point, and the appropriate distance between the point on the limiting curve and zero point. This simple engineering tool to assess structural integrity showed clearly that water proof test is not always recommended, because it disregards possible stable growth of cracks, which might reach critical size for unstable growth, i.e. it does not prove that failure will not happen in future under the same conditions.

Peer-review under responsibility of the Scientific Committee of ECF21.

Keywords: Risk based approach; structural integrity assessment; large pressure vessel

1. Introduction

Risk based approach is usually explained by the risk matrix, Fig. 1, using the simple definition of risk (product of probability and consequence). In the case of large pressure vessels, containing ammonia, this is even simpler task, since the consequence category is certainly the highest, thus reducing risk assessment to the probability category. Anyhow, there is still a question if one use the simple option (probability, which can be defined using previous experience, e.g. as the number of events in certain period of time, divided by the total number of pressure vessels operating in the same period of time) or more complicated one (e.g. API procedure, (American Petroleum Institute,

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10.1016/j.prostr.2016.06.454

2014, API 581, 2010), or its European competitor, RIMAP, Jovanovic (2011), both based on empirical rules). The first one is definitely not an option here, since it is oversimplified and has no relevance to any concrete problem, whereas the later one is based on experience, and it complexity does not necessarily leads to the correct prediction of probability. Therefore, yet another way to estimate the probability shall be applied here, based on fracture mechanics principles and structural integrity assessment, used to modify risk matrix approach.

Table 1.

		Consequence category				
		A	B	C	D	E
Probability category	1	Medium risk				Very high risk
	2				High risk	
	3			Medium risk		
	4		Low risk			High risk
	5	Very low risk				Medium risk

One should keep in mind that the most critical part of a pressure vessel is welded joint, Sedmak (1996). As the case study, leakage of large spherical tank, used for storage of ammonia, will be analysed here. It was caused by undetected micro-cracks in welded joint, which have grown through the thickness during proof testing (cold-water test with pressure up to 50% above the operating pressure), Sedmak (2011). The testing of storage tanks before and after inspection has clearly shown the adverse effect of proof test in service, since it has indicated large number of new cracks in the locations of "old" ones. The macroscopic view of a typical through crack causing leakage is given in

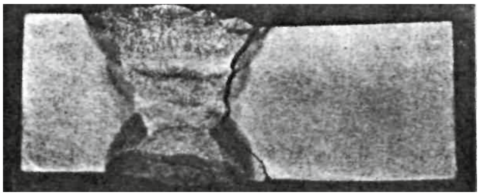

Fig. 1. Macroscopic view of a typical through crack

Nevertheless, the full scale tests of welded pressurized equipment are the most informative when safety is considered, Sedmak (2011). In some cases they are inevitable despite high cost because they can give realistic answers relating the service behavior of welded joints. Hydrostatic pressure proof test can be classified as the full scale test. Hydrostatic pressure for proof test is often calculated using the formula $p_i = 1.3 \cdot p_r$, where p_i is proof test and p_r is the design pressure. The logic behind this approach is that once a pressure vessel has withstood proof test, it will be safe in the exploitation under design pressure. Anyhow, there is a controversy behind this logic, because the proof test has provoked cracking and leakage, in number of cases, Sedmak (2011). Therefore, one of the main aims here is to show, even graphically, a detrimental effect of proof test on pressure vessel safety.

2. Risk Based Approach

The Extensive European project RIMAP, from 2001 until 2004, was introduced to offer a European standard for risk based management, including inspection, maintenance and control, Jovanovic (2011). It has produced four industry specific workbooks (petrochemical, chemical, steel and power generation industries), aimed to provide more specific guidance on how to apply the RIMAP approach. However, this approach is too complex, and will not be considered here. Instead, we present here only the risk matrix approach, as illustrated in Tab. 1. This approach uses well-known definition of risk being the product of the probability and the consequence.

In the risk matrix shown in Tab. 1, consequences are categorized, based on several parameters (health, safety, environment, business, security) as A to E; A indicates low, almost negligible consequences, and E refers to fatal and serious consequences. Probability categories are graduated 1 to 5, starting with very unlikely event, let day once in over a 100 years (1×10^{-4}), ending with highly probable event occurring at least once in a year (1×10^{-1}), Table 1. This is obviously oversimplified and somewhat arbitrary approach, as opposed to the complex ones, as defined in API and RIMAP documents. Anyhow, the concept of using risk matrix can be useful in combination with fracture mechanics approach and structural integrity assessment, as will be shown in the following text using large spherical storage tank as the case study.

3. Structural integrity assessment

In-service behavior of many structural components revealed that cracks lead to the fatal failure. One possibility to prevent such a scenario is to use Failure Assessment Diagramme (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), which can be interpreted as the probability of brittle fracture, and between the local stress and its critical value (X coordinate), 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. Probability of failure can be estimated in the same way, based on the distance from the point to the corresponding point at the limit curve.

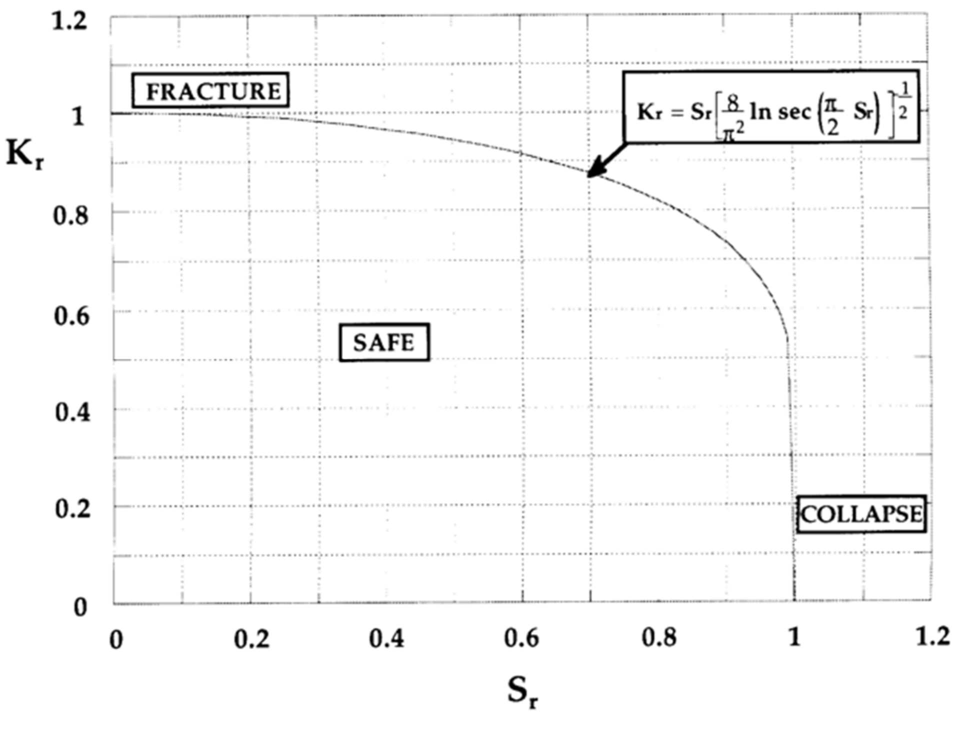

Fig. 2. Failure Assessment diagram

4. Case study – Large Spherical storage tank for ammonia

The analysis was performed on the spherical storage tanks for ammonia storage (volume 1000 m^3, diameter D=12500 mm and wall thickness t=25 mm, Fig. 3, Sedmak (2011)). The operating pressure was$p$=6 bar and proof test pressure p=10 bar was applied together with non-destructive testing (NDT). The tanks have been constructed using the microalloyed steel St.E460, (yield strength $R_{p0.2}$=480 MPa, ultimate tensile strength R_m=680 MPa, elongation A_5=28%). Welding of St.E460 turned out to be much more complicated than anticipated, causing a lot of problems regarding cracking and leakage. There have been many investigations of this problem, including testing of fracture toughness, focused on welded joints and their different regions, especially the heat-affected zone (HAZ). Based on results of such testing, we have adopted here K_{Ic}=2750 MPa√mm, as the minimum value for fracture toughness in HAZ.

Fig. 3. The spherical tank for ammonia storage

Different NDT methods (ultrasonic, dye penetrant and magnetic particles) have been used to test welded joints. The longitudinal cracks were considered as more dangerous due to their size (length up to 100 mm, depth up to 5 mm) and position (HAZ), Sedmak (2011). Macroscopic view of the crack is shown in Fig. 4.

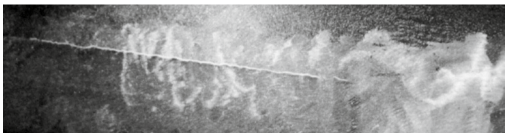

Fig. 4. Macroscopic view of the crack

In order to evaluate its significance, the crack is presented as an edge crack with length equal to its depth (5 mm), schematically shown in Fig. 5, as if it was along the whole circumference.

Fig. 5. Schematic view of the crack

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

- PV geometry (thickness t=25 mm, diameter D=12500 mm);
- St.E460 steel: R_{eh}=480 MPa, R_M=680 MPa; K_{Ic}=2750 MPa√mm;
- crack geometry (edge crack, length 5 mm, ratio length/thickness=0.2);

- loading (max. pressure p=0.6 MPa, stress $\sigma=p\cdot R/2\cdot t=75$ MPa, residual stress $\sigma_R=196$ MPa - max. value transverse to the weld, no measurements available, no post weld heat treatment, 40% of the Yield Stress, [5]);
- curvature effect is negligible ($t/R=25/12500\approx0.002$).
- The SIF is calculated from: $K_I=1.12\cdot(pR/2t+\sigma_R)\sqrt{\pi a}=(75+196)\sqrt{\pi\cdot5}=1075$ MPa$\sqrt{mm}$, leading to the ratio $K_R=K_I/K_{Ic}=1075/2750=0.39$.

The net stress is $\sigma_n=1.25\cdot pR/2t$,coefficient 1.25=25/20 due to the reduced cross-section (crack length 5 mm vs. thickness 25 mm), $\sigma_F=(R_{eH}+R_M)/2=580$ MPa; $S_R=(1.25\cdot75)/580=0.16$, the coordinates ($K_R$, S_R)=(0.39, 0.16). If one takes the ratio of distance from zero point to this point to zero point and distance between the zero point and the cross-section point on the limit curve, the result is 0.395, which can be taken as the probability of failure.

Now, the same calculation for the proof testing (pressure p=1 MPa) leads to the following results:$K_R=K_I/K_{Ic}=1288/2750=0.47$, $S_R=\sigma_n/\sigma_F=0.27$; the coordinates (0.47, 0.27) and the ratio 0.4.

The FAD is shown in Fig. 6, indicating these two pressure levels, 6 bar (design) and 10 bar (proof test), indicating detrimental role of the proof pressure.

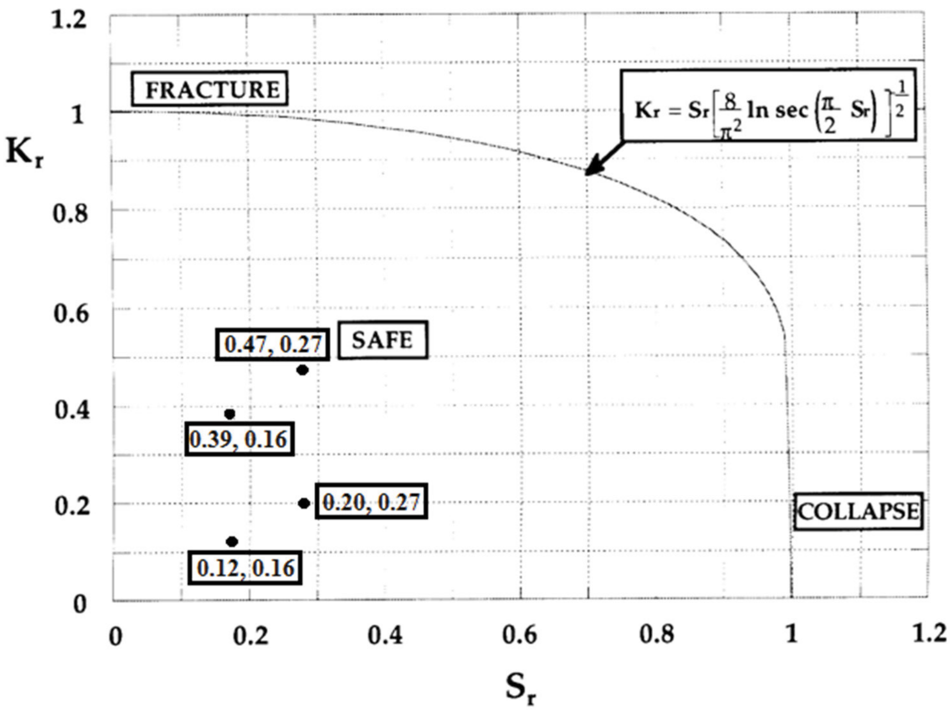

Fig. 6. The FAD for two pressure values

Finally, one should consider the option of such an analysis which does not take into residual stresses. In that case, these two points have the following coordinates: (0.12, 0.16) for pressure 6 bar, and (0.20, 0.27) for pressure 10 bar, leading to the following probabilities of failure: 18.2% for pressure 6 bar, and 30.3% for pressure 10 bar. In this case, the probability of failure is simply proportional to the level of pressure.

5. Conclusions

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

- Risk based approach can be useful tool for assessment of structural integrity, even if using simple graphical presentation, i.e. the risk matrix.

- Basic structural integrity tools, such as FAD, can be used in combination with the risk based approach to show detrimental effect of proof test in the case of large spherical storage tanks.
- Detrimental effect of proof test is even more pronounced if one does not take into accounts the effect of residual stresses.

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