Pressure Vessel Fitness-for-Service Evaluation Based on API579 and API581 Standards

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Abstract: Fitness-for-Service assessment is an important task for pressure vessels safety analysis, especially in oil and gas industry, including vessels used in exploration and production assets. Fitness-for-service is usually executed considering API-579 standard rules, which applies the FAD methodology to evaluate the severity of cracks located in pressurized equipment. This paper applies the probabilistic fracture mechanics in order to evaluate the failure probability of cracked pressure vessels, in contrast to the deterministic assessment method, recommended by API-579, with use of partial safety factors. This methodology is presented through a case study, where all the probabilistic parameters for the input variables were defined and followed by the application of both Monte Carlo and Advanced Second Moment methods to determine the failure probability of a cracked pressure vessel. Additionally, crack growth was estimated by means of the Walker equation, giving as a result the probability distribution for crack size as function of service cycles. The remaining life of the cracked pressure vessel was also evaluated, based on the risk associated to equipment service, according to API-579 risk acceptance criteria. Finally, the results obtained through future inspection events were used to define new crack size probability distribution using Bayes Theorem, considering the expected crack size defined theoretically as previous distribution corrected by the crack size measured by non-destructive testing. This new distribution was then used to update the expected failure probabilities and support the definition of a new inspection program.

Keywords: Fitness-for-service, Probabilistic fracture mechanics, Structural integrity, Pressure vessel, Bayesian update.

1. INTRODUCTION

Pressure vessels are the most important equipment of the process plants and also those of greater cost, reaching up to 60% of the total cost of a process plant. Its use in the process industries requires a high degree of reliability when compared to other applications, for the following reasons [1]:

- Continuous operation: pressure vessels are subjected to a severe operation regime, with no daily stops for maintenance and inspection;
- No redundancy: pressure vessels form a continuous path through which process fluids circulate. In general, there is no standby vessel in parallel. In this way, the failure of a vessel causes the entire installation to stop;
- Handle of hazardous fluids: in the process plants it is common to handle and to storage flammable, toxic and explosive fluids, sometimes, in high pressure and temperature.

For the above reasons, pressure vessels are categorized in industry as high risk equipment. Therefore its use and maintenance are strictly controlled based on code and regulations stated by government or companies [2].

Pressure vessels can undergo various failure modes, being the catastrophic failure the one of highest severity. This failure mode is characterized by rupture of the vessel and a complete loss of its function, as shown in figure 1. A possible root cause of such failure mode is the presence of one or more cracks in the vessel wall which grow during vessel operational life. It is important to note that the fracture in this case occurs under an applied stress below the yield stress of the material.

Figure 1 – Example of brittle fracture of a pressure vessel due to a crack [2].

New pressure vessels are generally free of cracks identified by non-destructive inspection methods because of the rigorous requirements of the applicable design codes. As an example, the ASME Boiler and Pressure Vessel Code [3] contains not only criteria and formulas for pressure vessels design, but also requirements for materials, manufacturing, inspection and testing. On the other hand, for vessels in service, cracks may be identified during periodic inspections. These cracks may nucleate from inclusions, surface scratches, coating delamination and welded repairs made in the field, [4]. Within this context, Fitness-for-service (FFS) assessments are performed to demonstrate the structural integrity of an in-service component containing a flaw or damage and are used to make run-repair-replace decisions aiming at keeping vessel safety conditions [5]. A residual life analysis can also be performed as part of the assessment, which can be used to set future inspection intervals. Used correctly, this tool provides good compromise between economy and safety, avoiding unnecessary interventions during the service life of the equipment.

There are a number of internationally recognized procedures for FFS assessment of cracked pressurized equipment. API-579 [6] has been developed to provide guidance on FFS assessments of commonly encountered flaws in the petrochemical industry, including cracks in pressure vessels. Other notable procedures available to evaluate cracked pressure vessels are the British standards BS 7910 and R6 methods. All the mentioned procedures for evaluating cracks incorporate a failure assessment diagram (FAD), which is the main failure criterion. The safety assessment though these standards recommends the application of partial safety factors (PSFs) on the mean value of the input variables, namely the material properties, crack dimensions and applied load, due to the uncertainties associated with these variables. These PSFs are often unknown and can lead to conservative decisions. As presented in reference [7], the use of fixed PSFs results in a non-uniform safety margin, once as the failure assessment diagram drops for higher load ratios, the analysis leads to quite safe assessments, but against the productivity of the plant.

An alternative to the traditional, deterministic, integrity assessment proposed by the standards is to consider the probabilistic nature of the input variables, characterized by their probability density functions (PDFs) and coefficients of variation (COVs), thus the uncertainties of the input variables are considered into the calculations, with no need to use PSFs. This is the probabilistic fracture mechanics approach. The main result of its application is the estimation of the failure probability of the equipment, providing valuable data to the plant operator about the risk associated to pressure vessel service. Once the risk is quantified, this information can be used to optimize the pressure vessel inspection plan, focusing inspection efforts on the process equipment with the highest risk, as part of a risk-based inspection strategy [8].

Thus, the present paper presents a framework, based on API-579 rules, for the application of probabilistic fracture mechanics to evaluate the reliability, to estimate the remaining life and to update the reliability based on recent inspection results of cracked pressure vessels, considering the fatigue as the single damage mechanism present in equipment service.

2. BACKGROUND

2.1. Fitness-For-Service Assessment of Cracked Pressure Vessels

The load carrying capacity of a cracked member can be evaluated through two distinct criteria. The first one, based on fracture mechanics, states that linear elastic stress intensity factor at the crack tip (K_I) must not be greater than the material fracture toughness (K_{mat}). The second criterion, based on mechanics of materials, states that the resultant stress on the remaining ligament (σ) must not be greater than the plastic collapse load (σ_c) of the flawed member. These criteria can be mathematically expressed as follows:

$$\frac{K_I}{K_{mat}} \leq 1 \tag{1}$$

$$\frac{\sigma}{\sigma_c} \leq 1 \tag{2}$$

The ratios intentionally introduced in the inequalities (1) and (2) are called, respectively, toughness ratio (K_r) and load ratio (L_r). Fracture mechanics theory clearly states that once the applied stress is increased, that means crescent L_r, the linear elastic stress intensity factor (K_I) underestimates the stress field near the crack tip due the plasticity effects and, therefore, there is a clear interaction between the two failure criteria presented by the inequalities (1) and (2). These two criteria grouped in a single expression result in the following inequality:

$$K_r \leq f(L_r) \tag{3}$$

The function *f* presented in inequality (3) is the so-called failure assessment curve, which was initially introduced in 1975 [9]. The last revisions of both API-579, BS 7910 and R6 methods are based on an updated failure assessment curve, formulated from the curve fitting of various failure assessment curves, considering the stress-strain behavior for various types of steels. This updated curve, presented in equation (4), is the most conservative fit, increasing the confidence of its application [10]. This curve is plotted in figure 2, as a failure assessment diagram (FAD), with the limits of maximum L_r, depending on the steel strain-hardening behavior.

$$f(L_r) = \left(1 - 0{,}14.L_r^{\,2}\right).\left(0{,}3 + 0{,}7.exp\left[-0{,}65.L_r^{\,6}\right]\right) \tag{4}$$

Fitness-for-service assessments of cracked pressure vessels through API-579 can be done considering the FAD method as a failure acceptance criterion. In order to evaluate a cracked component, the following data are required:

- Equipment design data (dimensions, thicknesses, material of construction, etc.);
- Equipment construction records (welding procedures, post weld heat treatment, material tests certificates, etc.);
- Flaw characterization (crack shape, crack dimensions, NDT method used);
- Inspection records (initial and periodic inspections);
- Maintenance and operation history (operation pressure range, crack mechanism, welded repairs etc.).

The extensive data previously presented may not be promptly available at the time of the assessment, which is a common situation, especially for aged installations. In this case, conservative assumptions may be needed. In order to determine the position of the assessment point within the FAD, it is then necessary to calculate the K_r and L_r ratios. For that, the main data required are the crack dimensions, material properties (σ_{ys} – yield strength, K_{mat}) and the service pressure (or the maximum allowable working pressure). At this point, it is important to highlight that API-579 standard recommends the application of partial safety factors (PSFs) on the previous mentioned variables, defined according to the COV of the primary loads and the tolerable probability of failure. The use of PSFs tends to shift the assessment point to the right and upwards in the diagram, increasing the severity of the flaw.

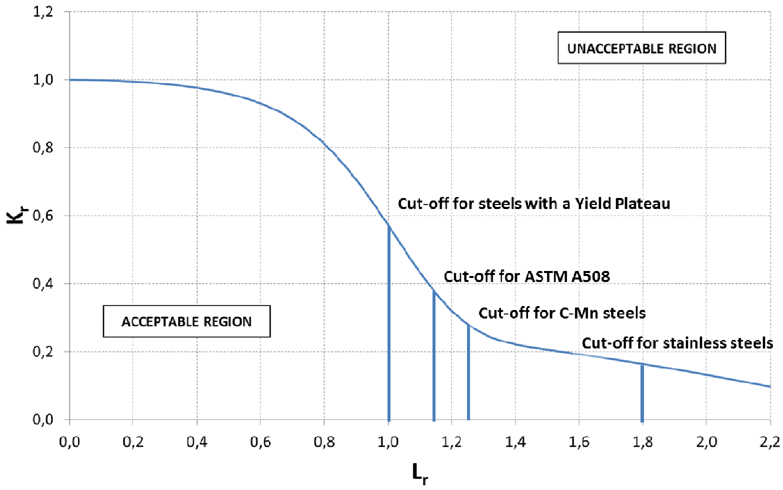


Figure 2 – FAD from API-579 standard with the recommended cut-off values for various types of steel.

Once all required data are gathered and the PSFs defined, the resultant stress (σ) and the stress intensity factor (K_I) can be calculated. To assist the user in this task, API-579 provides an extensive library of expressions to calculate K_I and σ for several pressurized components (cylinders, spheres, nozzles etc.) with different crack shapes (surface cracks, through-wall cracks, embedded cracks, etc.). The calculation of these quantities allows, therefore, the user to plot the assessment point within the FAD. For welded components, the weld residual stress must be accounted in the crack driving force. This is done by means of the superposition principle, adding up the stress intensity factors due to primary loads ($K_I^P = K_I$) and residual stresses (K_I^R). The term K_I^R is also multiplied by a plasticity interaction factor (ρ), which quantifies the crack driving force under situations of combined loading (primary and residual). Thus, in this case, K_r must be calculated though the following expression:

$$K_r = \frac{K_I^P + \rho . K_I^R}{K_{mat}} \tag{5}$$

A flaw is considered tolerable if the assessment point lies in the acceptable region of the FAD, otherwise the flaw is considered unacceptable. Some alternatives for the latter would be reassess the input variables, use less conservative PSFs, build a specific FAD based on actual material properties or rerate the equipment to a lower service pressure. API-579 also suggests the use of a probabilistic analysis in order assess the risk associated with equipment service in this condition.

2.2. Reliability Assessment of Cracked Pressure Vessels

The reliability of a pressure vessel can be defined as the probability that its structural strength (R) exceeds the applied loads (S). For a cracked pressure vessel, the strength is characterized by the material fracture toughness (K_{mat}) and the applied load by the stress intensity factors (K_I^P and K_I^R). In terms of the failure assessment diagram, the strength can be viewed as the maximum allowable toughness ratio, given by the FAD curve $f(L_r)$, and the applied load is the resultant toughness ratio (K_r). Thus, the definition of a limit state function Z can be useful in order to calculate the reliability of the component, expressed as follows:

$$Z = R - S = f(L_r) - \frac{K_I^P + \rho . K_I^R}{K_{mat}} \tag{6}$$

The failure of the component is expected to occur when Z < 0, while the safe state is expected for Z ≥ 0. The reliability (R_e) is then calculated from the failure probability of the component P(Z<0), given by the following integral:

$$P(Z < 0) = \int \dots \int g(X_1, X_2, \dots, X_N) dx_1 dx_2 \dots dx_N \tag{7}$$

where *g* is the joint PDF for the basic input data of the reliability assessment (X_1, X_2,…, X_N). Finally, the reliability is calculated as follows:

$$R_e = 1 - P(Z < 0) \tag{8}$$

Therefore, in order to evaluate the reliability of a cracked pressure vessel it is required to know the joint PDF *g*(.), and then calculate its integral over the domain Z < 0. In general, the joint PDF is unknown and alternative methods are required to solve this integral. In this paper, both Monte Carlo simulation and Advanced Second Moment (ASM) method were used for evaluate the reliability of a cracked pressure vessel.

2.2.1. Monte Carlo simulation for reliability calculation

Monte Carlo simulation is a well-known technique to evaluate the probabilistic characteristics of the limit state function Z. It's a method of direct simulation, which consists on the generation of random values for the input variables from their PDFs, using a random number generator. For each simulation point X(X_1, X_2, …, X_N) the function Z is evaluated and, for the simulations which result in Z < 0 a failure is accounted. After *n* simulations, the reliability is calculated as follows:

$$R_e = 1 - \frac{n_f}{n} \tag{13}$$

where n_f is the total of accounted failures after n simulation. Despite of its simplicity, the results from the Monte Carlo technique depend on the number of samples used and then are subjected to sampling errors. Consequently, it may take a large number of simulation cycles to achieve a specified accuracy, especially as the probability of failure is unknown, resulting in high computational efforts [11].

2.2.2. ASM method for reliability evaluation

ASM method is an analytical method recommended for non-linear limit state functions, for which the input random variables are non-normally distributed, as expected for crack assessment problems. The details of this method can be found in references [11], [12] and [13]. Basically, the limit state function is linearized using a Taylor series expansion at a point $X^*(X_1^*, X_2^*, \dots, X_N^*)$, located on the failure surface Z = 0 . The first-order terms of the series are truncated. A measure of reliability can be estimated by introducing the reliability index (β), which is based on iteratively solving the following set of equations [11]:

$$\alpha_i = \frac{\left(\frac{\partial Z}{\partial X_i}\right)\sigma_{X_i}}{\left[\sum_{i=1}^{n}\left(\frac{\partial Z}{\partial X_i}\right)^2 \sigma_{X_i}{}^2\right]^{1/2}} \tag{10}$$

$$X^* = \overline{X_i} - \alpha_i . \beta . \sigma_{X_i} \tag{11}$$

$$Z(X_1^*, X_2^*, \dots, X_N^*) = 0 \tag{12}$$

where α_i are the directional cosines, $\overline{X_i}$ are the mean value of the input variables and σ_{Xi} are the standard deviation of the input variables. The reliability of the component is finally calculated as:

$$R_e = \Phi(-\beta) \tag{13}$$

where Φ is the cumulative standard normal distribution function. For the input variables which are not normally distributed, equivalent normal distributions are needed. The standard deviation ($\sigma_{X_i}^N$) and the mean ($\bar{X}_i^N$) of the equivalent normal distribution for these variables are calculated as follows:

$$\sigma_{X_i}^N = \frac{\varphi(\Phi^{-1}[F_i(X_i^*)])}{f_i(X_i^*)} \tag{14}$$

$$\bar{X}_i^N = X_i^* - \Phi^{-1}[F_i(X_i^*)].\sigma_{X_i}^N \tag{15}$$

where F_i is the cumulative distribution function of X_i, f_i is the PDF of X_i and φ is the standard normal distribution function. The ASM method is iterative and its convergence depends on the nonlinearity of the performance function in the vicinity of the linearization point X^*.

2.3. Remaining Life Assessment of Cracked Components Subjected to Fatigue

Pressure vessels containing cracks may be subjected to fatigue degradation mechanism due to crack growth.

The methodology for crack growth estimation used in this paper is based on fracture mechanics approach. Thus, the growth of a pre-existing crack is controlled by the crack tip stress intensity factors (K_I^P and K_I^R). The crack growth rate (da/dN) is calculated by means of the Walker equation, which is an empirical relationship based on the classic Paris law [14]. This equation is well suited to account the effects of the load ratio R on the crack growth rate, as this parameter is relevant for welded components containing residual stresses. The Walker equation and its parameters are presented in the following equations:

$$\frac{da}{dN} = \frac{C_0.\Delta K^m}{(1-R)^{m.(1-\gamma)}} \tag{16}$$

$$\Delta K = K_{max} - K_{min} \tag{17}$$

$$R = \frac{K_{min}}{K_{max}} \tag{18}$$

where a is the crack depth, C_0, γ and m are material constants obtained from fatigue crack growth tests, K_{max} and K_{min} are the stress concentration factors in the loaded and unloaded conditions. For a component containing residual stresses, K_{min} is equal K_I^R and K_{max} is the sum of K_I^P and K_I^R. For elliptical surface cracks, the equations 16, 17 and 18 can be evaluated for both crack depth and length, from the specific ΔKs calculated for each direction. Crack growth is expected to occur when the stress intensity factor range (ΔK) is above a certain limit, which is called the fatigue crack growth threshold (ΔK_{th}). Thus crack growth increments in both directions can be calculated in each operation cycle (loading and unloading) through equation 16 and the updated crack dimensions can be assessed at all the cycles using the FAD presented in figure 2. As the crack grows, the assessment point tends to reach the failure assessment curve and then the remaining life of the component is estimated by simply counting the cycles until the failure point.

2.4. Reliability Update

The models used for reliability and crack growth rate calculation allow the user to quantify the actual reliability of the component and its evolution after some service cycles. These models contain major uncertainties that can be reduced by means of inspection, which provides information on the actual state of the component. Thus, in the event of an inspection, the reliability should be updated through Bayesian statistical methods, using the inspection results and the prior information available [15]. In this paper, Bayes theorem is applied to correct the expected crack size defined theoretically with crack size detected by non-destructive inspection. The corrected PDF is then used to update the expected reliability to support the definition of a new inspection program. The procedure applied for reliability update is presented below.

Considering that after N_{op} operation cycles, the crack depth (a) would be described by a PDF p(a), called prior distribution, obtained through the crack growth model presented in the item 2.3. Once the equipment achieve N_{op} cycles an inspection is done, giving that the crack depth follows another PDF L(a), called likelihood distribution. Both prior and likelihood distributions are then used to estimate a posterior distribution p′(a), which is finally used to update the expected reliability of the component. The posterior distribution is determined by means of the Bayes rule, as follows:

$$p'(a) = C.L(a).p(a) \tag{19}$$

where C is a normalizing constant determined by the condition that the integration of p′(a) over its domain must result in unity.

3. CASE STUDY

3.1. Presentation

The methodologies described in the previous sections were applied to the worked example presented in API-579 Example Problem Manual, section 9.5 [16]. This case deals with a deterministic assessment of a pressure vessel constructed of SA-516 Grade 70 steel with a semi-elliptical crack located in a longitudinal seam. The schematic dimensions of the cylindrical vessel and its internal crack are presented in figure 3. In order to run a probabilistic assessment of this defect, all COVs and PDFs of the input variables were determined based on literature survey, from the references listed in table 1. For the variables which the PDF were not found in the literature, uniform distributions were chosen for conservatism, to increase the dispersion of the variable around its mean value.

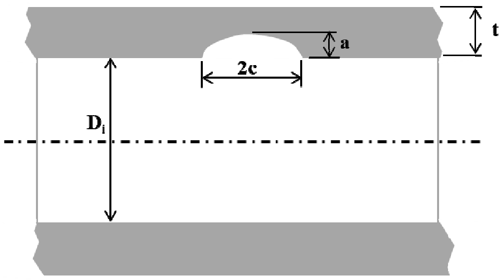


Figure 3 – Schematic dimensions and crack shape of the assessed pressure vessel.

Some remarks are presented below in order to clarify the input parameters used in the probabilistic assessment:

- Internal pressure (P): a COV of 10% is adopted considering that its value is well-known and controlled by sensors, corresponding to a low uncertainty on the primary loads applied to the vessel [6];
- Internal diameter (Di): according to reference [17], the tolerance on the perimeter for a pressure vessel of this size is ± 18 mm, which results in a ± 5.73 mm tolerance in diameter;
- Wall thickness (t): according to ASTM A20 [18], for a plate width of 1200 mm, the permissible variation in thickness is ± 1.52 mm. The COV is calculated based on a 95% confidence interval;

Table 1: Input Parameters used in the Probabilistic Assessment

Variable	Mean	COV [%]	Distribution	Reference
Internal pressure (P) [MPa]	1.38	10.0	Normal	[6]
Internal diameter (D_i) [mm]	3048	0.1	Uniform	[17]
Wall thickness (t) [mm]	25.4	3.0	Normal	[18]
Crack depth (a) [mm]	5.1	9.8	Normal	[19]
Crack length (2c) [mm]	81.3	0.6	Normal	[19]
Yield strength (σ_{ys}) [MPa]	329	5.0	Lognormal	[18]
Fracture Toughness (K_{mat}) [MPa.m½]	129	15.0	Lognormal	[20], [14], [21]
Walker Eq. Parameter (C_0)	$5.06.10^{-9}$	60.0	Lognormal	[14], [22]
Fatigue threshold limit (ΔK_{th})	2.00	60.0	Lognormal	[6], [22]
Walker Eq. Parameter (m)	3	-	Deterministic	[14]
Walker Eq. Parameter (γ)	0.65	31.1	Uniform	[14]

- Crack depth and length (a & 2c): crack dimensions were obtained from scheduled inspection through ultrasonic testing. The COVs were based on the typical accuracy of this method found in reference [19] (± 1 mm; 95% confidence interval);
- Yield strength (σ_{ys}): the mean value is based on actual material property instead of the minimum strength specified by the material standard. The adopted COV was based on ASTM A20, appendix X2 [18], which presents the standard deviation as 5% of the yield strength;
- Walker equation parameter (C_0): the coefficient given in API-579 is based on the worst-case scenario. A mean coefficient is calculated based on the results obtained from fatigue tests for ferritic-pearlitic steels [20];
- Fatigue crack growth threshold (K_{th}): the mean value proposed by API-579 [6] is adopted, with the same distribution parameters from the Walker equation parameter (C_0);
- Walker equation parameter (γ): according to reference [14], this parameter varies from 0.3 to 1.0 for metals. A uniform distribution was adopted between these extreme values;
- Weld residual stress (Qm): no information were available on the post weld heat treatment of this vessel. Thus, the residual stresses are considered, conservatively, equal to the material yield strength (σ_{ys}), according to API-579 [6] recommendation.

3.2. Structural Integrity Assessment

The integrity assessment of the pressure vessel from item 3.1 was done according to API-579 rules, using the FAD presented in the Figure 2 as the failure criterion, named Level 2 assessment procedure. The stress intensity factors, used to compute the toughness ratios, were calculated through equation 20, referred to as Raju-Newman solution [23], taken from the Annex C of API-579, which is a compendium of stress intensity factors for usual geometries found in the petroleum industry.

$$\boldsymbol{K_I} = \frac{p.R_o^2}{R_o^2 - R_i^2} \cdot \sqrt{\frac{\pi.a}{Q}} . F\left(\frac{a}{c}, \frac{a}{t}, \frac{R_i}{t}, \theta\right) \tag{20}$$

where R_O and R_i are, respectively, cylinder external and internal radius, F is a geometry factor, θ is the angle on crack surface (0º = crack tip, 90º = crack depth) and Q is a shape parameter. Similarly, the reference stresses (σ_{ref}), used to compute the load ratios, were calculated through equation 21 found in the Annex D of the standard.

$$\sigma_{ref} = \frac{g.P_b + \left[(g.P_b)^2 + 9\left(M_s.P_m.(1-\alpha)^2\right)^2\right]^{0,5}}{3(1-\alpha)^2} \tag{21}$$

where P_b and P_m are, respectively, the bending and membrane stresses, M_s is a surface correction factor, g is a reference stress bending parameter and α is a reference stress parameter. Figure 4 presents the results obtained after 10^5 Monte Carlo simulations for the input variables, with the resultant assessment points. Also, there is a comparison between the probabilistic and deterministic method from API-579, with the application of PSFs on the input variables.

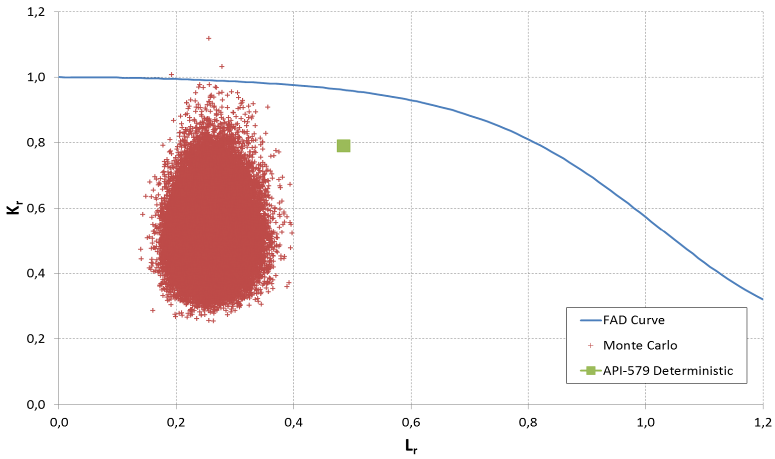


Figure 4 – Results from 10^5 Monte Carlo simulations of the cracked pressure vessel. The isolated point in the graph is the result from a deterministic assessment for this vessel.

From figure 4, it's possible to note that 3 out of 10^5 assessment points fall above the failure assessment curve in the unacceptable region, meaning a failure probability of 3.10^{-5}. The ASM method was also applied to this case and the resultant failure probability was 4.10^{-5}, showing good agreement with Monte Carlo simulations. Figure 4 also contains the result of the worked example from reference [16], which is a deterministic assessment with the application of PSFs on the input variables. The PSFs were chosen to result in a maximum failure probability of 10^{-3}. As a result of the application of PSFs, the assessment point is shifted to the right and upwards in comparison with the pure results from the probabilistic assessment. The maximum failure probability from the deterministic assessment is well above the resultant failure probability obtained through the probabilistic assessment. This difference can be decisive while doing a risk assessment and can completely change the final decision whether to stop or continue the pressure vessel operation.

The ASM method was also applied to generate new FAD curves for different failure probabilities. The results are presented in figure 5. The new FAD curves were generated by changing both crack size and operation pressure, resulting in various assessment points (L_r; K_r) which had their failure probabilities evaluated. The assessment points with equal failure probabilities were fitted by a curve. Figure 5 presents the resultant curves for failure probabilities of $2.3.10^{-2}$, 10^{-3} and 10^{-6}, which correspond, respectively, to small, medium and high consequences of failure according to API-579. For assessment points with L_r higher than 0.85 the convergence of the ASM method was not achieved and the results in this region are merely a visual adjustment of the fitted curves.

3.3. Remaining Life Assessment

The crack growth was also evaluated through Monte Carlo simulations based on Walker equation. The simulations were done for fixed operation cycles: 1250, 2500, 5000 and 10000 cycles. The crack dimensions obtained after N cycles were then used to estimate the PDFs for both crack depth (a) and length (2c). The resultant crack dimensions and PDFs were then used to evaluate the failure probability through the same procedure applied in item 3.2.

The resultant crack dimensions after N operation cycles are summarized in table 2. From this table, it is possible to note a very small crack growth in the length direction, as the stress intensity factor range at this position remains very close to the fatigue threshold limit (K_{th}). Nonparametric methods were used to found the nature of the PDFs for crack dimensions. Both crack depth and length can be well described by Lognormal distributions, as the probability plot of these variables resulted a good fit of the data, with correlation coefficients ranging from 0.82 to 0.99.

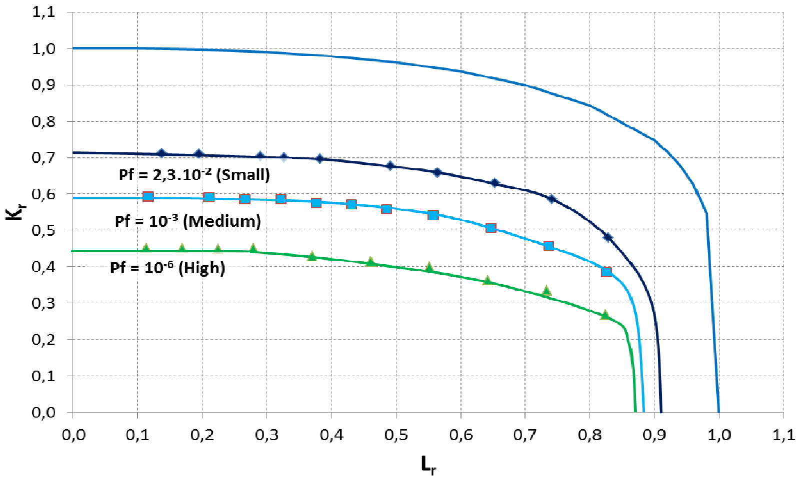


Figure 5 – FAD curves for different failure probabilities and consequences for the cracked pressure vessel.

Table 2: Crack dimensions and Lognormal parameters after N operation cycles.

N [cycles]	a [mm] Mean	COV [%]	2c [mm] Mean	COV [%]
1250	5.18	10.5	81.30	0.6
2500	5.32	11.7	81.30	0.6
5000	5.62	17.2	81.32	0.6
10000	6.17	29.8	81.43	0.8

Figure 6 presents the results of the probabilistic assessment of vessel integrity after each operational cycle based on crack dimensions defined on table 2. From these results, the remaining life of the cracked pressure vessel can be estimated, by simple comparison between the trend line and the limit failure probability level tolerated by the vessel application. These limits are plotted in figure 6, for both medium and small consequences of failure, which corresponds, respectively, in a remaining life of 5000 and 10000 operation cycles. According to the results, the vessel is not adequate for applications where a failure would result in high consequences, as the minimum failure probability (5.10^{-5}) is above the tolerable failure probability (10^{-6}). After 5000 loading cycles the vessel is not adequate for operational scenarios associated with medium failure consequences once the failure probability is higher than 10^{-3}.

3.4. Reliability Update

In this section, an example of reliability update analysis is presented by means of a hypothetical case which considers that an ultrasonic inspection is done after 2500 operation cycles (50% of the vessel remaining life, as recommended by reference [24]) detecting a crack depth of 6.0 mm, with the same measurement uncertainty given by table 1. As the measured crack depth is above the expected value obtained by simulation a reliability update analysis is performed. The resultant PDF for the posterior distribution is then obtained through equation 19, resulting in the following expression:

$$p'(a) = C.\boldsymbol{N}[6.0; 0.5].\boldsymbol{LN}[5.32; 0.62] \quad (22)$$

where N and LN represents, respectively, the normal (likelihood) and lognormal (prior) distributions. The constant C was obtained through numerical integration of equation 22 and is equal to 3.03094.

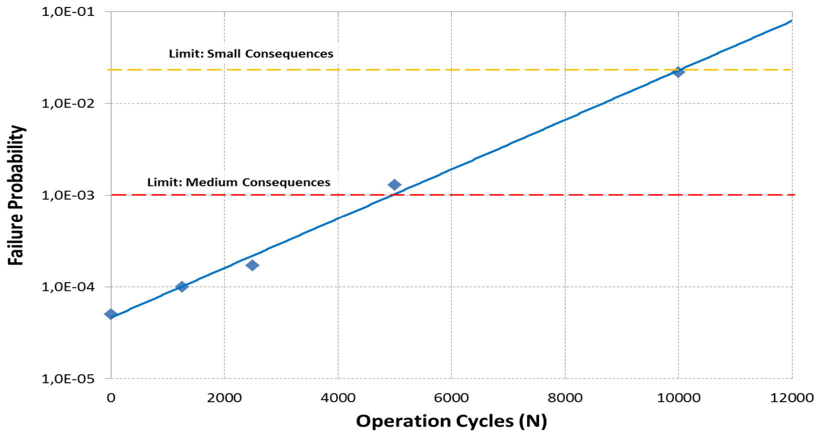
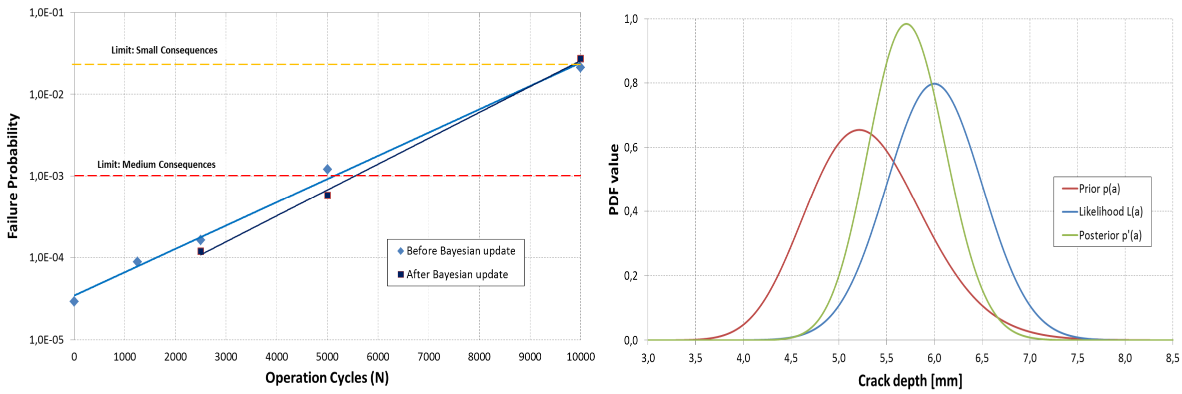


Figure 6 – Evolution of the failure probability according to the quantity of operation cycles.

The resultant expression for p'(a) was then used to generate random numbers for initial crack depth followed by calculation of crack growth and failure probability for 2500, 5000 and 10000 cycles. The updated failure probability is presented in figure 7a (dark blue curve) and is lower than the prior values, which is a no intuitive result, as the measured crack size is above the prior value. This behavior can be understood by comparing all the distributions involved, as presented in figure 7b. The posterior PDF has a lower standard deviation, resulting in a PDF with shorter tails (Normal PDF parameters are $\mu = 5.72$ and $\sigma = 0.41$). Thus, as more information is gained through inspection, the uncertainty upon the crack size is reduced, resulting lower failure probabilities. After Bayesian update, the remaining life of this vessel is estimated in 3000 cycles, against the previous value of 2500 cycles, considering a failure probability of 10^{-3} as the risk criterion. Therefore, the next inspection is recommended after 1500 service cycles.



a. Failure probability estimate update b. Crack dimension distribution

Figure 7 – Reliability before and after Bayesian update as function of operation cycles.

4. CONCLUSION

This paper presented the methodology and an example about the probabilistic safety assessment of cracked pressure vessels. This methodology is mentioned in API-579 as an alternative method for cracks which the assessment point falls in the unacceptable region of the FAD, but no details on its application are given by the standard. One of the objectives of this work is try to fulfill this gap, by presenting references where the PDF parameters can be estimated and a worked example to serve as a guide for the users of the probabilistic method.

According to the results from the example, the probabilistic method presented lower failure probability than that indicated by the deterministic methodology from API-579. Despite its complexity due to information required on the PDFs for the input data, the application of the probabilistic method brings relevant information to the plant operator to maximize equipment availability. Also, the use of the probabilistic method associated with Bayesian updated allowed the extension of the remaining life of the evaluated pressure vessel, although the measured crack was deeper than the prior crack obtained through simulation.

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