Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

Reliability analysis of a LPG sphere due to cracking in its welded joints

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ABSTRACT - The rupture probability of a LPG sphere is evaluated considering stress corrosion cracking in its welded joints. The model considers three factors: (a) crack incidence distribution; (b) reliability of the nondestructive testing (i. e., probability of detecting a crack by ultrasonic inspection); and (c) probability that a crack reaches its critical depth between successive sphere inspections. The rupture probability is obtained as the product of these three factors. The model limitations are discussed.

1. INTRODUCTION

Probabilistic fracture mechanics allows for determining the rupture probability of a metal structure by considering the crack incidence by means of probability distributions, the reliability of nondestructive testing employed for detecting them, and finally, the probability that a given crack reaches its critical depth before the next inspection is performed in the structure. This model allows for determining, for example, the rupture probability of a LPG storage sphere made of ASTM-A516-gr70 carbon steel due to the subcritical crack growth near its welded joint belt (thermally affected zone) caused by stress corrosion.

This problem can be approached by deterministic methods, in which a limiting state equation is chosen and discrete values of the relevant parameters (as, for example, mechanical strength and discontinuity dimensions) are inserted in it. However, the uncertainties associated with these parameters would not be considered and the results could be highly conservative.

In this sense, it is much more convenient to use probabilistic methods. Fracture mechanics is approached by considering explicitly that the parameters envolved in the analysis have uncertainties associated with them.

2. PROBABILISTIC FRACTURE MECHANICS APPROACH TO THE PROBLEM

It is necessary to evaluate the critical crack depth for the LPG storage sphere considering the incidence of cracks in its welded joints. It should be emphasized at this point that the critical crack depth was evaluated by deterministic methods, that is, no uncertainties were considered.

Basically, three probabilities affect the rupture probability of a LPG sphere due to stress corrosion cracking in its welded joints, Thompson (1987):

1) probability that a crack has an initial given depth;

2) probability that a crack is not detected by nondestructive testing;

3) probability that a crack grows from a given initial depth to its critical depth before the next sphere inspection is performed.

Some particularities must be commented at this point.

The first probability above is measured by considering the probability distribution of the initial crack depths. A distribution must be fit to these depths and a sample must exist for this fitting to be perfomed. This sample is obtained from nondestructive testing of spheres, performed in periodical inspections. These cracks detected at inspections are removed after being detected to avoid their propagation.

Some indications on the probability distribution to use in this context were analysed. Lidiard (1984) has suggested the use of an exponential distribution to describe the incidence of cracks in pressure vessels of pressurized water reactors (PWRs). On the other hand, Brückner & Munz (1983) have considered that the Weibull and the lognormal distributions are more adequate to represent the crack incidence in welded joints.

Crack incidence data for a typical LPG sphere of a Brazilian oil refinery were obtained and the goodness of fit analysis performed by graphical methods. Hypothesis testing indicated that the lognormal distribution was adequate to model the probability of findind a crack of a given depth.

Considering the aforementioned data, the probability of finding a crack with depth between x and $x+dx$ is equal to $a(x)dx$, where $a(x)$ is the lognormal density function:

$$a(x) = \frac{1}{\sqrt{2\pi}\,0.55x}\exp\left\{-1.6529\left[\ln\frac{x}{8.33}\right]^2\right\} \tag{1}$$

The second factor that affects the sphere rupture probability, concerns the nondestructive testing.

The probability of detecting cracks by nondestructive testing uses ultrasonic inspection methods. According to Haines (1983), the probability of detecting defects in welded joints depends on the following parameters:

1) the mean defect detection threshold;

2) the average received signal amplitude;

3) the standard deviation of signal amplitude between scans and between different nondestructive testing teams;

4) the defect depth.

Unfortunatelly, it was not possible to obtain data in order to adequately model the nondestructive testing reliability. In this sense, following Thompson (1987), a lognormal model for the nondestructive testing reliability was considered, according to which:

$$\overline{B}(x) = 1 = \Phi(z) \tag{2}$$

where $\overline{B}(x)$ is the nondestructive testing reliability and $\Phi(z)$ is the normal probability distribution function, for which:

$$z = \frac{\ln x - 3.135}{0.667} \tag{3}$$

The third factor mentioned before for evaluating the rupture probability of the LPG sphere is related to the chance that a given crack grows until it reaches its critical depth before the next sphere inpection is performed.

Considering the operational conditions of LPG spheres in oil refineries, the crack propagation occurs due to stress corrosion cracking. This means that the rate of propagation is constant. To obtain this rate of propagation, a steel with strength limit similar to that of the ASTM-A516-gr70 carbon steel in a H_2S solution has been considered, Chou *et alii* (1980). It should be emphasized, however, that the very LPG production process can generate H_2S which will be stored in the sphere. In this sense, the sphere must be devised to withstand this adverse condition. In practice, it is recognized that the H_2S concentration in spheres is in the range 10 ppm to 100 ppm. In this sense, the rate of propagation proposed in Chou *et alii* is highly conservative and so we have adopted a propagation rate that is lower that theirs by three orders of magnitude, and is given by:

$$\frac{da(x)}{dt} = 1.7x10^{-5} mm / \min \tag{4}$$

Finally, the probability that a crack reaches its critical depth before the next nondestructive testing is perfomed is obtained from the following equation:

$$p\left(x_c \,\middle|\, x, \frac{da}{dt}, \Delta t\right) = \frac{1}{\sqrt{2\pi}\, sx} \exp\left\{ -\frac{1}{2s^2}\left[\ln \frac{x + 1.7x10^{-5}\Delta t}{x_0} \right]^2 \right\} \tag{5}$$

where x_c is the crack critical depth and x_0 is the distribution median. On the other hand,

$$s = \frac{\ln r}{1.6449} \tag{6}$$

is the distribution variance, where r is known as the error factor.

The basic reason for approaching this propagation probability by a lognormal distribution is that higher propagation rates are more probable than lower ones and so it is reasonable to adopt a probability distribution with a tail on the right. Of course, a Weibull distribution could also be considered but another reason for choosing the lognormal distribution is that is it closely related to the Gaussian distribution.

The rupture probability for the LPG sphere can now be evaluated. It is given by:

$$p_{rv} = \int_0^{x_c} a(x)\overline{B}(x)\, p\left(x_c \,\middle|\, x, \frac{da}{dt}, \Delta t\right) dx \tag{7}$$

The evaluation of the crack critical depth, x_c, was performed by means of the elasto-plastic fracture mechanics.The so called crack opening displacement (COD) criterion, PD-6493 (1980), was used. One has in this case surface cracks of semielliptical shape with known length and depth. The crack depth is the most relevant dimension for higher stress intensity factors are occur in this direction. It was found that the critical crack depth is equal to 22.7 mm. Initially, the limiting state equation of the linear elastic fracture mechanics was considered. However, the minimum wall thickness of the sphere would have to be about 1.11 m and its real thickness is equal to 52.8 mm. For this reason, the elastoplastic fracture mechanics limiting state equation was employed.

3. RUPTURE PROBABILITY OF THE LPG SPHERE

As already mentioned, crack depth data obtained from a LPG sphere of an oil refinery lead us to the conclusion that the lognormal distribution could be used for determining the probability of finding a crack with depth in a given interval. Probability plots, Nelson (1982), were initially employed to this end. Hypothesis testing was developed afterwards to test the goodness of fit of the distribution with the parameters estimated by graphical methods. This analysis resulted in Eq. (1).

A second point that deserves consideration, is the use of Eq.(4). The variance depends on the distribution error factor and this latter is unknown. Specific data was searched for estimating the error factor but no information was available. To bypass this difficulty a sensitivity analysis was performed, considering a wide range of error factors, from 5 to 100.

Figure 1 presents the results for the three probabilities that are needed to use Eq. (6). It should be noted that the curve calculated from Eq. (5) was evaluated by considering an error factor equal to 10.

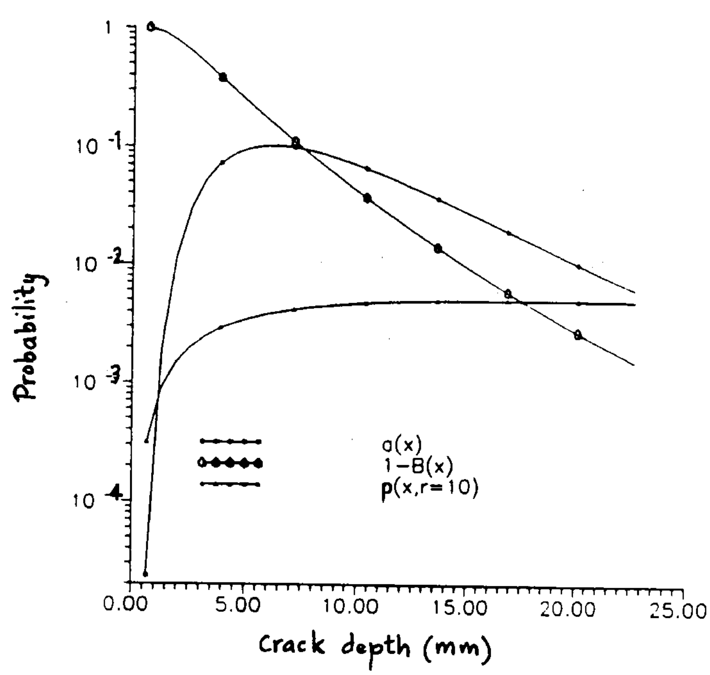

Figure 1. Curves of the three probabilitites used in calculating the sphere rupture probability.

The influence of the error factor r on the probability calculated by Eq. (5) may be inferred by considering the sensitivity analysis presented in Figure 2.

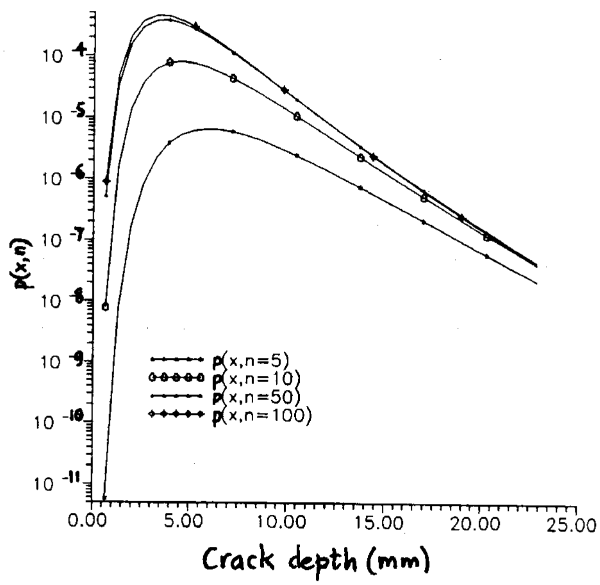

Figure 2. Influence of the error factor on the probability that a crack reaches its critical depth before the next inspection in the sphere

The curves shown in Figure 2 lead to the conclusion that the probability calculated by Eq. (5) reaches a maximum for lower values of the crack depth and this maximum is not much sensitive to the error factor as for r=100 it is around 3.5mm and for r=5 it is around 5 mm. On the other hand, the curves tend to collapse for higher crack depths for higher error factors ($r \geq 10$) showing that the probability is not much sensitive to higher crack depths up to the critical depth.

The rupture probability was calculated as a function of the error factor, considering the values shown in Table 1. It may be seen that the rupture probability is highly sensitive to the error factor, for a variation of r by a factor of 20 leads to a variation of about two orders of magnitude in the rupture probability. However, it is not reasonable to expect a rupture probability of about 10^{-3} in a period of 18 months, the time between inspections of the LPG sphere. Even considering lower error factors, the rupture probability is conservative. This point will be discussed in the next section.

Table 1 - Rupture probability of the LPG sphere as a function of the error factor

Error factor (r)	P_{rv}
5	4.2×10^{-5}
10	4.2×10^{-4}
50	1.7×10^{-3}
100	1.9×10^{-3}

4. A CRITIQUE OF THE RESULTS

It was considered in the whole analysis that the sphere internal pressure is constant. This is not true, because there are fluctuations in it. This uncertainty affects the calculation of the critical crack depth because it influences the calculation of the stress intensity factor.

A second point worh mentioning is related to the fact that the available data on crack depths was related to a unique inspection. It is very important to consider crack depth data from different inspections for this may lead to different conclusions concerning the probability distribution employed (the lognormal in the case of this work). Should this data be available, a Bayesian approach, Crowder *et alii* (1991), could be used to update the distribution.

It was considered in this work that the time between sphere inspections is equal to about 18 months. This is not very realistic because market demands turn this time a random variable.

The removal of cracks during inspection is not to be considered perfect for errors during inspection of crack removal may lead to overstressing. This same situation may apply to manufacturing errors. None of these has been taken into account in this work.

No plant specific information concerning the nondestructive testing was available. This is a source of model uncertainty that could not be assessed. The adopted model considers that the nondestructive testing reliability depends only on the crack depth. This is not entirely true as discussed earlier.

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