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ASSESSMENT OF CRACK-LIKE FLAWS IN PRESSURE VESSELS BASED ON API-579

by
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Abstract

This diploma thesis studies the behavior of crack-like flaws in pressure vessels. Firstly, crack-like flaws on pressure vessels may lead fracture without a warning ,releasing vast amounts of mechanical energy. So, the detection and the examination of the cracks are essential. There are many standardized procedures for assessing crack-like flaws, such as the API-579 Part 9 which specializes in cracks on pressure vessels. Linear elastic fracture mechanics sometimes are not applicable on pressure vessels due to extended plasticity. The API-579, however, uses the Failure Assessment Diagram (FAD) Approach which takes into account the plasticity and includes both brittle fracture and plastic collapse failure. Furthermore, it provides three levels of assessment that differ in difficulty and are applied depending on the circumstances. If the crack-like flaw is acceptable by the standard, then the pressure vessel can continue operating. If the flaw is not acceptable then the production line should stop in order to repair or to replace the vessel. So, the standard should carefully be applied as it is a matter of safety and has a substantial economic impact.

Key words: crack-like flaws, pressure vessel, standard procedure, API-579, fracture mechanics, linear elastic fracture mechanics, plasticity, safety, economic impact

ΑΞΙΟΛΟΓΗΣΗ ΡΩΓΜΩΝ ΣΕ ΔΟΧΕΙΑ ΠΙΕΣΗΣ ΜΕ ΒΑΣΗ ΤΟΝ ΚΩΔΙΚΑ API-579

ΜΙΧΑΗΛ ΑΛΤΑΝΗΣ

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Περίληψη

Η διπλωματική αυτή πραγματεύεται την συμπεριφορά ρωγμών σε δοχεία πιέσεως. Αρχικά, οι ρωγμές στα δοχεία πίεσης μπορούν να οδηγήσουν σε ολική θραύση χωρίς προειδοποίηση, απελευθερώνοντας μεγάλα ποσά μηχανικής ενέργειας. Επομένως ,είναι σημαντικό να εντοπίζονται και να αξιολογούνται με βάση κάποιον κώδικα. Υπάρχουν πολλοί κώδικες που χρησιμοποιούνται για την αξιολόγηση ρωγμών ,συγκεκριμένα όμως ο API 579 Part 9 εξειδικεύεται σε ρωγμές σε δοχεία πιέσεως. Η γραμμική θεωρία μηχανικής των θραύσεων δεν μπορεί να εφαρμοστεί σε πολλές περιπτώσεις λόγω εκτεταμένης πλαστικότητας. Το API-579 χρησιμοποιεί την μέθοδο FAD (Failure Assessment Diagram) η οποία ισχύει και για εκτεταμένη πλαστική περιοχή και συμπεριλαμβάνει δυο κριτήρια αστοχίας, της ψαθυρής θραύσης και της πλαστικής διαρροής. Επίσης, παρέχει τρία επίπεδα αξιολόγησης ,διαφορετικής δυσκολίας ,που εφαρμόζονται ανάλογα με την κάθε περίπτωση. Αν τελικά η ρωγμή είναι αποδεκτή τότε το δοχείο μπορεί να συνεχίσει να λειτουργεί κανονικά. Άμα η ρωγμή δεν είναι αποδεκτή τότε ίσως χρειάζεται να σταματήσει η γραμμή παραγωγής ώστε να εκτελεσθούν οι απαραίτητες ενέργειες αποκατάστασης ή επισκευής. Επομένως ,ο κώδικας θα πρέπει να εκτελεσθεί με προσοχή, καθώς είναι ζήτημα ασφάλειας και έχει μεγάλο οικονομικό αντίκτυπο.

Λέξεις-κλειδιά: ρωγμές, δοχεία πίεσης ,κώδικας, μηχανική θραύσεων,API-579,γραμμική ελαστική θεωρία των θραύσεων ,πλαστικότητα, ασφάλεια εργαζομένων, οικονομικό αντίκτυπο.

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Chapter 1: Introduction

Inspection plans have a crucial role in modern industry. Firstly, industrial components such as pipes, tanks and pressure vessels are exposed to service for long periods. During time some unfavourable flaws may appear. Structural flaws usually reduce the lifespan of the component and may cause unexpected failure with devastating consequences. For this reason, it is essential the industrial components to be examined regularly.

Usually, non-destructive examinations (NDE) are used due to their efficiency, accuracy and low-cost operation. The most popular examination methods are the Dye Penetrant (PT), magnetic particle (MT), ultrasonic (UT) and the Time-Of-Flight-Diffraction (TOFD) examination method. Dye Penetrant method uses a liquid that it is drawn into surface defects and makes the flaw visible. Secondly, the magnetic particle examination method uses small magnetic particles that are placed on the surface and magnetized by an electromagnet. If the magnetic field is disrupted, that means that there is a discontinuity near the surface. This method is only applicable only to ferromagnetic materials. Finally, Ultrasonic and Time-Of-Flight-Diffraction uses high-frequence acoustic waves to detect the flaw.

During inspections programmes, multiple categories of flaws may be detected. Every flaw is related to a certain damage mechanism such as metal loss from corrosion or erosion, plastic deformation, metallurgical changes and the existence of cracks. This study focuses on cracks, which may lead to fracture without any warning.

Multiple NDE methods are used to locate the crack and to measure its length, depth and the angle. For example, surface cracks are located usually with Magnetic Particle or dye Penetrant. On the other hand, Ultrasonic method is useful for both surface and embedded cracks, so some of the examination methods are not always applicable. Advises for the measurement and the characterization of the crack can be found on standardized codes for assessing crack-like flaws.

API-579 is fitness-for-service standard that provides guidance for assessing structural flaws on pressure vessels for chemical and power generation industries [1]. It was created by the American Petroleum Industry and the American Society of Mechanical Engineers, and the 9th part is about the assessment of crack-like flaws. API-579 uses the Failure Assessment Diagram (FAD) procedure that is applicable both to small- and large-scale plasticity. It includes two different failure mechanisms, the brittle fracture and plastic collapse. Eventually, the assessment procedure leads to a fitness-for-service decision, to continue operation, to repair, or to reject the component. Most times, the component is still operating when the crack-like flaw is detected by NDE methods and stopping the production line would be very expensive. The other solution is to do an assessment that will reveal if the component is still capable of working properly.

Thesis Organization

This thesis is organized in such an approach that it helps the reader to understand the assessment of crack-like flaws. The following chapter discusses the beginning of the fracture mechanics and analyzes the basics principles that will be used in the assessment, such as the stress intensity factor, the J-integral and the fracture toughness.

The third chapter is a summary of the assessment of crack-like flaws based on the API-579. More specifically, it analyzes the three different levels of assessment and explains the main steps. This chapter also discussed the limiting conditions that must be satisfied for each level of assessment.

The fourth chapter presents an example of an assessment of a crack-like flaw. The crack-like flaw is located on a pipe near to a weldment, so the effect of the residual stresses should be considered. Eventually, the flaw is acceptable to level 2, so the pipe can continue to work properly. Furthermore, the assessment procedure is repeated for larger flaw in order to define a critical size of the flaw that leads to brittle fracture. Other case studies can be found on the FFS-2 [2] which provides multiple solved problems for the better understanding of the standard.

Chapter 2: Literature review

2.1 The beginning of Fracture Mechanics

The beginning of the fracture mechanics is considered to be after the Second World War. Then, scientists tried to understand why the naval ships that were constructed during the war, especially the Liberty Ships, suffered from cracks, causing many accidents. More specifically , 2708 Liberty ships were constructed by the US navy ,1289 damages were reported (mostly cracks) and 233 were sunk or complete failed [3].

There are many reasons why the Liberties ships had so many damages related to brittle fracture. Firstly, the liberty ships had to be constructed very fast to replace the ships that were destroyed by the Germans. This was accomplished by using a welded hull instead of riveted for the first time. The disadvantage of this technic is that the welded hull behaves as a single metal and a growing crack could cut the entire ship into two pieces. To avoid that, the steel of the liberty ship should have high enough resistance to brittle fracture, but it did not. The steel of the hull was not selected carefully, leading to many accidents. However, the Liberty ships helped win the war successfully, even though the accidents that they had caused.

The figure 2.2 shows a liberty ship that failed the day after it was launched [4] , while the figure shows one of the few liberties ships left ,now it is operating as a museum at the Piraeus port of Athens [5].

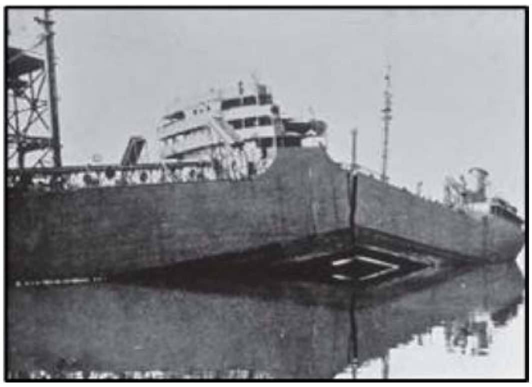


Figure 2.1 Figure Brittle Fracture of a Liberty Ship after the day it was launched

Figure 2.2 This picture shows the Hellas Liberty ship, it is operating as a museum

2.2 The Charpy's Test

Scientists, trying to explain fracture of the liberty ships, categorized the materials into brittle and ductile. Materials that absorb large amount of energy and have plastic deformation during fracture are called ductile. On the other hand, materials that absorb less energy and do not have large plastic deformation during fracture are called brittle.

An easy and low-cost test that measures the amount of energy absorbed by a material during fracture is the Charpy V-notch test (figure 2.1.1). This energy is measured by the difference in the pendulum height before and after the impact.

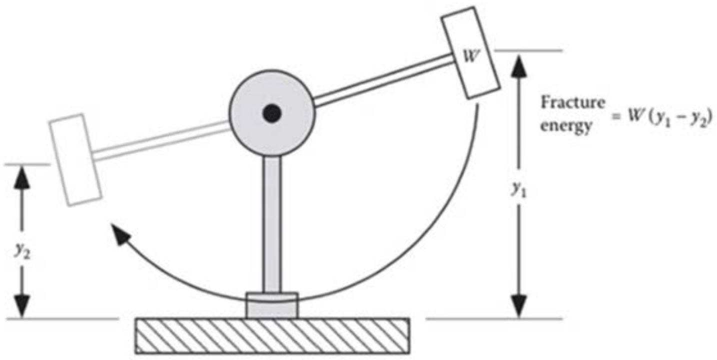


Figure 2.3 A heavy pendulum is released from a height, striking the specimen [6]

Furthermore, the amount of the absorbed energy differs with the material, the temperature and the size of the specimen. The following diagram represents the relationship between absorbed energy and temperature, which is known as V-Notch Transition Curve.

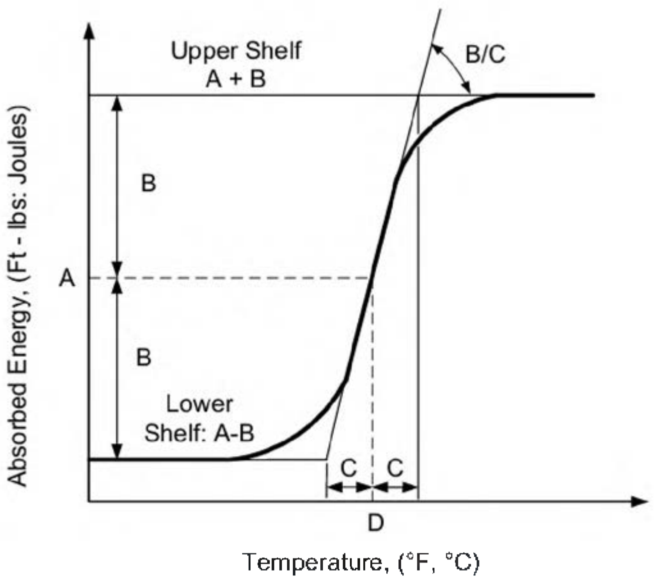


Figure 2.4 Typical data from Charpy Test for carbon and low-alloy steels,API-579

A typical curve-fit to CVN data is

$$C_v = A + B \times \tanh[\frac{(T-D)}{C}]$$

Where,

$$A = \frac{C_{V-US} + C_{V-LS}}{2}$$

$$B = \frac{C_{V-US} - C_{V-LS}}{2}$$

- C_V is the Charpy's V Notched Value
- C_{V-US} is the upper shelf value of V Notched Energy
- C_{V-LS} is the lower shelf value of V Notched Energy
- T is the temperature
- D, C parameters from Charpy's Test

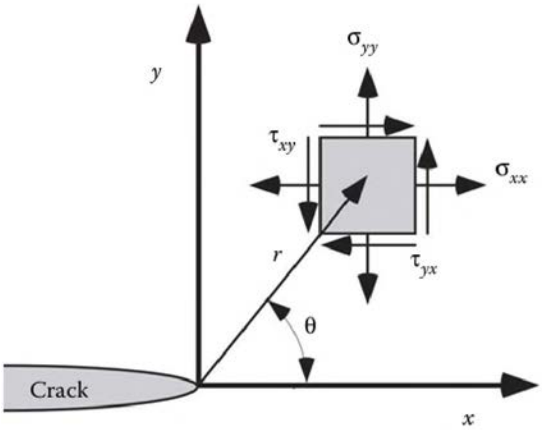
In low temperatures, the material has more brittle behavior and loses the ability to resist crack growth. This explains why the most accidents with the Liberties ships happened in the winter. The pressure vessels also should not operate at a very low temperature. More specifically, during the start-up process, pressure vessels should not be fully pressurized until the temperature of the vessel is high enough.

2.3 Basic parameters for assessment of crack-like flaws.

Fracture mechanics is the field of mechanics that studies the crack's behavior. Some useful parameters that describe this phenomenon are the stress intensity factor, the J integral, the material toughness and the load ratio.

a) Stress intensity factor

The stress intensity factor (K_I) describes the magnitude of the stress on a linear elastic material near the crack tip. It differs with the geometry of the flaw, the geometry of the component and the loading condition. The ffs provides a variety of intensity factors, usually for plates, cylinders, and spheres, however the are many handbooks that can be used for more specific occasions.



$$\sigma_{xx} = \frac{K_I}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\left[1-\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right]$$
$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\left[1+\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right]$$
$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{3\theta}{2}\right)$$

Figure 2.5 Stresses near the tip of a crack in an elastic material [6]

b) J-integral

J-integral is an integral expression that is named after its inventor James Rice. It equals the energy release rate for a cracked linear or no-linear elastic solid. The J-integral can be calculated with the finite element method with the following equation.

$$J = \int_S \left\{\left(U - \sigma_{11}\frac{\partial u_1}{\partial x_1} - \sigma_{21}\frac{\partial u_2}{\partial x_1}\right)dx_2 + \left(\sigma_{12}\frac{\partial u_1}{\partial x_1} + \sigma_{22}\frac{\partial u_2}{\partial x_1}\right)dx_1\right\}$$

- S is the boundary that contains the crack tip
- U is the strain energy density
- u is the displacement
- σ is the stress

The main advantage of J-integral is that it is path independent, so it would be reasonable to choose a path not very close to the crack where stress and displacement gradients are high (figure 2.5)[7].

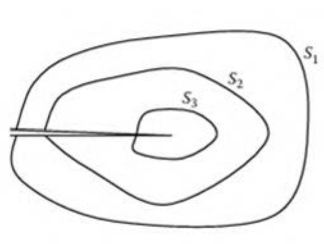


Figure 2.6 Three different contours for J-integral should give the same J-integral value [7]

The API-579 uses an equivalent stress intensity factor that derives from J-integral.

$$K_J = \sqrt{\frac{J \times E}{1-\nu^2}}$$

- K_J equivalent stress intensity factor derived from J integral
- J is the J-integral
- v is the Poisson's ratio
- E is the Young's modulus at the assessment temperature

c) Fracture Toughness

Another critical parameter is the fracture toughness, which describes the resistance of the material to crack initiation and propagation. The parameter that corresponds to fracture toughness for linear elastic materials is the critical stress intensity factor K_{IC} . An indication for the K_{IC} is predicted from the Charpy 's test.

An equivalent K_{IC}, denoted as K_{JC}, can be computed from the following equation.

$$K_{JC} = \sqrt{\frac{J \times E}{1-\nu^2}}$$

- K_{JC} is the fracture toughness established by converting J_{crit} to an equivalent K
- J_{crit} is the critical J-integral value
- v is the Poisson's ratio
- E is the Young's modulus at the assessment temperature

It is not always easy to find the fracture toughness of the material. Some metallurgical changes that happen due to the environmental condition may affect the fracture toughness of the metal. It is of paramount importance to detect any metallurgical changes such as aging, degradation or hydrogen embrittlement.

2.4 Categorization of flaws

The inspectors use NDE methods to measure the length, depth and the angle of the crack. The API-579 provides recommendations on which NDE method should be used and how to idealize the geometry of surface or embedded flaws. For example, if an embedded flaw is very close to the surface, it should be re-categorized as a surface flaw. This re-categorization may lead to more accurate results.

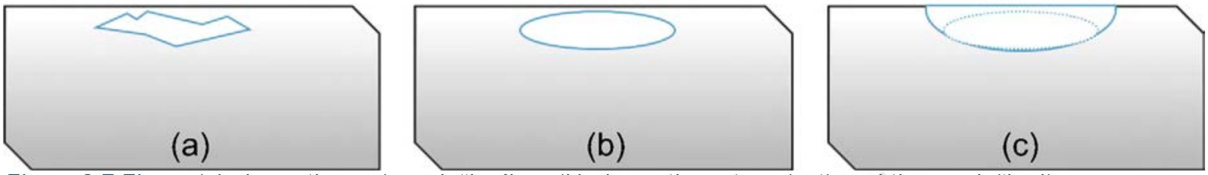


Figure 2.7 Figure (a) shows the real crack-like flaw, (b) shows the categorization of the crack-like flaw as elliptical embedded flaw, (c) when the embedded flaw is too close to surface, it must be re-categorized as elliptical surface crack-like flaw

Another technic is using equivalent size of flaw, for example when the crack is not oriented perpendicular to the plane of the maximum principal tensile stress (figure 2.2.2).The following equation derives from energy release rate consideration.

$$\frac{c}{c_m} = \cos^2\alpha + \frac{(1-B)\sin\alpha\cos\alpha}{2} + B^2\sin^2\alpha$$

- "c_m" the measured half-length
- "c" the equivalent half-length of the cracked
- "a" the angle
- "B" the biaxiality ratio defined as $B=\sigma_1/\sigma_2$

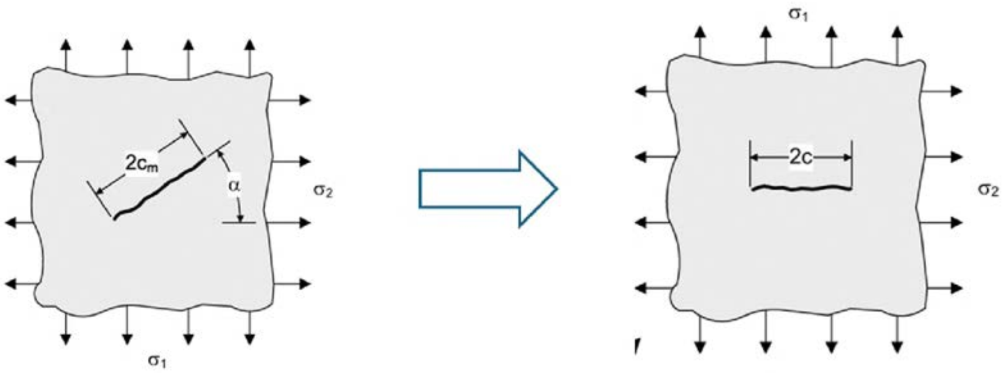


Figure 2.8 The initial flaw at the left side and the equivalent flaw at the right side

2.4 Primary and Secondary stresses

The stress analysis method is based on the ASME code VIII-2 which provides rules for the construction of pressure vessels. Firstly, stresses are divided into two categories primaries and secondaries. Primaries are load-controlled stresses, while secondary are displacement-controlled stresses. An example of primary stress is the hoop stress due to internal pressure in a pipe. On the other hand, thermal stresses are considered secondary and not primary due to the reason that thermal expansion leads to displacements. Another one example of secondaries stresses is the residual stresses at a welded joint. Pressure vessels, pipes and storage tanks are constructed with many weldments. During welding progress, high gradient of temperature leads to displacement and thermal stresses. These stresses have a crucial role as they can contribute to fracture.

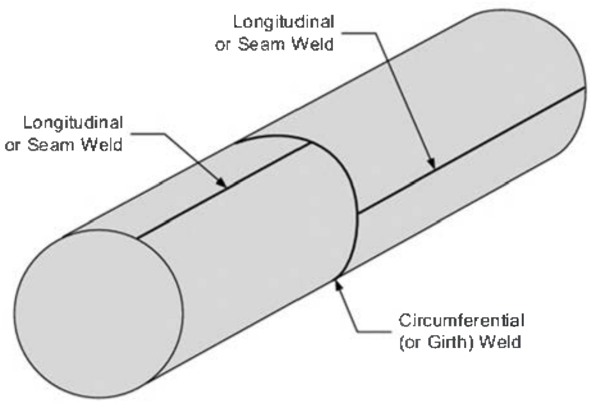


Figure 2.9 types of welding used in pressure vessels

For linear elastic fracture the distinguishment between primary and secondary loads is not important. However, when plastic deformation occurs then secondary stress, like residual stresses, redistributed and may cause mechanical stress relief. In other words, when plasticity is extensively widespread, the residual stresses have insignificant impact on the failure stress. However, when the structure behaves mostly elastically with small plastic zone the residual stresses.[8]

The plastic factor "Φ" illustrates this phenomenon. The diagram below illustrates the relation between the plasticity factor and the load ratio. The load ratio will be defined in the next chapter, it depends mostly on the loads and yield strength but also on the geometry. At low loads the plastic factor is greater than one due to plasticity, and at high loads the plastic factor may be decreased due to plastic relief.

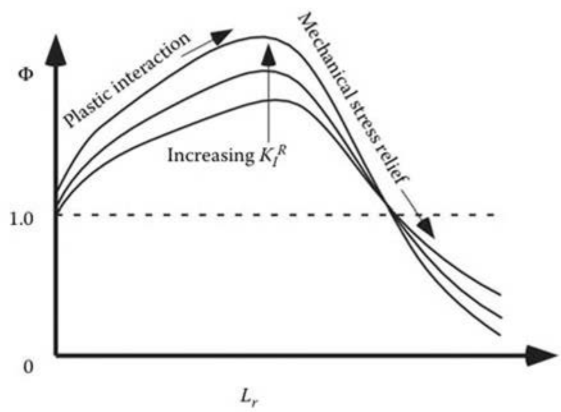


Figure 2.10 The relation between the plasticity factor and the load ratio [6]

2.5 The first Failure Assessment Diagram

Failure Assessment Diagram is the main tool of the assessment of crack-like flaws according to API-579. This diagram combines two failure criteria: brittle fracture and plastic collapse. The concept of the FAD origins with Burdekin and Stone, as they calculated a correction factor due to plasticity for a through crack in an infinite plate in plane stress. The API-579 uses a different and more accurate diagram, but the reference to Burdekin and Stone is noteworthy and will contribute to the readers' understanding.

So, the following equation calculates the corrected stress intensity factor for a through crack in a plate, for plane stress, according to Burdekin and Stone.

$$K_{eff} = \sigma_{YS}\sqrt{\pi\alpha}\left[\frac{8}{\pi^2}\ln\sec\left(\frac{\pi\,\sigma}{2\sigma_{YS}}\right)\right]^{1/2}$$

Or for real structures

$$K_{eff} = \sigma_{C}\sqrt{\pi\alpha}\left[\frac{8}{\pi^2}\ln\sec\left(\frac{\pi\,\sigma}{2\sigma_{c}}\right)\right]^{1/2}$$

Where,

- K_{eff} is the effective stress intensity factor
- σ_c is the collapse stress, it depends on the tensile properties of the material and on the flaw size relative to the structure.
- a is the crack length

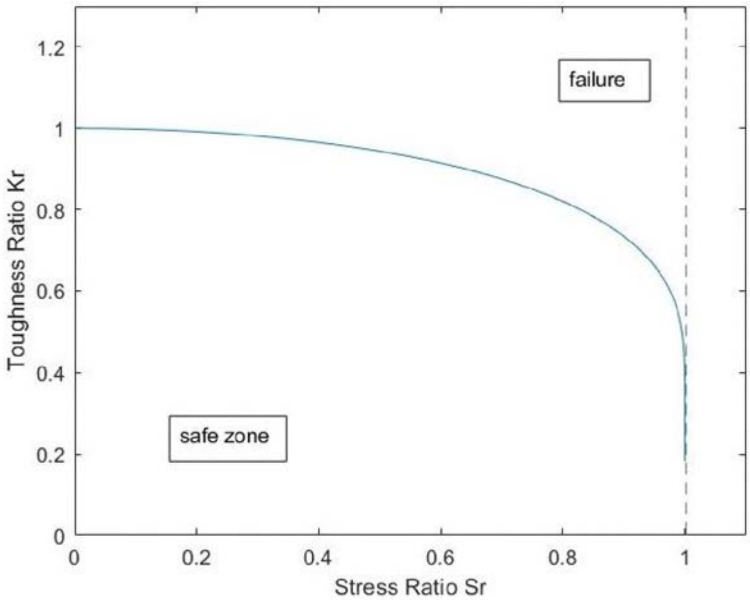
The next step is to derive effective stress intensity factor with the linear stress intensity factor in order to remove geometry dependence.

$$\frac{K_{eff}}{K_I} = \frac{\sigma_c}{\sigma}\left[\frac{8}{\pi^2} lnsec\left(\frac{\pi}{2}\frac{\sigma}{\sigma_c}\right)\right]^{0.5}$$

The ratios $\frac{K_I}{K_{eff}}$ and $\frac{\sigma}{\sigma_C}$ are called toughness ratio (K_r) and stress ratio (S_r) respectively.

Consequently,

$$K_r = S_r[\frac{8}{\pi^2}\ln\sec\left(\frac{\pi}{2}\ S_r\right)]^{-0.5}$$



2.11 The first Failure Analysis Diagram (FAD)

This diagram is called the Failure Analysis diagram, and the curve distinguishes two different zones: the safe zone below the curve and the unsafe zone above the curve. When the fracture toughness (K_r) tends to be one, then a brittle fracture occurs and when the stress ratio (S_r) tends to be one, then plastic collapse occurs. In fact, the curve illustrates the effect of the plastic zone on the brittle fracture, API-579 uses other curve that derives from semiempirical equations.

Chapter 3: FFS assessment using API 579 – Part 9

The API-579 fitness for service assessment has fourteen different parts. The first part is the introduction and describes the responsibilities of the inspector, the engineer and the owner of the pressurized component. The second part provides some useful information that is common in many parts, such as tensile strength of different materials. The 9th part discusses the crack-like flaws assessment and provides three different levels of assessment. Level 1 is the easiest assessment; however, it is very conservative and has many limitations. The second assessment has more calculations, has less limitations and it is less conservative than level one. The third level of assessment is more sophisticated and should be used only by an engineering specialist, as it includes numerical techniques such as finite element method.

a) Applicability of Level 1 and Level 2 of part 9

Firstly, the component must be constructed with a recognized code. Furthermore, phenomena such as creep range or dynamic effects such as earthquakes are not considered.
In addition, the first and second levels of assessment should not be applied when the crack is expected to grow in service.API-579 provides another assessment for growing crack which includes corrosion, fatigue, stress-corrosion cracking and crack growth by hydrogen assisted cracking. The reader has to understand first the assessment for no-growing cracks.

b) Additional limitations of the level 1 assessment.

Especially, the first level of assessment has more limiting conditions about the material, geometry and loads. Firstly, the material is carbon steel, and the component must be a plate, sphere, or cylinder with a wall thickness less than 38 mm and at least five times smaller that the radius (R/t>=5). Furthermore, level 1 does not examine the effect of other discontinues, for this reason the crack-like flaw must be located at a distance greater than or equal to $1.8\sqrt{(Dt)}$ where D is the diameter and t the thickness of the vessel. As for the loading conditions, the loading on the component is from pressure that produces only a membrane stress field. These are the most important limitations for the first level.

The level two assessments have less limitations and it is applicable for more complicated geometries and stress fields. This is succeeded by introducing more parameters such as stress intensity factor, fracture toughness, the plastic factor, the reference strength and the load ratio.

These are the most important limitations for level one and level two assessment. The reader should have read all the limitations from API-579 before starting an assessment of any level.

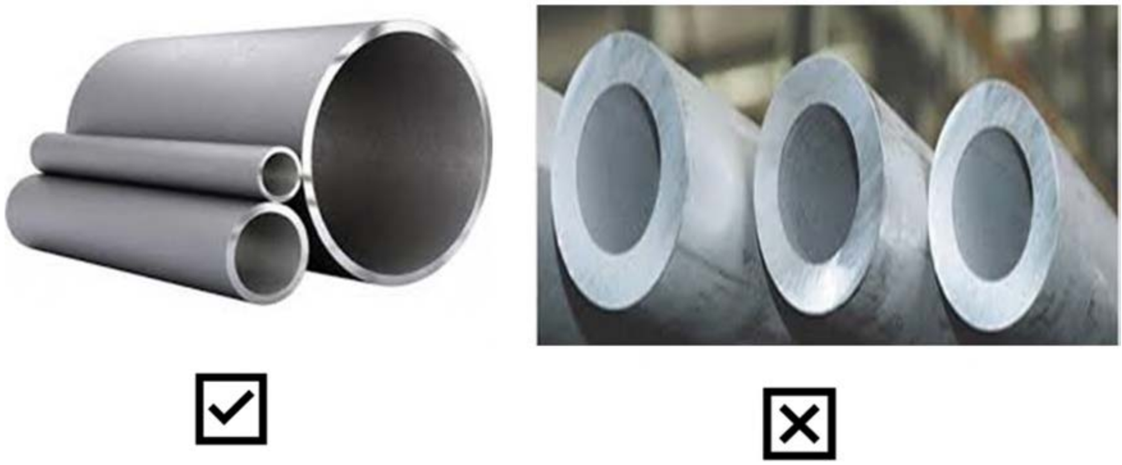


Figure 3.1 Level 1 is not applicable to very thick cylinders.

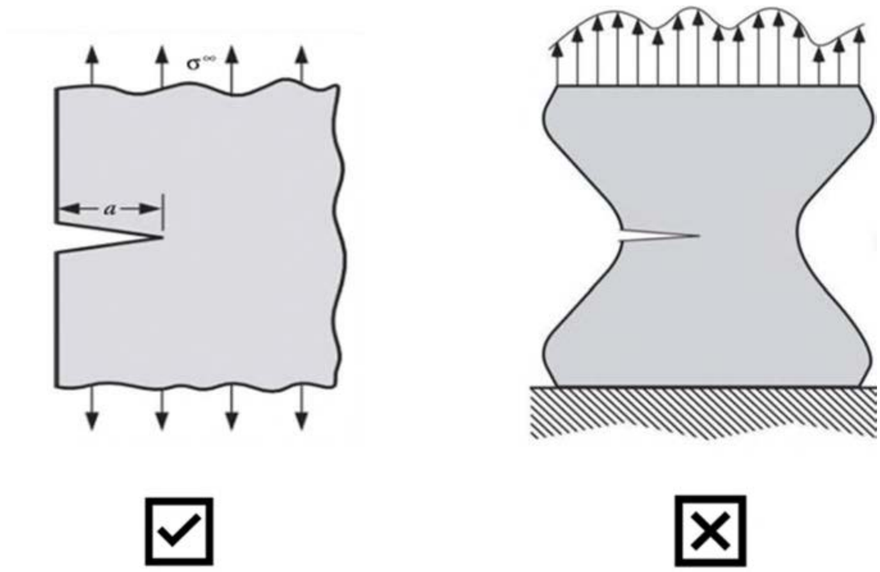


Figure 3.2 Level 1 is only applicable to membrane stress field. [6]

Figure 3.3 Level 1 is not applicable for nozzle intersections.

Level 1 Assessment

The API-573/ASME FFS1 provides many diagrams like this for the level 1 assessment. Each diagram corresponds to different components' geometry (exp. plate, cylinder, sphere) and crack orientation with respect to the weld joint. These diagrams show the maximum length of the crack (vertical axes) related to the temperature (horizonal axis).

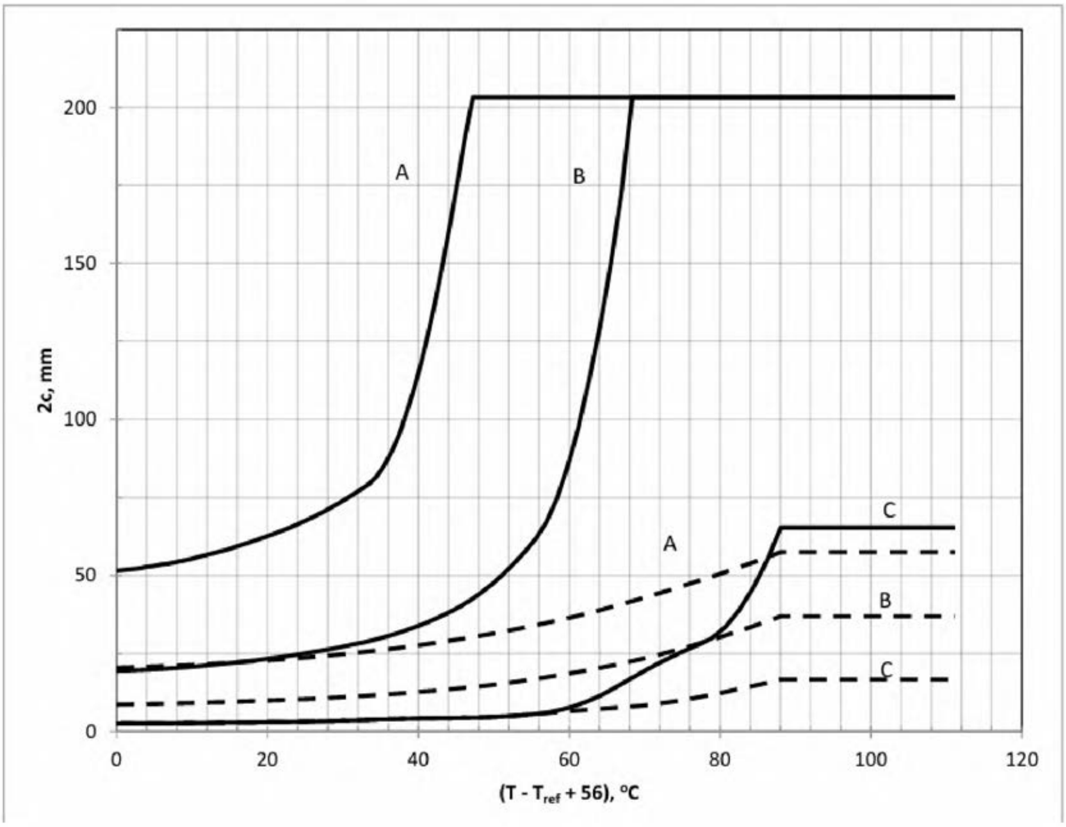


Figure Level 1 Assessment -Flat plate

Furthermore, the location of the flaw plays an important role. If the crack is located on the base metal, the curve with the letter A is used. The letter B is used when the crack like flaw is on the weld metal and has been subject to PWHT, if not, the letter C is used. Eventually, the table below shows whether the solid line or the dashed line is used.

For t<=25mm	a<=t/4	Solid line
	a>t/4	Dashed line
For 38mm >=t>25 mm	a<=6	Solid line
	a>6	Dashed line

where "a" the depth and" t" the thickness

A critical point in the level 1 assessment is the determination of the Critical Exposure Temperature (CET). The CET is defined as the coldest metal temperature at the maximum credible coincidence combination of pressure and supplemental loads that result in general primary membrane tensile stress (greater than 55 MPa ,8 ksi). So, the critical exposure temperature should be chose carefully, considering the start point, the operation and the shutdown

Additionally, scientists noticed that ferritic steels exhibit toughness-temperature curves with similar shapes, but with ductile-brittle transitions at different temperatures. When the fracture toughness is plotted against a temperature relative to a reference transition temperature, these data tend to collapse onto a common trend. Consequently, the code provides only one diagram for all ferritic steels which has "(T-Tref+56 C)" for horizontal axis. For the determination of the reference temperature for ferritic steels, tables 3.2 and 9.2 are needed.

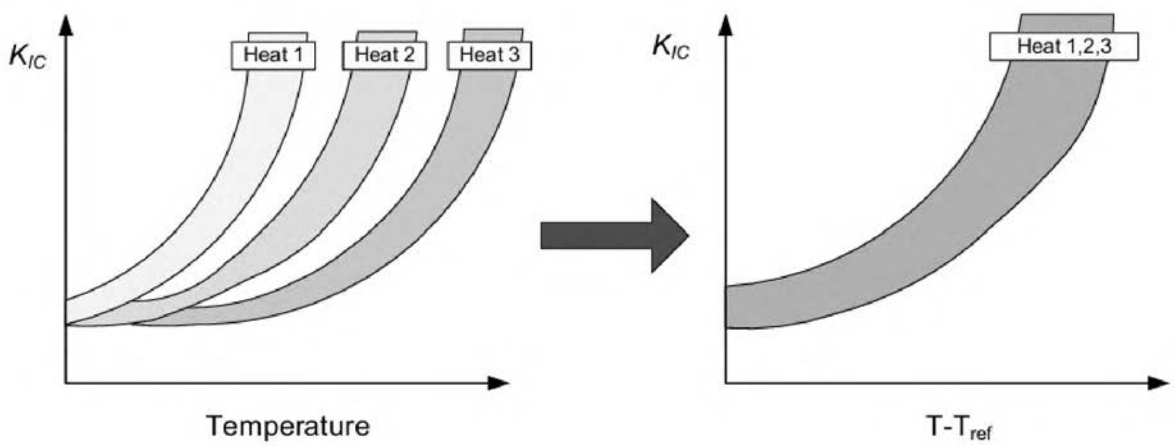


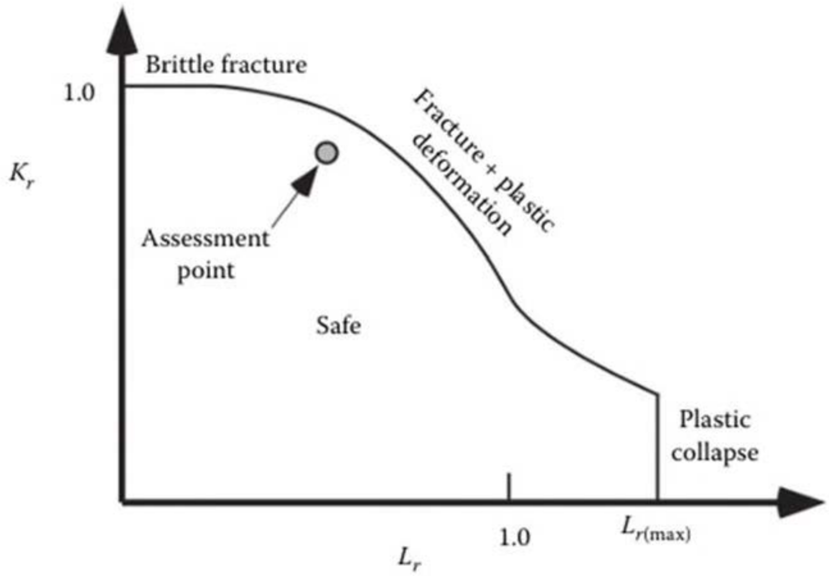
Figure 3.4 Fracture Toughness Indexing Approach API-579

Material
(table 3.2 API-579)
+
Specified Minimum Yield Strength
(table 9.2 API-579)

} Reference Temperature for ferritic steels (T_{ref})

Level 2 assessment

The level two assessment is based on the Failure Assessment Diagram (FAD) that presents a curve, which distinguishes the safe and the unsafe zone, and an assessment point. The pressure component is safe to operate, according to level two, only if the assessment point is below the curve.



The FAD method uses a *curve* to distinguish the safe and the unsafe zone. This curve is given by the following semiempirical equation that derives from J-integral.

$$K_r = [1 - 0.14 \times (L_r)^2] \times \{0.3 + 0.7 \times \exp[-0.65 \times (L_r)^6]\}$$

- Kr is the y-coordinate of the diagram
- Lr is the x-coordinate of the diagram

When the strain-stress data of the material is unknown a different curve can be used which has a relatively larger safe zone (see Level 3 Method B).

The next step is to calculate the coordinates of the assessment point. The horizontal coordinate is the load ratio Lr, and the vertical is the toughness ratio Kr. These parameters are result from stress analysis, stress intensity factor and from properties of the material. Each assessment is represented with a point on the diagram, if the point is underneath the curve, then it can continue to operate safely. It should be noted that the Failure Assessment Diagram includes two types of failure: unstable facture and load collapse. The first one controls fracture for small flaws and brittle materials, while the second one for large flaws and materials with high fracture toughness.

Stress intensity factor K_I

Firstly, stress analysis of the uncracked component's geometry is needed for the calculation of the stress intensity factor. The stresses are divided into two categories primary and secondary, so there are two stress intensity solutions. If the stress distribution is highly un-linear, then it can be represented by a 4th degree polynomial.

$$\sigma(x) = \sigma_o + \sigma_1 \times \left(\frac{x}{t}\right) + \sigma_2 \times (\frac{x}{t})^2 + \sigma_3 \times (\frac{x}{t})^3 + \sigma_4 \times (\frac{x}{t})^4$$

Equivalent membrane and bending stress distributions for the fourth order polynomial stress distribution are usually used to find the stress intensity factor.

$$\sigma_m = \sigma_0 + \frac{\sigma_1}{2} + \frac{\sigma_2}{3} + \frac{\sigma_3}{4} + \frac{\sigma_4}{5}$$

$$\sigma_b = -\frac{\sigma_1}{2} - \frac{\sigma_2}{2} - 9 \times \frac{\sigma_3}{20} - 6 \times \frac{\sigma_4}{15}$$

All these stress parameters are used for the calculation of the stress intensity factor. For example, the below stress intensity factors are for

$$K_I = [G_0(\sigma_0 + p_c) + G_1\sigma_1(\frac{\alpha}{t}) + G_2\sigma_2(\frac{\alpha}{t})^2 + G_3\sigma_3(\frac{\alpha}{t})^3 + G_4\sigma_4(\frac{\alpha}{t})^4]\sqrt{\pi\alpha}$$

(Plate – Surface Crack, Infinite Length, Through-Wall)

- G: influence coefficient, it is function of geometry, crack dimension and the power law exponent n.

Load ratio

The load ration and the reference strength were introduced to normalize the horizontal axe of the failure analysis diagram and be geometrically indented.

$$L_r = \frac{P_l}{P_{ly}}$$

- P_l is generalized loading parameter, such as pressure
- P_{ly} value of the generalized loading parameter evaluated for the component with a crack-like flaw at the yield stress.

An equivalent equation for the load ratio is

$$L_r = \frac{\sigma_{ref}}{\sigma_{yield}}$$

Where the reference stress is $\sigma_{ref} = \frac{P_l}{P_{ly}} \times \sigma_{yield}$

API-579 provides a variety of reference stress solutions for each geometry and loading condition. For example, the following equation gives the reference stress solution for a plate with a through-wall crack.

$$\sigma_{ref} = \frac{P_b + (P_b^2 + 9 \times P_m^2)^2}{3 \times (1 - \frac{c}{W})}$$

- P_m is the equivalent membrane stress
- P_b is the equivalent bending stress
- c is the half-length of the flaw
- t is the thickness of the plate
- distance from the center of the flaw to the free edge of the plate

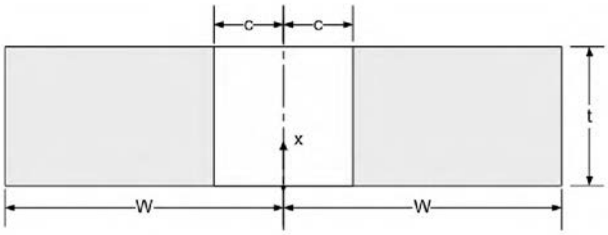


Figure 3.5 Plate – Through-Wall Crack, Through-Wall Membrane and Bending Stress, API-579

The y-axe is calculated with the following equation

$$K_r = \frac{K_I^P + \Phi \times K_I^{SR}}{K_{mat}}$$

- K_I^P is the stress intensity factor for primary stresses
- K_I^{SR} is the stress intensity factor for secondary stresses
- K_{mat} is the fracture toughness
- Φ is plasticity factor, it is function of the intensity factor of residual stresses, the load ratio and the crack depth (table 9.3 API-579)

Eventually, the coordinate of the assessment point is (Lr, Kr) and the curve that distinguishes the acceptable and the unacceptable zone is given by the following equation, and it is illustrated at the next figure.
It is important to determine a cut-off on the failure diagram for very high load ratio as it is illustrated in the diagram. When stress-strain data of the material is unknown then the maximum load ratio should be equal to one.

$$K_r = [1 - 0.14 \times (L_r)^2] \times \{0.3 + 0.7 \times \exp[-0.65 \times (L_r)^6]\}$$

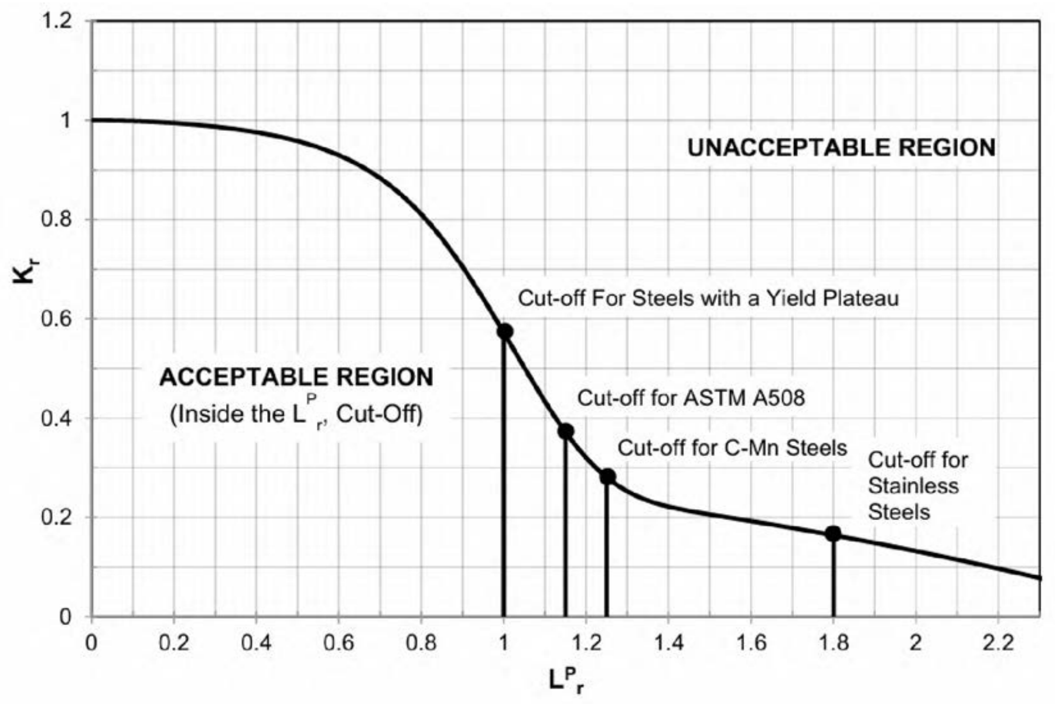


Figure 3.6 Failure Assessment Diagram (FAD), API-579

Leak-before-break assessment based on level 2

Leak-before-break (LBB) means that a detectable leak will appear before a catastrophic rupture. This is of paramount importance as the leak constitutes an early warning sign preventing any accidents. It should be mentioned that the first approach to LBB procedure was by Irwin using linear elastic fracture mechanics to an axial flaw in a pressure vessel for missile application. API-579 suggests performing LBB procedure when the crack is acceptable per level two, and it is expected to grow.

The LBB procedure is based on re-categorization of the crack to through wall crack flaw (figure).

The following equation calculates the half-length of the through wall crack flaw.

$$2c_{LBB} = 2c + t$$

Where,

- c_{LBB} half-length of the through-wall flaw
- c is the half length of the initial crack-like flaw
- t is the thickness of the component containing the crack-like flaw including metal loss and future corrosion

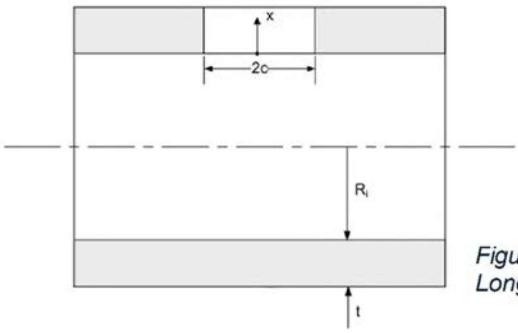


Figure 3.7 Cylinder – Through-wall Crack, Longitudinal Direction, API-579

Furthermore, it should be noted that the leak-before-break is not always applicable. Leak before break is not applicable when the component contains hazardous fluid, or other liquids with a low boiling point due to auto-refrigeration phenomenon (exp or light hydrocarbon liquids). During this phenomenon, liquid changes to vapor, absorbing thermal energy and reducing locally the temperature. This phenomenon makes the LBB procedure impractical. Finally, high residual stresses may lead to growth in the surface direction rather than in the depth direction. In that occasion, API-579 suggests to apply Leak before break assessment only if the component has been subject to PWHT.

Assessment level 3

The third level of assessment gives the best estimation of structural integrity. It uses the Failure Analysis Diagram but the assessment point or the fad curve differ with level two assessment.
The third level of assessment is also used when the crack is expected to grow in service due to fatigue, corrosion and hydrogen assisted cracking. The assessment is repeated for different sizes of the crack using crack growth data. For example, for fatigue the Paris Erdogan equation can be used.

Level 3 Assessment Method B

Method B suggests completing the level 2 assessment using a different fad-curve given by the following equation. The fad-curve distinguishes the acceptable and the unacceptable zone of the failure analysis diagram. The following equation is a semiempirical equation that includes the actual material properties of the component[8]. For this method, stress-strain data is required. It should be noted that this method should not be used when the crack-like flaw is in the heat affected zone, because the material stress strain-curve is changed

Level 3, Method B

$$K_r(L_r^P) = \left(\frac{E \times \varepsilon_{ref}}{L_r^P \times \sigma_{ys}} + \frac{(L_r^P)^3 \times \sigma_{ys}}{2 \times E \times \varepsilon_{ref}}\right)^{-1/2}$$

for $0 < L_r^p \leq L_{r,max}^p$

- ε_{ref} reference strain obtained from the true stress-strain curve at a true stress equal to $Lr{*}\sigma_{ys}$

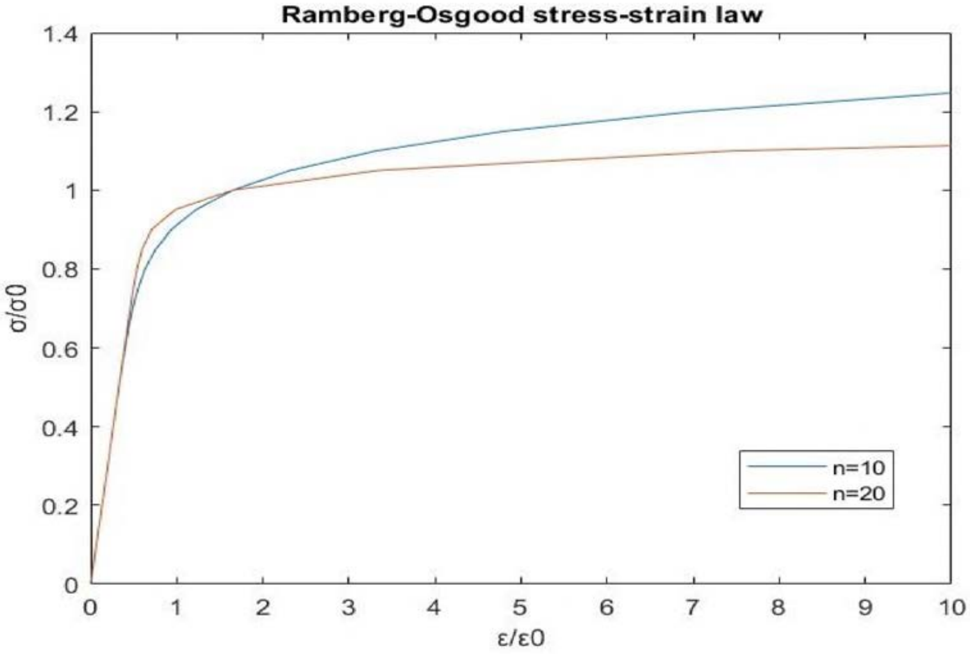
  The fad curve can be calculated using data from tensile stress experiment, reference strain (ε_{ref}) is equal to true strain and the reference stress is equal with true stress.

Level 2 FAD curve:

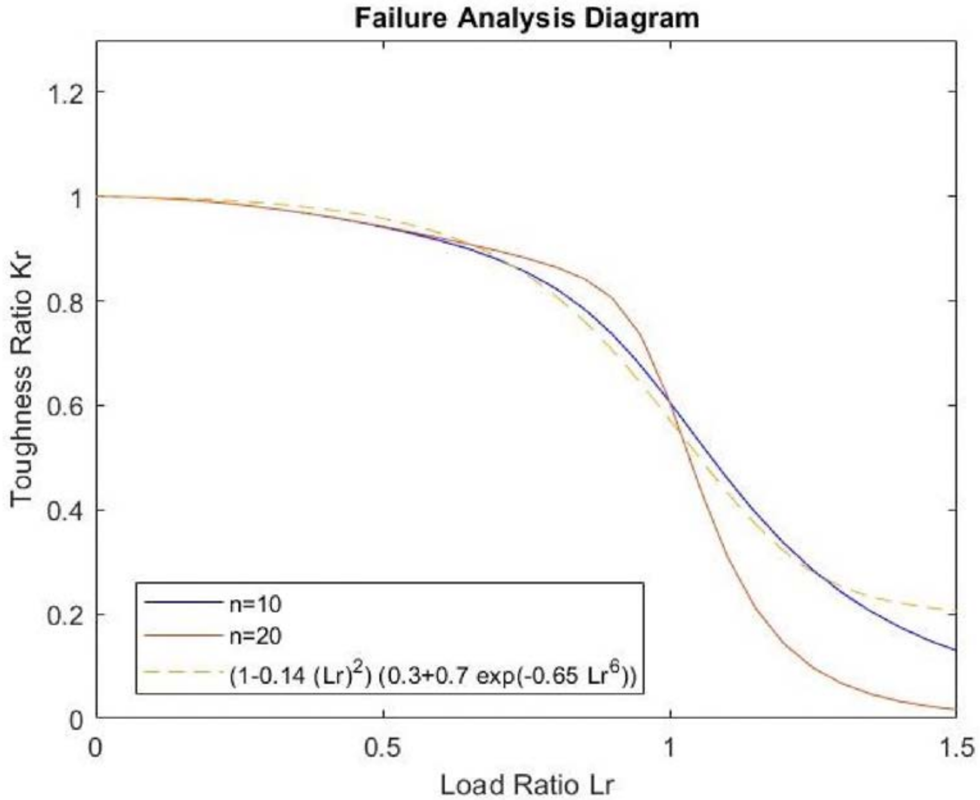
$$K_r = [1 - 0.14 \times (L_r)^2] \times \{0.3 + 0.7 \times \exp[-0.65 \times (L_r)^6]\}$$

The following diagram (Figure) shows the stress-strain data derived from the Ramberg-Osgood equation (for α=1 and ε_0=0.002).

$$\varepsilon_{11} = \frac{\sigma_{11}}{E} + \alpha \times \varepsilon_0 \times \left(\frac{\sigma_{11}}{\sigma_0}\right)^n$$



The following diagram shows two fad curves from materials with different strain hardening coefficient and the fad curve from level two assessment. When the load ratio is lower than one the fad curves are slightly different. However, when the load ratio is greater than one, the fad curves show significant differences and that is why the level two assessment has a maximum load ratio value .



Level 3 method C

The basis of this method is the Level 2 Assessment procedure except that the failure analysis diagram is constructed using finite element method. This method is very useful when more complex geometries and stress fields are examined and especially when the stress intensity solution for the certain load and geometry is not provided from the API. Most importantly, the third level is less conservative than the second level as the fad is based on the actual material properties, load condition and geometry. It should be noted that this approach is not valid when the primary stresses are not applied simultaneously.

Mesh Design:
It is suggested to use a spider web shaped mesh that consecrates at the crack's tip, like the following picture. Tools to implement mesh are available to many finite element programs.

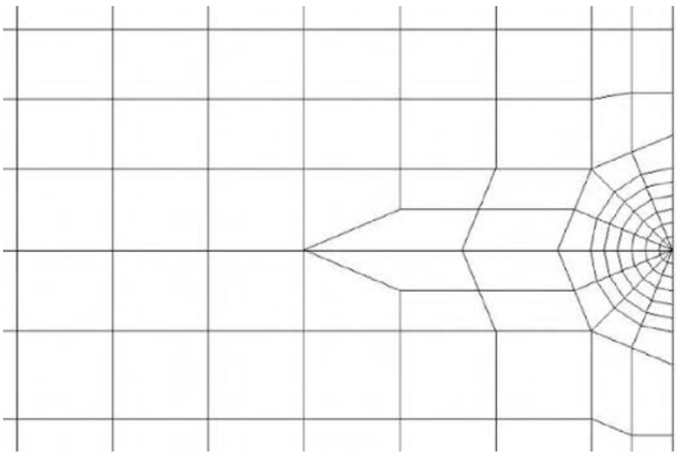


Figure 3.8 Focused or Spider Web Mesh with Elements Concentrated at the Crack Tip, API-579

The next step is to construct an elastic-plastic finite element model including only the primary stresses, in order to compute the J integral. This step is repeated, increasing the primary loads and computing the J integral for each step. At each step, the j integral is converted to K_J using the following equation.

$$K_J = \sqrt{\frac{J \times E_y}{1 - \nu^2}}$$

- *K_J is stress intensity factor derived from J integral*
- *E_y Young's modulus at the assessment temperature*

The elastic stress intensity factor K_I^P is derived from the initial slope of the plot K_J versus applied stress. This is accurate when the applied stresses are increased gradually. Otherwise, the stress intensity factor can be derived from a separate elastic finite element analysis, not plastic.

The vertical coordinate of the failure analysis diagram is computed at each step with the following equation. Remember, the stress intensity factor is constant, but the K_J is related to the applied stresses.

$$K_r = \frac{K_I^P}{K_J}$$

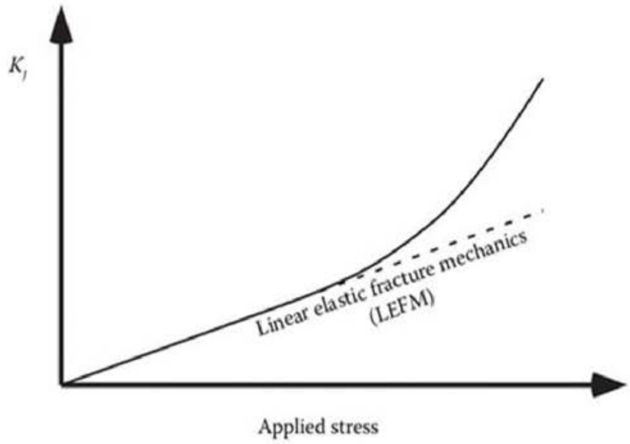


Figure 3.9 Schematic plot of driving force versus applied stress[6]. The initial slope is equal with the linear stress intensity factor K_I.

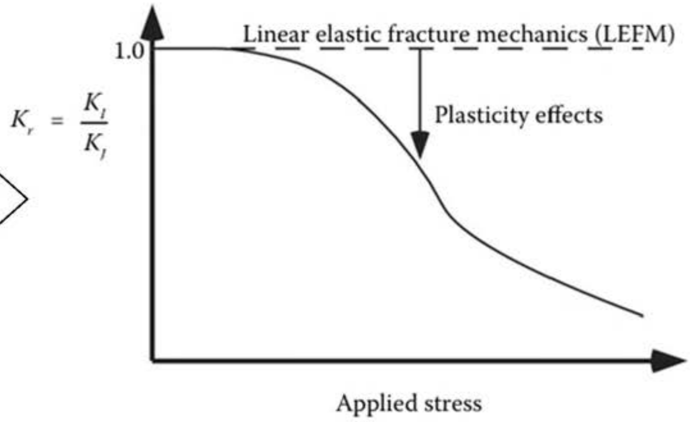


Figure 3.10 Definition of The Vertical Axis Of The FAD.

The next step is to normalize the x-axis

$$L_r = \frac{\sigma_{ref}}{\sigma_{yield}}$$

The reference stress solution is given by the following equation.

$$\sigma_{ref} = (\frac{\sigma_{ys}}{\sigma_{Lr=1}^{P}}) \times \sigma^P$$

$where\ \sigma_{Lr=1}^{P}$ is the load parameter at which the load ratio is equal with

$$K_r\big|_{L_r=1} = \left[1+\frac{0.002E_y}{\sigma_{ys}}+\frac{1}{2}\left(1+\frac{0.002E_y}{\sigma_{ys}}\right)^{-1}\right]^{-0.5}$$

The previous equation is derived from the following for Lr=1 and ε_{ref}=0.002, it was used on level 3 method B, it is a semi-empirical equation.

$$K_r(L_r^P) = \left(\frac{E \times \varepsilon_{ref}}{L_r^P \times \sigma_{ys}} + \frac{(L_r^P)^3 \times \sigma_{ys}}{2 \times E \times \varepsilon_{ref}}\right)^{-1/2}$$

All these steps lead to the determination of the FAD curve that distinguishes the safe and the unsafe zone. If the assessment point is underneath the curve, then the component can continue to operate.

Y coordinate of the assessment point

$$K_r = \frac{K_I^P + \Phi \times K_I^{SR}}{K_{mat}}$$

- K_I^P is the stress intensity factor for primary stresses. It was calculated in previous steps
- Φ is plasticity factor, it is function of the intensity factor of residual stress, the load ratio and the crack depth (table 9.3 from API-579). It is calculated with the same process as level two assessment.
- K_{mat} is the fracture toughness
- K_I^{SR} is the stress intensity factor for secondary stresses that derives from a separate elastic analysis.

X coordinate of the assessment point

$$L_r = \frac{\sigma_{ref}}{\sigma_{yield}}$$

The crack-like flaw is acceptable when the assessment point is below the curve. For only primary loads and provided that $Lr \leq Lr_{max}$ then,

$$K_{r,assesment\ point} < K_{r,curve} \Rightarrow \frac{K_I}{K_{mat}} < \frac{K_I}{K_J} \Rightarrow K_J < K_{mat} \Rightarrow \sqrt{\frac{J \times E_y}{1 - \nu^2}} < \sqrt{\frac{J_{crit} \times E_y}{1 - \nu^2}} \Rightarrow J < J_{crit}$$

That means that there is no substantive difference between the FAD method and a conventional *J* analysis [6].

Remediation Methods

The API-579 provides some references where the reader can found details about remediation methods. Some of the remediation methods are the following. It should be mentioned that most methods can be used when the vessel is not operating.

a) The crack can be removed by bled griding, creating a groove. The groove should be repaired by a welding procedure and treated with post weld heat treatment, otherwise the groove should be assessed as local metal loss (API-579 Part 5).
b) drilling holes at the end of the crack can reduce the crack driving force.
c) Another method is the weld overlay to the surface opposite to the crack's surface. In this way, the thickness of the component is increased and at the same time the residual stress field that is created prevents crack growth.
d) Using a device that is called crack arrestor, that may stop unstable crack growth. Crack arrestors have been successfully tested to pipelines with large diameters for natural gas. An experiment that has been done by the Engineering Mechanics Corporation of Columbus ended successfully, however only the longest arrestor worked.[10],[10]

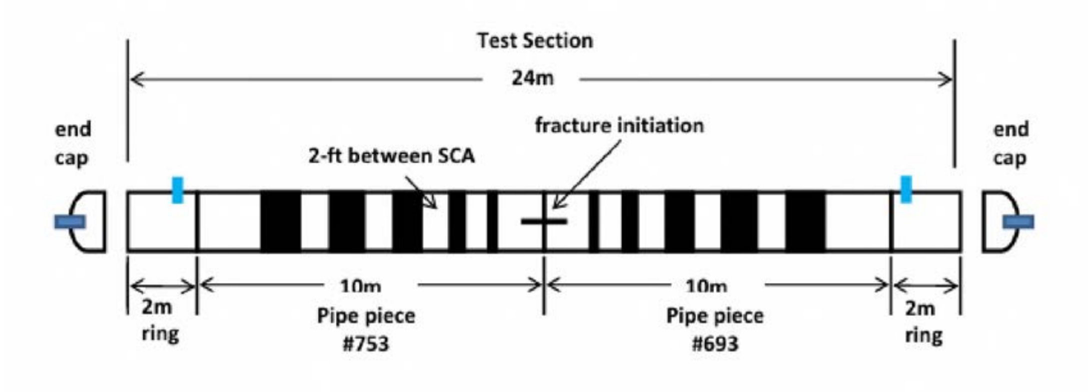


Figure 3.11 The picture shows the pipe and the crack arrestors before the experiment, ten crack arrestors were installed and only the last and bigger one was not completely damaged.[10]

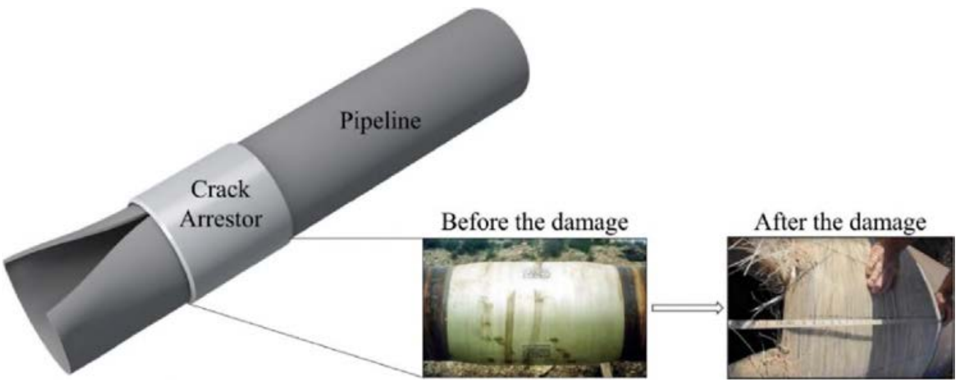


Figure 3.12 Crack arrestor on a pipe, before and after the damage [10]

Chapter 4: Case study

A crack-like flaw is found on the inside surface of a pipe. This crack-like flaw may grow catastrophically or not and in order to determine the behavior of the crack, a fitness for service code must be used.
The pipe is fabricated from SA-516 Grade 70 steel, and it is designed to operate at 70ºC temperature and at 2 500 kPa pressure.
The inside diameter of the pipe is 3.05 m, and the fabricated thickness is 0.0254 m. Furthermore, the weldments of the pipe have not been subjected to post weld heat treatment.

Start-up and Shutdown process

The vessel is not fully pressurized until the temperature is 40ºC.Bellow this temperature, the startup pressure remains under 1000 KPa. At shutdown, the pressure vessel decreases to 1000 KPa before letting the temperature drop below 40ºC.

Inspection data

The flaw is located in the heat affected zone of a longitudinal weld seam on the inside surface of the vessel. The longitudinal seam is a double V-groove weld. The flaw is parallel to the weld seam. The depth of the flaw was measured 0.0101 meters using the ultrasonic method. The flaw length was established by magnetic particle testing and is 0.0813 m. The distance of the crack-like flaw to the nearest structural discontinuity is 0.8 meters.

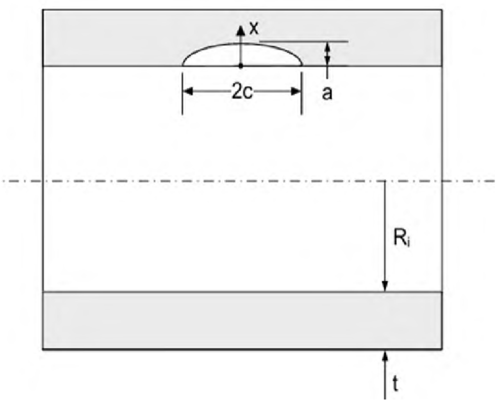


Figure 4.1 Cylinder – Surface Crack, Longitudinal Direction – Semi-Elliptical Shape, inside surface

- c is the half-length of the crack
- a is the depth of the crack
- t is the thickness of the pipe
- R_i is the inside radius of the pipe

Level 1 Assessment

- The critical exposure temperature is 40°C, during start up
- The diagram for the level 1 assessment is the following one (Cylinder, Longitudinal Joint, Crack-Like Flaw Parallel to the Joint).
- $t \leq 25\ mm\ and\ a \leq \frac{t}{4}$ So, the solid-line curves will be used.
- When the location of the flaw is within two times the nominal plate thickness measured from the centerline of the weld, then the curve for the weld metal should be used. Furthermore, the weld has not been treated with Post weld heat treatment so the curve with the letter C will be used.
- The following inputs are used in order to determine the reference temperature.
  Table Part 3 table 3.2
  Material: SA-516 Grade 70
  The yield stress is 262 000 KPa
  Table 9.2 from API-579

  $T_{ref} = 10.3 \Rightarrow T - T_{ref} + 56 = 85{,}7$°C

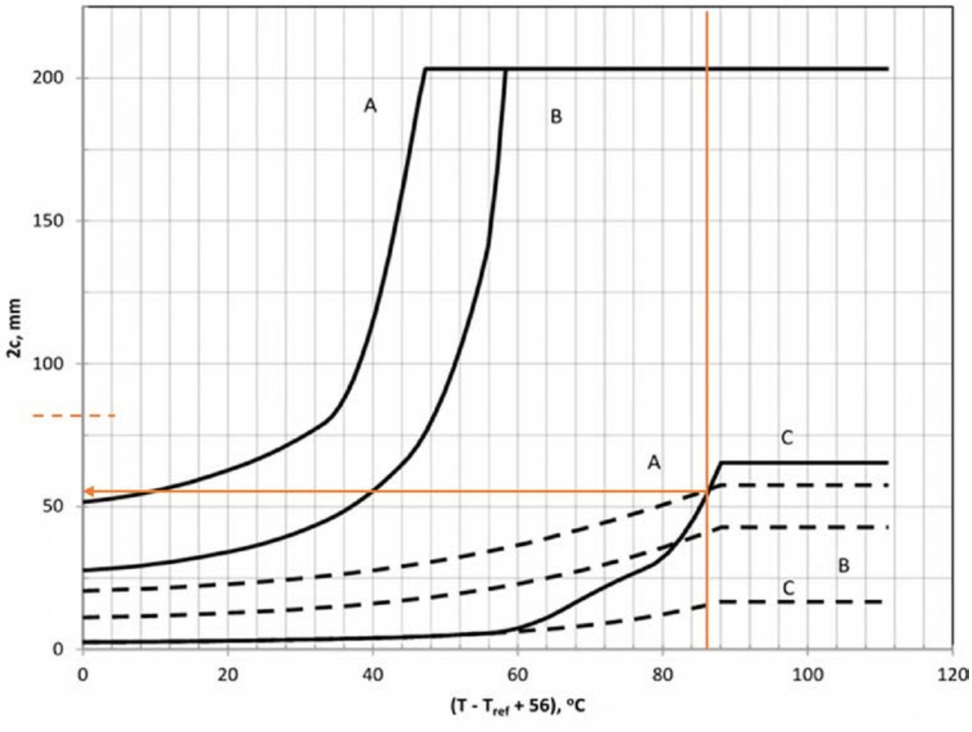


Figure 4.2 This diagram is for Cylinder, Longitudinal Joint and Crack-Like Flaw Parallel to the Joint API-579.The orange lines were created by the author for this example. The output of this diagram is the maximum permitted length of the crack at the "y" axes.

The crack of the pipe is 83 mm while the maximum permitted length for level one assessment is 52 mm. Consequently, crack like flaw is unexpectable per level 1 procedure, and one of the following actions that can been taken.

- *Better determination of the size of the flaw, using additional NDE methods*
- *Rerate (for example the temperature), replace, repair the component*
- *Perform a Level 2 or a level 3 Assessment*

Example of Level 2 Assessment

The level two assessment is based on the failure analysis diagram that illustrates a curve that is derived from a semiempirical equation and an assessment point. Level two is acceptable only if the assessment point is on or below the curve, so the coordinates of the assessment point must be found. The y-coordinate is the fracture ratio $K_{r,}$ and the x-coordinate is the load ratio $L_{r.}$

y-coordinate of the assessment point

$$K_r = \frac{K_I^P + \Phi \times K_I^{SR}}{K_{mat}}$$

- K_I^P is the stress intensity factor for primary stresses
- K_I^{SR} is the stress intensity factor for secondary (residual) stresses
- K_{mat} is the fracture toughness
- Φ is plasticity factor, it is function of the intensity factor of residual stresses, the load ratio and the crack depth (table 9.3 API-579)

The pipe has primaries stresses due to pressure and secondaries stresses due to residual stress from the weldment. As for primary stresses, the stress intensity factor for this geometry and loading condition is named KCSCLE1 (Cylinder – Surface Crack, Longitudinal Direction – Semi-Elliptical Shape, Internal Pressure API-579 equation 9B.187)

$$K_1 = \frac{pR_o^2}{R_o^2 - R_i^2}\left[2G_0 - 2G_1\left(\frac{a}{R_i}\right) + 3G_2\left(\frac{a}{R_i}\right)^2 - 4G_3\left(\frac{a}{R_i}\right)^3 + 5G_4\left(\frac{a}{R_i}\right)^4\right]\sqrt{\frac{\pi a}{Q}}$$

Where,

- p is the pressure
- R_O is the outer radius of the pipe
- R_i is the inner radius of the pipe
- Q is a parameter to compute stress intensity factor
- a is the crack's depth
- G is influence coefficient and it is geometrically dependent

For the assessment, the stress intensity factor for both the base and the edge of the flaw must be calculated. The following ratios are used in order to calculate influence of coefficients (G_0, $G_1 \ldots G_4$) from tables.

$$\left.\begin{aligned} t/_{R_{in}} &= {}^{0.0254}/_{1.525} = 0.0167 \\ a/_{c} &= {}^{0.0051}/_{0.0406} = 0.1255 \\ a/_{t} &= {}^{0.0051}/_{0.0254} = 0.2008 \end{aligned}\right\} \quad G_0, G_1, G_2, G_3, G_4$$

Table 1 Influence of coefficients that were used for this assessment, which were calculated based on some tables and equations from the API-579 annex B

	G0	G1	G2	G3	G4
At the deepest point of the crack	1.507485	0.824150	0.599228	0.485869	0.416643
At the free surface	0.494848	0.062552	0.021744	0.010696	0.006284

Therefore,

- $K_I^P = 40\ 343 kPa\sqrt{m}$ for the deepest point of the crack
- $K_I^P = 13\ 280\ kPa\sqrt{m}$ for the free surface of the crack

Residual stress

The influence coefficients are related only to geometry, and that is why for the residual stress intensity factor the same influence of coefficients will be used.

$$K_I^{SR} = [G_0\sigma_0^{SR} + G_1\sigma_1^{SR}(\frac{\alpha}{t}) + G_2\sigma_2^{SR}(\frac{\alpha}{t})^2 + G_3\sigma_3^{SR}(\frac{\alpha}{t})^3 + G_4\sigma_4^{SR}(\frac{\alpha}{t})^4]\sqrt{\frac{\pi\alpha}{Q}}$$

The following equation describes the distribution of residual stresses perpendicular to the weld seam (API-579 Annex D, equation 9D.22)

$$\sigma^r = \sigma_{ys}^r[1.230 - 9.269\left(\frac{x}{t}\right) + 17.641(\frac{x}{t})^2 - 8.660(\frac{x}{t})^3]$$

Where,

- x is measured from the side opposite of the widest weld groove width or last pass (typically the inside surface)
- t is the shell thickness
- σ_{ys}^r is the yield strength plus 69 000 kPa due to hardening effects caused by the welding procedure. $\sigma_{ys}^r = \sigma_{ys} + 69\ 000\ KPa =$

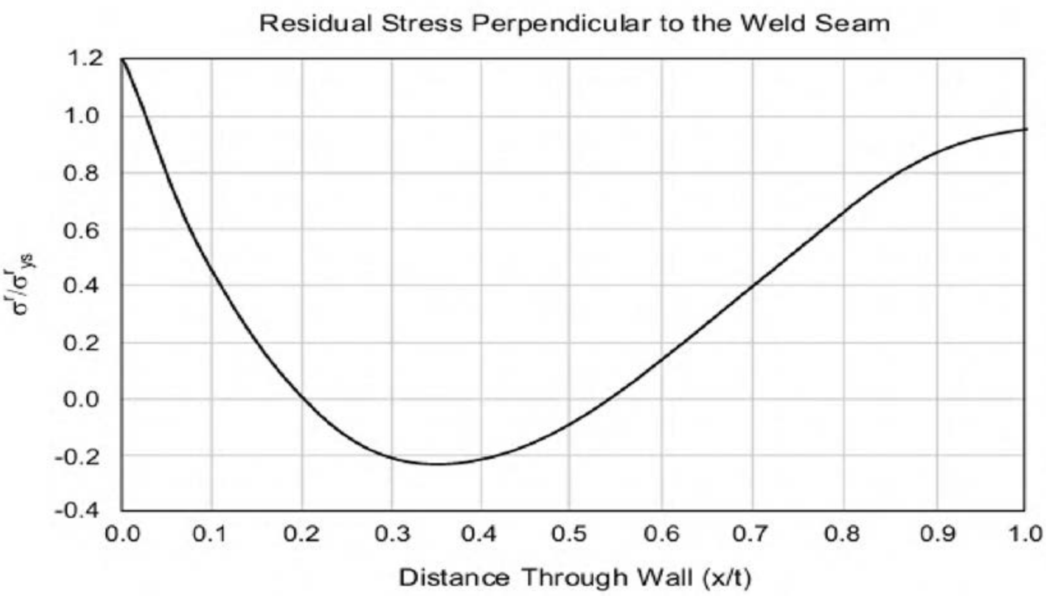


Figure 4.3 Residual stress Perpendicular to the weld seam, API-579

$324\ 020\ KPa$

The residual stresses are given in a fourth order polynomial distribution.

$$\sigma^r = \sigma_{ys}^r[1.230 - 9.269\left(\frac{x}{t}\right) + 17.641(\frac{x}{t})^2 - 8.660(\frac{x}{t})^3]$$

Consequently,

$\sigma_0 = 1.230 \times \sigma_{ys}^r$, $\sigma_1 = -9.269 \times \sigma_{ys}^r$,$\sigma_2 = 17.641 \times \sigma_{ys}^r$, $\sigma_3 = -8.66 \times \sigma_{ys}^r$,$\sigma_4 = 0$

The influence coefficients (G_0, $G_{1...}G_4$) are different for the deepest point of the crack and for the free surface. Therefore,

$$K_I^{SR} = [G_0\sigma_0^{SR} + G_1\sigma_1^{SR}(\frac{\alpha}{t}) + G_2\sigma_2^{SR}(\frac{\alpha}{t})^2 + G_3\sigma_3^{SR}(\frac{\alpha}{t})^3 + G_4\sigma_4^{SR}(\frac{\alpha}{t})^4]\sqrt{\frac{\pi\alpha}{Q}}$$

- $K_I^{SR} = 12\,481 KPa\,\sqrt{m}$ for the deepest point of the crack
- $K_I^{SR} = 24\,446 KPa\,\sqrt{m}$ for the free surface

The fracture toughness is calculated based on the indexing method with the following equation (API-579 9F.44). The reference temperature is $T_{ref} = 10.3\ ^\circ\mathrm{C}$ from the level 1 assessment. It should be noted that with the following equation, the fracture toughness tends to be infinite as the temperature rises, so there is a cut off. For example, for low sulfur steels the maximum value of the fracture toughness is 225 MPa $m^{0.5}$.

$$K_{MAT} = 36.5 + 3.084 \times \exp[0.036 \times (T - T_{ref} + 56)] =$$
$$= 36.5 + 3.084 \times exp[0.036 \times (40 - 10.3 + 56)] =$$
$$= 103.952\ MPa\sqrt{m}\ or\ 103\,952\ KPa\sqrt{m}$$

- K_{MAT} is the fracture toughness (MPa m^0.5)
- T is the assessment temperature at Celsius
- T_{ref} is calculated in the level 1 assessment

The above equation is illustrated in the following diagram. The K_{IC} curve is used for this assessment. The K_{IR} is more conservative, and it is used when the environment may have affected the material's integrity (exp hydrogen charging affect)

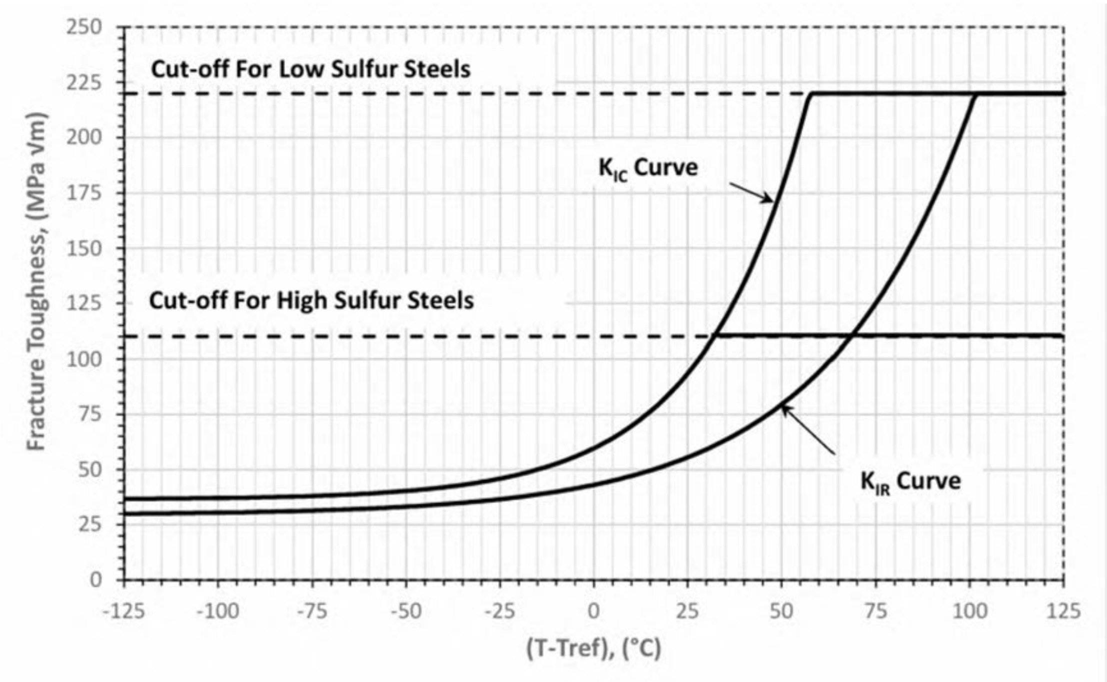


Figure 4.4 Lower-Bound Fracture Toughness Curves for ferritic Steels, API- 579.

The plastic factor is calculated easily from API-579 equations (9.12), (9.13), (9.14), (9.15), (9.16), (9.17) and Table 9.3. Therefore, the plastic factor Φ is

$\Phi = 1.1562$ *At the deepest point of the crack*

$\Phi = 1.2185$ *At the free surface of the crack*

Finally, the y-coordinates are

- At the deepest point of the crack
$$K_{r1} = \frac{K_I^P + \Phi \times K_I^{SR}}{K_{mat}} = \frac{40\,343 + 1.1562 \times 12\,481}{103\,952} = 0.5269$$
- *At the free surface of the crack*
$$K_{r2} = \frac{K_I^P + \Phi \times K_I^{SR}}{K_{mat}} = \frac{13\,280 + 1.2185 \times 24\,446}{103\,952} = 0.4143$$

So, the lasts steps that remains are to find the x-coordinate and draw the failure analysis curve.

x-coordinate of the assessment point

The x-coordinate of the assessment point is the load ratio, and it is defined as

$$L_r^P = \frac{\sigma_{ref}^P}{\sigma_{ys}}$$

Where

- σ_{ys} is the yield strength of the material
- σ_{ref}^P is called reference stress, API-579 Annex C provides reference stress solutions for many geometries and loads

The following reference stress intensity solution is named RCSCLE1 (Cylinder, Surface Crack, Longitudinal Direction – Semi-Elliptical Shape, Internal Pressure)

$$\sigma_{ref} = \frac{g \times P_b + [(g \times P_b)^2 + 9(M_s \times P_m \times (1 - a_2)^2)^2]^{0.5}}{3 \times (1 - a_2)^2}$$

Where,

- P_m is the equivalent membrane stress and it is equal with
$$P_m = \frac{p \times R_{in}}{t} = 2500\ KPa * \frac{1.525}{0.0254} = 15\ 010 KPa$$
- P_b is the equivalent bending pressure for internal crack
$$P_b = \frac{p}{2} = 1\ 250\ KPa \ll P_m$$
- The following parameters are correction factors for cells due to local bulging.

$$\lambda_\alpha = \frac{1.818 \times c}{\sqrt{R_i \times a}} = \frac{1.818 \times \frac{0.0813}{2}}{\sqrt{1.525 \times 0.0102}} = 1.1871$$

$$M_{t-\lambda\alpha} = (\frac{1.02 + 0.4411 \times {\lambda_\alpha}^2 + 0.006124 \times {\lambda_\alpha}^4}{1 + 0.02642 \times {\lambda_\alpha}^2 + 1.533 \times 10^{-6} \times {\lambda_\alpha}^4})^{0.5} = 1.2627$$

$$M_s^{NS} = \frac{1}{1 - \frac{\alpha}{t} + \frac{\alpha}{t} \times \frac{1}{M_{t-\lambda\alpha}}} = 1.0908$$

$$a2 = \frac{a/_t}{1 + t/_c} = 0.3048$$

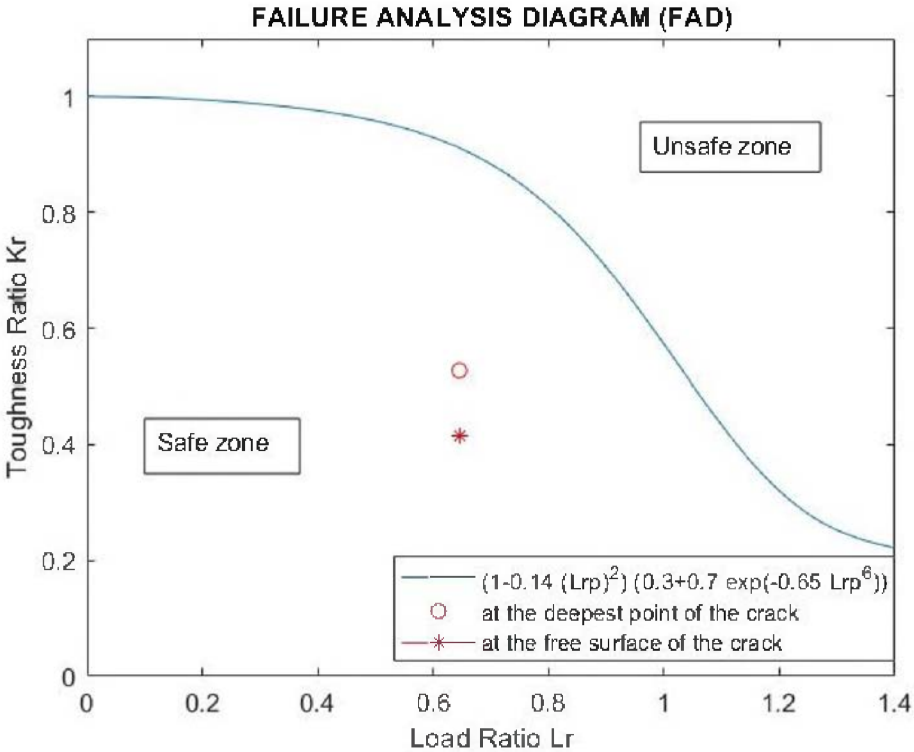
$$g = 1 - 20(\frac{a}{2c})^{0.75} \times a_2^3 = 0.9292$$

- α is the depth of the flaw
- c is the half length of the flaw
- t is the thickness of the pipe
- R_i is the inside diameter of the pipe
- G is a reference stress bending parameter
- λα is surface correction parameter for shells

Eventually, the reference stress for the primary stresses is $\sigma_{ref} = 164\,530\ KPa$ and the x-coordinate of the assessment point is

$$L_r = \frac{\sigma_{ref}}{\sigma_{ys}} = \frac{164\,530}{255\,025} = 0.6452$$

Therefore, the assessment points are (K_r, Lr) = (0.6452,0.5269) at the deepest point of the crack and (0.6452,0.4143) at the free surface of the crack. These points are located at the safe zone of the failure analysis diagram, so the pipe is acceptable per level 2 assessment.



Minimum allowable temperature (MAT)

Minimum allowable temperature is the coldest temperature of the component that can resist to brittle fracture for certain material, loads and flaw size. Firstly, the temperature decreases the fracture toughness and the yield strength of the material. These parameters affect also the residual stresses, the load ratio and the toughness.

$$L_r^P = \frac{\sigma_{ref}^P}{\sigma_{ys}^{T\ assume}}$$

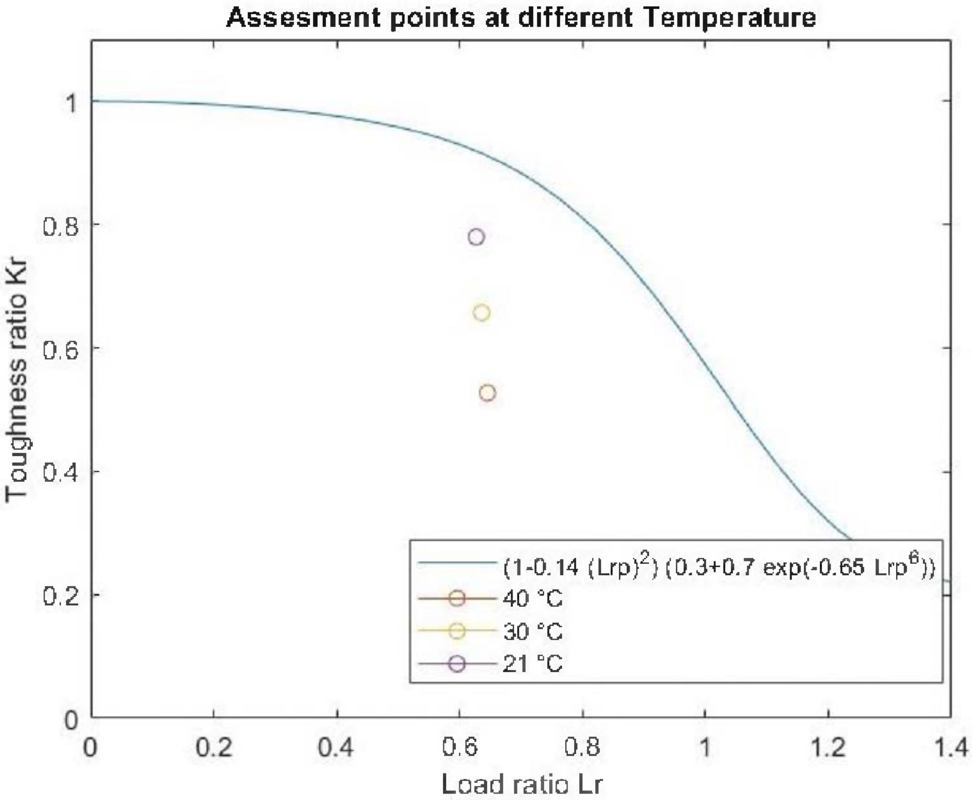
$$K_{r1} = \frac{K_I^P + \Phi \times K_I^{SR}}{K_{mat}^{T\ assume}}$$

$$\sigma_{ys} = \sigma_{ys}^{rt} \cdot \exp\left[C_0 + C_1T + C_2T^2 + C_3T^3 + C_4T^4 + C_5T^5\right] \quad \left({}^oC, MPa\right)$$

- σ_{ys}^{rt} is the yield strength of the material at room temperature
- C_0, C_1, C_2, C_3, C_4, C_5 are parameters from table API-579 2E.2
- T is the temperature; this equation is valid for carbon steels only for 593°C ≥T≥21°C
- Residual stresses are related to yield stress, which is a function of temperature.

In order to determine the minimum allowable temperature, the crack will be assessed with level two assessments for many temperatures. If the assessment point is on the safe side of the fad for certain temperature, then the mat is lower and level two should be repeated for lower temperature until the assessment point is on the fad curve.

Temperature	Load Ratio L_r	Toughness Ratio K_r
T=40°C	0.6452	0.5269
T=30°C	0.6358	0.6569
T=21°C	0.6270	0.7799



As the temperature drops, the assessment points tend to get closer to the FAD-curve. At twenty-one Celsius temperatures, the assessment point is still below the curve, that means that the component can operate at this temperature. Always a safety factor must be used, for this reason the temperature of the metal should not lower.

Limiting flaw size

Sometimes, it is useful to calculate the limiting flaw size of the crack-like flaw, which is the largest possible flaw that does not lead to brittle fracture. This size can be calculated by repeating the level two assessment for different sizes until the assessment point is on the fad curve. If the assessment point is underneath the curve, then the limiting flaw size is larger and if the assessment point is above the curve the limiting flaw size is smaller.

There are two methods to calculate the new depth and the length of the crack during the limiting flaw size assessments. The first method is to increase the flaw size based on the flaw aspect ratio and the second method is based on the ratio of the stress intensity factor values at the surface and deepest part of the crack

$$a = a_0 + \Delta a_1 + \Delta\alpha_2 \ldots$$
$$c = c_0 + \Delta c_1 + \Delta c_2 \ldots$$

Where

- α_0 is the initial depth of the cracks
- c_0 is the initial length the crack
- a and c are the new dimensions of the crack

$$\frac{\Delta\alpha}{\Delta c} = \frac{a_0}{c_0} \; or \; \frac{\Delta\alpha}{\Delta c} = \frac{K_r \; at \; the \; deepest \; point}{K_r \; at \; the \; free \; surface}$$

- K_r is the toughness ratio

For the case study the second method will be used. For the first increment $\Delta\alpha = 0.2 \times t$ =0.0051 where t is the thickness of the vessel, then

$$\Delta c = \frac{K_{r \, free \, surface}}{K_{r \, deepest \, point}} \times \Delta\alpha = 0{,}004 \, m$$

The depth of the crack is

$$a = a_0 + \Delta\alpha = 0.0102 + 0{,}0051 = 0.0153 \, m$$

And the new length of the crack is

$$c = c_0 + \Delta c = 0.0813 + 0.004 = 0.0853 \, m$$

The new flaw must be assessed with the level two assessment. Some parameters have been changed as they are geometrically dependent, such as the influence coefficient parameters (G_0, $G_{1...}G_4$) from the stress intensity solution. The assessment point is below the FAD-curve as it is shown in the following diagram, so the flaw is acceptable. The next increment leads to an unexpectable flaw as the assessment point is above the FAD curve. The following diagram shows six assessments points, as three different flaws were assessed at the deepest point and at the free surface of the crack.

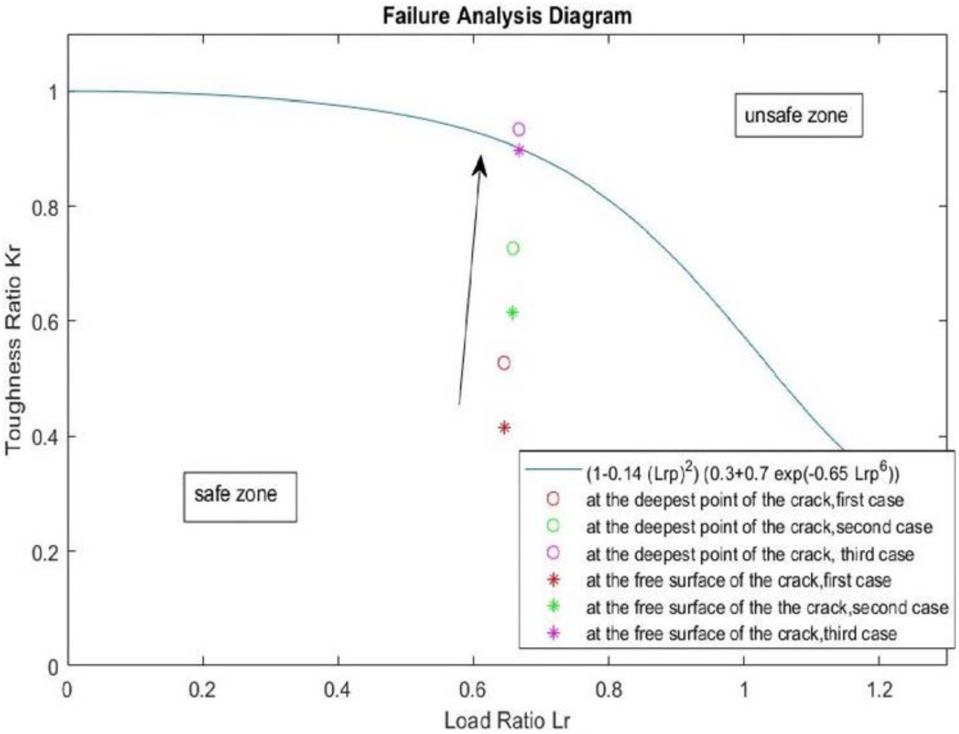
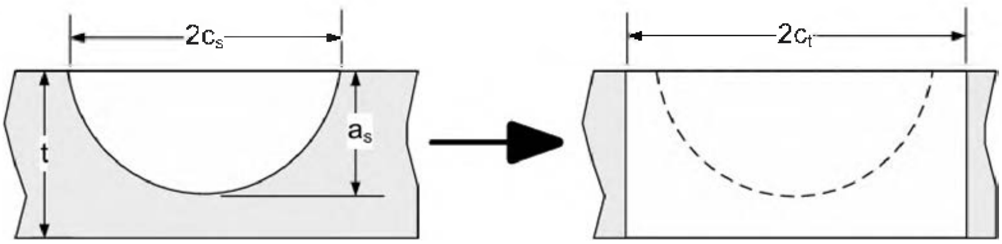


Figure 4.5 The FAD diagram that shows the three elliptical cracks with different sizes that were assessed.

The limiting flaw depth is $0.6t \leq a_{limiting} \leq 0.8t$ where t is the thickness of the vessel because for α=0.6t the flaw is acceptable and for α=0.8t the is unacceptable.

It should be noted that the API-579 suggests that if the depth of a surface elliptical flaw is 80% of the thickness of the vessel, then the flaw should be re-categorized as a *through wall flaw* for more accurate results. Through wall flaws have different stress intensity solution and different reference stress solution. The assessment of through wall flaws uses less geometric parameters than the elliptical surface flaws, so the assessment is easier. The new geometry is illustrated in the next figure and the new dimension of the flaw is calculated with the following equation.

Eventually, through wall flaw is unacceptable per level two assessment so it does not affect the outcome of the previous assessment.



4.6 Surface flaw re-categorized as a through-wall flaw, API-579

$$2c_t = 2c_s + 2(t - a_s)$$

Where, c_t is the half-length of the through-wall flaw, t is the thickness of the vessel, c_s is the half-length and α_s the depth of the elliptical surface flaw.

The following tables show the parameters that were calculated using MATLAB software in order to find the limiting flaw size.

At the deepest point of the crack								
a (m)	c (m)	K_I^P (kPa $m^{0.5}$)	K_I^{SR} (Kpa $m^{0.5}$)	Φ	σ_{ref} (kPa)	L_r	K_r	$K_{r\ max}$
0.0102	0.0830	40 343	12 481	1.1562	164 530	0.6452	0.5269	0.9115
0.0153	0.0853	57 144	15 837	1.1623	167 890	0.6583	0.7268	0.9054
0.0204	0.0896	65 442	32 106	1.1790	170 090	0.6670	0.9937	0.9012

Table 2 Parameters at the deepest point of the flaw that are calculated using MATLAB software

Table 3 4 Parameters at the free surface of the flaw that are calculated using MATLAB software

At the free surface of the crack								
a (m)	c (m)	K_I^P (kPa $m^{0.5}$)	K_I^{SR} (kPa $m^{0.5}$)	Φ	σ_{ref} (kPa)	L_r	K_r	$K_{r\ max}$
0.0102	0.0830	13 280	24 446	1.2185	16 453	0.6452	0.4243	0.9115
0.0153	0.0853	24 599	3.2529	1.2075	167 890	0.6583	0.6145	0.9054
0.0204	0.0896	42 317	42 217	1.2074	170 090	0.6670	0.8980	0.9012

Table 5 Influence coefficients that are used for the calculation of the stress intensity solution at the deepest point of the flaw, φ=90, and at the free surface of the flaw φ=0. These parameters are geometrically dependent

a (m), c (m)		G0	G1	G2	G3	G4
(0.0102 ,0.083)	$\varphi=90^0$	1.507485	0.824150	0.599228	0.485869	0.416643
	$\varphi=0^0$	0.494848	0.062552	0.021744	0.010696	0.006284
(0.0153,0.0853)	$\varphi=90^0$	1.774543	0.917318	0.648366	0.517141	0.438839
	$\varphi=0^0$	0.761300	0.134945	0.054647	0.029356	0.018267
(0.0204,0.0896)	$\varphi=90^0$	1.796596	0.945962	0.673842	0.539389	0.458448
	$\varphi=0^0$	1.156734	0.237338	0.099778	0.544282	0.034134

Chapter 5: Conclusions

The crack-like flaw, that is found on the longitudinal direction of the pipe, is eventually acceptable. Firstly, it was examined with the level one assessment from API-579. This assessment is easy, and it requires the minimum time. However, it is very conservative and can only be applied in specific cases, such as simple geometries. The maximum permitted length of the crack per level one assessment is less than the pipe's crack, which leads to level two assessment.

The level two assessment is more complicated and time consuming than the level one. However, it is less conservative. It uses the Failure Analysis Diagram approach, and the crack-like flaw corresponds to an assessment point. The coordinates of the point derives from stress analysis, stress intensity factor and limit load solutions, and fracture toughness. The assessment point of the pipe's crack is underneath the fad-curve, so the flaw is *acceptable* per level two criteria.

The examination of the crack usually ends when the flaw is characterized as acceptable, but further examination may be useful. Firstly, the level two assessment was repeated at lower temperatures. The temperature, as it is well known, affects the yield strength ,the fracture toughness and the residual stresses. The assessment's temperature was decreased from 40 to 21 Celsius, and the flaw was still acceptable, however the assessment point got closer to the fad curve which means that the safety factor decreased.

Furthermore, the crack like flaw is not expected to grow as there is neither fatigue nor corrosive environment, however it useful to calculate the limiting size of the flaw. The level two was repeated another two times using MATLAB software. Each time the depth and the length of the flaw was increased based on the stress intensity factor on the deepest point and at the free surface respectively. The limiting depth of the flaw is between sixty and eighty percent of the thickness of the pipe. If the crack was expected to grow, then smaller increments of the size would be necessary for better determination of the limiting size.

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