PRESSURE VESSEL FAILURE ANALYSIS

Pablo Vinícius Bassani, pablo.bassani@gmail.com
Heraldo José Amorim, hjamorim@brturbo.com.br
Ignacio Iturrioz, ignacio@mecanica.ufrgs.br

Abstract. *The purpose of this paper is to study a pressure vessel that collapsed during a Hydrostatic Test. This study will be carried using ASME code Section VIII and API 579 Fitness-For-Service assessment for a crack-like flaw in the spot where the failure happened. The acceptability of the damage will be determined by Failure Assessment Diagram (FAD). By the studies carried it is conclude that cracks-like flaw in the cylindrical shell of this pressure vessel should be of great magnitude to cause brittle fracture without leaking, indicating that the collapse wasn't caused due to this kind of damage.*

Keywords*: Pressure Vessels, ASME, API 579, Crack-like Flaw, Failure Assessment Diagram (FAD), Hydrostatic Test, Leak Before Break*

1. INTRODUCTION

Pressure vessels are very important equipment in the industry, being responsible for storing fluids at high pressures. Because of the high pressure, they can be very dangerous equipments, and to prevent any structural problem it is very important that its conception respects recongnonized project codes. However, design codes of pressure vessel doesn´t cover the fact that the equipment degrades while in service or the fact that deficiencies may be found. But, it is well know that these equipments may continue operating depending on working conditions and type and dimensions of these defects. The collapse of a pressure vessel during a Hydrostatic Test, required to attend the Brazilian Standard NR-13, caught the attention to the study of damages.

This paper aims to simulate a discontinuity on the collapsed vessel and determine which would be the size of the discontinuity that would take this equipment to fail. The simulated discontinuity will be a crack-like flaw, placed in the same spot where the failure took place.

In order to achieve this goal, first it will be determined the Maximum Allowed Working Pressure of this vessel using the ASME code and then an assessment will be conduct using methodologies of the API 579.

2. PROBLEM PRESENTATION

Most of industries use compressed air, which is usually provided by an air compressor and stored on a pressure vessel, popularly called "air lung". The studied vessel is one of these equipments. This specific air lung is designed to attend an 1.27 MPa MAWP, has internal radius of 220 mm, built with a nominal thickness of 3 mm, and has liquid storage capacity of 0.183 m³. Both heads are elliptical. The assumed material to this vessel is the SA-414 Gr C, with a maximum allowed stress of 108 MPa. A sketch of this vessel is showed in Fig. 4. Ultrasonic inspection showed that the thickness of the shell was varying between 2.9 mm and 3.1 mm, and no defects were found.

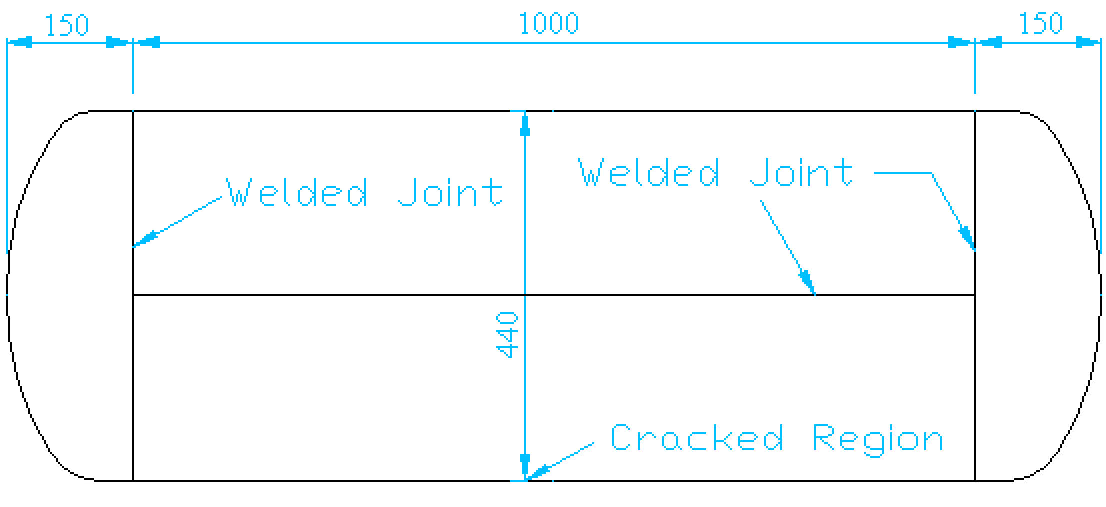

Figure 1. Dimensions of the pressure vessel

In order to attend Brazilian Standard NR-13 this vessel should be hydrostatically tested “in situs” before it starts to operate. This test took the equipment to fail. The assumed pressure was close to 1.9 MPa. The location of the failure is shown in Fig. 1. It wasn’t observed any leaking during the test.

The failure consisted on a longitudinal crack at the lowest point of the pressure vessel. This crack has an approximated length of 600 mm. Thickness of plate near the crack was measured close to the end of the crack, and showed smaller values than the rest of the vessel, suggesting material conformation before rupture. The collapsed vessel and the spots of ultrasonic thickness measurements are shown on Fig. 2.

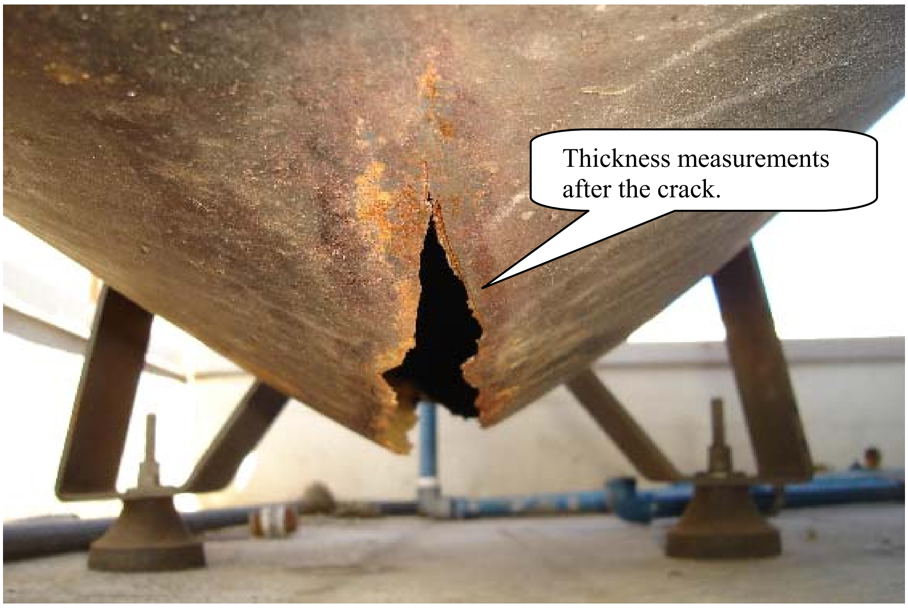

Figure 2. The pressure vessel after the failure

3. BASIC THEORY

3.1. The project of a pressure vessel

Brazilian Standard NR-13 requires the design of a pressure vessel to be based on a globally recognized standard. Examples of these standards are: AD Merkbatter (German), the standard BS-5500 (English), the Code SNCTTI (French) and the ASME code (American).

In Brazil, the ASME code is the most used. In this standard, Section VIII provides basics rules for construction of pressure vessels, and will be used to estimate the Maximum Allowed Working Pressure (MAWP) and the Hydrostatic Test Pressure (HTP).

This section has three divisions. Division 1 simply imposes rules for construction of pressure vessels, not requiring any detailed analysis for the actuating stresses. The integrity of the vessel project by this division is ensured by larges safeties factors. Division 2 consists of a more refined analysis, thus allowing higher MAWP than the same vessels projected with Division 1. Division 3 shall be used to project high pressure vessels.

In this paper it will be calculated only the MAWP for the cylindrical shell and the heads. Nozzles and openings will not be evaluated, since the fracture did not occur near these elements. For this purpose, formulae of Division 1 are enough for the project.

3.2. ASME code, Divison 1

This division provides basic rules to design of pressure vessels based mainly on the membrane and Lamè theories. According to Paragraph UG-23 of this code: *“The wall thickness of a vessel computed by these rules shall be determined such that, for any combination of loadings listed in UG-22 that induce primary stress and are expected to occur simultaneously during normal operation of the vessel, the induced maximum general primary membrane stress does not exceed the maximum allowable stress value in tension.”*

The maximum allowable stress of a material according to ASME is the lowest value between $S_{TS}/3.5$ and $2/3*S_{YS}$, where S_{TS} is the Tensile Strength and S_{YS} is the Yield Strength. The material assumed for the vessel under study has its maximum allowable stress with the value of $S_{TS}/3.5$, according to ASME Section II.

The determination of the MAWP for the cylindrical shell is presented in paragraph UG-27 of ASME VIII, Division 1. When the welded joints efficiency (determined by grade of inspection and the type of joint in paragraph UW-12) are equal, circumferential stress has twice the magnitude of longitudinal stress. Since the welded joints of this vessel are of same type and are assumed to have the same type of inspection, then circumferential stress is the critical case. The MAWP and minimum thickness required for the cylindrical shell can be calculated using Eq. (1).

$$P = S*E_{long}*t / (R_i+0,6*t) \tag{1}$$

Where "P" is the MAWP, "S" is the maximum allowed stress for the material, "t" is the thickness, "E_{long}" is the longitudinal joint efficiency and "R_i" is the inner radius.

The ASME code presents five main head shapes. Since measurements and inspection pointed the heads to be elliptical, the calculations will be carried according to ASME paragraph 1-4 of the referred code. The MAWP and minimum thickness required for the ellipsoidal head are determined from Eq. (2) and Eq. (3):

$$P = 2*S*E*t / (K*D + 0.2*t) \tag{2}$$

$$K = 1/6 * [2 +(D / 2h)^2] \tag{3}$$

Where "D" and "h" are as shown in Fig. 3 below:

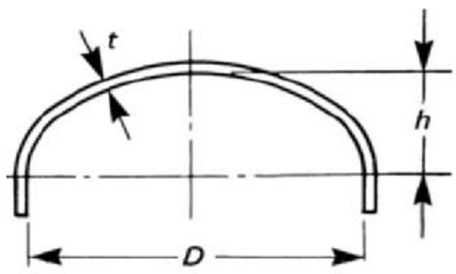

Figure 3. Main Dimensions of Elliptical Heads

3.3. The Hydrostatic Test

ASME code requires Hydrostatic Test after the manufacture of the pressure vessel. This test consists on applying pressure, using an uncompressive fluid (water), beyond the MAWP. That overpressure is the HTP and should be hold for some time. Until 2004, this standard demanded a Hydrostatic Test Pressure equivalent to 1.5 times the MAWP. Since the vessel was projected before this year, it will be assumed in this work a hydrostatic test pressure equal to 1.5*MAWP. This is done to test the integrity of welded joints with a relative safety, since pressurized water would not cause the vessel to blow.

The assumed material for this pressure vessel has a maximum allowable stresses of 108 MPa and a Yield Strength of 205 MPa according to ASME, Section II, Table 1A at a temperature between -30°C and 350°C. So the HTP will cause a stress of 162 Mpa (1.5*MAWP), which is less than the Yield Strength.

Brazilian Standard NR-13 requires periodical Hydrostatic Tests depending on the volume and working conditions of the pressure vessel. For large volumes and great pressures this test may be required every six years. This standard also requires a Hydrostatic Test in the pressure vessel final installation place before the equipment begins to operate and after any welded repair.

3.4. Fracture Mechanics

Fracture Mechanics is the field of mechanics in which the API 579 standard is based on. This field is concerned with the study of the formation of cracks in materials and its fundamental can be found in "Wang, 1996". Fracture Mechanics can be compared with Solid Mechanics like show in Tab. 1.

K_I is the Stress Intensity Factor and can be easily found in literature like Tada, 2003, and Donato, 2008. In this paper the determination of K_I will be carried out according to API 579.

Fracture Toughness (K_{IC}) is the numerical parameter that determines if the material will suffer a brittle fracture. The determination of this parameter is usually done using Charpy-V Impact Test. In this paper, determination of K_{IC} will be performed using Appendix F of API 579.

It is important to carry this analysis because the presence of a small crack would ratter cause the pressure vessel to leak during the Hydrostatic Test, indicating the presence of the defect. Witch means that, it would need a large crack to bring the vessel to a collapse. API 579 assessments will be used to determine the minimal dimensions of a crack that would lead the pressure vessel to a brittle fracture.

Table 1. Comparison of Solid Mechanics and Fracture Mechanics

Solid Mechanics	Fracture Mechanics
Basic Criteria: Actuating stress must be lower than the material yield strength.	Basic Criteria: Stress Intensity should be lower than fracture toughness.
$\sigma_{MAX} \leq \sigma_{YS}$	$K_I \leq K_{IC}$
Stress or deformation in structure.	Stress intensity near the discontinuity.
Mechanical propriety of Material.	Fracture toughness.
The fail occurs when the actuating stress reaches the yield strength.	The fail occurs when the Stress Intensity near the discontinuity reaches the fracture toughness.

3.6. Failure Assessment Diagram (FAD)

According Pereira and Santos, 2004, *this diagram (Fig. 4) consists on the combined analysis of the elastic and elastoplastic material behavior. When* $K_R = K_I / K_{IC} \geq 1$ *a brittle collapse is expected and when* $L_R = S_{ref} / S_{YS} \geq 1$ *a plastic collapse is expected. For combinations of* K_r *and* L_r *the failure will be expected if this coordinates exceeds the curve given by Eq. (4) below:*

$$K_R = (1\text{-}0{,}14{*}L_R^2){*}[0{,}3+0{,}7EXP(-0{,}65{*}L_R^6)] \quad (4)$$

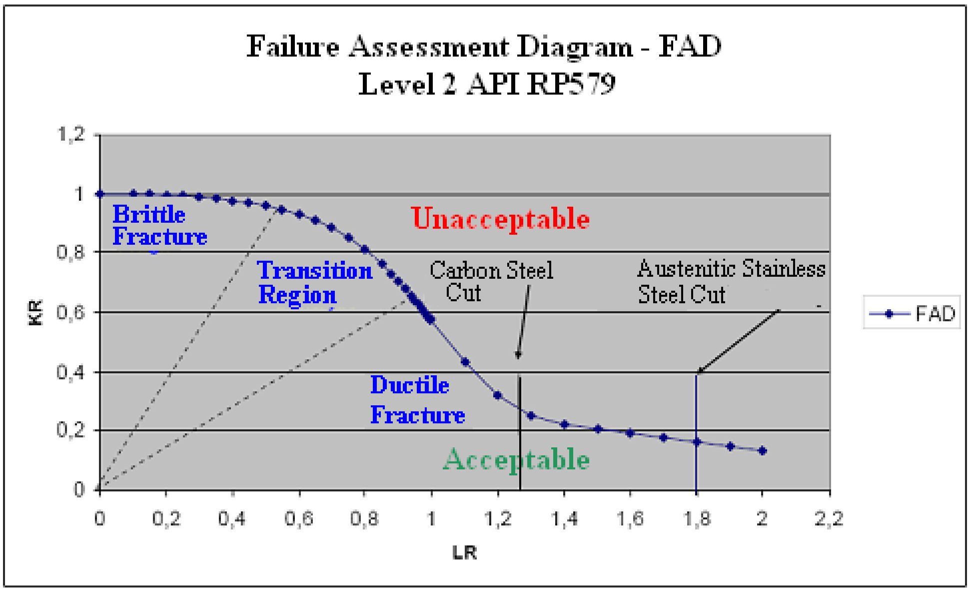

Figure 4. Failure Assessment Diagram

3.7. API 579

It is said in the introduction of API 579 that this document "*provides guidance for conducting Fitness for Service (FFS) assessments using methodologies specifically prepared for equipment in the refining and petrochemical industry. The guidelines provided in this recommended practice can be used to make run-repair-replace decisions to help ensure that pressurized equipment containing flaws which have been identified by inspection can continue to operate safely.*"

The methodologies are prepared specifically for equipment in the refining and petrochemical fields, but, since the normal operating conditions of the pressure vessel in study are less severe than these, the methodology can be applied in this case.

API 579 is organized in sections and each section deals with a particular type of damage. Crack-like flaws are treated by Section 9. Each section has 3 levels of assessments. Level 1 assessment is usually conservative and doesn't necessarily demand an engineer's supervision. Level 2 assessment is less conservative and requires better knowledge of the defect; it must be carried by an engineer with some experience. Level 3 assessment addresses numerical simulation (finite element analysis) and requires high detail of the equipment and the evaluated defect.

Level 2 assessment requires information such as the flaw depth and length. The procedure requires calculations like stress concentration factor on the edge of the flaw and the fracture toughness of the material. Table 3 below is a summary of API 579 Level 2 assessment procedures.

Table 2. Level 2 Assessment Procedures

Step	Description
1	Determine loads and temperatures to be used.
2	Determine the stress distributions at the location of the flaw based on the applied loads in Step 1
3	Determine the material properties; yield stress, tensile strength and fracture toughness for the conditions being evaluated from Step 1.
4	Determine the crack-like flaw dimensions from inspection data.
5	Modify the primary stress, material fracture toughness, and flaw size using the Partial Safety Factors. Once the real value is to be determined, this step will not be carried out.
6	Compute the reference stress for primary stresses, σ_{ref}^{P}
7	Compute the Load Ratio L^{R}, the abscissa of the FAD
8	Compute the stress intensity attributed to the primary loads, K_I^{P}
9	Compute the reference stress for secondary and residual stresses, σ_{ref}^{SR}
10	Compute the stress intensity attributed to the secondary and residual stresses, K_I^{SR}
11	Compute the plasticity interaction factor, Φ,
12	Determine toughness ratio K_R, ordinate of the FAD
13	Evaluate results.

4. RESULTS

4.1. MAWP, HTP and Minimum Thickness

The calculated MAWP resulted on a value of 1.46 MPa to the cylindrical body (Eq. 1) and 1.47 MPa to the heads (Eq. 2). From these, it can be conclude that the cylindrical body is the critical element of the equipment. The MAWP will be adopted as 1.27 MPa according to the pressure vessel documentation. That established, the hydrostatic test pressure should be 1.91 MPa. At this pressure, the thickness required for the cylindrical shell to reach the material's Yield Strength is 1.8 mm and a thickness of 1.1 mm would reach the Tensile Strengh.

4.2. API 579 Assessment

The procedure will be done to three types of flaw: a trough-wall crack, an infinite length inside surface crack and a semielliptical surface crack. Each kind of flaw was evaluated to different dimension as applicable. The results are shown in Tab. 4.

Table 4. Results of Level 2 Assessment

	2*c [mm]	a [mm]	σ_{ref} [MPa]	K_I [MPa*m^{0,5}]	L_r	K_R
Trough-wall crack	60	through	233	89	1,01	0,70
infinite length inside surface crack	infinite	0,75	186	9	0,81	0,07
	infinite	1,2	232	18	1,01	0,14
	Infinite	1,8	348	41	1,51	0,32
	infinite	2,4	696	120	3,03	0,94
semielliptical surface crack	200	0,75	178	8	0,77	0,06
	55	0,75	165	8	0,72	0,06
	80	1,2	188	16	0,82	0,12
	120	1,8	240	31	1,04	0,12
	120	2,4	298	53	1,30	0,24
	60	2,4	216	42	0,94	0,33

A better visualization of the values is shown in Fig. 5 below:

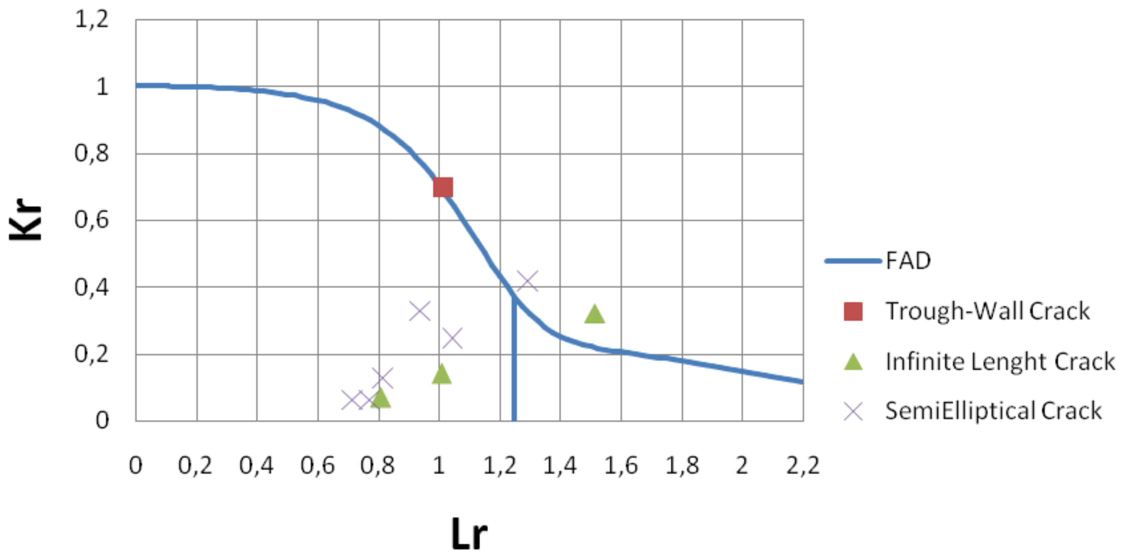

Figure 5. Results plotted in FAD

4.3. Conclusions

For the calculations done and procedures taken it was found that those kinds of damages are not critical to cause the equipment to collapse. Cracks-like flaw in cylindrical shell should be of great magnitude to cause brittle fracture and, in that case, a simple visual examination during the fabrication would have detected the defect. If the crack had grown while in service, than the expected result of the equipment while in Hydrostatic Test was to leak. And the leaking would have revealed the damage. Therefore, the reason this pressure vessel collapsed wasn't due only to a crack-like flaw.

It wasn't considered in this paper overload or corrosion, but the significant reduction of thickness close to the failure is a clear indication that strong plastic deformation occurred before failure, which indicates that overload have took place.

4. REFERENCES

API RP579, Jan/2000 - Fitness for Service, Recommended Practice, First Edition, American Petroleum Institute Publishing Services, Washington D C, USA

ASME, 2004, Section II, Part D, Material Properties (Metric).

ASME, 2004, Section VIII, Division 1. Boiler & Pressure Vessel.

ABNT, 1995.NR-13, 1995, Norma Regulamentadora 13 do Ministério do Trabalho e Emprego, Governo Federal.

Donato, G. V. P., 2008, Avaliação de Integridade Estrutural API 579/ASME FFS-1 Fitness For Service.

WILKOWSKI, G., 2000. Leak-before-break: What does it really mean? Journal of Pressure Vessel Technology, Vol. 122, Issue 3, pp. 267-272.

Pereira Filho, J. S., 2004, Análise de Efeitos de Teste Hidrostático em Vaso de Pressão.

Tada, H., 2003, The Stress Analysis of Cracks Handbook.

Wang, C.H., 1996, Introduction to Fracture Mechanics, Airframes and Engines Division Aeronautical and Maritime Research Laboratory.

5. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.