APLICATION OF A PROCEDURE TO ASSESS STRUCTURAL INTEGRITY AND REABILITY OF STATIC EQUIPMENTS IN REFINING INDUSTRY

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Abstract. *Petroleum refining is a complex physico-chemical engineering process. And most of these processing tasks take place inside static equipments, such as pressure vessels, furnaces and heat exchangers, among others. Moreover, it is common these equipments be designed for extreme pressure and temperature conditions. In case of failure, they could represent catastrophic damages for both environment and people.*
Non destructive tests usually detects many defects considered safe for the equipment (regarding conservative design codes criteria). However, some of them require a more detailed assessment by using techniques such as Fracture Mechanics and Stress Analysis using Finite Elements Method.
This work presents a real pressure vessel study case in which several cracks where detected during turnover maintenance in the torispherical head and cylindrical shell girth weld. Since such defects were not predicted by the inspection before opening the equipment, there was no even budget allocated nor available time for immediate repair, due to refining logistics requirements. Therefore, in order to assess the structural integrity of this equipment without needing a big repair on it, a Fracture Mechanics study was performed using the British Standard procedure BS-7910, that requires a good stress analysis evaluation which was done using the Finite Element Method.

Keywords *Pressure Vessels, Fracture Mechanics, Finite Element Method, Structural Integrity*

1. INTRODUCTION

In contrast to the straightforward and conservative calculations that are typically found in design codes (ASME BPVC, BS-5500, API 650, etc), more sophisticated assessment of metallurgical conditions and analyses of local stresses and strains would precisely indicate whether operating equipment is fit for its intended service or whether particular fabrication defects or in-service deterioration threaten its integrity. Such analyses offer a sound basis for decisions to continue to run as is or to alter, repair, monitor, retire or replace the equipment. This logic is what specialized publications calls "Fitness for Service" assessments, which can be defined as quantitative engineering evaluations that are performed to demonstrate the structural integrity of an in-service component that may contain a flaw or damage.

The most used codes for this purpose are the American Petroleum Institute API 579 (API, 2007) and the British Standard BS-7910 (Guide to methods for assessing the acceptability of flaws in metallic structures). Both addresses evaluation methods for several kinds of damages, such as localized and generalized thickness loss, fatigue, creep and cracks. API 579 addresses more failure mechanisms, but BS-7910 is easier to apply when the damage is a crack. For this reason, it is more commonly used at Petrobras.

Differently from the requirements desired for new equipments, the fitness for service purposes for equipments depends on specific questions made for specific problems, such as (Anderson, 2005):

- What if a weld contains an unacceptable flaw?
- Is the flaw harmful?
- Could a repair make matters worse?
- What if material does not meet design specifications?
- What if the cracks occur in service?
- Can a structure be used beyond its design life?

The answer for these questions concerns the main idea of applying the fitness for service philosophy: a flaw can be acceptable provided the conditions for failure are not reached in the required service lifetime.

There are several reasons for a structure failure. Subsequent studies to catastrophic failures showed that most of them occur by low temperature fragile fracture where the stresses are below yielding point. Furthermore, cracks usually have its source close to geometric discontinuities or in pre-existent defects. In other words, it became evident that a failure will occur only if a combination of these three factors happens: materials properties, stresses and flaws geometry.

Fracture mechanics has showed how these factors could be related to characterize both the actions that might cause failure and the resistance offered by the component (Fig. 1) and BS-7910, by using fracture mechanics and strength of materials concepts, provides extensive guidance on the treatment of flaws in welded structures. The main emphasis of the procedures is on the avoidance of failure by fast fracture/plastic collapse or extension of flaws by fatigue crack growth.

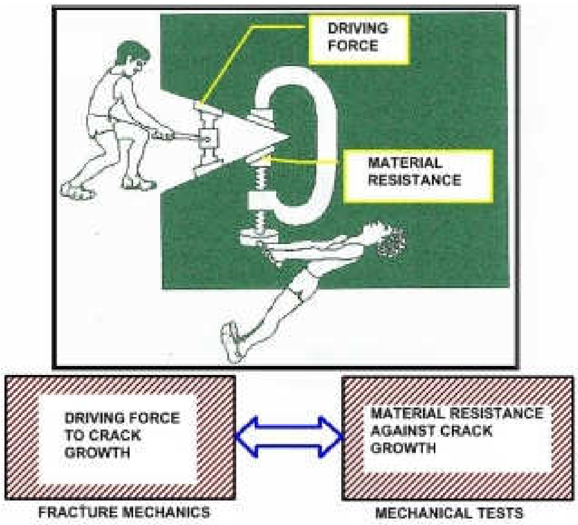

Figure 1 – Fracture mechanics X materials strength.

This work presents the appliance of the BS-7910 methodology to some cracks found in a weld of a DEA (diethanol amine) process tower, in order to determine whether the damages should be immediately repaired, generating extra costs, loss of production or a better planning could be done in order to repair them on another occasion. In the next sections, not only the analyzed problem will be described with the followed steps to its solution, but also the main engineering topics related to this study.

2. FITNESS FOR SERVICE EVALUATION OF THE DEA PROCESS TOWER

2.1. Overview

At the end of scheduled turnover maintenance in a DEA absorber process tower in a Petrobras Unit, the inspection team had found some cracks that could represent danger to the safe operation of this equipment, and to the people working at this unit. The first opinion was to repair all the cracks. But this would represent an incredibly huge amount of extra work and money, because the tower was already ready to operate again, and all maintenance team had been already demobilized. For this reason, a fitness for service study was performed, in order to decide if the defects could remain in the equipment.

Figure 2 shows a simple schematic DEA Treatment Unit (Parkash, 2003):

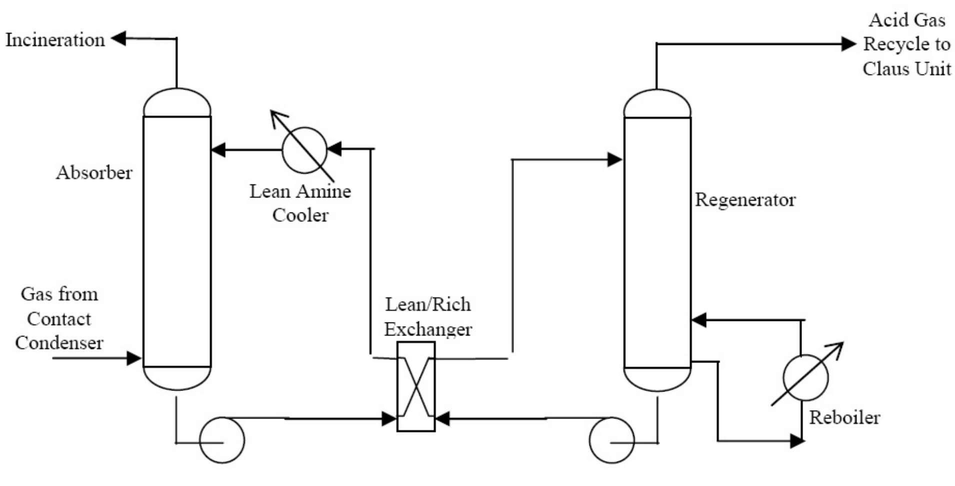

Figure 2 – Simplified amine treatment unit.

The objective of an amine treatment unit is to remove H_2S, CO_2 and mercaptan compounds from various gas streams, such as recycled gas in hydrotreating and hydrocracking processes, hydrogen plant feed and fuel gas systems.

The H_2S recovered is burned in the flare or used as feed for the sulfur recovery unit. In this process (DEA), the hydrogen sulfide is removed from a gas stream by contact with an aqueous solution of diethanol amine.

In order to improve the chemical reaction efficiency, the absorber tower operates under high pressure (7.6 MPa) and medium temperature (80ºC) conditions. At lower temperatures, aqueous amine is not too corrosive to carbon steel, but the high pressure and the impossibility to keep the chemical process always as designed, Stress Corrosion Crack (SCC) represents a possible damage mechanism for this equipment.

2.2. Crack evaluation steps

Any kind of structural integrity evaluation requires the analyst to follow some logic steps, in order to obtain a reliable result: identify the flaw type, i.e. planar, non-planar or shape; establish the essential data, relevant to the particular structure; determine the size of the flaw and determine the limiting size for the final modes of failure.

In the scope of fitness for service philosophy, establishing essential data means to define the nature, position and orientation of flaw, structural and weld geometry, fabrication procedure, stresses (pressure, thermal, residual or resulting from any other type of mechanical loading) and material mechanical properties.

Summarizing, it is necessary to determine the type of defect, its location and orientation with respect to the stresses (this task is preferably performed using ultrasonic, non-destructive x-ray or gamma radiography tests); equipment geometry (using engineering draws); stresses in the cracks location (using analytical equations or finite element analysis) and mechanical properties of both weld and parent metal (performing mechanical tests or tabular data, such ASME Sec. II).

BS-7910 presents three assessment levels, named Level 1 (Simplified Assessment), Level 2 (Normal Assessment) and Level 3 (Ductile Tearing Instability Assessment). Due to the available data to perform analysis, Level 2 steps are followed in this report.

The main goal of this evaluation is to determine if a given crack is safe. In terms of BS-7910, a safe crack must fall inside the Failure Assessment Diagram (FAD), based on the Dugdale's R6 method. The vertical axis (K_r) of the FAD is a ratio of the applied conditions, in fracture mechanics terms, to the conditions required to cause fracture, measured in the same terms. The horizontal axis (L_r) is the ratio of the applied load to that required to cause plastic collapse. An assessment line is plotted on the diagram. Calculations for a flaw provide either the co-ordinates of an assessment point or a locus of points. The positions of these are compared with the assessment line to determine the acceptability of the flaw.

2.3. Problem description

This study assesses the encountered cracks considering that all design process variables are kept controlled, in order to avoid uncontrolled crack propagation due to SCC damage mechanism. Figure 3 shows the geometry used to build the finite element model used to perform the stress analysis.

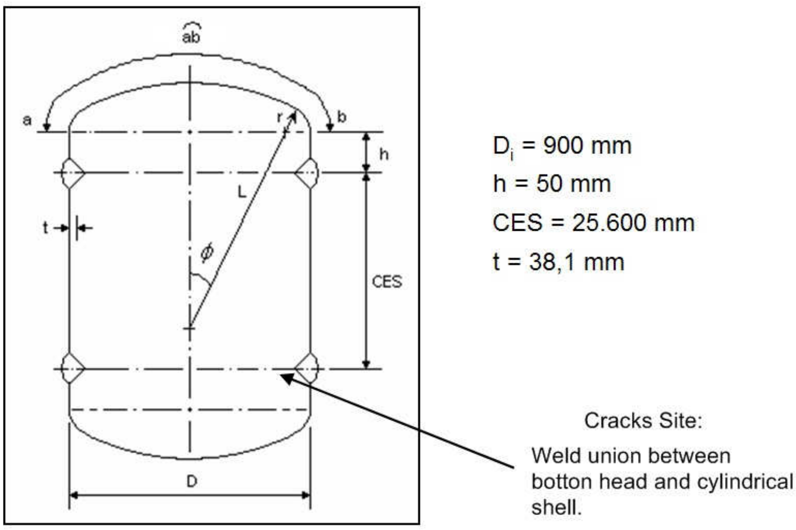

Figure 3 – DEA absorber tower main geometry.

After ultra-sonic examination, some cracks were found around the girth weld between the bottom head and the cylindrical shell. Before analyzing the safety of the defective equipment, it is necessary to re-characterize the cracks, because they can interact with themselves. BS-7910 addresses this issue, by using a set of simple geometric rules.

Figure 4 shows schematically the location were the cracks were found, and its representation, after the BS-7910 proposed interaction criteria:

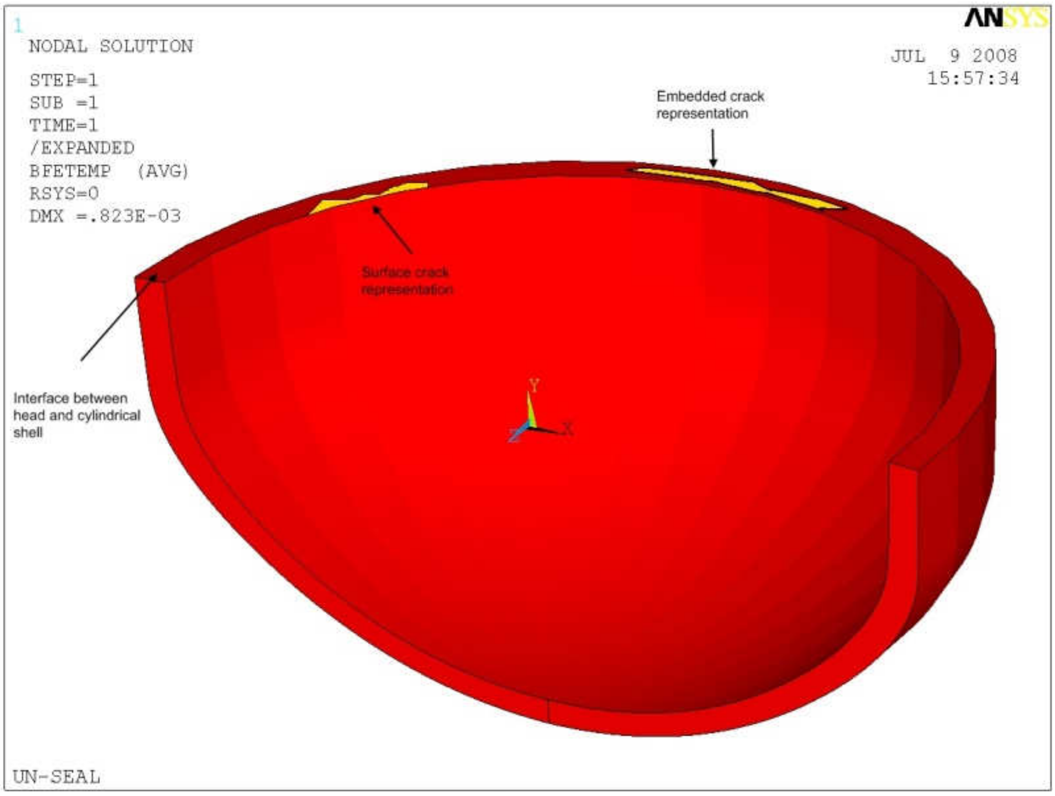

Figure 4 – Geometric representation of the cracks location.

Due to their morphologic characteristics and concerning the operational historic of this equipment, inspection team has concluded that the cracks were really caused by the humid H_2S.

2.4. Material mechanical properties (strength and toughness)

Material properties play an important hole in determining the fitness for service of equipments. Poor mechanical resistance, for example, can lead the whole structure to plastic collapse failure, and a crack would never propagate. On the other hand, very high resistance materials can present fragile behavior, what could foment the undesired brittle fracture.

According to the procedure, mechanical properties shall be estimated for the site and at the temperature where cracks are located (weld metal, in this case). However, it is common to use mechanical properties of parent metal rather than weld metal. Further, it is conservative, since mechanical properties of parent metal are usually worst.

This process tower is made of the SA-516 grade 70, an ASME Section II Part A specification for low carbon plate steel for moderate temperatures. Table 1 shows mechanical properties for this material evaluated in two temperatures: designed and ambient temperatures:

Table 1. Mechanical properties of SA-516 grade 70, obtained from ASME Section II, Part D.

	15ºC	80ºC
Tensile strength (S_u)	483 MPa	483 MPa
Yield strength (S_y)	262 MPa	240 MPa
Elastic modulus (E)	202.700 MPa	198.500 MPa
Poisson ratio	0.3	0.3

It is also very important to accurately determine the material toughness. This parameter is related to the material capability to avoid cracks propagation. For some kind of services (cryogenic, or gas storage spheres, for example), Charpy test is a design requirement, since it is possible to correlate the Charpy energy to the toughness.

However, in most practical cases, there are no available fracture toughness data available from the Charpy test. In those situations, it is necessary to estimate it, by employing an indexing procedure based on a reference temperature, which can provide a conservative lower-bound estimate of fracture toughness for a ferritic material. This method does not apply for austenitic materials, which do not have a transition temperature in Charpy energy curve.

In the late 1960s and early 1970s, a large fracture toughness data set was collected for multiple heats of low alloy pressure vessel steels and was plotted against relative temperature. The curve K_{IC} was then drawn, which represents a lower envelope to all of the fracture toughness tests loaded at quasi-static rates. Equation (1) represents K_{IC} curve, used for determining the Lower Bound Critical Stress Intensity Factor:

$$K_{IC} = 36.5 + 3.084e^{0.036\left(T - T_{ref} + 56\right)} \tag{1}$$

In Eq. (1), K_{IC} is the Critical Stress Intensity Factor (the toughness parameter, in $MPa\sqrt{m}$), T is the assess temperature and T_{ref} is the reference temperature, both in ºC, estimated from the ASME Section VIII Division 1 UCS-66 curve, reproduced on Fig. 5, for the studied case in this report:

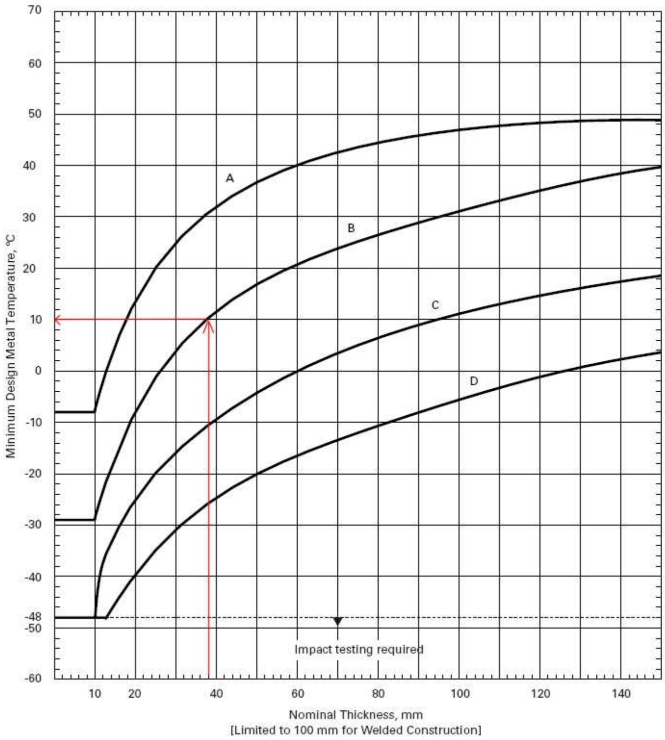

Figure 5 – Curve UCS-66. The red arrows represent the studied case, a 38 mm thickness SA-516 grade 70 plate.

Primarily, the UCS-66 curve is used for determining the need of impact testing for a combination of minimum design metal temperature and thickness which is below the curve assigned to the subject material. According to ASME, if a minimum design metal temperature and thickness combination is on or above the curve, impact testing is not required.

Each curve represents a group of materials with similar toughness behavior. The SA-516 grade 70 is characterized by Curve B. UCS-66 is also referred by API 579 to determine the reference temperature for the lower bound toughness computation.

From the Fig. 5, it can be seeing 10ºC as the reference temperature for a 38 mm SA-516 gr. 70 plate. Substituting these data in Eq. (1), the lower bound toughness obtained is $K_{IC} = 64.2 MPa\sqrt{m}$.

2.5. Stress analysis

A very important step in a fitness for service evaluation is the correct stress determination. The stresses to be considered in the assessment are those which would be calculated by a stress analysis of the unflawed structure. For several geometries, there are analytical results that can be used for stress calculations. However, close to structural discontinuities such as welds and nozzles it is more complicated to determine the correct stress distribution. In these cases, the actual stress distributions may be used or the stresses may be linearized. The latter method will normally provide overestimates but has the advantage that linearization does not need to be repeated with crack growth. It is essential that account is taken of the primary membrane and bending stresses, the secondary stresses and the magnification of the primary stresses caused by local or gross discontinuities or by misalignment.

For these reasons, the Finite Element Method (FEM) is widely used. Basically, FEM is a mathematical tool used to solve differential equation (equilibrium theory, in this case). For any physical problem, a discretized mathematical model is generated and solved, and a solution is obtained in terms of displacements. Figure 6 shows an overview of the method (Mac Donald, 2007):

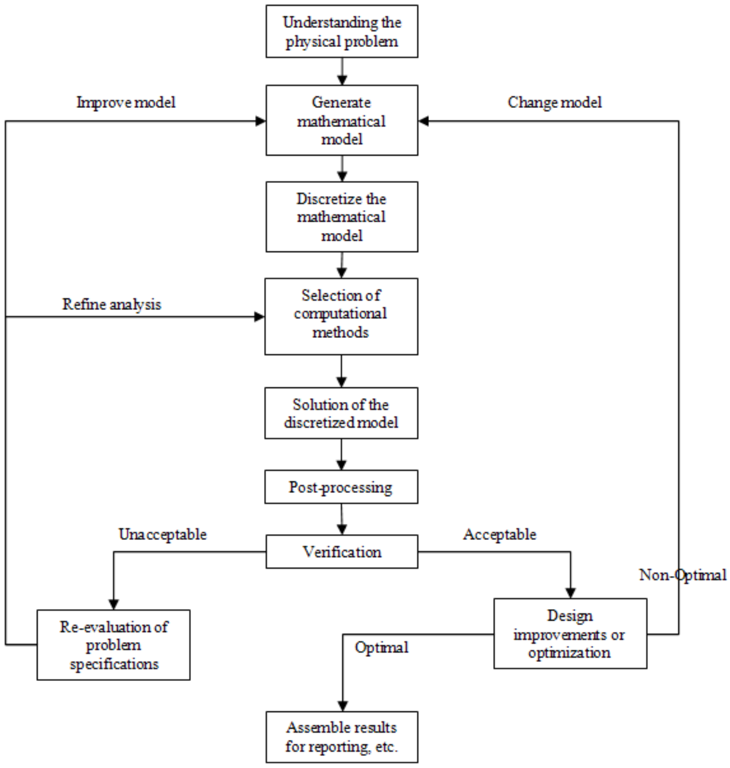

Figure 6 – Overview of consecutive stages of and FEM analysis.

The process tower studied in this work has axial symmetry. Thus, the finite element model can be simplified in order to reduce the computational costs. Figure 7 shows the finite element model: only the lower part of the tower was modeled. The design conditions (structural pressures and boundary conditions) are also represented. The main dimensions of the equipment are shown in Fig. 3:

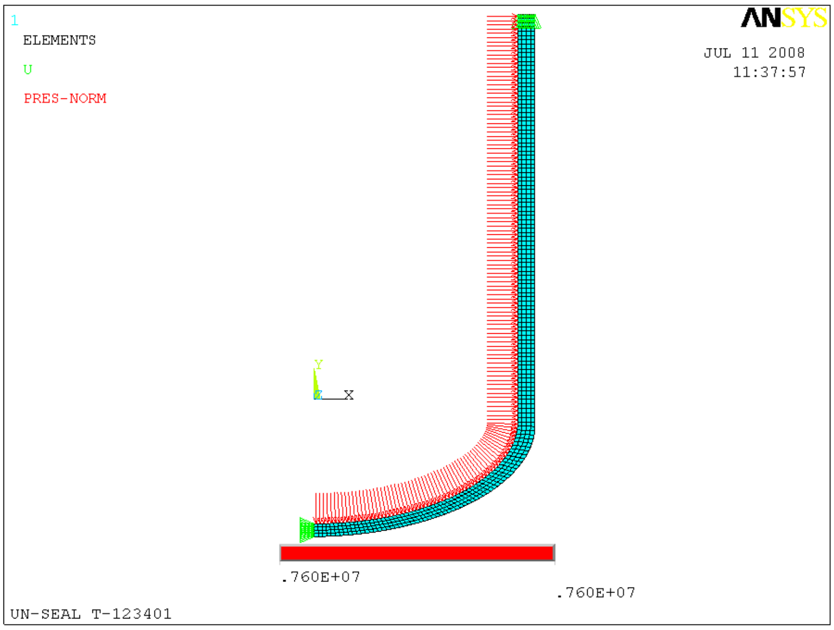

Figure 7 – Axi-symmetric FEM model of the DEA tower. Design pressure = 7.6 MPa.

A linear elastic analysis was performed in Ansys Mechanical v. 11.0, in order to obtain the stress status and define which stress is mode I crack opening (the most critical). Figure 8 shows the principal directions, the planes where only normal stresses acts.

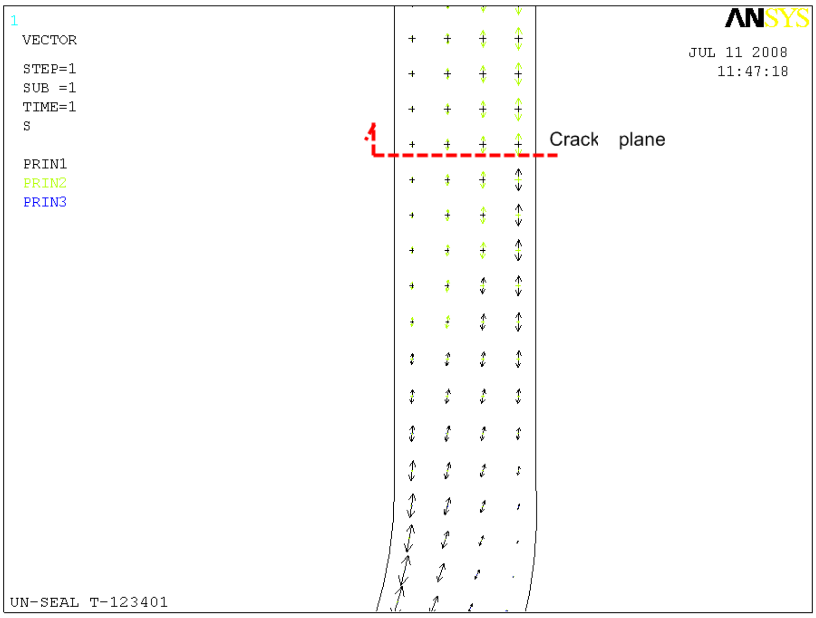

Figure 8 – Plot of the principal stresses.

From Fig. 8, it is possible to conclude that the Mode I crack opening stress is the Middle Principal stress (S2). In this case, this stress is equivalent to the normal stress in y direction (Sy). Figure 9 shows the Sy distribution along the geometry. The cracks' site is also highlighted.

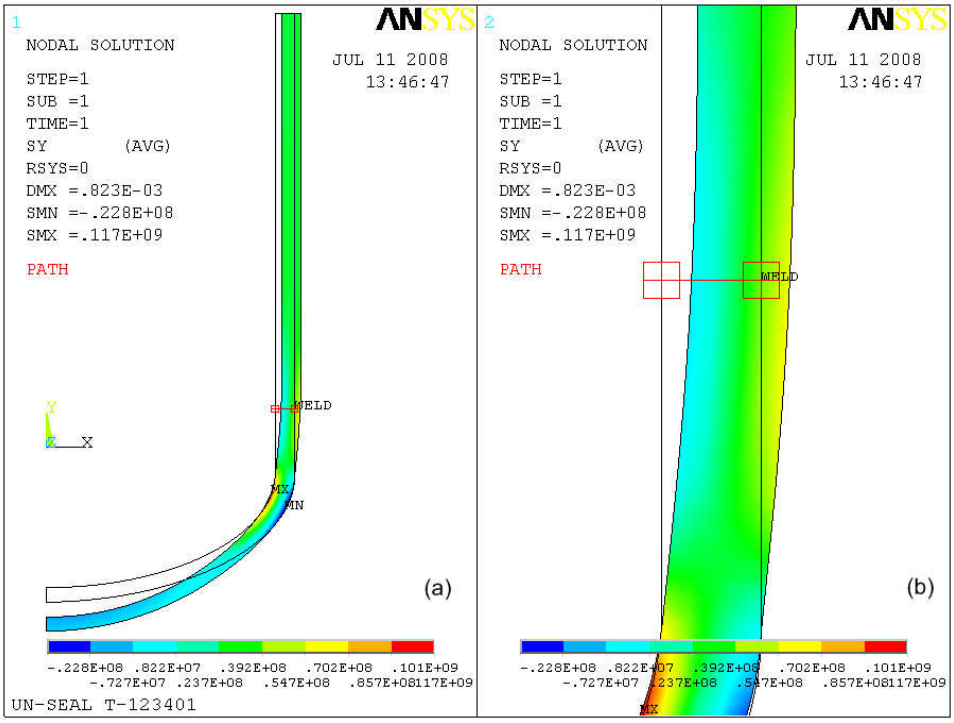

Figure 9 – (a) Longitudinal stress (Sy) distribution in the tower. (b) Detail of the stress distribution close to the cracks' site. The underformed configuration is also represented (black lines). Stresses are shown in Pa.

From the stress distribution shown in Fig. 9, a big amount of bending can be seen. BS-7910 methodology requires stress linearization. Primary membrane stresses (Pm) are calculated with Eq. (2) and primary (and secondary) bending stresses (Pb) are computed with Eq. (3). Figure 10 shows the stress linearization used for computations:

$$P_m = \frac{S_y^{inside} + S_y^{outside}}{2} \tag{2}$$

$$P_b = \frac{\left| S_y^{inside} - S_y^{outside} \right|}{2} \tag{3}$$

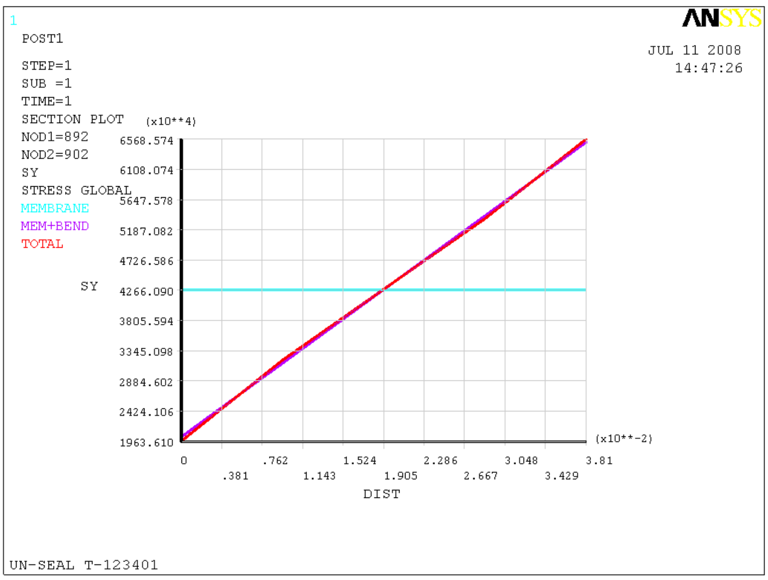

Figure 10 – Graph of linearized stresses. Pm = 42,76 MPa; Pb = 22,46 MPa.

BS-7910 also addresses secondary stress calculations. Differently from the primary stresses (those caused by the loads), secondary stresses are caused by structural geometric accommodations, thermal gradients (next to welds, for example). Despite contributing to the crack opening, secondary stresses do not lead to gross plastic collapse. Yield stress (262 MPa) is a good estimate for its value. However, when heat treated, those stresses can be relieved up to 30 %, depending on the flaw orientation with respect to the primary stresses. This is the case for DEA process towers, which work with hydrogen.

3. CRACKS ASSESSMENT

After applying the interaction criteria, there are only two embedded discontinuities to be analyzed. For safety reasons and due to the uncertainly of some measurements and material properties data, BS-7910 strongly recommends the utilization of partial safety factors. For this equipment, it was selected the safety factors corresponding to a non-redundant equipment where a severe failure could occur, this is, 1.50 for stresses, 1.85 for flaw size and 2.60 for toughness. Figure 11 shows the dimensions of both embedded re-characterized cracks:

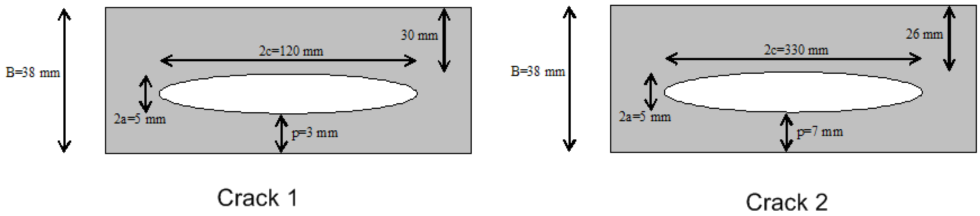

Figure 11 – Flaw sizes according to BS-7910 nomenclature.

The BS-7910 procedure is implemented in a software called Crackwise. All the collected data is informed in appropriated screens inside the software. Results of this analysis are shown in a FAD diagram, shown in Fig. 12:

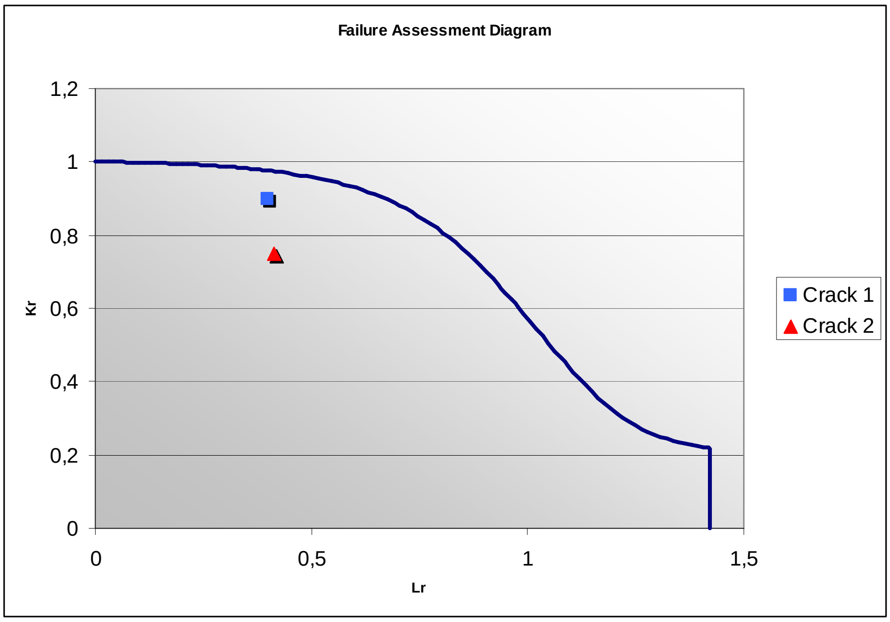

Figure 12 – Flaw sizes according to BS-7910 nomenclature. Dots below the blue line are considered safe.

Despite the fact that both cracks are considered stable, crack 1 is very close to the safe limit (the boundary of FAD diagram). Two extra simulations are then performed, in order to identify the critical size of both discontinuities. For this, the crack height (*2a*) was kept constant, varying the length (*2c*) against the ligament (*p*). Results are shown in Fig. 13:

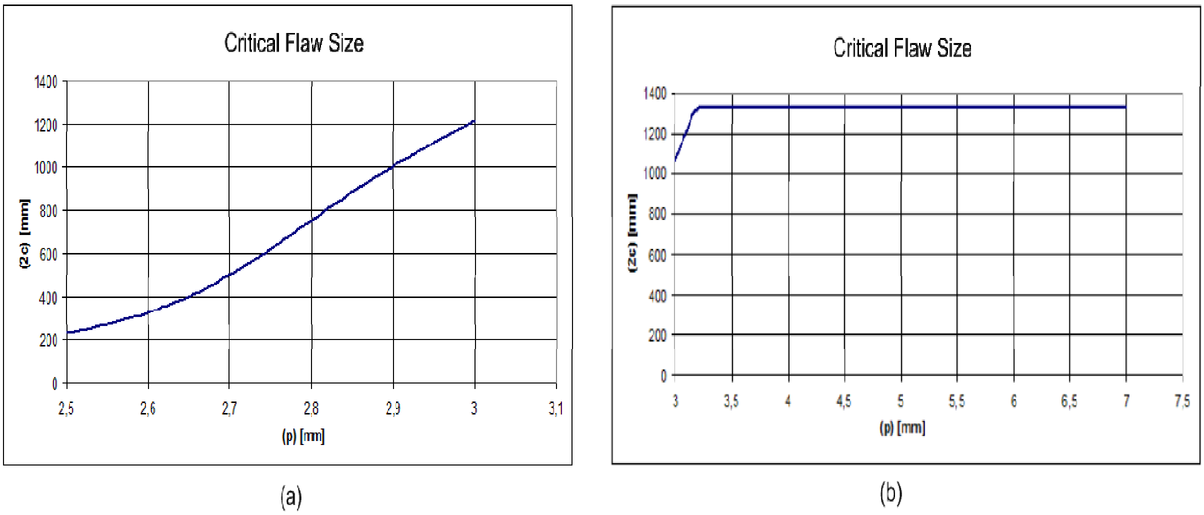

Figure 13 – Critical flaw sizes for (a) crack 1 and (b) crack 2. Height is constant, while varying length (2c) against ligament (p).

This hypothesis is valid due to the stress field in the flaw position: stresses that activate mode I crack opening are much higher than the components would tend to open in other modes (such as those which would increase the crack height).

4. CONCLUSIONS

After applying fracture mechanics to the re-characterized flaws in the DEA process tower, we conclude both are stable, and the equipment can be operated safely during its campaign. But on the other hand, this pressure vessel works highly pressurized, and DEA can be corrosive and lean to carry hydrogen, which can cause stress corrosion cracks.

Stress corrosion crack growth is still a phenomenon not well described by mathematical laws. For this reason, the hypothesis of a non environment assisted crack was utilized. This is valid only if the chemical process is well controlled and kept stable or, in other words, the DEA tower must be operated in its design conditions.

Finally, in order to support this hypothesis, it was recommended to the inspection apply a polymeric resin on the cracks location, by avoiding the direct contact of the fluid with the base metal. This procedure is commonly used in several equipments and has been showing good results.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE