MAINTENANCE ENGINEERING: CASE STUDY OF FITNESS FOR SERVICE ASSESSMENTS

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ABSTRACT
The current needs of the industrial market, such as the increasing production capacity, the conservation of the plant property, the reduction of the probability of plant shutdown, strongly lead to the discipline of Maintenance Engineering. As part of the pressure equipment, such as pressure vessels, piping, and tanks, the maintenance processes must be managed with a risk management logic. Through, Fitness For Service (FFS) method, pressure equipment presenting a structural degradation can be maintained in operation, with close monitoring. This study illustrates the application of the design code for FFS according to API RP 579 and BS 7910 in the case of a longitudinal defect (crack-like flaw) on a pipe in pressure conditions. The comparison is carried using both codes in order to assess the stability of the defect. The calculation shows that the defect is stable, if the pipe is stressed with a steady load equal to the maximum admissible load in operation. The most conservative result has been obtained from BS 7910.

Keywords: fitness for service, FFS, API RP 579, BS 7910, crack-like flaw, risk management

1 INTRODUCTION

Over the last few years different strategies have been followed, with the application of the well-known policies of corrective, preventive and predictive maintenance methods and through the implementation of high value-added products such as : RCM, FFS, MAGEC, ACM, HAZOP, FMEA, FMECA, etc.
As part of the pressure equipment, such as pressure vessels, piping, and tanks, the maintenance processes must ensure in addition to business continuity the maintenance of the degree of risk to acceptable levels through a safety policy (risk management) for the prevention of possible negative consequences in the event of a leak.
The usual methods are computational techniques aimed at assessing the equipment and the integrity of its components that show for instance: generalized corrosion, blisters and laminations, cracks, etc..

2 FITNESS FOR SERVICE

Fitness For Service checks are quantitative engineering evaluations that are carried out to demonstrate the structural integrity of a component in service, even though it is damaged, it shows defects or cracks. The guidelines in a manual of FFS procedures can be used to make decisions "follow-on/ repair / replacement”, to ensure that a component that presents damage or defects, can continue to be kept in operation for a definite period of time .
A list of key reference documents, codes and standards is as follows:

- API RP 579 Recommended Practice for Fitness-in-Service Assessment, 2000;
- API 579-1/ASME FFS-1, Fitness-for-Service, 2007;
- API 579-2/ASME FFS-2, Fitness-for-Service Example Problem Manual, 2009;
- SAQ Handbook – A Procedure for Safety Assessment of Components with Cracks, 1991;
- Exxon, Fitness-for-Service Guide, 1995;
- The Engineering Treatment Model EFAM ETM, GKSS of Greestacht, 1995;
- ASME XI Boiler and Pressure Vessel Code, Rules for In-service Inspection of Nuclear Power Plant Components, Division 1, 1995;
- Fitness-for-Service Evaluation Procedures for Operating pressure vessels, tanks and piping in refinery and chemical service (FS 26), The Materials Properties Council, 1995;
- BS 7910, Guidance on methods for assessing the acceptability of flaws in metallic structures. British Standards Institution, 2005;

- R6 Method (rev. 3), Assessment of the Integrity of Structures Containing Defects, Nuclear Electric, 1997;
- R5 Method (rev. 1), Assessment procedure for the high temperature response of structures, Nuclear Electric, 1996.

Surely with BS 7910 and API 579, FFS rules are the most comprehensive and structured.

The API 579 procedure for evaluating cracks incorporates a failure assessment diagram (FAD) methodology very similar to that in other documents, such as the British Energy R6 approach and the BS 7910 method.

Assessment techniques are included to evaluate flaws including: general and localized corrosion, widespread and localized pitting, blisters and laminations, weld misalignment and shell distortions, long term creep damage and crack-like flaws including environmental cracking.

Analytical procedures, material properties including environmental effects, NDE guidelines and documentation requirements are included in the fitness for service assessment procedures. Qualitative and quantitative guidance for establishing remaining life and in service margins for continued operation of equipment are provided in regards to future operating conditions and environmental compatibility.

The basic assumption is that the flawed body could fail by one of two extreme failure modes - fracture or plastic collapse (overload).

There are three different levels of FFS assessment:

- Level 1 FFS assessments ("Simplified assessment") provide conservative screening criteria that require the least amount of inspection and component information. Level 1 assessments usually do not require extensive calculations. Either inspectors or plant engineers will conduct a Level 1 assessment.

- Level 2 FFS assessments ("Normal Assessment") involve a more detailed evaluation of components and usually require an accurate measurement of flaws or damage. Most Level 2 FFS assessments require calculation of the required component thickness or of component stress. Either plant engineers or engineering specialists will conduct level 2 assessments.

- Level 3 FFS assessments ("Ductile Tearing Instability") require detailed evaluation of components. Component flaws or damage must be accurately determined, and calculation methods often involve numerical analysis such as the finite element method. Level 3 assessments often require the services of engineering specialists experienced in advanced stress analysis, fracture mechanics, etc.

The assessment of the stability of the defect of this study is done through the use of the Failure Assessment Diagram (FAD). On this diagram the assessment point is determined through the load ratio and toughness ratio coordinates calculated according to the chosen level of assessment.

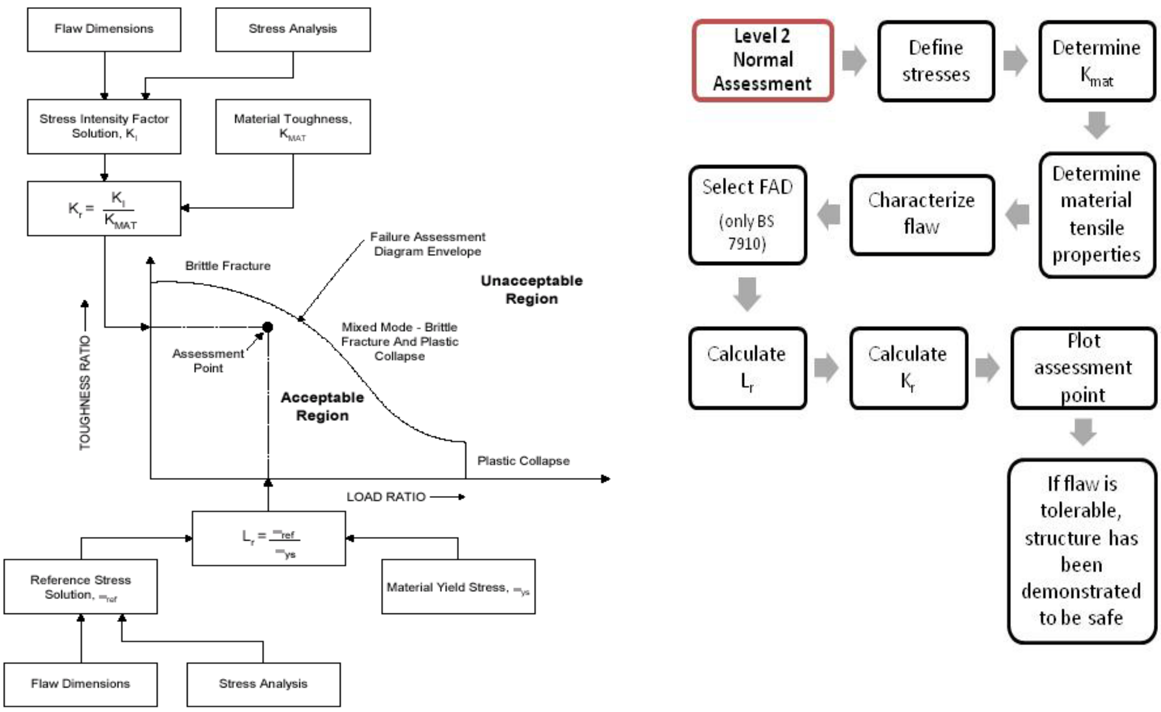


Figure 1. Overview of an FFS Analysis for crack like flaws using the Failure Assessment Diagram (FAD) – Level 2

The data required for a FFS assessment depend on the flaw type or damage mechanism being evaluated. Data requirements may include: original equipment design data, information pertaining to maintenance and operational history, expected future service, and data specific to the FFS assessment such as flaw size, state of stress in the component at the location of the flaw, and material properties.
FFS procedure is applicable to four major stages of a typical component life:

- Design of New Structures
- Fabrication Support and Quality Assurance
- Assessment of In-Service Damage
- Failure Analysis

Typical applications are:

- Periodical structural verifications of laws (e.g. stability assessment due to the decrease of thicknesses of the shell and/or head pressure vessel; Crack detected in-service on weldings stressed under fatigue conditions in lifting equipment; extended operating of furnace working in high temperature – creep).
- Upgrading of existing facilities free of periodic law checks (e.g. piping objects of fire damage).

2.1 code API RP 579

Fitness-for-service (FFS) assessment is a multi-disciplinary approach to determine, as the name suggests, whether a structural component is fit for continued service. In 2000, the American Petroleum Institute (API) published API 579, a Recommended Practice for FFS assessment. Although this document was intended primarily for refining and petrochemical assets, it has seen widespread use in a wide range of industries that utilize.
API 579 covers a wide range of flaws and damage mechanisms, including local metal loss, pitting corrosion, blisters, weld misalignment, crack-like flaws and fire damage. The API document contains an extensive compendium of K_I solutions, including a number of new cases generated specifically for API 579. In the initial release of the document, API has adopted existing reference stress solutions for the calculation of L_r in the FAD procedure. In addition to the Appendices of K_I and reference stress solutions, API 579 includes appendices that provide guidance on estimating fracture toughness and weld residual stress distributions.
The procedures in API RP 579 utilize the design and construction rules and methods in the ASME Boiler and Pressure Vessel Code, Section I and Section VIII, Divisions 1 and 2, the ASME B31.1 and B31.3 piping codes, and the API 650 and 620 storage tank standards. API RP 579 also provides guidance on adopting its procedures to equipment built to non ASME / API codes and standards.

2.2 code BS 7910

BS 7910, the UK procedure for the assessment of flaws in metallic structures, was first published almost 30 years ago in the form of a fracture/fatigue assessment procedure, PD6493. It provided the basis for analyzing fabrication flaws and the need for repair in a rational fashion, rather than relying on long-established (and essentially arbitrary) workmanship rules. The UK offshore industry in particular embraced this new approach to flaw assessment, which is now widely recognised by safety authorities and specifically referred to in certain design codes, including codes for pressure equipment. Since its first publication in 1980, PD6493/BS 7910 has been regularly maintained and expanded, taking in elements of other publications such as the UK power industry's fracture assessment procedure R6 (in particular the Failure Assessment Diagram approach), the creep assessment procedure PD6539 and the gas transmission industry's approach to assessment of locally thinned areas in pipelines. The FITNET European thematic network, run between 2002 and 2006, has further advanced the state of the art, bringing in assessment methods from SINTAP (an earlier European research project), R6, R5 and elsewhere. In particular, the FITNET fracture assessment methods represent considerable advances over the current BS 7910 methods; for example, weld strength mismatch can be explicitly analysed by using FITNET Option 2, and crack tip constraint through Option 5. Corrosion assessment methods in FITNET are also more versatile than those of BS 7910, and now include methods for vessels and elbows as well as for pipelines. In view of these recent advances, the BS 7910 committee has decided to incorporate many elements of the FITNET procedure into the next edition of BS 7910.
Provides methods for: fracture assessment procedures, fatigue assessment procedures and assessment of flaws operating at high temperatures.
Sequence of operation, according to BS 7910:

- Identify the flaw type;
- Establish the essential data;
- Determine the size of the flaw;
- Assess possible material damage mechanisms and damage rate;
- Determine limiting size of the flaw;
- Based on the damage rate, assess whether the flaw will grow to this final size within the remaining life of the structure or in-service inspection interval, by sub-critical flaw growth assess the consequence of failure;
- Carry out sensitivity analysis;
- If the flaw could not grow to the limiting size, including appropriate factor of safety, it is acceptable. Ideally, the safety factors should take account of both the confidence in the assessment and the consequence of failure.

In addition, BS 7910 can provide, if the stress-strain plot of the material used is known, a FAD graph expressly established for that material giving a more accurate assessment.

2.3 Synthesis

API RP 579

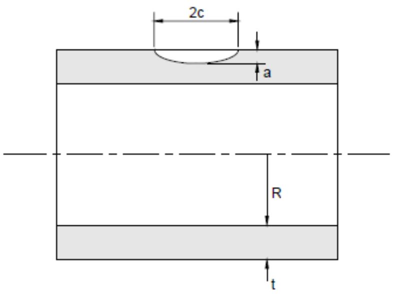
- is supported by a number of organizations based in the USA where most experience resides.
- is designed at level 1 for use by plant inspectors and plant engineering personnel with the minimum amount of information from inspection and about the component.
- covers a wide range of damage types typically found in refining and petrochemicals application, and gives procedures for different types of metal loss, physical damage, low and high temperatures, and crack like defects.
- is intended for equipment designed using the ASME code and materials and gives results consistent with the original ASME design safety margins.
- may be used for equipment designed to other codes but users should be prepared to interpret the procedures in an appropriate manner.

BS 7910

- was developed in the UK where TWI is the main source of expertise, training and software.
- is applicable to all metallic structures and materials and is written in a more generalized manner without reference to a particular industry, design code or material thereby allowing users to decide safety margins.
- requires some technical expertise in fracture mechanics and access to fracture parameter solutions and toughness data at all levels.
- deals comprehensively with fatigue and fracture of defects in and around welded joints and gives annexes covering advanced aspects such as mismatch, mixed mode loading, residual stress effects and leak before break.

3. CASE STUDY

The case study has been carried out for as defect classified as a longitudinal crack on a pressurized pipe.



a = 2 mm
2c = 8 mm
2R = 1125 mm
t = 13 mm
material: ferritic steel
$\sigma_{Y.S.} = 211\ N/mm^2$
$\sigma_{U.S.} = 346\ N/mm^2$

Figure 2. Pipe geometry and its mechanical properties

The possible stresses are due to :

a) internal pressure
b) pipe self weight
c) point load (saddle)

d) overpressure due to water hammer
e) thermal expansion (negligible value)
Bending due to pipe's weight does not influence crack opening and for this reason it will not be taken into account. The stress of 129 MPa used in the calculation is determined by the sum of single stresses taken at their highest admissible value.

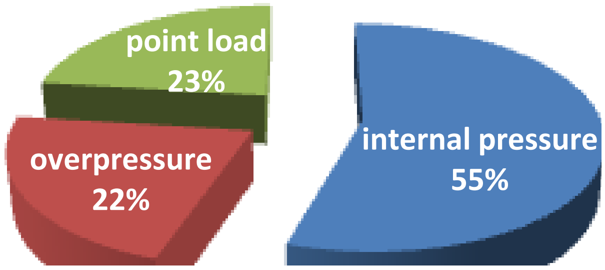


Figure 3. Percentual interaction of each typology stresses

In the case of stresses due to internal pressure and overpressure, considering the theory of thin cylinders, stresses will be constant within the thickness.
The stress caused by the presence of saddles instead leads to a localized bending in the point of contact between saddle and pipe. In this study, it is possible to consider this stress constant across the thickness, this consideration leads to a conservative and acceptable approach considering the tiny thickness of the pipe.
Discussed below are the results of applying the codes API RP 579 and BS 7910.

3.1 Approach using API RP 579

Using a Level 2 assessment we proceed with the calculation in accordance with paragraph 9.4.3 of Section 9 (assessment of crack-like flaws).
For the determination of the coordinates of the assessment point, it is necessary to calculate the Load Ratio (L_r) and Toughness Ratio (K_r).
The standard requires characteristic input data of the problem in order to assess the reference stress needed for the calculation of L_r. This effort is taken from the code and it is defined as follows:
This effort it is defined as follows in the code:

$$\sigma_{ref}^{P} = \frac{gP_b + [(gP_b)^2 + 9(M_S P_m)^2]^{0,5}}{3} \tag{1}$$

where P_m and P_b are the Primary membrane stress and Primary bending stress, and M_s and g are dimensionless coefficients affected by crack size.
Using the reference stress, it is possible to determine the dimensionless coefficient L_r abscissa of the FAD graph. L_r is defined as:
L_r is defined as:

$$L_r = \frac{\sigma_{ref}^{P}}{\sigma_{ys}} = \frac{195\,MPa}{211\,MPa} = 0,927 \tag{2}$$

For the determination of K_r,two values of K_I^P are calculated to take into account the possible instability of the defect in the longitudinal and radial directions.

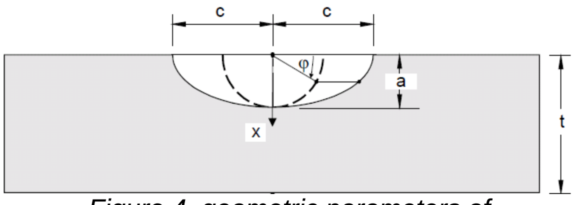


Figure 4. geometric parameters of semi-elliptical flaws

$$K_I^P(\varphi = 0) = 15,46\,MPa\sqrt{m}$$
$$K_I^P\left(\varphi = \frac{\pi}{2}\right) = 18,75\,MPa\sqrt{m} \tag{3}$$

From which it is possible to determine K_r

$$K_r = \frac{K_I^P}{K_{mat}} \tag{4}$$

Taking into account the different values of K_I^P we obtain the following results:

$$K_r = \frac{K_I^P(\varphi = 0)}{K_{mat}} = \frac{15{,}46\ MPa\sqrt{m}}{36{,}5\ MPa\sqrt{m}} = 0{,}4235$$

$$K_r = \frac{K_I^P\left(\varphi = \frac{\pi}{2}\right)}{K_{mat}} = \frac{18{,}75\ MPa\sqrt{m}}{36{,}5\ MPa\sqrt{m}} = 0{,}5137 \tag{5}$$

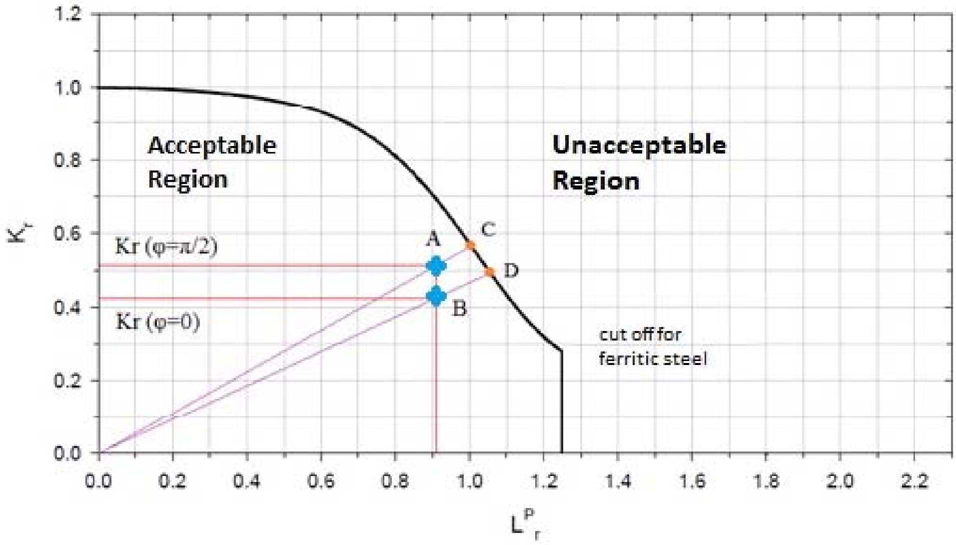


Figure 5. Assessment points using API RP 579 code

Now is it possible to Assess a safety factor η_{API} relative to the position of the assessment point respect the limit curve of acceptability. The following ratings are obtained:

$$\eta_{API}\left(\varphi = \frac{\pi}{2}\right) = \frac{\overline{OC}}{\overline{OA}} = 1{,}09$$

$$\eta_{API}(\varphi = 0) = \frac{\overline{OD}}{\overline{OB}} = 1{,}14 \tag{6}$$

Through an assessment of Level 2, the rule concludes that, because the point at the intersection of the value of the abscissa and ordinate of the FAD graph lies below the line of admissible defect, the crack in the pipe can be considered stable for an analysis with invariant loads. The results also reflect what was expected :a worst condition for the inner cavity of the crack. It reflects the direction in which the defect will mainly develop in the presence of time varying loads, and this view is also confirmed by a lower factor of safety obtained.

3.2 Approach using BS 7910

BS 7910 allows the application of a Level 2 assessment, which assumes the same conditions of use of the API 579. For that level of esteem, the same rule provides a block diagram showing the steps to follow for a proper analysis.

This method, considering the sensitive input data, gives the two coordinates on the FAD graph: K_r and L_r.

After the definition of crack size, BS 7910 allows to choose, for a given assessment of level 2, between two FAD graphs. The first is characterized by a trend of the stability curve already defined in API 579, while the second takes into account the characteristic stress-strain curve of the test material.

The analysis leads to evaluate L_r coefficient which is defined as follows:

$$L_r = \frac{\sigma_{ref}}{\sigma_{ys}} \tag{7}$$

Where σ_{ref}, as in the previous case, is obtained through an evaluation of the efforts related to geometry of the component. A wide range of cases of geometry and crack locations are presented in

Annex P. Several analytical methods for the determination of this stress are presented. The case study shown in the figure 6 below uses the standard nomenclature defined in the code.

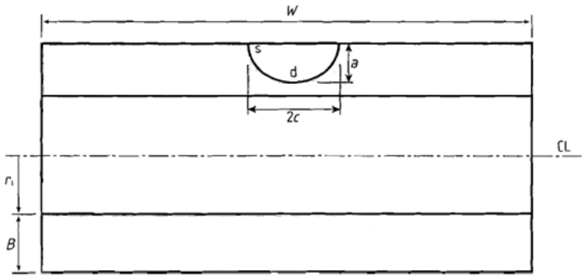


Figure 6. Section of the pipe with semi-elliptical crack-like flaw and its parameters for BS 7910

Unlike the previous code, σ_{ref} is defined as follows:

$$\sigma_{ref} = 1{,}2 M_S P_m + \frac{2P_b}{3(1-\alpha)^2}, \quad (8)$$

Where P_m and P_b are the Primary membrane stress and Primary bending stress, M_s and α are dimensionless coefficients influenced by the size of the crack.

The value of load ratio obtained from this assessment is:

$$L_r = \frac{\sigma_{ref}}{\sigma_{ys}} = \frac{195{,}1\,MPa}{211\,MPa} = 0{,}9247 \quad (9)$$

The next step requires the evaluation of Toughness Ratio (K_r). As in the previous case, it takes the form $K_r = \frac{K_I}{K_{mat}}$, where K_I is the stress intensity factor, while the K_{mat} identifies the toughness of the component. BS 7910 defines:

$$K_I = (Y\sigma)\sqrt{\pi a} \quad (10)$$

Where (Yσ) is calculated by means of factors presented in tables for different cases and sizes of the defect. In this case it is necessary to evaluate the intensity factor for the deepest point (d) in the flaw and where the flaw intersects the free surface (s).

Two Toughness Ratios results :

$$K_r\,(d) = \frac{K_I(d)}{K_{mat}} = 0{,}41$$

$$(11)$$

$$K_r\,(s) = \frac{K_I(s)}{K_{mat}} = 0{,}30$$

Now it is possible to determine the assessment point on the FAD graph.

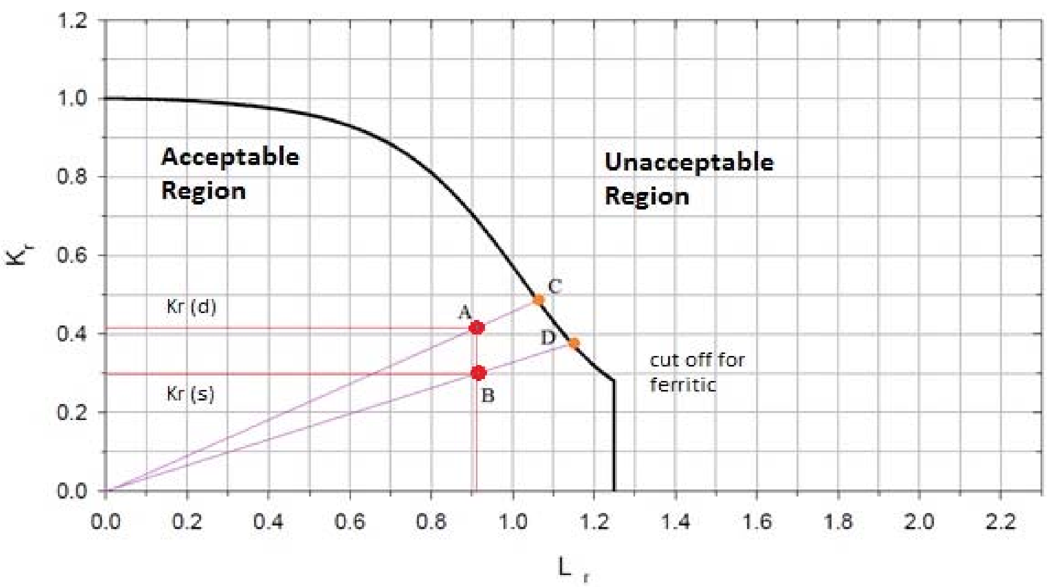


Figure 7. Assessment points using BS 7910 code

Once the equation of the limit curve that delimits the zone of acceptability of the crack, is known, the safety factor of the limit condition has to be determined.
The coefficients are defined as follows:

$$\eta_{API}(d) = \frac{\overline{OC}}{\overline{OA}} = 1{,}16$$

$$\eta_{API}(s) = \frac{\overline{OD}}{\overline{OB}} = 1{,}25 \quad (12)$$

Through an assessment of Level 2, the defect present in the pressurized pipe is safe under static loads. The values obtained reflect a greater instability of the inner cavity of the defect than that assessed in the corner. This consideration is also confirmed by the values of safety factors, although they are very modest.

4. CONCLUDING REMARKS

In conclusion, as the evolution from design methods based on analysis ("design by analysis") to methods based on rules ("design by rule"), as similarly, the maintenance process today is based on an approach "Engineering Critical Assessment".
The risk management approach allows a careful and continuous monitoring of the main factors that influence the maintenance and are intended to reduce levels of risk.
The application of standards API 579 and BS 7910 has produced results in agreement that highlight in particular the stability of the defect. Since the equation of the curve of the FAD graph is the same for the two codes, it is possible to plot the results on the same graph in Figure 8.

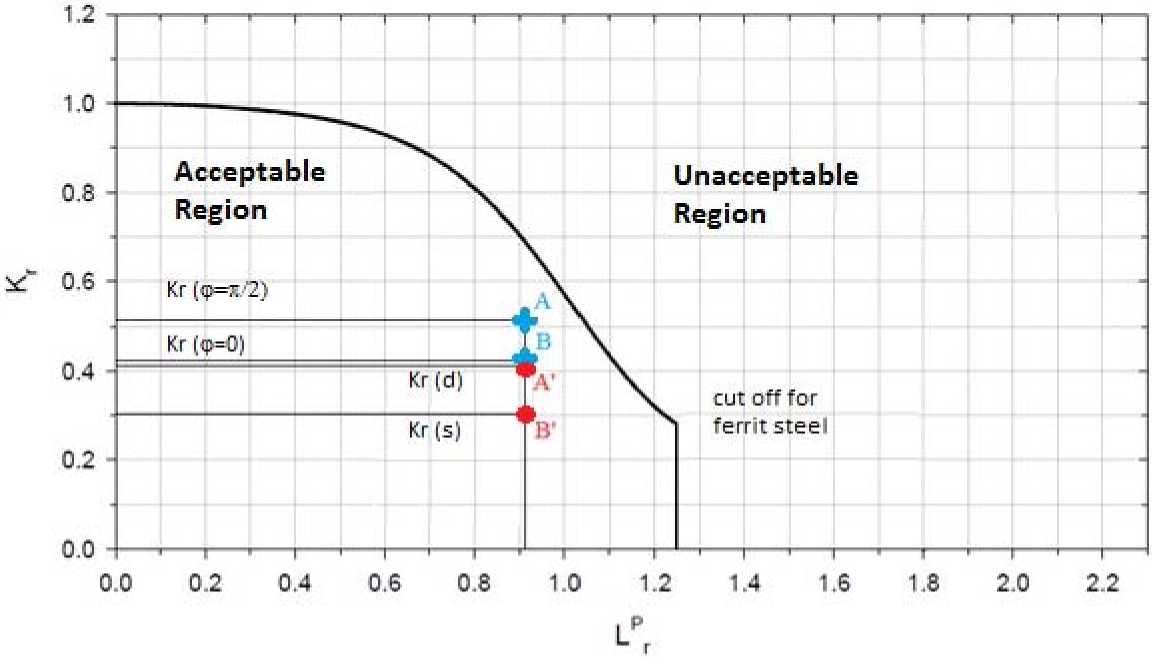


Figure 8. Comparison between API RP 579 (blu cross) e BS 7910 (red circle)

In blue are the values resulting from the application of API RP 579, in red those from BS 7910. As it is possible to see, there is a certain similarity between the two evaluations, in particular the L_r coefficient is the same for both standards. This equality is justified by an equivalent assessment of the reference stresses for both standards.
API 579 produces K_r (estimated as $K_r = \frac{K_I}{K_{mat}}$) values slightly higher than those estimated by the standard BS 7910. This result is influenced by the different methodology used to calculate the intensity factor of efforts in the two standards. The two evaluations, however, lead to an estimate almost identical of the difference between K_r evaluated in an internal cavity and one for the edge with the outer surface.

A further reason of the difference between the two results is due to a different safety factor PSF, defined by the individual rules applied to the size of the defect.
It is noted that differences in the target failure probabilities adopted in the PSF derivations mean that comparison can only strictly be made for the target failure probability of 10^{-3} which is used in both BS 7910 and API 579.
For the cases compared, PSFs of API 579 applied on stresses are bigger than the corresponding values recommended in BS 7910. However, the reverse trend is seen in terms of both fracture toughness and flaw size. In addition, the BS 7910 PSFs on fracture toughness are very much higher than the corresponding values in API 579 especially for low uncertainty level in applied stress. The net position is likely to be that assessments conducted to the BS 7910 would be much more conservative than those to API 579.
Results obtained confirm those presented in literature [9].
There are no significant differences between the two standards for their application to this case, however, BS 7910 has a wider range of applications than the one of API 579.
In particular, certain procedures developed in Europe (BS 7910, SINTAP, R6, ETM) are in many aspects (mismatch, constraint, probabilistic aspects) even more advanced than the U.S. product. However, the American standard API 579 is perhaps the code that better analyze the best combination of damage mechanisms. API 579 not only contains all the appropriate computational tools to support at the described analysis in appendices (formulas for the calculation of the efforts residual stress intensity factors, shown by the NDT crack etc..), but also it is the only procedure which offers many reference curves for the properties of materials used in the FFS analysis.

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