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PART 9 – ASSESSMENT OF CRACK-LIKE FLAWS

CONTENTS

9.1 General

9.1.1 Assessment Procedures for Crack-Like Flaws

Fitness-For-Service (FFS) assessment procedures for evaluating crack-like flaws in components are covered in this Part. These assessment procedures are based on the Failure Assessment Diagram (FAD) method. Details regarding the background and development of the methodology and assessment procedures can be found in Annex 9A.

9.1.2 ASME B&PV Code, Section VIII, Division 2 (VIII-2)

The stress analysis concepts and methods in this Part are based on ASME B&PV Code, Section VIII, Division 2 (VIII-2), Part 5, and reference to VIII-2 is made directly.

9.1.3 Crack-Like Flaw Definition

Crack-like flaws are planar flaws that are predominantly characterized by a length and depth, with a sharp root radius. Crack-like flaws may either be surface breaking, embedded, or through-wall. Examples of crack-like flaws include planar cracks, lack of fusion and lack of penetration in welds, sharp groove-like localized corrosion, and branch type cracks associated with environmental cracking.

9.1.4 Treatment of Volumetric Flaws as Crack-Like Flaws

In some cases, it is conservative and advisable to treat volumetric flaws such as aligned porosity or inclusions, deep undercuts, root undercuts, and overlaps as planar flaws, particularly when such volumetric flaws may contain micro-cracks at the root. This is because an NDE examination may not be sensitive enough to determine whether micro-cracks have initiated from the flaw.

9.1.5 Use of Assessment Procedures to Evaluate Brittle Fracture

The assessment procedures in this Part may be used to compare the relative flaw tolerance or evaluate the risk of brittle fracture of an existing component for screening purposes by postulating a standard reference flaw with a depth equal to 25% of the wall thickness and a length equal to six times this depth.

9.1.6 Service Environment and Material Interactions with Crack-Like flaws

a) Crack-like flaws may be associated with a wide variety of process environment/material interactions and material damage mechanisms. These environmental/material interactions and the associated damage mechanisms tend to be industry specific; however, the mechanisms associated with similar services (e.g. steam) are common for all industries.

b) An overview of the failure modes and damage mechanisms that are covered by this Standard is given in Annex 2B. Knowledge of the damage mechanism may affect decisions regarding the following:

   1) The choice of material properties to be used in a FFS assessment.

   2) The choice of an appropriate crack growth rate.

   3) The permissible amount of crack extension prior to the final fracture or the time between inspections.

   4) The mode of final failure, e.g. unstable fracture, yielding due to overload of remaining ligament, or leak.

   5) The interaction between damage mechanisms, e.g. corrosion and fatigue, creep and fatigue, hydrogen embrittlement and temper-embrittlement, or environmental assisted cracking.

c) Environmental cracks typically occur in multiples and may be branched. The assessment procedures in this Part can be applied to such cracks provided a predominant crack whose behavior largely controls the structural response of the equipment can be identified. The predominant crack in the presence of multiple cracks or branched cracks can be defined through the flaw characterization techniques described in paragraph 9.3.6. When a predominant crack cannot be defined even after re-characterization, more advanced FFS techniques such as damage mechanics, which are outside the scope of this document, are available.

9.2 Applicability and Limitations of the Procedure

9.2.1 Overview

The assessment procedures of this Part can be used to evaluate pressurized components containing crack-like flaws. The pressurized components covered include pressure vessels, piping, and tanks that are designed to a recognized code or industry standard. Specific details pertaining to the applicability and limitations of each of the assessment procedures are discussed below.

9.2.2 Applicability of the Level 1 and Level 2 Assessment Procedures

The Level 1 and 2 Assessment procedures in this Part apply only if all of the following conditions are satisfied:

a) The original design criteria were in accordance with Part 2, paragraph 2.2.3.

b) The component is not operating in the creep range (see Part 4, paragraph 4.2.3).

c) Dynamic loading effects are not significant (e.g. earthquake, impact, water hammer, etc.).

d) The crack-like flaw is subject to loading conditions and/or an environment that will not result in crack growth. If a flaw is expected to grow in service, it should be evaluated using a Level 3 Assessment, and the remaining life should be evaluated using the procedures of paragraph 9.5.

e) The following limiting conditions are satisfied for a Level 1 Assessment.

1) Limitations on component and crack-like flaw geometries:

i) The component is a flat plate, cylinder, or sphere.

ii) Cylinders and spheres are limited to geometries with $R/t \geq 5$ where R is the inside radius and t is the current thickness of the component.

iii) The wall thickness of the component at the location of the flaw is less than 38 mm (1.5 inches).

iv) The crack-like flaw geometry can be of the surface or through-thickness type, specific limitations for the crack-like flaw depth are included in the Level 1 Assessment procedure (see paragraph 9.4.2). The maximum permitted crack length is 200 mm (8 inches).

v) For cylindrical and spherical shell components, the crack-like flaw is oriented in the axial or circumferential direction (i.e. perpendicular to a principal stress direction) and is located at a distance greater than or equal to $1.8\sqrt{Dt}$ from any major structural discontinuity where D is the inside diameter and t is the current thickness of the component. For a flat plate, the crack-like flaw is oriented such that the maximum principal stress direction is perpendicular to the plane of the flaw. If the crack-like flaw is oriented such that it is not perpendicular to a principal stress plane, then the flaw may be characterized by the procedure in paragraph 9.3.6.2.b.

2) Limitations on component loads:

   i) The loading on the component is from pressure that produces only a membrane stress field. Pressurized components subject to pressure that result in bending stresses (e.g. head-to-cylinder junction, nozzle intersections, rectangular header boxes on air-cooled heat exchangers) and/or components subject to supplemental loading (see Annex 2C) shall be evaluated using a Level 2 or Level 3 Assessment.

   ii) The membrane stresses during operation are within the design limits of the original construction code.

   iii) If a component being evaluated is to be subject to a pressure test, the component's metal temperature shall be above the MAT during the test (see Part 3, paragraph 3.1.6 and paragraph 3.6.2.3). After the pressure test, the crack-like flaw shall be re-examined to ensure that the flaw has not grown.

   iv) The weld joint geometry is either a Single-V or Double-V configuration; the residual stresses are based on the solutions provided in Annex 9D.

3) The material meets the following limitations:

   i) The material is carbon steel (P1, Group 1 or 2) with an allowable stress in accordance with the original construction code that does not exceed 172 MPa (25 ksi).

   ii) The specified minimum yield strength for the base material is less than or equal to 276 MPa (40 ksi), the specified minimum tensile strength for the base material is less than or equal to 483 MPa (70 ksi), and the weldments are made with an electrode compatible with the base material.

   iii) The fracture toughness is greater than or equal to the lower bound K_{IC} value obtained from Annex 9F. This will be true for carbon steels where the toughness has not been degraded because of environmental damage (e.g., fire damage, over-heating, graphitization, etc.).

9.2.3 Applicability of the Level 3 Assessment Procedure

A Level 3 Assessment should be performed when the Level 1 and 2 methods cannot be applied or produce overly conservative results. Conditions that typically require a Level 3 Assessment include the following.

a) Advanced stress analysis techniques are required to define the state of stress at the location of the flaw because of complicated geometry and/or loading conditions.

b) The flaw is determined or expected to be in an active subcritical growth phase or has the potential to be active because of loading conditions, e.g. cyclic stresses, and/or environmental conditions, and a remaining life assessment or on-stream monitoring of the component is required.

c) High gradients in stress, (either primary or secondary as defined in VIII-2) material fracture toughness, or material yield and/or tensile strength exist in the component at the location of the flaw (e.g. mismatch between the weld and base metal).

9.2.4 Assessment Procedures for Notches in Groove-Like Flaws

Assessment procedures to evaluate a notch at the base of a groove-like flaw are covered in Part 12.

9.3 Data Requirements

9.3.1 General

9.3.1.1 The information required for a Level 1 Assessment is shown below:

a) Original Equipment Design Data (see paragraph 9.3.2).

b) Maintenance and Operating History (see paragraph 9.3.3).

c) Material reference temperature, i.e. toughness curve.

d) Flaw Characterization (see paragraph 9.3.6).

9.3.1.2 The information required to perform a Level 2 or Level 3 Assessment is covered in paragraphs 9.3.2 through 9.3.7. The choice of input data should be conservative to compensate for uncertainties. In a Level 3 assessment, a sensitivity analysis, partial safety factors or a probabilistic analysis shall be used to evaluate uncertainties.

9.3.1.3 The datasheet shown in Table 9.1 should be completed before the FFS assessment is started. This ensures that all of the pertinent factors are considered, communicated, and incorporated into the assessment. The information on this datasheet is used for a Level 1 or Level 2 Assessment. In addition, this information is generally applicable for a Level 3 Assessment. Guidelines for establishing the information to be entered on this datasheet are provided in paragraphs 9.3.2 through 9.3.7.

9.3.2 Original Equipment Design Data

9.3.2.1 An overview of the original equipment data required for an assessment is provided in Part 2, paragraph 2.3.1.

9.3.2.2 Equipment data is required in order to compute the stress intensity factor and reference stress solution based on the geometry of the component at the crack location.

a) For pressure equipment with uniform thickness such as vessels, pipes, and tanks, the important dimensions are the inside diameter and wall thickness.

b) For pressurized equipment with a non-uniform thickness, or where structural discontinuities are involved, e.g. vessel head-to-shell junctions, conical transitions, nozzles, piping tees, and valve bodies, the dimensions required include the diameter, wall thickness, and the local geometric variables required to determine the stress distribution at a structural discontinuity.

9.3.3 Maintenance and Operating History

9.3.3.1 An overview of the maintenance and operating history required for an assessment is provided in Part 2, paragraph 2.3.2.

9.3.3.2 Maintenance and operational input should be provided by personnel familiar with the operational and maintenance requirements of the component containing the crack-like flaw. This data provides a basis for determining the following:

a) The most probable mechanism of the cracking.

b) Whether or not the crack is growing.

c) Reasonable estimates for the flaw size based on prior records of cracking or experience with other components in a similar service.

d) The most probable mechanism of the failure expected.

e) Potential remediation measures.

9.3.4 Required Data/Measurements for a FFS Assessment – Loads and Stresses

9.3.4.1 Load Cases

The stress distribution at the cracked region of the component should be determined for all relevant loads based on the planned future operating conditions. An overview of the load cases to consider in a stress analysis is provided in Annex 2C and Annex 2D. It is important that the combination of pressure and temperature be determined for all load cases because of the dependence of the material fracture toughness with temperature.

9.3.4.2 Stress Computation

The stress distributions from each load case are calculated based on the uncracked component geometry using loads derived from the future operating conditions.

a) A non-uniform stress distribution may occur through the wall thickness or along the surface of the component. Examples include the through-wall stresses in a pressurized thick wall cylinder, the stress attenuation that occurs at a major structural discontinuity (e.g. nozzle-to-shell and head-to-shell junctions), and the stress distribution caused by a thermal gradient that typically occurs at a skirt-to-vessel attachment. The method used to determine the state of stress in a component should include capabilities to compute stress distributions based on loading conditions and structural configuration.

b) Stress analysis methods based on handbook solutions may be used if these solutions accurately represent the component geometry and loading condition. Otherwise, numerical analysis techniques such as the finite element method shall be used to determine the stress field at the crack location.

c) If it is necessary to linearize computed through-wall stress profiles into membrane and bending stress components to compute a stress intensity factor and reference stress for certain crack geometries and load conditions, then the linearization of the through-wall stress field in the presence of a crack shall be performed in accordance with VIII-2, Part 5.

d) If it can be verified that the crack-like flaw in the component occurred after application of load, then the stress distribution may be computed using an elastic-plastic analysis.

e) Stress computation shall be performed with a weld joint efficiency equal to 1.0.

9.3.4.3 Stress Classification

The stress analysis methods in this Part are based on VIII-2, Part 5. For each loading condition under consideration, the stress distributions at the cracked region of the component shall be classified into the following stress categories in order to complete a Level 2 Assessment.

a) Primary Stress – The stress distribution developed by the imposed load-controlled loading that is necessary to satisfy the laws of equilibrium (see VIII-2, Part 5). In addition, the primary stress shall also include any recategorized secondary stresses. In accordance with VIII-2, Part 5, primary stresses are categorized as follows:

- General Primary Membrane Stress
- Local Primary Membrane Stress
- Primary Membrane (General or Local) Plus Primary Bending Stress

b) Secondary Stress – A secondary stress distribution is developed by the constraint of adjacent parts or by self-constraint of a component (sees VIII-2, Part 5). If it is uncertain whether a given stress is a primary or secondary stress, it is more conservative to treat it as primary stress. It should be noted that in certain cases secondary stresses that are self-equilibrating over the entire structure or component might still result in plastic collapse in the net-section local to the crack-like flaw. This can occur when the flaw is small compared to the spatial extent of the secondary stress distribution, or there is significant elastic follow-up from the surrounding structure. In these cases, the secondary stress should be treated as a primary stress in the assessment. In accordance with VIII-2, Part 5, Secondary Stresses may be comprised of both membrane and bending stresses.

c) Residual Stress – Crack extension can occur locally if the crack tip is located in a tensile residual stress field. Therefore, residual stresses resulting from welding shall be included in the assessment. The magnitude and distribution of residual stress shall be determined using Annex 9D.

9.3.5 Required Data/Measurements for a FFS Assessment – Material Properties

9.3.5.1 Material Yield and Tensile Strength

The yield and tensile strength of the material are required in the FFS assessment to determine the effects of plasticity on the crack driving force, estimate the residual stress, and evaluate the fracture toughness using correlations with other material toughness parameters.

a) If heat-specific yield and tensile strengths for the material and/or weldments are not available, then estimates may be made using the information in Annex 2E. Otherwise, the specified minimum values of yield stress and tensile stress for the base and weld material shall be used.

b) In general, use of minimum values of yield and tensile strengths will result in a conservative assessment. However, if there are residual stresses in the region of the crack-like flaw, the use of the specified minimum yield strength will tend to under estimate the magnitude of the residual stresses. Therefore, when estimating the magnitude of residual stresses, the actual yield strength should be used. If the actual yield strength is not known, the value of the minimum yield strength shall be adjusted using the procedure in Annex 9D before the residual stresses are computed.

c) The material yield and tensile strength for the region(s) ahead of the crack tip should be adjusted, as appropriate, to take account of temperature, strain aging, thermal aging, or other prevalent forms of degradation.

d) The material stress-strain curve or Ramberg-Osgood constants are required if a J-integral evaluation or elastic-plastic stress analysis is performed as part of the assessment.

9.3.5.2 Material Fracture Toughness

The fracture toughness of the material is a measure of its ability to resist failure by the onset of crack extension to fracture.

a) Guidance for determining fracture toughness for various materials and environments is provided in Annex 9F.

b) The process environment, service temperature envelope, and any related material/service degradation mechanisms such as embrittlement shall be accounted for when determining the fracture toughness.

c) Local variations in the fracture toughness near the crack tip shall be considered in the assessment.

d) When material specific toughness is not available, then lower bound values may be used.

9.3.5.3 Crack Growth Model

A crack growth model and associated constants are required if an estimate of the remaining life of the component with a crack-like flaw is to be made based on a fracture mechanics approach. An overview of crack growth models and data are provided in Annex 9F. The model chosen for the assessment shall account for environmental effects, and may be related to cyclic behavior (da/dN), time to failure (da/dt), or both.

9.3.5.4 Material Physical Constants

Material properties such as the elastic modulus, Poisson's ratio, and the thermal expansion coefficient may be required to perform an evaluation. Guidelines for determining these quantities are provided in Annex 9F.

9.3.6 Required Data/Measurements for a FFS Assessment – Flaw Characterization

9.3.6.1 Overview

The flaw characterization rules allow existing or postulated crack geometry to be modeled by a geometrically simpler one in order to make the actual crack geometry more amenable to fracture mechanics analysis. The nomenclature and idealized shapes used to evaluate crack-like flaws are shown in Figure 9.1. The rules used to characterize crack-like flaws are necessarily conservative and intended to lead to idealized crack geometries that are more severe than the actual crack geometry they represent. These characterization rules account for flaw shape, orientation and interaction.

9.3.6.2 Characterization of Flaw Length

If the flaw is oriented perpendicular to the plane of the maximum principal tensile stress in the component, then the flaw length to be used in calculations (c or $2c$) is the measured length c_m or $2c_m$. If the flaw is not oriented in a principal plane, then an equivalent flaw dimension with a Mode I orientation shall be determined by one of the following options.

a) Option 1 – The flaw dimension, c, to be used in the calculations shall be set equal to the measured length, c_m, irrespective of orientation. For fracture assessments, the plane of the flaw shall be assumed to be normal to the maximum principal tensile stress.

b) Option 2 – The procedure for defining an equivalent Mode I flaw dimension is shown in Figure 9.2.

   1) STEP 1 – Project the flaw onto a principal plane. In the case of uniaxial loading, there is only one possible principal plane. When the loading is biaxial (e.g., a pressurized component which is subject

to a hoop stress and an axial stress), there is a choice of principal planes on which to project the flaw. In most cases, the flaw should be projected to the plane normal to the maximum principal tensile stress (the σ_1 plane), but there are instances where the σ_2 plane would be more appropriate (e.g., when the angle between the flaw and the principal plane (α) is greater than 45°).

2) STEP 2 – Compute the equivalent flaw length.

i) For the plane of the flaw projected onto the plane normal to σ_1:

$$\frac{c}{c_m} = \cos^2\alpha + \frac{(1-B)\sin\alpha\cos\alpha}{2} + B^2\sin^2\alpha \tag{9.1}$$

ii) For the plane of the flaw projected onto the plane normal to σ_2:

$$\frac{c}{c_m} = \frac{\cos^2\alpha}{B^2} + \frac{(1-B)\sin\alpha\cos\alpha}{2B^2} + \sin^2\alpha \tag{9.2}$$

iii) In the Equations (9.1) and (9.2), the dimension c corresponds to the half flaw length (or total length for corner or edge cracks) to be used in calculations, c_m is the measured half-length for the flaw oriented at an angle α from the σ_1 plane, and B is the biaxiality ratio defined using Equation (9.3). If stress gradients occur in one or more directions, the sum of membrane and bending components shall be used for computing σ_1 and σ_2.

$$B = \frac{\sigma_2}{\sigma_1} \qquad \textit{where } \sigma_1 \ge \sigma_2 \textit{ and } 0.0 \le B \le 1.0 \tag{9.3}$$

iv) Equations (9.1) and (9.2) are only valid when both σ_1 and σ_2 are positive. If σ_2 is compressive or equal to zero, then Equation (9.1) shall be used to compute the equivalent flaw length with $B = 0$, or

$$\frac{c}{c_m} = \cos^2\alpha + \frac{\sin\alpha\cos\alpha}{2} \tag{9.4}$$

v) The relationship between c/c_m, α, and B is shown in Figure 9.3.

9.3.6.3 Characterization of Flaw Depth

The part through-wall depth of a flaw can be considerably more difficult to estimate than the length. Either a default value or a value based on detailed measurements may be used for the flaw depth in the assessment. In services where the owner determines that a leak is not acceptable, the flaw size shall be characterized by actual measurement in accordance with paragraph (b) below.

a) Flaw Depth by Default Values

1) Through-Wall Flaw – If no information is available about the depth of a flaw, a conservative assumption is that the flaw penetrates the wall, i.e., $a = t$ for a surface flaw. In pressurized components, an actual through-wall flaw would most likely lead to leakage, and thus would not be acceptable in the long term. However, if it can be shown that a through-wall flaw of a given length would not lead to brittle fracture or plastic collapse, then the component should be acceptable for

continued service with a part-through-wall flaw of that same length. Additional special considerations may be necessary for pressurized components containing a fluid where a leak can result in autorefrigeration of the material near the crack tip, or other dynamic effects.

2) Surface Flaw – Flaw depths less than the full wall may be assumed if justified by service experience with the type of cracking observed. If service experience is not available, then the assumed flaw depth should not be less than the following where length of the flaw is $2c$ (see Figure 9.1(b)).

$$a = \min\left[t,\, c\right] \tag{9.5}$$

b) Flaw Depth from Actual Measurements

1) The definition of the appropriate depth dimensions, a for a surface flaw, and $2a$ and d for an embedded flaw, when relatively accurate measurements are available is illustrated in Figures 9.1 and 9.4. If the flaw is normal to the surface, the depth dimension, a, is taken as the measured dimension, a_m. However, if the flaw is not normal to the surface, e.g. a lack of fusion flaw that is parallel to the bevel angle or a lamination (see Figure 9.4) the following procedure may be used to compute the depth dimension, a.

i) STEP 1 – Project the flaw onto a plane that is normal to the plate surface, designate this flaw depth as a_m.

ii) STEP 2 – Measure the angle to the flaw, θ, as defined in Figure 9.4, and determine W using the Equations (9.6) and (9.7) or Figure 9.5 where θ is measured in degrees.

$$W = \max[W_{Theta},\ 1.0] \tag{9.6}$$

$$W_{Theta} = \begin{pmatrix} 0.99999 + 1.0481\left(10^{-5}\right)\theta + 1.5471\left(10^{-4}\right)\theta^2 + \\ 3.4141\left(10^{-5}\right)\theta^3 - 2.0688\left(10^{-6}\right)\theta^4 + 4.4977\left(10^{-8}\right)\theta^5 - \\ 4.5751\left(10^{-10}\right)\theta^6 + 1.8220\left(10^{-12}\right)\theta^7 \end{pmatrix} \tag{9.7}$$

iii) STEP 3 – Multiply a_m by W to obtain the dimension a, which is used in calculations. Note that the dimension d for buried flaws may decrease when the flaw depth is determined using this approach.

2) If the remaining ligament is small, it may be necessary to recategorize the flaw depending on the remaining ligament size. An embedded flaw may be recategorized as a surface flaw and a surface flaw may be recategorized as a through-wall flaw. Rules for flaw recategorization are provided in paragraph 9.3.6.6.

9.3.6.4 Characterization of Branched Cracks

Determination of an idealized flaw is complicated when a branched network of cracks forms in a component because the idealized flaw must be equivalent to the network of cracks from a fracture mechanics approach. The methodology for assessing a network of branched cracks is shown in Figure 9.6. As shown in this figure, the network is idealized as a single planar predominant flaw by means of the following procedure:

a) STEP 1 – Draw a rectangle around the affected region. Define the measured flaw length, $2c_o$, as the length of the rectangle (see Figures 9.6(a) and (b)).