CORROSION DAMAGE MODULE

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9 Corrosion damage module

Scope

The FITNET FSS Procedure in this Section provides guidelines on the appropriate steps to take when an environmental assisted, either by stress corrosion or corrosion fatigue, crack as well as a local thin area (LTA) has been detected in service and an assessment of the implications for structural integrity has to be done. Such an evaluation should be made in the context of the perceived consequences of failure using appropriate risk-based management methodologies. Since this is plant/component specific it is beyond the scope of this procedure.

Hence, this section deals primarily with the Fitness-for-Service assessments of damage types due to ;

a) Environmental assisted cracking (EAC)

a1) Stress corrosion cracking,

a2) Corrosion fatigue, and

b) Local Thin Area (LTA)

9.1 Assessment of stress corrosion cracking and corrosion fatigue

9.1.1 Introduction

When assessing the integrity of structures with cracks or crack-like defects, it is necessary to consider whether sub-critical crack growth is a potential factor. If so, an estimate of the amount of tolerable growth during the design lifetime or between in-service inspections is required. In that context, structural integrity assessment has to take into account the distinct characteristics of the damage processes associated with environmental assisted cracking (EAC). The conditions in which EAC occurs is often represented by Figure 9.1 and involves a combination of stress, environment and microstructural susceptibility, although it should be emphasised that this interaction occurs at a highly localised level and it is the *local* characteristics of these variables rather than the nominal bulk values that are critical.

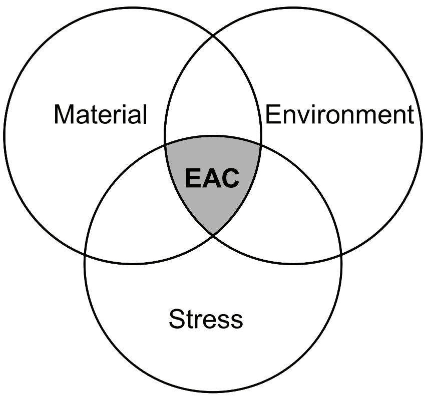


Figure 9.1 – Venn diagram showing the inputs that lead to the formation of EAC (Stress Corrosion Cracking and Corrosion Fatigue).

In this section, subcritical crack growth due to stress corrosion cracking (predominantly static load or slow rising load) and corrosion fatigue (predominantly cyclic load) is considered, with crack growth rate prediction in service based principally on the application of fracture mechanics in terms of either stress intensity factor (K) in the case of stress corrosion cracking, or the range of stress intensity factor (ΔK), in corrosion fatigue. Underlying that assumption is the presumption that the flaws or cracks are of a dimension that allows a description of the mechanical driving force by linear elastic fracture mechanics (LEFM). In practice, for some systems, a significant amount of life may occur in the short crack regime that, if known, should be taken into account in the assessment. Figure 9.2 illustrates the transition in mechanical driving force with flaw size for a stress corrosion crack; similar behaviour is observed for corrosion fatigue cracks.

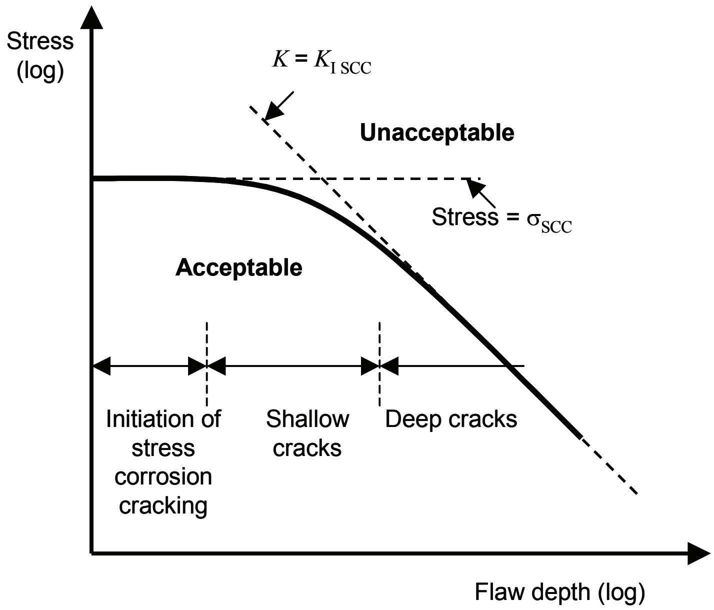


Figure 9.2 – Schematic diagram of the two-parameter approach to stress corrosion cracking

Here, cracks may have initiated from the surface at irregularities created by surface roughness or at locations of stress concentration, from pits or other localised corrosion sites, or from shallow defects (e.g. at the toe of a weld). The threshold stress, σ_{SCC}, applied to nominally plain surfaces is the stress above which any initiated crack will continue to propagate. It is not simply a threshold for initiation as cracks may initiate but then stop growing. K_{ISCC} is the threshold stress intensity factor for sustained crack growth (above this value any initiated crack will continue to grow and below, growing cracks will arrest). The full line in Figure 9.2 delineates the conditions for sustained crack growth. Below this line, any crack developed will become non-propagating. In many practical applications cracks are often not detected until the depth is of a size commensurate with the application of linear elastic fracture mechanics but there are exceptions where relatively long but shallow cracks may be detected. In that case, an approach to crack growth and life prediction must account for the extent of growth in the shallow crack regime, as this may be a significant fraction of the life.

A major challenge in prediction of crack growth in service is to account for the particular service history, including scheduled and uncontrolled variations in stress, temperature and water chemistry. These can impact on judgement as to when the crack initiated and also whether the growth is quasi-continuous or in response to particular transients. For example, cracking that is detected after several years of service may have occurred over the space of several hours or days when atypical operating conditions were present; no cracking may have occurred before or after this upset. An average crack growth rate, obtained by dividing the crack size by the total time in service, would be meaningless in such instances. Simulation of service conditions in the laboratory can be difficult and thus the crack growth database may not be ideal. These varied uncertainties, allied to expert judgment, feed into the risk assessment when adopting a risk-based inspection methodology.

In this section, a procedural approach to evaluating the evolution of damage due to environment assisted cracking is presented that includes: establishing the origin and nature of the crack; defining the service operational conditions and history; applying crack growth calculations.

All cases in which subcritical crack growth are included in structural integrity assessment should be referred to and analysed by an engineer sufficiently knowledgeable about the interactions between cracks, environment, component (structural) design, and loading history (including cyclic loads).

9.1.2 Procedural approach assessment of stress corrosion cracking and fatigue

9.1.2.1 Step 1: Characterise the nature of the crack

Once a crack has been detected, a first step is to develop a complete physical evaluation in terms of its shape and dimensions, with any uncertainty in size from the particular detection method taken into account. This evaluation should include an assessment of the crack location in relation to local stress concentrators, welds, crevices (e.g. at fasteners, flanges), and also the details of the crack path and crack orientation, if feasible. If more than one crack is present, the crack density and the spacing between the cracks should be noted in view of possible future coalescence. Also, the state of the surface should be assessed for general or localised corrosion damage. Where coatings are present, the state of the coating should be assessed. The possibility of cracks in other similar locations should be evaluated and inspection in those regions undertaken accordingly.

9.1.2.2 Step 2: Establish cause of cracking

Identifying the cause of cracking in terms of the mechanistic process, i.e. stress corrosion or corrosion fatigue, may be challenging unless service conditions allow ready discrimination; for example, an absence of significant cyclic loading. Characterising the crack as a stress corrosion crack may be possible from visible observation, e.g. significant crack branching (although such branching would preclude simple stress analysis and warrant removal of the crack). In most cases it is deduced from prior experience for the service conditions and awareness of the likelihood of other failure modes, but recognising that loading in service does not correspond usually to the simple static load tests often conducted in the laboratory. Thus, there may be dynamic straining associated with occasional transient temperature changes. Distinction between a "conventional" stress corrosion failure mechanism based on anodic reaction and a hydrogen embrittlement mechanism may not be possible but this is not a critical issue provided that the laboratory data used for assessment relate to the particular service conditions.

Where cyclic loading is apparent, corrosion fatigue should be considered to be the primary mechanism of crack growth. However, the loading frequency is a key factor with the influence of the environment on crack propagation decreasing in significance as the frequency increases and for many systems often being insignificant at frequencies greater than about 10 Hz. However, as the crack proceeds, the possibility of activating stress corrosion failure modes should be considered. Otherwise, the role of corrosion under high frequency loading may be constrained to its effect on initiation, e.g. by creating corrosion pits that act as crack precursors.

9.1.2.2.1 Define service condition

The service conditions that need to be defined include the stress state and the environmental conditions.

9.1.2.2.1.1 Stress

It is necessary to define or make reasonable assumptions about the possible stresses on the structure (both past and future) including normal operational stresses (primarily static or random cyclic), transient stresses associated with start-up and shut-down or systems upsets, residual stresses at welds or on cold-worked surfaces, the existence of multi-axial stress states, and stress concentrations. Transient stresses are often critical in inducing or propagating stress corrosion cracks but historically have often been overlooked in laboratory testing.

9.1.2.2.1.2 Service environment

The intended service environment is normally well characterised but it is critical to recognise that it may be a local environment change or an excursion from normal water chemistry or of temperature that is responsible for driving the cracking process.

9.1.2.2.1.2.1 Development of local environments (crevicing, hideout/evaporation, deposits)

Crevice corrosion and under-deposit corrosion risks can normally be evaluated by an appropriate expert and the degree of concentration of impurity anions such as chloride by ion migration under the influence of a known potential difference (when an oxidising agent is present at the pit or crevice mouth) can be estimated. Concentration processes due to hideout/evaporation under heat transfer conditions can be much more powerful than those due to ion migration. The theoretical limit of concentration can be estimated from the solubility of impurity solutes at the operating temperature and the local superheat available. A solute will concentrate until it raises the boiling point until boiling no longer occurs given the local superheat and system pressure or until it reaches its solubility limit if that intervenes beforehand, in which case the locally superheated zone becomes steam blanketed (which may not necessarily be better from a stress corrosion viewpoint).

It is critical is testing or adopting laboratory crack growth data to assess its relevance to the conditions for cracking.

9.1.2.2.1.2.2 Excursions

The probability of a leaking condenser, ion-exchange failure, residue from chemical cleaning, cooling water failure (giving temperature rise), oxygen ingress etc., all require objective assessment. The concern with a transient increase in temperature or change in service environment is that it may move the system into a domain for activation of stress corrosion cracking, which would otherwise not be a concern. Thus, in assessing the significance of a crack, the exposure history should be examined and the extent of available data for predicting the likelihood of growth, and the growth rate at the normal temperature or chemistry following an excursion evaluated.

9.1.2.2.1.2.3 Corrosion (or system) monitoring

Corrosion monitoring can be an important tool in assessing the aggressivity of the service environment and is particularly useful when plant conditions fluctuate due to transients in water chemistry, contamination etc. If these transients can be identified as the occasions when stress corrosion cracks may develop and propagate, then a more informed basis for prediction may be generated based on the number of damaging cycles, rather than simply the elapsed time of exposure. This may also allow benchmarking of the onset of initial damage, from the first transient or when a coating or other protective systems has failed.

9.1.2.3 Step 3: Define the material characteristics

The first step is to ensure that the material of relevance actually corresponds to that specified at the design stage. In essence, this relates primarily to the quality control aspects of fabrication and installation and means assessing the traceability of the materials selection and welding process relative to the design specification. In some cases, in-situ measurement such as hardness may be undertaken. There are a number of factors that may subsequently affect the performance of the material.

9.1.2.3.1 Surface finish and cold work

In much of laboratory testing, specimens are usually wet-ground ground to a well-controlled surface finish, typically with a roughness value Ra less than 1 μm, the primary purpose being to ensure repeatability of data and avoid any influence of surface cold work. In service, materials are often ground fairly crudely (or indeed may be supplied with retained cold work from processing). Poorly controlled (abusive) machining can cause surface overheating. Correspondingly, there may be significant surface stresses, deformation layers, increased hardness, and for some metastable alloys the possibility of microstructural transformation (e.g. bainite to untempered martensite). High dislocation densities and associated short circuit diffusion pathways can enhance some types of stress corrosion. For this reason, cracking in service may not be reliably predicted from laboratory tests without attention to these details. The cold work layer is a near surface layer and an area of uncertainty in prediction is the extent to which cracks initiated in this layer will continue to propagate once they have grown beyond the cold worked region. There are situations in service where non-propagating cracks have been observed but there are also indications that if the depth of cold work is sufficient the cracks will continue to propagate. The problem is that characterisation of the degree and depth of cold work in-situ may not be straightforward but may be inferred from experience with the material preparation route.

9.1.2.3.2 Welding

Assuming that radiographic assessment has ensured that there were no physical flaws of significance (care must be taken as radiography may not detect all cracks, depending on the angle of the beam and crack direction and the extent of crack "gaping"), the issue for welded sections as far as propagation of cracks is concerned is primarily in relation to residual stress, hardness, and local microstructural and/or microchemical changes, although joint geometry could have an influence on the mechanical driving force and local environment chemistry.

The concern for welds in relation to the microstructural and microchemical aspects is the possible departure from the weld procedure qualification, with perhaps too high a heat input, inappropriate filler leading to sensitisation at grain boundaries or at precipitate particles, elongated and clustered inclusions, local hard spots. It is not really possible to measure these characteristics in-situ but it is necessary to account for these possible factors when conducting tests. In the latter context, there is increasing recognition of the need to test in the as-welded state.

9.1.2.3.3 Thermal ageing

Materials operated at high temperature for extended periods can undergo thermal aging induced microstructural and microchemical changes that often increase stress corrosion susceptibility. Common examples include cast stainless steels undergoing spinoidal decomposition of the ferrite with very significant hardening and aging of precipitation-hardened stainless steels such as 17-4PH. Once hardness values exceed 350HV experience shows that the risk of environmentally induced cracking in aqueous environments increases and above 400HV cracking failures are practically guaranteed. Another problem is thermally induced sensitisation of austenitic stainless steels (particularly if the C-content exceeds 0.03% and they are not stabilised by Nb or Ti) due to the precipitation of chromium carbides at the grain boundaries on prolonged service at (or slow cooling through) temperatures in the range 425°C (or less for low temperature sensitisation) to 875°C.

Besides the effect on crack propagation rate and threshold conditions, microstructural changes, e.g. in high pressure/intermediate pressure turbine components, can lead to a deterioration in toughness (ageing embrittlement) and hence in the decrease of the critical flaw size for unstable fracture, reducing then the residual life during propagation.

9.1.2.3.4 Irradiation damage

Irradiation damage, in so far as it may lead to significant hardening, may have a similar effect to thermal aging described above. Another effect observed in austenitic stainless steels subject to high neutron irradiation doses exceeding about one displacement per atom is a significant change in grain boundary composition due to the migration of point defects to sinks such as grain boundaries (as well as dislocations and free surfaces). The most notable consequence in common austenitic stainless steels is a reduction in the chromium concentration in a very narrow band about 10 nm wide at grain boundaries leading to IGSCC in oxidising high temperature water. It is sometimes called irradiation-induced sensitisation but there are no grain boundary carbides as with thermally induced sensitisation.

9.1.2.3.5 Material processing and microstructural and microchemical orientation

The material processing and welding history may lead to orientated microstructures and microchemistry. The orientation of the microstructure relative to the principal stresses can influence the evolution of stress corrosion cracking. This is a particular issue where there is an elongated grain structure and significant differences in properties between the longitudinal and transverse directions, as observed for example in aluminium alloys.

9.1.2.4 Step 4: Establish data for stress corrosion cracking assessment

9.1.2.4.1 K_{ISCC} determination

The concept of K_{ISCC} is not trivial and the value is sensitive to the environmental conditions, temperature and loading characteristics. Accordingly, data obtained for one condition should not be transposed to another. Consequently data from literature should be used with care.

It is apparent from Figure 9.2 that initiation and growth can occur in the domain for which linear elastic fracture mechanics is inapplicable. The growth rate in the short crack domain and its relation to the relevant mechanical driving force is poorly characterised in stress corrosion cracking and needs further research. In some circumstance, it could be envisaged that cracks may start and then stop unless there is sufficient mechanical driving force to maintain their development.

When the crack is of a length commensurate with the application of fracture mechanics, a threshold stress intensity factor for stress corrosion crack propagation, K_{ISCC}, is often defined. For long cracks, the behaviour is typically as represented as in Figure 9.3.

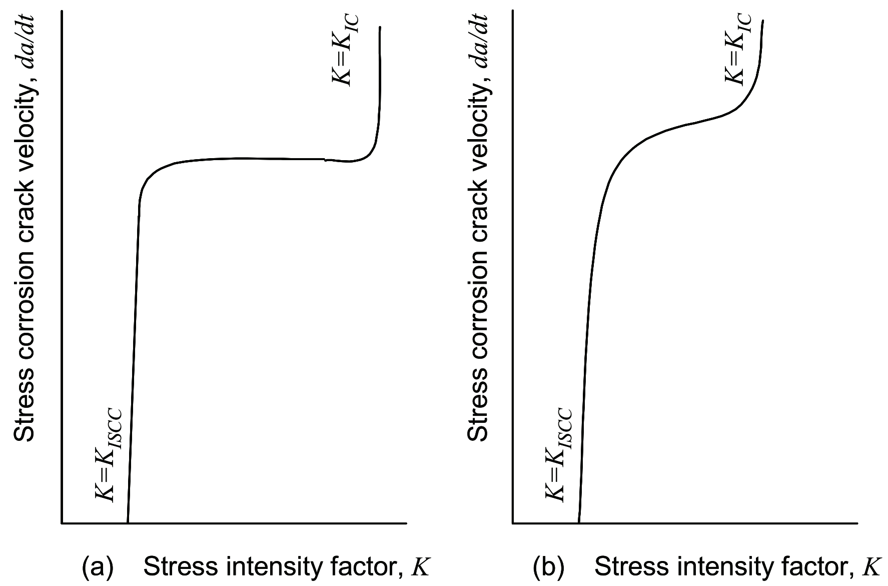


Figure 9.3 – Schematic illustration of typical crack growth behaviour in stress corrosion cracking showing a relatively distinct plateau region of crack growth (a) and a more gradual change in crack growth rate with K (b), [9.1]

However, K_{ISCC} should not be regarded as an intrinsic characteristic of the material as it will depend sensitively on the environment and loading conditions, which should reflect those for the service application. Also, there may be long-term changes in the material due to exposure that are not reflected in short term laboratory tests. The definition implies no crack growth, or crack arrest, below this value, which intrinsically brings in issues of resolution of the crack size measuring method and the patience of the experimenter.

It is common to conduct K_{ISCC} tests under static load conditions and accordingly results unrepresentative of service are often obtained. Structures are seldom subjected to purely static loading and it is well known that the value of K_{ISCC} can be considerably reduced if a dynamic loading component is involved; for example a thermal transient, following an outage, or superimposed cyclic loading, even of small magnitude.

Should it be decided that K_{ISCC} values obtained under static loading are appropriate, these can be determined using the procedures described in ISO 7539 Part 6 [9.2]. This document describes both crack initiation and crack arrest methods using fatigue pre-cracked, fracture mechanics type specimens tested under constant load or constant displacement. For some systems, the value may vary depending on the method of measurement, e.g. increasing K or decreasing K experiments. As a fatigue precrack is somewhat artificial and may affect the transition to a stress corrosion crack, a decreasing K, crack arrest, type of experiment may be more pertinent.

The procedure for testing under rising load or rising displacement conditions is described in ISO 7539 Part 9 [9.3]. The loading or crack mouth opening displacement rate is the critical parameter and it is best to test over a range to obtain conservatively the minimum, lower shelf, value of K_{ISCC}. This may be lower than that obtained by conventional static loading or fixed displacement test under otherwise identical test conditions.

When there is a cyclic component to the loading, tests should appropriately incorporate that feature, with the loading frequency and waveform sensibly reproduced. If the stress amplitude is very small so that conventional fatigue is not expected, the concept of K_{ISCC} may be still be used but if the amplitude is more significant it is important to assess the significance of flaws in terms of the threshold range in stress intensity factor, ΔK_{th}, for the growth of fatigue cracks under the environmental and loading conditions of interest; see Chapter 7 on fatigue and 9.1.7.

9.1.2.4.2 Stress corrosion crack growth determination

The crack velocity during stress corrosion testing of pre-cracked fracture mechanics specimens can be measured using the procedures given in ISO 7539-6 [9.2] and the crack monitoring methods given in ISO 7359-9 Annex C [9.3]. These techniques enable the stress corrosion crack velocity, da/dt, to be determined as a function of the stress intensity factor, K, as illustrated in Figure 9.3. It is most relevant to obtain crack growth date for the conditions of practical relevance and to then fit the data with a growth law appropriate to the data. For example:

$$\frac{da}{dt} = C\left(K_I\right)^n \qquad K_{ISCC} \le K \le K_C \tag{9.1}$$

is often applicable where C and n are fitting parameters and K_C is the dynamic fracture toughness. However, the detailed functional relationship will be system dependent and may not be as simple as this power relationship. Usually, n is taken as zero to give a K-independent growth rate (plateau region of Figure 9.3).

Where there is a spread in the literature data for the conditions of relevance, it is most conservative to adopt an upper bound growth law but with an intelligent assessment that accounts for unrealistic outliers. Alternatively, in instances where a stress corrosion mechanism prevails in service, it may be possible to estimate crack velocity conservatively by appropriate inspection of the equipment at suitable intervals. This involves careful determination of the size of service flaws, either from samples taken from the equipment or in-situ using suitable metallographic techniques. Clearly considerable skill and care are necessary in making such measurements. If it is decided that it is necessary to assess the growth of flaws by a stress corrosion cracking mechanism, these expressions can be integrated numerically to predict the anticipated amount of growth during the design life of the structure or the relevant inspection period, whichever is appropriate. If, as a result of this growth, the flaws do not reach the maximum tolerable size for other failure mechanisms (e.g. brittle or ductile fracture – see Section 6 on Fracture) the flaws are acceptable. If, on the other hand, the calculated crack size at the end of the design life or inspection interval exceeds the tolerable size for other failure mechanisms, the flaws are unacceptable.

9.1.2.4.3 Establish data for corrosion fatigue assessment

9.1.2.4.3.1 ΔK_{th} determination

The threshold value of the stress intensity factor range (ΔK_{th}) in corrosion fatigue is influenced by crack size and by the stress ratio. In the short crack regime, cracks can grow at ΔK values seemingly below ΔK_{th}, because the latter is commonly determined from long crack measurement and because LEFM becomes invalid (Figure 9.2). Also, in the long crack regime, increasing the stress ratio, $R = \sigma_{\min} / \sigma_{\max}$, will usually reduce the threshold value because of diminished impact of crack closure. For that reason a high R value for the threshold is a sensible conservative assumption. In the same context as stress corrosion cracking, it is important to simulate sensibly the service conditions in terms of the environment and loading conditions, particularly frequency and waveform. Consequently data from literature should be used with care. The ISO 11782-2 standard on corrosion fatigue crack propagation [9.4] provides guidance on determination of ΔK_{th}.

9.1.2.4.3.2 Crack growth determination

Crack growth rates can be determined based on the ISO standard. The form of the crack growth rate curves cannot be generalised as they are system specific. Some schematic examples for constant amplitude loading are shown in Figure 9.4.

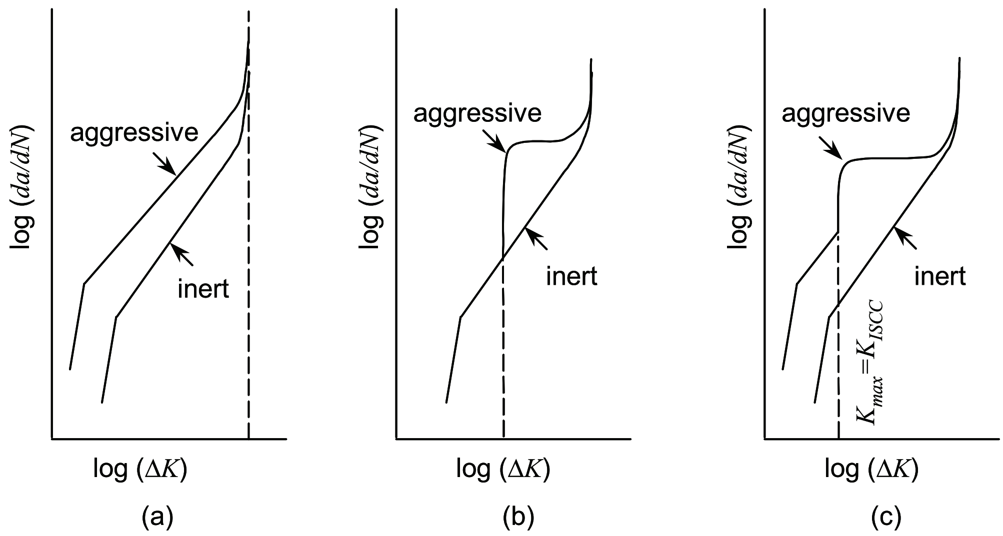


Figure 9.4 – Basic types of corrosion fatigue crack growth behaviour [9.5].

Here, a 'cyclic stress corrosion cracking' threshold, K_{FSCC}, as proposed by Komai [9.6] is a better concept to have in mind in relation to Figure 9.4, rather than K_{ISCC}, as it will prevent the simple transfer of data from static load testing.

The growth law should be derived to fit the relevant data but often take the form:

$$\frac{da}{dN} = A(\Delta K)^m \tag{9.2}$$

where da/dN is the cyclic crack growth rate and A and m are fitting parameters.

It is not really meaningful to assign a growth rate to variable amplitude loading; rather the increment in crack extension per cycle needs to be numerically calculated with allowance for load interaction effects (see below). It is especially problematic for corrosion fatigue because of the additional crack closure mechanisms, time-dependent effects, and loading rate sensitivity.

9.1.2.4.3.3 Corrosion fatigue crack growth data

The BS7910 [9.1] fatigue crack growth data for steels, excluding austenitic and duplex stainless steels, in a marine environment are given in this section. The values of constants A and m in equation (9.2) given in Table 9.1 are recommended for assessing low strength steels. They are applicable:

- to steels (excluding austenitic and duplex stainless steels) with yield or 0.2 % proof strengths ≤ 600 MPa;
- when operating in marine environments at temperatures up to 20 °C.

Table 9.1 – Recommended fatigue crack growth laws for steels in a marine environment[a]

R	Stage A				Stage B				Stage A / Stage B transition point ΔK N/mm$^{3/2}$	
	Mean curve		Mean + 2SD		Mean curve		Mean + 2SD			
	A [b]	m	A [b]	m	A [b]	m	A [b]	m	Mean curve	Mean + 2 SD
Steel freely corroding in a marine environment										
<0.5	3.0×10^{-14}	3.42	8.55×10^{-14}	3.42	1.27×10^{-7}	1.30	1.93×10^{-7}	1.30	1336	993
≥0.5	5.37×10^{-14}	3.42	1.72×10^{-13}	3.42	5.67×10^{-7}	1.11	7.48×10^{-7}	1.11	1098	748
Steel in a marine environment with cathodic protection at -850 mV (Ag/AgCl)										
<0.5	1.21×10^{-26}	8.16	4.37×10^{-26}	8.16	5.16×10^{-12}	2.67	1.32×10^{-11}	2.67	462	434
≥0.5	4.80×10^{-18}	5.10	2.10×10^{-17}	5.10	6.0×10^{-12}	2.67	2.02×10^{-11}	2.67	323	290
Steel in a marine environment with cathodic protection at -1100 mV (Ag/AgCl)										
<0.5	1.21×10^{-26}	8.16	4.37×10^{-26}	8.16	5.51×10^{-8}	1.40	9.24×10^{-8}	1.40	576	514
≥0.5	4.80×10^{-18}	5.10	2.10×10^{-17}	5.10	5.25×10^{-8}	1.40	1.02×10^{-7}	1.40	517	415

[a] Mean + 2SD values for $R\geq0.5$ recommended for assessing welded joints.
[b] For dA/dN in mm/cycle and ΔK in N/mm$^{3/2}$.

The values in Table 9.1 are based on data obtained either in artificial seawater or in 3 % NaCl solution at temperatures in the range 5 °C to 20 °C and cyclic frequencies in the range of 0.17 Hz to 0.5 Hz. Use of the recommended crack growth laws for operating conditions outside these ranges requires justification. Note in particular that significantly higher crack growth rates have been observed in certain steel HAZ microstructures tested in seawater with cathodic protection under long duration loading cycles due to combined fatigue and stress corrosion.

Threshold stress intensity factor, ΔK_{th}, values are strongly dependent on environment and R [9.1]. ΔK_{th} is found to increase with decrease in R. Recommended values for some conditions are given in Table 9.2. It is recommended that the lower bound value obtained at high R values in the relevant environment is adopted for all assessments of flaws in welded joints.

Table 9.2 – Recommended fatigue crack growth threshold, ΔK_{th}, values for assessing welded joints

Material	Environment	ΔK_{th} N/mm$^{3/2}$
Steels, including austenitic	Air or other non-aggressive environments up to 100 °C	63
Steels, excluding austenitic	Marine with cathodic protection, up to 20 °C	63
Steels, including austenitic	Marine, unprotected	0
Aluminium alloys	Air or other non-aggressive environments up to 20 °C	21

The values of ΔK_{th} in Table 9.2 for austenitic steels and unprotected steels operating in a marine environment are also applicable for assessing unwelded components. However, for unwelded steel components, account may be taken of R. Based on published data for steels (excluding austenitic) in air and with cathodic protection in marine environments at temperatures up to 20 °C, the following values of ΔK_{th} (in N/mm$^{3/2}$) are recommended:

$$\Delta K_{th} = 63 \quad \text{for } R \geq 0.5$$

$$\Delta K_{th} = 170 - 214R \quad \text{for } 0 \leq R < 0.5 \tag{9.3}$$

$$\Delta K_{th} = 170 \quad \text{for } R < 0$$

However, the value used should not exceed 63 N/mm$^{3/2}$ for assessments of surface-breaking flaws less than 1 mm deep.

9.1.2.5 Step 5: Undertake structural integrity assessment

Analysis of equipment containing growing cracks requires specialized skills, expertise, and experience because of the inherent complexity of the crack advance mechanism. The analysis involves the use of a fracture assessment (see Chapter 6 on fracture) and the numerical integration of a crack growth law.

a) Step 5a – Perform a fracture assessment for the initial crack size, based on the measured detected value or upon a maximum value reflecting the uncertainty in detection. If the component is demonstrated to be acceptable, i.e. well within the Fracture Assessment Diagram (FAD) boundary of Figure 9.5 and, where applicable, the crack depth is small compared with through-wall thickness, then remedial measures to prevent further crack growth should be considered. Remedial measures may include reducing the stress so that $K < K_{ISCC}$ (or $\sigma < \sigma_{SCC}$ if the crack is not of a size compatible with LEFM) and crack arrest ensues, modifying the environment or the temperature.

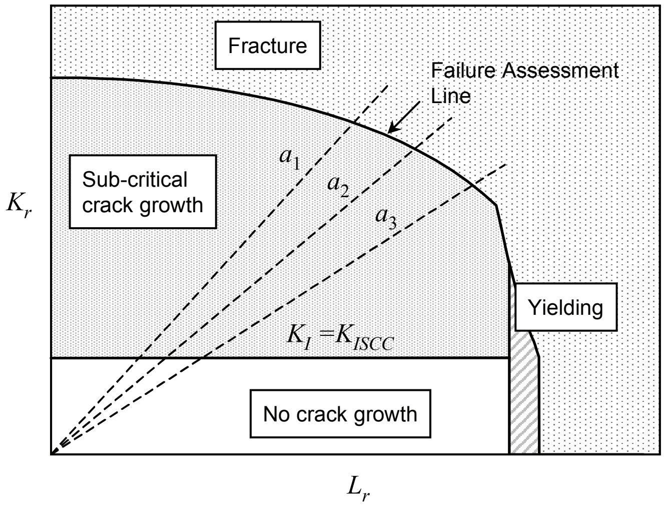


Figure 9.5 – Fracture assessment diagram

b) Step 5b – If effective remedial measures are not possible and/or slow subcritical crack growth can be tolerated, then apply sections 9.1.2.1-9.1.2.3 to fully characterise the nature of the crack and the service conditions driving it. Establish whether a crack growth law exists for the material and service environment. If a crack growth law exists, then a crack growth analysis can be performed. Otherwise, where applicable, a leak before break (LBB) analysis should be performed to determine if an acceptable upper bound crack size can be established.

c) Step 5c – Compute the stress at the flaw, including any dynamic components, based on anticipated future operating conditions. In these calculations, all relevant operating conditions including normal operation, start-up, upset, and shut-down should be considered.

d) Step 5d – Determine the evolution of the crack size based on the previous flaw size, K or ΔK value and crack growth laws. If a surface flaw is being evaluated, the crack depth is incremented based on the stress intensity factor at the deepest portion of the crack and the length is incremented based on the stress intensity factor at the surface. For corrosion fatigue cracks, a cycle by cycle numerical calculation of crack extension accounting for loading frequency, stress ratio and closure effects is required. A description of methodologies for performing crack growth calculations subject to constant amplitude and variable amplitude loading is contained in the FITNET Fatigue Module (Section 7).

e) Step 5e – Determine the time or number of stress cycles for the current crack size (a_0, c_0) to reach the limiting flaw size in relation to the FAD or LBB criteria. The component is acceptable for continued operation provided: the time or number of cycles to reach the limiting flaw size, including an appropriate in-service margin, is more than the required operating period; the crack growth is monitored on-stream or during shut-downs, as applicable, by a validated technique; the observed crack growth rate is below that used in the remaining life prediction as determined by an on-stream monitoring or inspections during shutdowns; upset conditions in loading or environmental severity are avoidable or are accounted for in the analysis. If the depth of the limiting flaw size is re-categorised as a through-wall thickness crack, the conditions for acceptable LBB criteria should be satisfied. At the next inspection, establish the actual crack growth rate and re-evaluate the new flaw conditions per procedures of this section. Alternatively, repair or replace the component or apply effective mitigation measures. An outline of the process is highlighted by the flowchart of Figure 9.6.

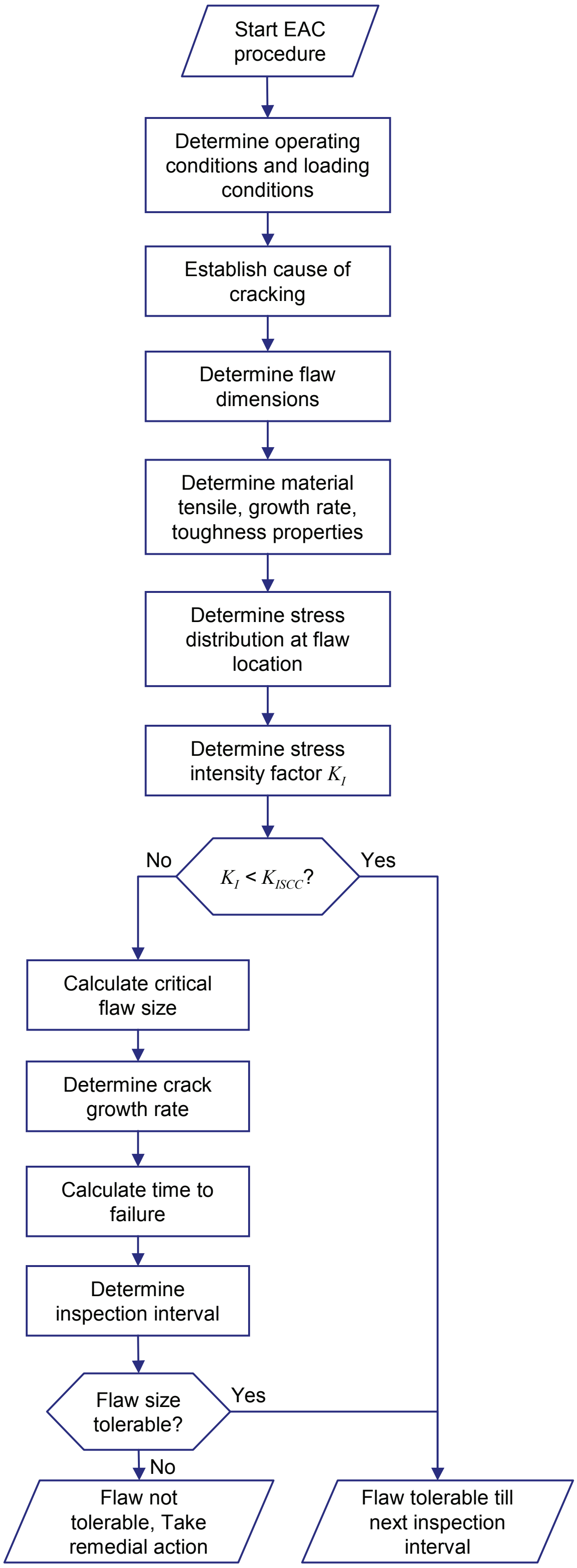


Figure 9.6 – Flowchart for EAC Procedure

9.2 Assessment of Local Thin Areas (LTA)

9.2.1 Introduction

The methods specified in this section may be used to assess Local Thin Area (LTA) flaws in pipes and pressure vessels that have been designed to a recognized design code. The chapter deals with LTA flaws in pipes and cylindrical vessels in 9.2.5.3. Spherical vessels and vessel ends are treated in 9.2.5.4

The guidance does not cover every situation that requires a fitness for purpose assessment and further methods may be required. Non-linear analysis such as finite element modelling may be used. Such analysis may be required for complex geometries and where external loadings are significant.

9.2.2 Step 1: Establish cause of wall thinning

Establish the cause of wall thinning e.g. due to corrosion, erosion, or grinding damage. Determine the rate of wall thinning due e.g. corrosion or erosion. Special attention should be given to those cases where the corrosion/erosion rate is non-linear with time e.g. caused by up-set conditions or during start-up or shut-down of the equipment.

When the cause of corrosion/erosion cannot be removed, the corrosion damage should be analysed taking future wall loss into account.

9.2.3 Step 2: Define service condition

Determine the service conditions. Typical required information is the operating pressure and the operating temperature. The required information could be different for the assessment of a LTA flaw caused by corrosion than for the assessment of a LTA caused by erosion. Establish the future service conditions to estimate the corrosion/erosion rate.

9.2.4 Step 3: Collect material properties

For the LTA assessment a number of material properties are required. As a minimum the material specified minimum yield stress (SMYS) and material specified minimum ultimate tensile stress (SMUTS) are required.

9.2.5 Step 4: Analysis

When future thinning cannot be excluded, the LTA assessment should be performed taking into account possible future thinning. Inspection in-accuracy must also be taken into account.

9.2.5.1 Applicable flaws

Local thin area (LTA) flaws due to corrosion, erosion, or blend grinding which exceeds, or is predicted to exceed the corrosion allowance can be assessed using this chapter. The LTA flaws may be located:

a) at the inner surface (e.g. internal corrosion);

b) at the outer surface (e.g. external corrosion);

c) in the parent material;

d) in or adjacent to longitudinal and circumferential welds, with the following provisos.

   – There should be no significant weld flaw present that may interact with the corrosion flaw.

   – The weld should not undermatch the parent steel in strength.

   – Brittle fracture should be unlikely to occur.

It should be noted that the limiting condition might not be failure due to the applied hoop stress. This can occur in cases where there is significant additional external loading (axial and/or bending), and/or when the circumferential extent of the LTA is greater than the longitudinal extent (e.g. preferential girth weld corrosion).

When assessing LTA flaws, due consideration should be given to the measurement uncertainty of the flaw dimensions and the structural geometry. The limitations of the measurement techniques (e.g. intelligent pigs, ultrasonic testing) should be taken into account. Possible future growth should also be taken into account.

9.2.5.2 Exclusions

The following are outside the applicability of this LTA flaw procedure:

a) materials with specified minimum yield strengths exceeding 550 MPa or values of $\sigma_{yield}/\sigma_{uts}$ exceeding 0.9;

b) cyclic loading;

c) sharp flaws (i.e. cracks) (see Section 6 on Fracture);

d) combined LTA flaws and cracks;

e) corrosion in association with mechanical damage;

f) metal loss flaws attributable to mechanical damage (i.e. gouges);

g) fabrication flaws in welds;

h) environmentally induced cracking (see section 9.1);

i) flaw depths greater than 80% of the original (i.e. not corroded) wall thickness (i.e. remaining ligament less than 20% of the original wall thickness);

The assessment procedure is only applicable to ductile linepipe and pressure vessel steels that are expected to fail through plastic collapse. The procedure is not recommended for applications where brittle fracture is likely to occur. These may include the following:

1) any material that has been shown to have a full-scale fracture initiation transition temperature above the operating temperature;

2) material of thickness 13 mm and greater, unless the full scale initiation transition temperature is below the operating temperature;

3) flaws in mechanical joints, fabricated, forged, formed or cast fittings and attached appurtenances;

4) flaws in bond lines of flash welded (FW) or low frequency electric resistance welded (ERW) butt-welded pipe;

5) lap welded or furnace butt-welded pipe.

In such materials, fracture toughness tests should be carried out to confirm that they are operating above their brittle to ductile transition temperature. If they are, the procedures of this chapter may be used. If they are not, the LTA flaws should be treated as cracks and should be assessed according to the procedures of Section 6 on Fracture.

9.2.5.3 Cylindrial body

9.2.5.3.1 Safe working pressure estimate cylindrical body

Determine the safe working pressure to prevent longitudinal failure (hoop stress).

a) Calculate the failure pressure of an unflawed pipe or vessel cylinder (P_o):

$$P_o = \frac{2t\sigma_{cyl}}{(D_o - t)} \tag{9.4}$$

where

$$\sigma_{cyl} = \left(\frac{1}{2}\right)^n \sigma_{uts} \tag{9.5}$$

$$n = \frac{65}{\sigma_{yield}} \tag{9.6}$$

b) Calculate the length correction factor (Q):

$$Q = \sqrt{1 + 0.8\frac{l^2}{D_o.t}} \tag{9.7}$$

c) Calculate the remaining strength factor for longitudinal failure (rsf_L):

$$rsf_L = \left[\frac{\frac{t_{mm}}{t}}{1 - \left(1 - \frac{t_{mm}}{t}\right)\frac{1}{Q}}\right] \tag{9.8}$$

d) Calculate the failure pressure of the corroded pipe or vessel (P_{fL}) for longitudinal failure:

$$P_{fL} = P_o \cdot rsf_L \tag{9.9}$$

e) Calculate the usage factor (f_L) to ensure a safe margin between the operating pressure and the failure pressure of the LTA flaw and to avoid general yielding:

$$f_L = \min\left[\frac{\sigma_A}{\sigma_{yield}}; \frac{\sigma_{yield}}{\sigma_{cyl}}\right] \tag{9.10}$$

Typical code allowable stresses (σ_A) for pressure vessels are listed in Table 9.3 and for pipelines and piping in Table 9.4.

e) Calculate the safe working pressure (P_{sw}) of the corrode pipe of vessel:

$$P_{sw} = P_{fL} f_L \tag{9.11}$$

Note: The operating pressure may not exceed the calculated safe working pressure and the code design pressure.

9.2.5.3.2 Safe working system stress estimate cylindrical body

Determine the safe working system stress to prevent circumferential failure (axial stress).

a) Calculate the remaining strength factor rsf_C:

$$rsf_C = 1 + \frac{d}{t}\left[0.707\cos^{-1}\left\{0.45\sin\left(\frac{w}{D}\right)\right\} - 0.318\frac{w}{D} - 1.111\right] \tag{9.12}$$

b) Calculate the nominal axial failure stress of the corroded pipe or vessel for circumferential failure:

$$\sigma_{zf} = \sigma_f rsf_C \tag{9.13}$$

where the flow stress (σ_f) is given by:

$$\sigma_f = \frac{\sigma_{yield} + \sigma_{uts}}{2} \tag{9.14}$$

c) Calculate the usage factor (f_C) for the system stresses:

$$f_C = \left(\frac{\sigma_{SA}}{\sigma_y} - \frac{X_1}{2}\frac{\sigma_A}{\sigma_f}\right) \tag{9.15}$$

where

$$X_1 = \max\left(\frac{\sigma_{yield}}{\sigma_A}; \frac{\sigma_{cyl}}{\sigma_{yield}}\right) \tag{9.16}$$

and where σ_A is the code allowable hoop stress end σ_{SA} the code allowable axial stress. Typical code allowable stresses for pressure vessels are listed in Table 9.3 and for pipelines and piping in Table 9.4.

d) Calculate the safe working system stress (excluding the axial stress contribution due to internal pressure):

The maximum nominal safe system stress for a full thickness pipe ($\sigma_{ud,sys_{sw}}$) at the maximum allowable design circumferential stress, including the safety factor, X_1:

$$\sigma_{ud,sys_{sw}} = \sigma_f f_C \tag{9.17}$$

The safe allowable nominal system stress for a damaged pipe ($\sigma_{d,sys_{sw}}$) is given by:

$$\sigma_{d,sys_{sw}} = \sigma_f f_C rsf_C \tag{9.18}$$

9.2.5.3.3 Minimum allowable remaining wall thickness cylindrical body

Step 1 – Determine the allowable remaining wall thickness to prevent longitudinal failure (hoop stress)

a) Calculate the nominal failure stress of an unflawed pipe or vessel cylinder (σ_{cyl}) using equations (9.5) and (9.6).

b) Calculate the hoop stress (σ_h):

$$\sigma_h = \frac{P\left(D_o - t\right)}{2t} \tag{9.19}$$

The hoop stress should be less than the code allowable stress. Typical code allowable stresses for pressure vessels are listed in Table 9.3 and for pipelines and piping in Table 9.4.

c) Calculate the minimum required remaining strength factor ($rsf_{L\min}$) for the nominal hoop stress (σ_h):

$$rsf_{L\min} = \max\left[\frac{\sigma_{yield}}{\sigma_A}\frac{\sigma_h}{\sigma_{cyl}};\frac{\sigma_h}{\sigma_{yield}}\right] \tag{9.20}$$

The hoop stress (σ_h) should not be higher than the code allowable stress. Typical code allowable stresses (σ_A) for pressure vessels are listed in Table 9.3 and for pipelines and piping in Table 9.4.

d) Calculate the length correction factor (Q) using equation (9.7):

e) The minimum allowable remaining wall thickness to prevent longitudinal failure (t_{mL}) is given by, Figure 9.8:

$$t_{mL} = t\frac{rsf_{L\min}\left(1 - \frac{1}{Q}\right)}{\left(1 - \frac{rsf_{L\min}}{Q}\right)} \tag{9.21}$$

Step 2 – Determine the allowable remaining wall thickness to prevent circumferential failure (axial stress)

a) Calculate the flow stress (σ_f):

$$\sigma_f = \frac{\sigma_{yield} + \sigma_{uts}}{2} \tag{9.22}$$

b) Calculate the hoop stress (σ_h):

$$\sigma_h = \frac{P\left(D_o - t\right)}{2t} \tag{9.23}$$

c) Calculate the minimum required remaining strength factor $rsf_{C\min}$ for circumferential failure for the system stress axial stress (σ_{sys}):

$$rsf_{C\min} = \frac{1}{\sigma_f}\left[X_1\frac{\sigma_h}{2} + X_2\sigma_{sys}\right] \tag{9.24}$$

$$X_1 = \max\left(\frac{\sigma_{yield}}{\sigma_A};\frac{\sigma_{cyl}}{\sigma_{yield}}\right) \tag{9.25}$$

$$X_2 = \frac{\left(\sigma_{SA}\frac{\sigma_f}{\sigma_{yield}} - \frac{X_1}{2}\sigma_A\right)}{\left(\sigma_{SA} - \frac{\sigma_A}{2}\right)} \tag{9.26}$$

where σ_A is the code allowable hoop stress end σ_{SA} the code allowable axial stress. Typical code allowable stresses for pressure vessels are listed in Table 9.3 and for pipelines and piping in Table 9.4.

d) The minimum allowable remaining wall thickness to prevent circumferential failure (t_{mC}) is given by, Figure 9.9:

$$t_{mC} = t \cdot \left[1 - \frac{rsf_{C\min} - 1}{\left[0.707\cos^{-1}\left\{0.45\sin\left(\frac{w}{D}\right)\right\} - 0.318\frac{w}{D} - 1.111\right]}\right] \tag{9.27}$$

Step 3 – Determine the allowable remaining wall thickness

The minimum allowable remaining wall thickness (t_m) for combined internal pressure and axial loading is given by:

$$t_m = \max\left[t_{mL}; t_{mC}\right] \tag{9.28}$$

Table 9.3 – Summary typical allowable design stresses for pressure vessels

Design Code	Allowable stress $\sigma_A = \min\left(\frac{\sigma_{yield}}{Z_y}, \frac{\sigma_{uts}}{Z_u}\right)$	
	Z_y	Z_u
ASME VIII division 1 (Pre-1999 rules)	1.5	4
ASME VIII division 1 (1999 rules)	1.5	3.5
ASME VIII division 2	1.5	3
EN13445	1.5	2.4
BS5500 (BS1515)	1.5	2.35
Stoomwezen	1.5	2.25
Stoomwezen [1]	1.5	2
AD Merkblätter	1.5	-

[1] The value of Z_u =2 is allowed if stress concentrations are reduced or eliminated.

Table 9.4 – Summary typical allowable design stresses for typical pipelines and piping

	Design code			
	B31.3 Chemical Plant and Refinery Piping	B31.4 Liquid Transportation Systems for Hydrocarbons	B31.8 Gas Transmission and Distribution Piping Systems	ISO 13623 Petroleum and natural gas industries pipelines
Allowable Circumferential stress	$\min\left(\frac{SMYS}{1.5};\frac{UTS}{3}\right)$	0.72 $SMYS$	Ranging from 0.40 to 0.80 $SMYS$ depending on location class	0.45-0.83 $SMYS$ depending on location class and product
Allowable total axial stress for non-incidental loads	$\min\left(\frac{SMYS}{1.5},\frac{UTS}{3}\right)$	0.54 $SMYS$	0.75.$SMYS$ for onshore pipeline 0.8.$SMYS$ for offshore riser and pipeline	$\approx SMYS$ depending on location class and product
Allowable external stresses at full design pressure	$\frac{\min\left(\frac{SMYS}{1.5},\frac{UTS}{3}\right)}{2}$	0.18 $SMYS$	0.35 - 0.55.$SMYS$ depending on location class	$\approx$ 0.58-0.77 $SMYS$ depending on location class and product

9.2.5.4 Sphere and vessel end

a) Calculate the effective outer radius (R_{eff}) of the shell. As an approximation the radius at the apex of an elliptical end should be used in the equation for damage located in the vessel end.

1) Sphere and spherical vessel end:

$$R_{eff} = \frac{D_o}{2} \tag{9.29}$$

2) Elliptical vessel end:

ASME B&PV Code, Section VIII Division 1, Appendix 1:

$$R_{eff} = \frac{D_o}{6}\left[2+\left(\frac{D_o}{2h}\right)^2\right] \tag{9.30}$$

BS5500:

$$R_{eff} = D_o\left[0.25346+0.13995\left(\frac{D_o}{2h}\right)+0.12238\left(\frac{D_o}{2h}\right)^2-0.015297\left(\frac{D_o}{2h}\right)^3\right] \tag{9.31}$$

Equations (9.30) and (9.31) are plotted in Figure 9.10.

3) Torispherical vessel end:

$$R_{eff} = R_{tor} \tag{9.32}$$

Note: The solutions should not be applied at shell junctions. The differences in radial stiffnesses between shells of different geometries can produce large bending stresses, and sometimes compressive hoop stress or elevated hoop stresses due to the mismatch.

b) Calculate the failure pressure of the unflawed sphere (P_o):

$$P_o = \frac{2t\sigma_{sphere}}{\left(R_{eff} - 0.5t\right)} \tag{9.33}$$

where

$$\sigma_{sphere} = \left(\frac{1}{3}\right)^n \sigma_{uts} \tag{9.34}$$

$$n = \frac{65}{\sigma_{yield}} \tag{9.35}$$

c) Calculate the length correction factor (Q_S):

$$Q_S = \sqrt{1 + 0.8\frac{S^2}{2R_{eff}.t}} \tag{9.36}$$

d) Calculate the remaining strength factor (rsf_S):

$$rsf_S = \left[\frac{\frac{t_{mm}}{t}}{1 - \left(1 - \frac{t_{mm}}{t}\right)\frac{1}{Q_S}}\right] \tag{9.37}$$

e) Calculate the failure pressure of the corroded pipe or vessel (P_f):

$$P_f = P_o \cdot rsf_S \tag{9.38}$$

f) Calculate the minimum required safety factor (f_S):

$$f_S = \min\left[\frac{\sigma_A}{\sigma_{yield}}; \frac{\sigma_{yield}}{\sigma_{sphere}}\right] \tag{9.39}$$

Typical code allowable stresses (σ_A) for pressure vessels are listed in Table 9.3 and for pipelines and piping in Table 9.4.

g) Calculate the safe working pressure of the corroded spherical vessel (P_{sw}):

$$P_{sw} = P_f f_S \tag{9.40}$$

Note: The operating pressure may not exceed the calculated safe working pressure and the code design pressure.

9.2.5.5 Elbow

9.2.5.5.1 Safe working pressure estimate

Determine the safe working pressure to prevent longitudinal failure (hoop stress)

a) Calculate the failure pressure (P_o) of an unflawed elbow:

$$P_o = \frac{2t\sigma_{elbow}}{\left(D_o - t\right)} \tag{9.41}$$

where

$$\sigma_{elbow} = \alpha_{elbow}\left(\frac{1}{2}\right)^n \sigma_{uts} \tag{9.42}$$

$$\alpha_{elbow} = \frac{1 - \dfrac{R}{R_b}}{1 - \dfrac{R}{2R_b}} \tag{9.43}$$

$$n = \frac{65}{\sigma_{yield}} \tag{9.44}$$

b) Calculate the length correction factor (Q):

$$Q = \sqrt{1 + 0.8\frac{l^2}{D_o.t}} \tag{9.45}$$

c) Calculate the remaining strength factor for longitudinal failure (rsf_L):

$$rsf_L = \left[\frac{\dfrac{t_{mm}}{t}}{1 - \left(1 - \dfrac{t_{mm}}{t}\right)\dfrac{1}{Q}}\right] \tag{9.46}$$

d) Calculate the failure pressure of the elbow with LTA (P_{fEL}) for longitudinal failure:

$$P_{fEL} = P_o \cdot rsf_L \tag{9.47}$$

e) Calculate the usage factor (f_{EL}) to ensure a safe margin between the operating pressure and the failure pressure of the LTA flaw and to avoid general yielding:

$$f_{EL} = \min\left[\frac{\sigma_A}{\sigma_{yield}};\frac{\sigma_{yield}}{\sigma_{elbow}}\right] \tag{9.48}$$

Typical code allowable stresses (σ_A) for pressure vessels are listed in Table 9.3 and for pipelines and piping in Table 9.4.

e) Calculate the safe working pressure of the corroded spherical elbow (P_{sw}):

$$P_{sw} = P_{fEL} f_{EL} \tag{9.49}$$

Note: The operating may not exceed the calculated safe working pressure and the code design pressure.

9.2.5.5.2 Safe moment estimate

Determine the safe moment to prevent circumferential failure (axial stress).

a) Calculate the elbow geometric parameter (λ) for an elbow with bend radius R_b, pipe outer diameter D_o, and wall thickness t, see Figure 9.11:

$$\lambda = \frac{tR_b}{R^2} \tag{9.50}$$

where $R = (D_o - t)/2$.

b) Calculate the limit moment of an unflawed elbow:

$$M_o = \beta_{elbow} Z \sigma_f \tag{9.51}$$

where

$$\sigma_f = \frac{\sigma_{yield} + \sigma_{uts}}{2}$$

$$\beta_{elbow} = \frac{\lambda^{2/3}}{0.9} \tag{9.52}$$

$$Z = \frac{\pi}{32} \frac{\left(D_o^4 - D_i^4\right)}{D_o} \tag{9.53}$$

where D_o is the pipe outer diameter and D_i is the pipe inner diameter.

c) Calculate the remaining strength factor (rsf_C):

$$rsf_C = 1 + \frac{d}{t}\left[0.707\cos^{-1}\left\{0.45\sin\left(\frac{w}{D}\right)\right\} - 0.318\frac{w}{D} - 1.111\right] \tag{9.54}$$

d) Calculate the limit moment of the corroded elbow:

$$M_{fEC} = M_o rsf_C \tag{9.55}$$

e) Calculate the usage factor (f_{EC}) to ensure a safe margin between the system induced moment and the limit moment:

$$f_{EC} = \min\left[\frac{\sigma_A}{\sigma_{yield}}; \frac{\sigma_{yield}}{\sigma_f}\right] \tag{9.56}$$

Typical code allowable stresses (σ_A) for pressure vessels are listed in Table 9.3 and for pipelines and piping in Table 9.4.

f) Calculate the safe system moment of the corroded elbow (P_{sw}):

$$M_{sw} = M_{fEC} f_{EC} \tag{9.57}$$

Note: The system moment may not exceed the calculated safe moment and the code design allowable moment.

9.2.5.5.3 Minimum allowable wall thickness elbow

Step 1 – Determine the allowable remaining wall thickness to prevent longitudinal failure (hoop stress).

a) Calculate the nominal failure stress for an unflawed straight pipe (σ_{cyl}) using equations (9.5) and (9.6).

b) Calculate the elbow parameter α_{elbow} using equation (9.42).

c) Calculate the elbow hoop stress ($\sigma_{h,elbow}$):

$$\sigma_{h,elbow} = \frac{P}{\alpha_{elbow}} \frac{(D_o - t)}{2t} \tag{9.58}$$

Note: The elbow hoop stress should be less than the code allowable stress.

d) Calculate the minimum required remaining strength factor ($rsf_{EL\min}$) for the nominal hoop stress ($\sigma_{h,elbow}$):

$$rsf_{EL\min} = \max\left[\frac{\sigma_{yield}}{\sigma_A}\frac{\sigma_{h,elbow}}{\sigma_{cyl}};\frac{\sigma_{h,elbow}}{\sigma_{yield}}\right] \tag{9.59}$$

The elbow hoop stress ($\sigma_{h,elbow}$) should not be higher than the code allowable stress. Typical code allowable stresses (σ_A) for pressure vessels are listed in Table 9.3 and for pipelines and piping in Table 9.4.

e) Calculate the length correction factor (Q) using equation (9.7):

f) The minimum allowable remaining wall thickness to prevent longitudinal failure (t_{mEL}) is given by:

$$t_{mEL} = t\frac{rsf_{EL\min}\left(1-\frac{1}{Q}\right)}{\left(1-\frac{rsf_{EL\min}}{Q}\right)} \tag{9.60}$$

Step 2 – Determine the allowable remaining wall thickness to prevent circumferential failure (axial stress).

a) Calculate the axial bending stress (σ_z) for moment M of a pipe without corrosion:

$$\sigma_{z,elbow} = \frac{M}{\beta_{elbow} Z} \tag{9.61}$$

where

$$\beta_{elbow} = \frac{\lambda^{2/3}}{0.9} \tag{9.62}$$

$$Z = \frac{\pi}{32}\frac{\left(D_o^4 - D_i^4\right)}{D_o} \tag{9.63}$$

b) Calculated the flow stress (σ_f):

$$\sigma_f = \frac{\sigma_{yield} + \sigma_{uts}}{2} \tag{9.64}$$

c) Calculate the minimum required remaining strength factor for circumferential failure for the axial stress (σ_z):

$$rsf_{EC\min} = \max\left[\frac{\sigma_{yield}}{\sigma_A}\frac{\sigma_{z,elbow}}{\sigma_f};\frac{\sigma_{z,elbow}}{\sigma_{yield}}\right] \tag{9.65}$$

The axial stress (σ_z) should not be higher than the code allowable stress. Typical code allowable stresses (σ_A) for pressure vessels are listed in Table 9.3 and for pipelines and piping in Table 9.4.

d) The minimum allowable remaining wall thickness to prevent circumferential failure (t_{mEC}) is given by, Figure 9.9:

$$t_{mEC} = t \cdot \left[1 - \frac{rsf_{EC\min} - 1}{\left[0.707\cos^{-1}\left\{0.45\sin\left(\frac{w}{D}\right)\right\} - 0.318\frac{w}{D} - 1.111\right]}\right] \tag{9.66}$$

Step 3 – Determine the allowable remaining wall thickness.

The minimum allowable remaining wall thickness (t_m) for combined internal pressure and axial loading is given by:

$$t_m = \max\left[t_{mEL};t_{mEC}\right] \tag{9.67}$$

9.2.5.6 Nozzles

The general approach to assessing nozzles is to check that the shell of the vessel and the nozzle have sufficient remaining wall to resist the following failure modes:

Mode 1: Rupture of the vessel shell in either the longitudinal or circumferential modes of failure

Mode 2: Shear of the nozzle from the vessel by external nozzle loads due to shear through the vessel wall at cross section x - x in Figure 9.12 and Figure 9.13.

Mode 3: Longitudinal failure of the nozzle along its axis due to internal pressure.

Mode 4: Circumferential failure of the nozzle at cross sections z - z due to external nozzle loads.

Failure modes 1 and 2 can be avoided by minimum wall thickness requirements in the vessel shell. The minimum wall thickness requirements in the vessel shell against rupture are also related to wall losses in the nozzle reinforcement area.
Failure modes 3 and 4 can be avoided by minimum wall thickness requirements in the nozzle.
All minimum wall thickness requirements have to be satisfied for losses in and around nozzles to be accepted.
A diagram of idealised corrosion losses in the shell and in the nozzle itself is given in Figure 9.12 and Figure 9.13.

Applicability:

a) Nozzle diameter less or equal 30% of vessel diameter.

b) The wall loss in the vessel within a distance of two times the nozzle diameter must be less than 50% of the vessel wall thickness.

9.2.5.6.1 Determine minimum allowable wall thickness of the vessel shell

Step 1 – Determine the allowable remaining wall thickness to prevent longitudinal failure (hoop stress).

a) Calculate the nominal failure stress of an unflawed pipe or vessel cylinder (σ_{cyl}) without a nozzle using equations (9.5) and (9.6).

b) Calculate the minimum required remaining strength factor:

$$rsf_{NL\min} = \max\left[\frac{\sigma_{yield}}{\sigma_{cyl}};\frac{\sigma_A}{\sigma_{yield}}\right] \tag{9.68}$$

Typical code allowable stresses (σ_A) for pressure vessels are listed in Table 9.3 and for pipelines and piping in Table 9.4.

c) Calculate the length correction factor (Q) using equation (9.7).

d) Calculate the minimum allowable remaining wall thickness to prevent longitudinal failure (t_{mNL}).

$$\alpha_{mNL} = \frac{\dfrac{rsf_{NL\min}}{0.89}\left(1-\dfrac{1}{Q}\right)}{\left(1-\dfrac{rsf_{NL\min}}{0.89Q}\right)} \tag{9.69}$$

For corrosion in the vessel wall only:

$$t_{mNL} = t_v \alpha_{mNL} \tag{9.70}$$

For corrosion in the nozzle and vessel wall:

$$t_{mNL} = t_v \frac{\alpha_{mNL}}{\left(1-\dfrac{t_r - r_r}{2t_r}\right)} \quad \text{for a corrosion length } L \geq 2D_r \tag{9.71}$$

$$t_{mNL} = t_v \frac{\alpha_{mNL}}{\left(1-\dfrac{D_r(t_r - r_r)}{Lt_r}\right)} \quad \text{for a corrosion length } L < 2D_r \tag{9.72}$$

Step 2 – Determine the allowable remaining wall thickness to prevent circumferential failure (axial stress).

a) Calculate the flow stress (σ_f):

$$\sigma_f = \frac{\sigma_{yield} + \sigma_{uts}}{2} \tag{9.73}$$

b) Calculate the minimum required remaining strength factor $rsf_{NC\min}$ for circumferential failure for the axial stress (σ_z):

$$rsf_{NC\min} = \max\left[\frac{\sigma_{yield}}{\sigma_f}; \frac{\sigma_A}{\sigma_{yield}}\right] \tag{9.74}$$

Typical code allowable stresses (σ_A) for pressure vessels are listed in Table 9.3 and for pipelines and piping in Table 9.4.

c) The minimum allowable remaining wall thickness to prevent circumferential failure (t_{mNC}) is given by, Figure 9.9:

$$\alpha_{mNC} = \left[1 - \frac{\dfrac{rsf_{NC\min}}{X_N} - 1}{\left[0.707\cos^{-1}\left\{0.45\sin\left(\dfrac{w}{D}\right)\right\} - 0.318\dfrac{w}{D} - 1.111\right]}\right] \tag{9.75}$$

For corrosion in the vessel wall only:

$$t_{mNC} = t_v \alpha_{mNC} \tag{9.76}$$

For corrosion in the nozzle and vessel wall:

$$t_{mNC} = t_v \frac{\alpha_{mNC}}{\left(1 - \dfrac{t_r - r_r}{2t_r}\right)} \quad \text{for a corrosion length } L \geq 2D_r \tag{9.77}$$

$$t_{mNC} = t_v \frac{\alpha_{mNC}}{\left(1 - \dfrac{D_r\left(t_r - r_r\right)}{Lt_r}\right)} \quad \text{for a corrosion length } L < 2D_r \tag{9.78}$$

Step 3 – Determine the allowable remaining wall thickness to prevent nozzle pull out.

a) Calculate the shear stress (τ)

For corrosion in the vessel wall only, Figure 9.12:

$$\tau = \frac{\sigma_A}{2}\sqrt{\frac{1}{\beta}\left\{4\left(\frac{t_p}{t_v}\right)^2 + 1\right\} - \frac{2}{\beta}\left(\frac{t_p}{t_r}\right) + \left(\frac{t_p}{t_r}\right)^2} \tag{9.79}$$

where

$$\beta = t_m / t_v \tag{9.80}$$

For corrosion in the nozzle and vessel wall, Figure 9.13:

$$\tau = \frac{\sigma_A}{2}\sqrt{\frac{1}{\beta}\left\{4\left(\frac{t_p}{t_v}\right)^2 + 1\right\} - \frac{2}{\beta}\left(\frac{t_p}{r_r}\right) + \left(\frac{t_p}{r_r}\right)^2} \tag{9.81}$$

b) Calculate the minimum required wall thickness (t_{mF}):

The following equation should be satisfied:

$$\tau \le \frac{\sigma_{yield}}{2} \tag{9.82}$$

The minimum value of β satisfying equation (9.82) gives the minimum required wall thickness to avoid nozzle pull out (t_{mF}):

$$t_{mF} = \beta t_v \tag{9.83}$$

Step 4 – Determine the allowable remaining wall thickness in the vessel wall around the nozzle

The minimum allowable remaining wall thickness (t_m) for combined internal pressure, axial loading and nozzle pull out is given by:

$$t_m = \max\left[t_{mNL}; t_{mNC}; t_{mNF}; 0.5t_v\right] \tag{9.84}$$

9.2.5.6.2 Determine minimum allowable wall thickness of the nozzle

The minimum allowable wall thickness of the nozzle can be determined using section 9.2.5.3.3, assuming the code allowable stress for both the axial stress and the hoop stress.

9.2.5.7 Interaction rules

The interaction rules [9.1] given below apply solely to LTA flaws. Adjacent LTA flaws can interact to produce a failure pressure that is lower than that due to either of the isolated flaws (if they were treated as single flaws). For the case where interaction occurs, the single flaw equation is no longer valid and the rules given in section 9.2.5.8 should be applied.

A flaw can be treated as isolated if:

a) its depth is less than 20% of the wall thickness; and

b) the circumferential spacing between adjacent flaws (ϕ) exceeds the angle given by the following:

$$\phi > 360\frac{3}{\pi}\sqrt{\frac{t}{D}} \text{ (in degrees); and} \tag{9.85}$$

c) the axial spacing between adjacent flaws (s) exceeds the value given by the following:

$$s > 2.0\sqrt{Dt} \tag{9.86}$$

Two adjacent flaws within $2.0\sqrt{Dt}$ (axial spacing) will interact if:

$$\left(\frac{1-\frac{d_1}{t}}{1-\frac{d_1}{tQ_1}}\right) > \left\{\frac{1-\frac{1}{t}\left(\frac{d_1 l_1 + d_2 l_2}{l_1 + l_2 + s}\right)}{1-\left(\frac{1}{tQ_{12}}\right)\left(\frac{d_1 l_1 + d_2 l_2}{l_1 + l_2 + s}\right)}\right\} \quad (9.87)$$

or

$$\left(\frac{1-\frac{d_2}{t}}{1-\frac{d_2}{tQ_2}}\right) > \left\{\frac{1-\frac{1}{t}\left(\frac{d_1 l_1 + d_2 l_2}{l_1 + l_2 + s}\right)}{1-\left(\frac{1}{tQ_{12}}\right)\left(\frac{d_1 l_1 + d_2 l_2}{l_1 + l_2 + s}\right)}\right\} \quad (9.88)$$

where

$$Q_1 = \sqrt{1 + 0.8\left(\frac{l_1}{\sqrt{Dt}}\right)^2} \quad (9.89)$$

$$Q_2 = \sqrt{1 + 0.8\left(\frac{l_2}{\sqrt{Dt}}\right)^2} \quad (9.90)$$

and

$$Q_{12} = \sqrt{1 + 0.8\left(\frac{l_1 + l_2 + s}{\sqrt{Dt}}\right)^2} \quad (9.91)$$

Figure 9.15 shows the key dimensions for flaw interaction.

9.2.5.8 Interacting flaws

9.2.5.8.1 General

The minimum information required for an assessment comprises the following:

a) the angular position of each flaw around the circumference;

b) the axial spacing between adjacent flaws;

c) the length of each individual flaw;

c) the depth of each individual flaw;

d) the width of each individual flaw.

9.2.5.8.2 Safe working pressure estimate

The safe working pressure of a colony of interacting flaws can be estimated from the following procedure[1].

a) For regions where there is general metal loss (less than 10% of the wall thickness), the local wall thickness and flaw depths should be used (see Figure 9.16).

b) The corroded section of the pipe or vessel should be divided into sections of a minimum length of $5.0\sqrt{Dt}$, with a minimum overlap of $2.5\sqrt{Dt}$. Steps c) to l) should be repeated for each sectioned length to assess all possible interactions.

c) Construct a series of axial projection lines with a circumferential spacing calculated from the following:

$$\phi > 360\frac{3}{\pi}\sqrt{\frac{t}{D}} \text{ (in degrees)} \tag{9.92}$$

d) Consider each projection line in turn. If flaws lie within $\pm\phi$, they should be projected onto the current projection line (see Figure 9.17).

e) Where flaws overlap, they should be combined to form a composite flaw. This is formed by taking the combined length, and the depth of the deepest flaw (see Figure 9.18).

f) Calculate the failure pressures ($P_1, P_2, \ldots, P_N$) for each flaw, to the N^{th} flaw, treating each flaw, or composite flaw, as a single flaw (see section 9.2.5.3.1):

$$P_i = P_o \frac{\left(1-\frac{d_i}{t}\right)}{\left(1-\frac{d_i}{tQ_i}\right)} \qquad i=1\ldots N \tag{9.93}$$

where

$$Q_1 = \sqrt{1+0.8\left(\frac{l_1}{\sqrt{Dt}}\right)^2} \tag{9.94}$$

g) Calculate[2] the combined length of all combinations of interacting flaws (see Figure 9.19 and Figure 9.20). For flaws n to m the total length is given by the following equation:

---

[1] Within the colony of interacting flaws, all single flaws, and all combinations of adjacent flaws, are considered in order to determine the minimum predicted failure pressure.

Combined flaws (i.e. those that are deemed to interact) are assessed with the single flaw equation, using the total length (including spacing) and the effective depth (based on the total length and a rectangular approximation to the corroded area of each flaw within the combined flaw).

[2] The calculations described in g) to i) are to estimate the failure pressures of all combinations of adjacent flaws. The failure pressure for the combined flaw nm (i.e. defined by single flaw n to single flaw m, where $n=1\ldots N$ and $m=n\ldots N$) is denoted P_{nm}.

When equals m, the failure pressure is identical to that for an individual flaw, as calculated in f).

Mathematically, the process is to estimate the failure pressure along the generator as:

$$l_{nm} = l_m + \sum_{i=n}^{i=m-1} \left(l_i + s_i \right) \qquad n, m = 1 \ldots N \tag{9.95}$$

h) Calculate the effective depth of the combined flaw formed from all of the interacting flaws from n to m, as follows (see Figure 9.19):

$$d_{nm} = \frac{\sum_{i=n}^{i=m} d_i l_i}{l_{nm}} \tag{9.96}$$

i) Calculate the failure pressure for the combined flaw from n to m (P_{nm}), (see Figure 9.19), using l_{nm} and d_{nm} in the single flaw equation (see section 9.2.5.3.1):

$$P_{nm} = P_o \frac{\left(1 - \frac{d_{nm}}{t}\right)}{\left(1 - \frac{d_{nm}}{tQ_{nm}}\right)} \tag{9.97}$$

where

$$Q_{nm} = \sqrt{1 + 0.8 \left(\frac{l_{nm}}{\sqrt{Dt}} \right)^2} \tag{9.98}$$

j) The failure pressure, for the current projection line, is taken as the minimum of the failure pressures for all of the individual flaws (P_1 to P_N) and for all the combinations of individual flaws (P_{nm}), on the current projection line.

$$P_f = \min\left(P_1, P_2, \ldots P_N, P_{nm}\right) \tag{9.99}$$

k) Calculate the safe working pressure (P_{sw}) for the interacting flaws on the current projection line:

$$P_{sw} = f_L \times P_f \tag{9.100}$$

l) The safe working pressure for the section of corroded pipe or vessel is taken as the minimum of the safe working pressures calculated for each of the projection lines around the circumference.

m) Repeat steps c) to m) for the next adjacent section of the corroded component.

$$P_f = \sum_{n=1}^{N} \sum_{m=n}^{m=N} X_{nm} P_{nm}$$

where X_{nm} equals unity if the value of P_{nm} is the minimum of all estimates, else X_{nm} equals zero.

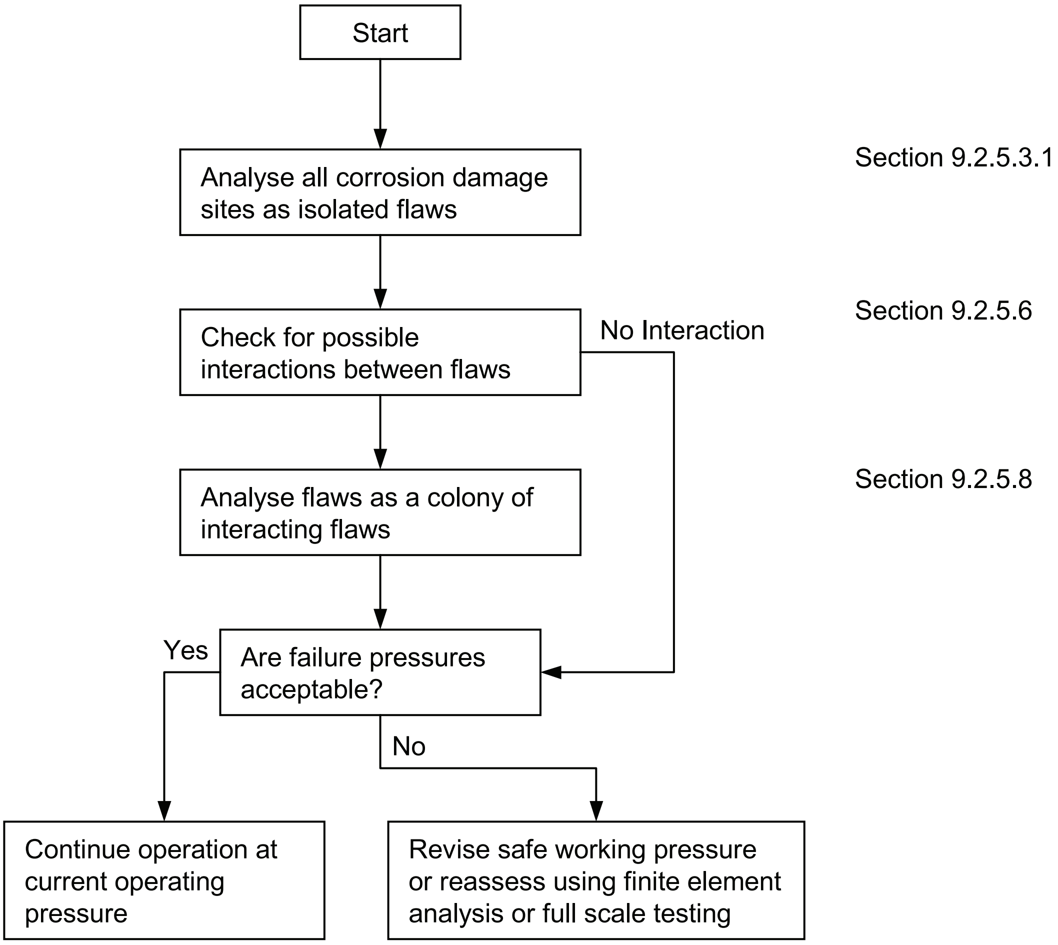
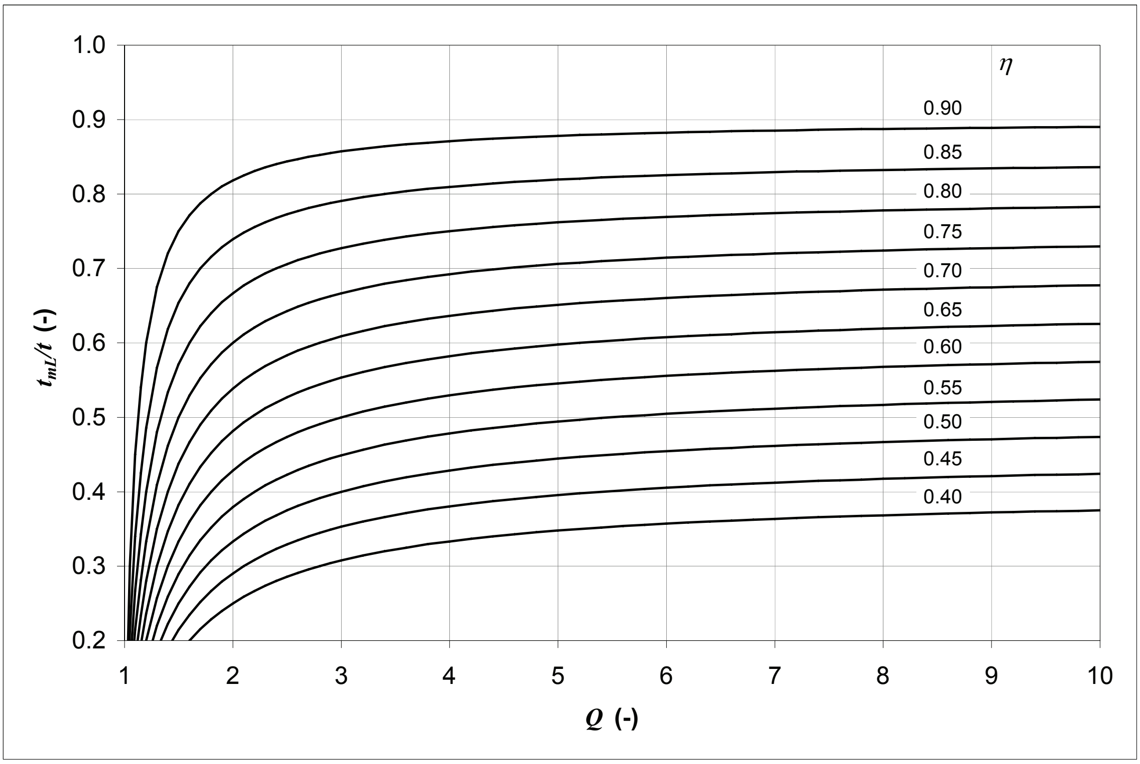
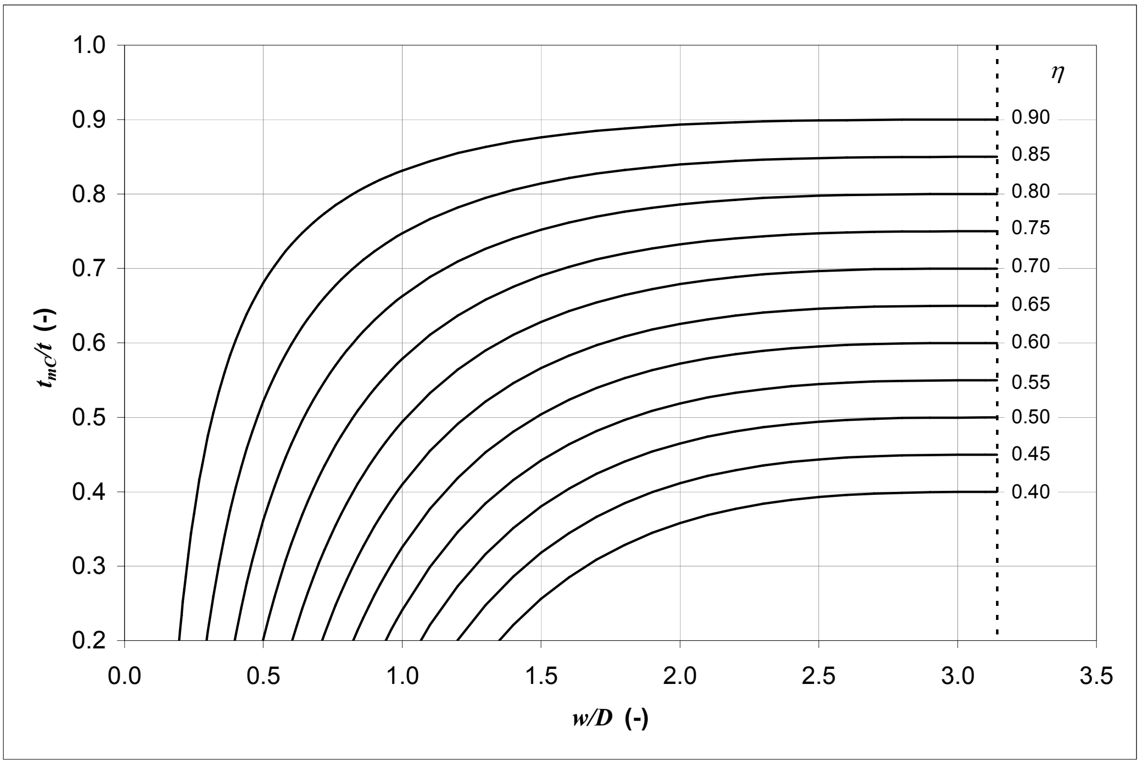


Figure 9.7 – Flow chart LTA assessment procedure [9.1].



$$\frac{t_{mL}}{t} = \frac{\eta\left(1-\frac{1}{Q}\right)}{\left(1-\frac{\eta}{Q}\right)}$$

Figure 9.8 – Allowable remaining wall thickness of an axially oriented LTA flaw. Note: The parameter η is a function of the minimum required remaining strength factor and geometry.



$$\frac{t_{mC}}{t} = \left[1 - \frac{\eta - 1}{\left[0.707\cos^{-1}\left\{0.45\sin\left(\frac{w}{D}\right)\right\} - 0.318\frac{w}{D} - 1.111\right]}\right]$$

Figure 9.9 – Allowable remaining wall thickness of a circumferentially oriented LTA flaw. Note: The parameter η is a function of the minimum required remaining strength factor and geometry.

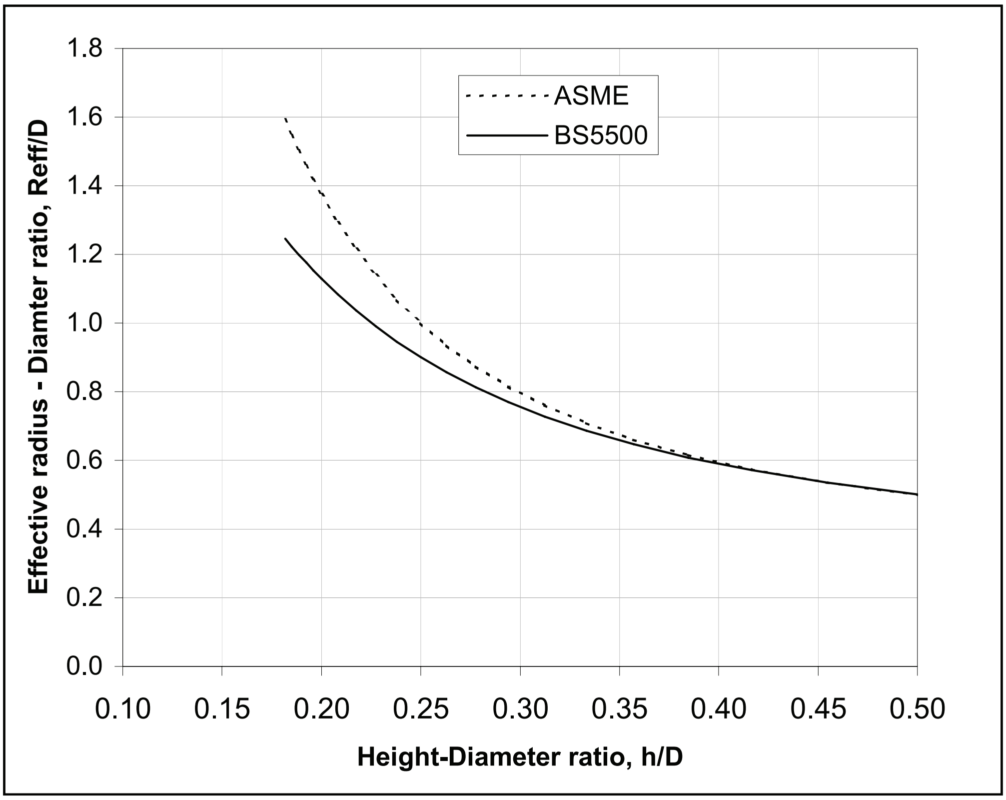


Figure 9.10 – Effective radius for an elliptical head, (9.30) and (9.31) for the BS5500 and the ASME B&PV Code, Section VIII, Division 1.

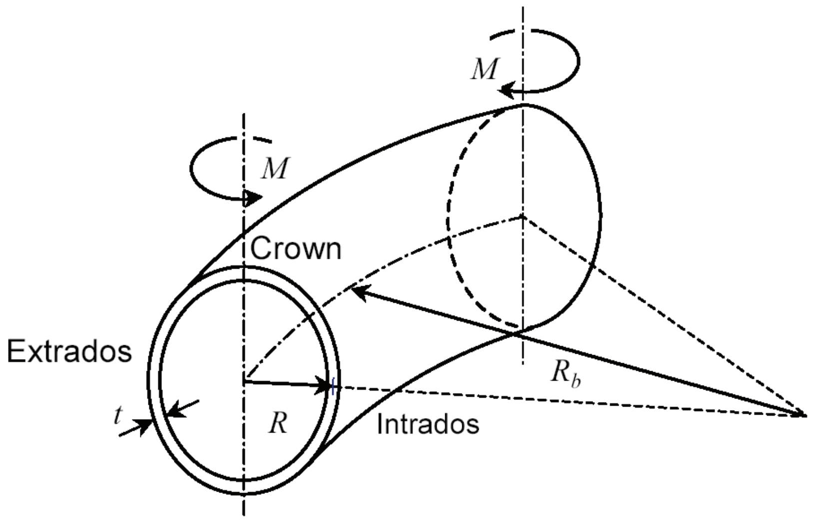


Figure 9.11 – Elbow dimensions

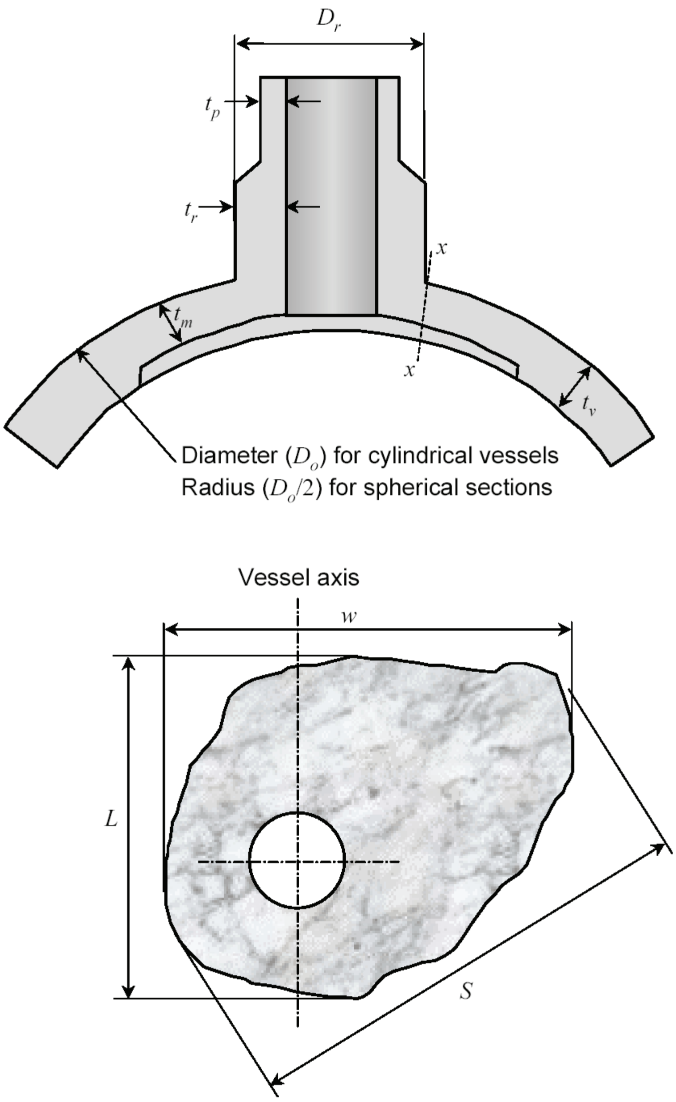


Figure 9.12 – Nozzle dimensions with corrosion in vessel wall

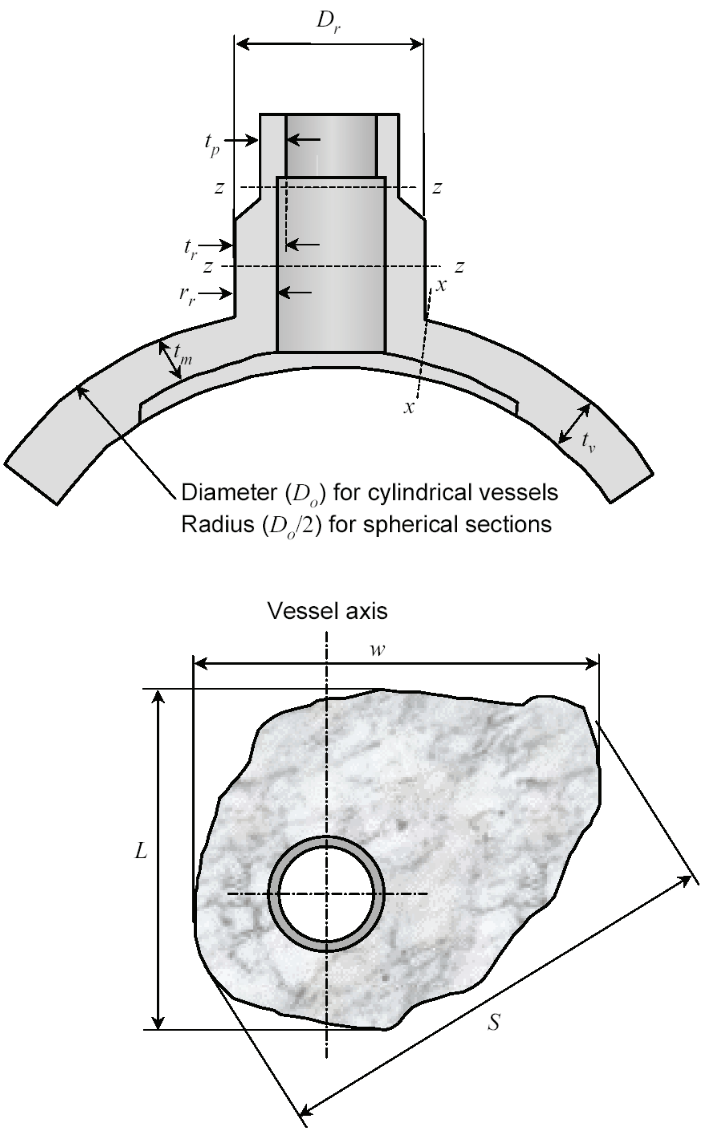


Figure 9.13 – Nozzle dimensions with corrosion in vessel wall and nozzle wall.

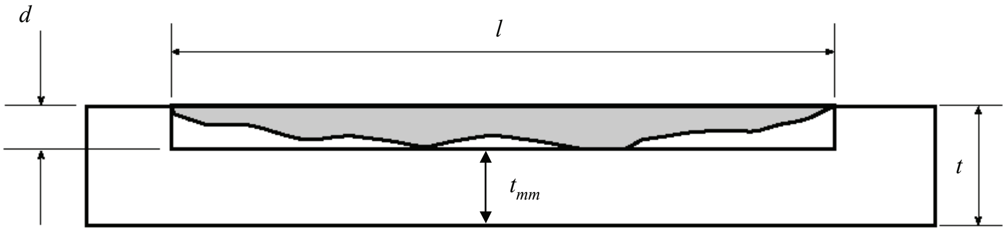


Figure 9.14 – Single flaw dimensions.

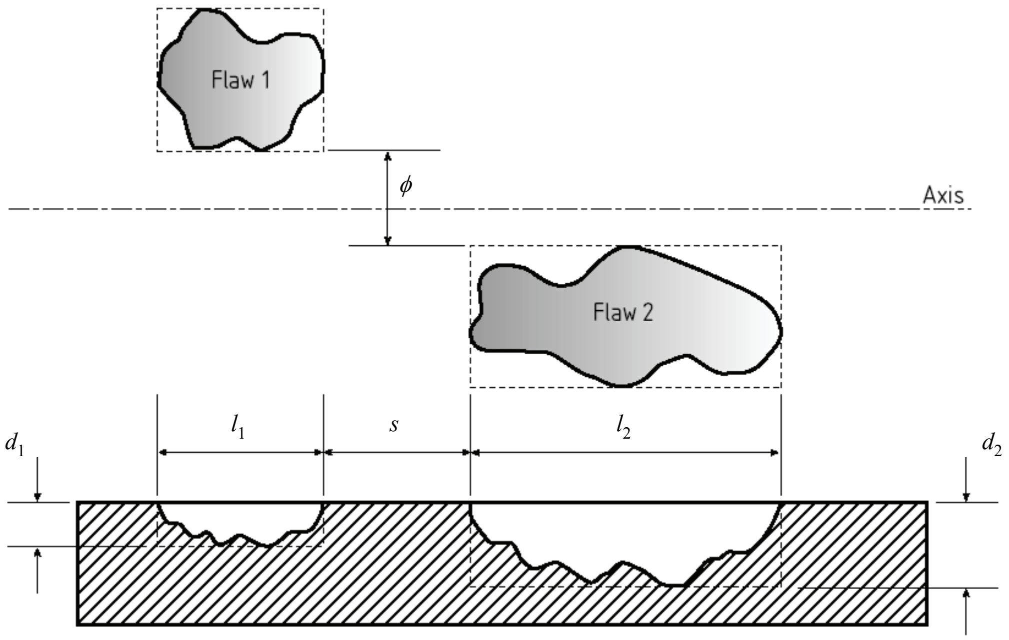


Figure 9.15 – Interacting flaw dimensions [9.1].

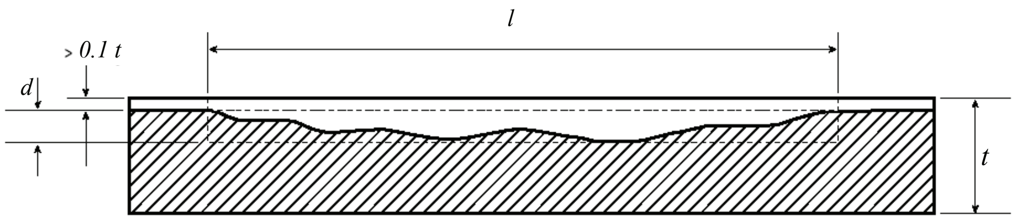


Figure 9.16 – Corrosion depth adjustment for flaws with background corrosion [9.1].

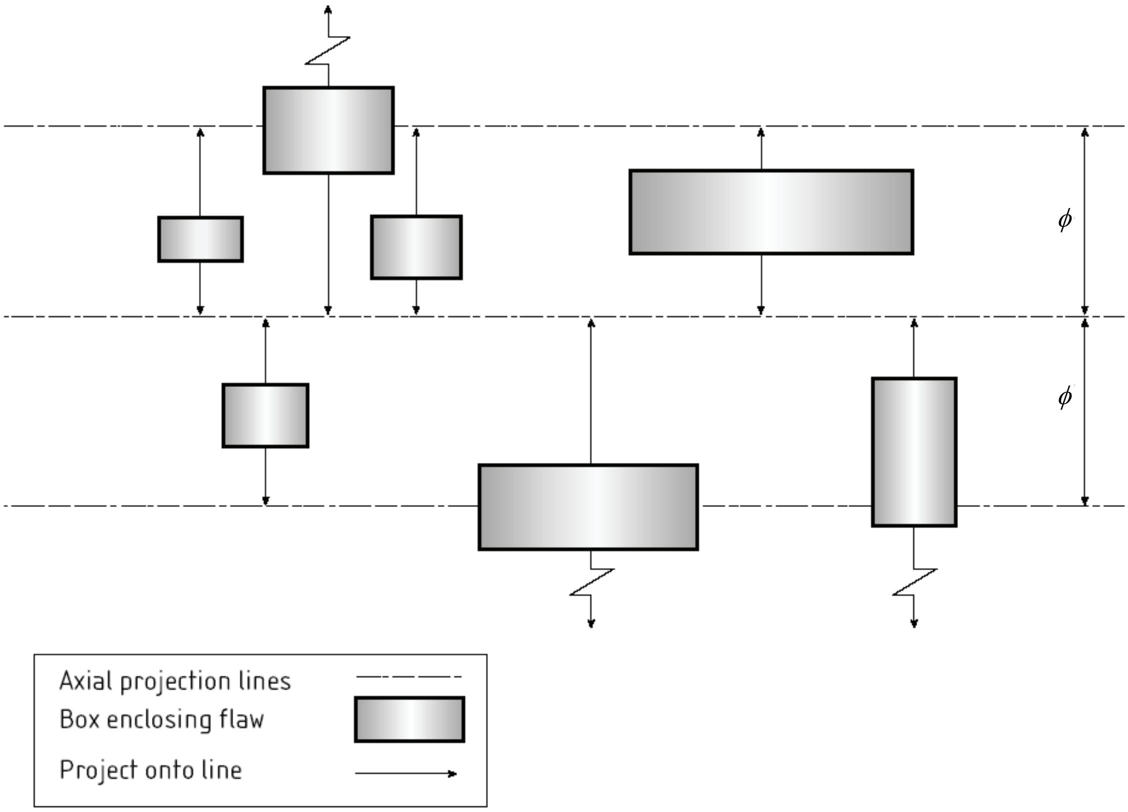


Figure 9.17 – Projection of circumferentially interacting flaws [9.1].

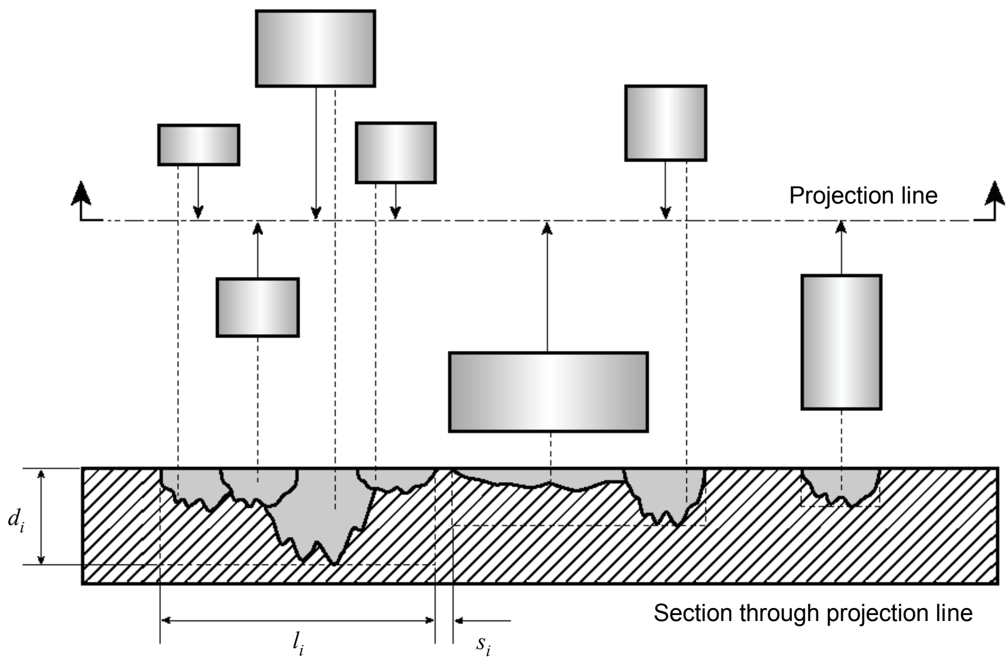
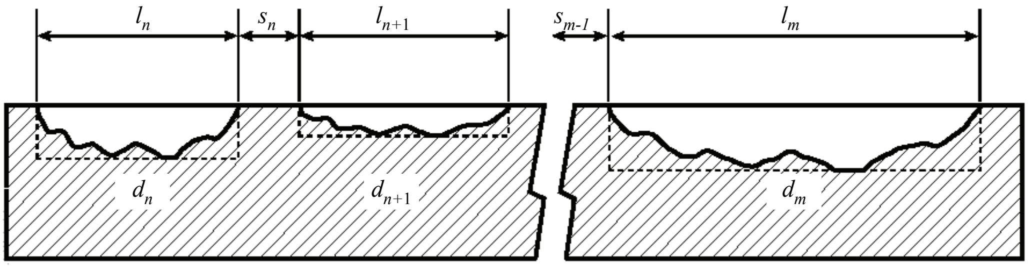


Figure 9.18 – Projection of overlapping sites onto a single projection line [9.1].



$$l_{nm} = l_m + \sum_{i=n}^{i=m-1} (l_i + s_i)$$

$$d_{nm} = \frac{\sum_{i=n}^{i=m} d_i l_i}{l_{nm}}$$

Figure 9.19 – Combining interacting flaws [9.1]

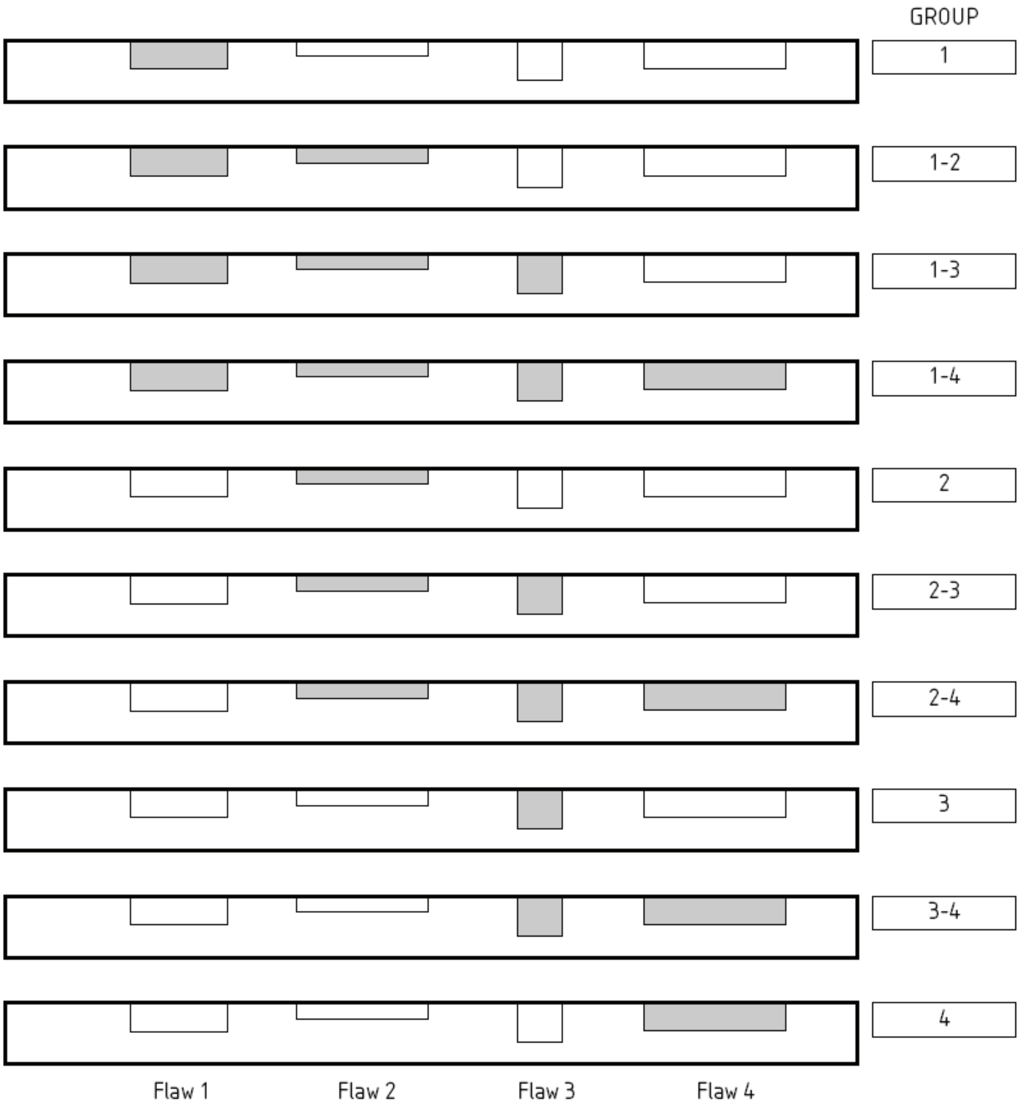


Figure 9.20 – Example of the grouping of adjacent flaws for interaction to find the grouping that gives the lowest estimated failure pressure [9.1].

9.3 Bibliography

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[9.6] Komai, K., "Proceedings of EVALMAT '89, Kobe, 1989", Iron and Steel Institute of Japan, Tokyo 1989, pp 121-134.