Guidelines for Establishing Fitness for Purpose of Welded Structures

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Author
P. Bristoll M.Sc.

Editor
dr.ir. A.H.M. Krom
015 276 3239
alfons.krom@tno.nl

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Paul Bristoll
TNO Industrial Technology

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Steering Committee (SC) and Working Group (WG) Members

name	affiliation	Membership of SC and WG
Ing. F.H. Dijkstra	Röntgen Technische Dienst	SC and WG (Written Contribution)
Ing. M. van Eyk	Röntgen Technische Dienst	WG (part time)
Ir. G.E. Kerkveld	Shell Global Solutions Amsterdam	SC
Ir. R.W.J. Koers	Shell Global Solutions Amsterdam	SC and WG (Written Contribution)
Dr.Ir. A.H.M. Krom	TNO Industrial Technology	SC and WG (Written Contribution)
Ing. C. van Sevenhoven EWE	Ministerie van Defensie	SC
Ir. L.A.J.L. Sarton	Ministerie van Defensie	SC
Ir. J.P.H. Wuister	Stoomwezen B.V.	SC and WG
Ing. E. Zeelenberg	Stoomwezen B.V.	Sub-group NDE of WG
Ing. J.L.J. Verkooijen	AEA Sonamatic B.V.	SC + Sub-group NDE of WG
Ing. W. J. Stikvoort	NAM B.V.	SC
Ir. A.N. de Jong	Schelde Technology Services	SC and WG
Ing. W.F. Burk	Schelde Technology Services	WG part time
J. Quist	Schelde Technology Services	WG part time
Ir. J.H.A.M. Heerings	TNO Industrial Technology	SC
Ir. H. van de Weijde	Bouwdienst Rijkswaterstaat	SC
Ir. G.H.G. Vaessen	Projectbureau PMP	SC
Dr.Ir. J.A.M.M. Kops	Projectbureau PMP	SC
Ing. T.P.A.M. van Bavel	DSM-MPS	SC and WG (Written Contribution)
P. Bristoll M.Sc.	TNO Industrial Technology	SC and WG (chairman) (Written Contribution)
ir. M.J.G. Broekhoven	BMC	SC (chairman) and WG

disclaimer

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API RP 579	defect assessment method	5
ASME	American Society for Mechanical Engineering	5
ASTM	American Society for Testing Materials	14.5
BS	British Standard	14.5
BS 7910	defect assessment method	5
R6	defect assessment method	5
CTOD	crack tip opening displacement	4.1
Cv	Charpy V	11.3, item 3.3
DNV	Det Norske Veritas	13.6
EDSU	Engineering Science Data Unit	11.3, item 3.3
EFAM	engineering flaw assessment method	5
EPRG	European Pipeline Research Group	5
EPRI	Electric Power Research Institute	5
ESIS	European Structural Integrity Society	14.5
ETM	Engineering Treatment Model	5
ET	eddy current testing	8.3.2.5
FAD	failure assessment diagram	4.2.1
FFP	fitness for purpose	2
FFS	fitness for service	2
GWMS	good workmanship	3.2.2
J	J-integral	4.1
K	stress intensity factor	4.1
Kmat	fracture toughness	4.2.1
Kr	FAD parameter	4.2.1
Lr	FAD parameter	4.2.1
LBB	leak before break	4.2.5
LOF	lack of fusion	13.3
LOSF	lack of sidewall fusion	13.3
MFL	magnetic flux leakage	8.3.2.3
MM	mismatch	
MPI	magnetic particle inspection	8.3.1.2
MT	magnetic testing	8.3.1.2
MUT	mechanised ultrasonic testing	8.3.2.1
NDE	non destructive examination	8.1
NDT	non destructive testing	8.1
NIL	Nederlands Instituut voor Lastechniek (Dutch Welding Institute)	
PE	pulse echo	8.3.1.5
POS	probability of sizing	8.4.3
POD	probability of detection	8.4.2
PT	liquid penetration testing	8.3.1.3
PWHT	post weld heat treatment	3.2.2

RBI	risk based inspection	3.2.3.2
RT	radiographic testing	8.3.1.4
SCF	stress concentration factor	
SMYS	specified minimum yield strength	
SMTS	specified minimum tensile strength	
SMUTS	specified minimum ultimate tensile strength	
TOFD	time of flight diffraction	8.3.2.2
TWI	The Welding Institute (UK)	
UT	manual ultrasonic testing	8.3.1.5
VI	visual inspection	8.3.1.1

Summary

Equipment is defined as *fit for purpose* when equipment complies with all operational and safety requirements during its planned lifetime. This definition is rather broad and certain operational and safety aspects are not covered in the Guidelines. The Guidelines are limited to mainly the mechanical integrity of welded structures, which are always assumed to contain defects. A fitness for purpose assessment is needed when there is a significant deviation from the original design requirements, or from the acceptable outcome of a previous fitness for purpose assessment.

The general nature of the Guidelines means that they can be applied in many different fields of engineering. The Guidelines are for use by a wide range of participants in the fitness for purpose process (designers, fabricators, owners, operators, inspectors, authorised bodies and analysts and other key expertise). Use of the Guidelines should stimulate the proper involvement of those responsible for taking decisions and of different relevant expertise throughout the process. The integrated application of the key disciplines of fracture mechanics, physical metallurgy, corrosion and non-destructive testing and evaluation that are needed for many assessments is a theme throughout the Guidelines. The main decisions and deliberations indicated concern the consequences failure, scope of a fitness for purpose assessment, the critical evaluation of an assessment, the taking of remedial measures to achieve fitness for purpose and the final agreement and decision on fitness for purpose.

In order to help the involvement of different expertise and decision-makers, the Guidelines provide an overview of the fitness for purpose process and provide a number of checklists. The intention is to achieve a consistent and efficient way of applying the fitness for purpose process and procedures throughout the life cycle, from the design phase through to the in-service phase. The availability of information is shown to increase as the life cycle progresses to the in-service stage. The consistent use of the Guidelines throughout the life cycle is given as a way of improving the quality in fitness for purpose assessment.

The Guidelines are not directed at any particular defect assessment and must not be used as a substitute for the available defect assessment codes, which must always be used, with the Guidelines. A number of the different defect assessment codes and fitness for purpose Guidelines being developed elsewhere are briefly reviewed. fitness for purpose is presented as a complimentary approach to good workmanship criteria that can be used in special circumstances. Good workmanship criteria are viewed as the basis of good engineering practice.

The influence of the uncertainties in the input data as a result of scatter and assumptions is discussed in some detail. In order to help assess the uncertainties in non-destructive testing, one of the main input parameters, the physics of methods is described along with their different performances. In particular issues concerning the probability of sizing and detection and the effect of inspectability on the performance of non-destructive evaluation (practical difficulties in carrying out an inspection) figure prominently.

In order to help decide whether a fitness for purpose assessment is worthwhile, an idea on how to perform a cost benefit analysis has been given. Some information on some of the possible costs of a fitness for purpose assessment and the opportunities that fitness for purpose may offer have been listed. A simplified defect assessment method has been provided for senior plant inspectors to help them decide whether to request a more complete assessment by an FFP analyst.

The first part of the Guidelines is intended for all involved in the fitness for purpose process. For those who are directly involved in assessments, the second and third parts of the Guidelines give more detailed information on the fitness for purpose assessments.

The understanding of the fitness for purpose process is aided by worked examples in part three. The examples are intended to demonstrate the process of fitness for purpose and the interplay between fracture mechanics and non-destructive testing and evaluation. The section on worked examples does not show detailed calculations but instead refers the reader to references where calculations are demonstrated.

1 Introduction

1.1 Overview of the FFP Guidelines

The Guidelines form the third phase of the NIL/PMP R&D programmes on Fitness for Purpose. The previous phases were concerned with the development of defect assessment methods via fracture mechanics and were vehicles that were intended to raise the level of awareness of FFP in the Netherlands.

The Guidelines have been written for a large number of potentially interested parties, many of whom were represented in the steering group overseeing the drawing up of the Guidelines. As a result the aims of the Guidelines are fairly diverse with guidance being given for simple to fairly complex FFP assessments and for a large range of applications.

The intention of the Guidelines is to overcome the large barrier to the application of FFP in spite of significant technical advances in fracture mechanics and non-destructive testing and evaluation. A significant part of the problem is the lack of overview of the FFP process. This concerns a lack of knowledge of individual participants of the role of others in the FFP process (e.g. designers, fabricators, owners (asset holders), operators, inspectors, authorised bodies, non-destructive evaluators and analysts). The problems are increased by the fact that many of the participants in an FFP process may be working for different organisations. Some of the lessons learnt from the previous phases of the NIL/PMP R&D programmes and experiences of the contributors to the Guidelines have been incorporated. Also the experiences documented in the current defect assessment codes and attempts elsewhere to draw up Fitness for Purpose Guidelines have been used and referenced.

The Guidelines recommend good workmanship criteria should be used to check the quality of fabrication. FFP is recommended when there are sound reasons for going beyond GWMS. FFP is needed in service because good workmanship criteria are no longer applicable to assess growing defects. Here GWMS criteria give little or no help. There are more reasons for applying an FFP approach than just assessing fabrication or in-service defects that fall outside of GWMS criteria. For example, the FFP methods could be used to take advantage of new developments in design, materials and non-destructive testing. An idea of some of the opportunities an FFP approach offers have been given in Section 4.6.1.

The Guidelines can be used as a reference work and help the implementation of FFP in a structured, rational manner. In addition, parts of the Guidelines can be abstracted and used as stand-alone aids to FFP assessment possibly after the relevant contents of this guideline have been modified by a user to suit specific needs.

There is much emphasis on the input data, which make or break an FFP assessment. In progressing from the phase of designers concept to fabrication and finally to the operation phase of equipment, it is shown that in situations where FFP approach is introduced early that the FFP approach can be gradually developed into a comprehensive approach in the service phase. As a result more structured and complete input data becomes available in each successive stage. The Guidelines promote the use of an FFP approach throughout the lifecycle in a structured way in order to improve the quality of the assessments and to make the process of application of FFP assessments more efficient.

There are three parts. The first part deals with the FFP process and its possible applications and should be understood by all participants in the FFP process. The second part is more for active users of FFP and gives more detailed information on the interaction between fracture mechanics and non-destructive testing and evaluation. There are also checklists to help the user of FFP technology. Some worked examples that demonstrate the FFP process rather than the mechanics of a defect assessment calculation are presented in the third part. The references are ordered in Sections according to subject. The references provide both background information to the development of the current FFP technology and provide a number of sources of data.

1.2 Objective of FFP Guidelines

- To provide an overview of the interdisciplinary process of fitness for purpose;
- To aid the timely and proper involvement in the FFP process of individuals with different relevant skills and responsibilities;
- To guide the application of fitness for purpose in a structured, consistent, efficient manner;
- To make a clear link between fracture mechanics and inspection;
- To indicate some the opportunities for the application of fitness for purpose;
- To guide the user to a number of different defect assessment and fracture control methods.

1.3 The limitations of the Guidelines

The Guidelines are limited in their scope. The Guidelines:

- are not a new defect assessment document and must be used with current standards and defect assessment Guidelines.
- are mainly limited to ferritic welded construction materials.
- are limited to mainly temperatures below the creep regime, although assessments of creep damage are mentioned.
- include fatigue degradation mechanisms. Other degradation mechanisms such as corrosion and stress corrosion cracking receive limited attention.
- are applicable to most common situations but are unable to cover every possible conceivable situation where FFP may be needed.

1.4 For whom are the Guidelines intended?

The Guidelines are for both experts and non-experts, who may occasionally become involved in FFP assessments. Those deeply involved or on the periphery all need to have an overview of the FFP process, the context of their own involvement, the involvement of others and the potential applications of FFP. More specifically, each party must understand the importance of and their role in the different decision processes. Typically, the following specialists and non-specialists will be involved:

- designers
- inspectors and maintainers
- authorised bodies
- fabricators
- operators/owners (asset holders)
- specialists

<u>notes</u>

- The plant inspector should be a senior inspector (e.g. extensive expertise and experience) and should be knowledgeable about the equipment containing the defect, (e.g. the processes involved, the materials and corrosion responses, and the consequences of failure) and a basic knowledge of FFP assessment.

- An authorised body is a body in which authority is invested by law and through appointment by government. (e.g. "notified bodies" and "user inspectorates" for pressure equipment).
- Specialists in FFP assessments are persons involved regularly in FFP assessments (FFP analysts, fracture mechanics testers, non-destructive testing and evaluation personnel, metallurgists, welding engineers, corrosion engineers). The FFP specialist responsible for the overall assessment should able to oversee evaluate the inputs of different specialists.
- The NDE specialist should be an NDE inspector SKO level 3[1] or equivalent qualification.

Table 1 Sections of the Guidelines of interest to different parties involved in FFP assessments

	designer	fabricator	owner/operator (asset owners)	authorised body	inspectors & maintainers	FFP-specialists	NDE-specialists	page number
1 Introduction	A	A	A	A	A	A	A	12
Part I Overview of Fitness for Purpose								
2 Definition of Fit For Purpose	A	A	A	A	A	A	A	18
3 The Need for Fitness For Purpose Assessments	A	A	A	A	A	A	A	19
4 The FFP Process	A	A	A	A	A	A	A	34
4.1 Input data for the analysis	A	A	A	A	A	A	A	35
4.2 The analysis	A	A	A	A	A	A	A	37
4.3 Dealing with uncertainty	A	A	A	A	A	A	A	46
4.4 Mitigation measures as a way of achieving FFP		A	A	A	A	A	A	50
4.5 Reporting, feedback and development of databanks	U	U	U	A	U	U	U	50
4.6 Elapsed time and cost/benefit of FFP assessments	A	A	U	A	A	U	A	51
Part II - Fitness for Purpose in More Detail								
5 Defect Assessment Methods					A	U		59
6 Probabilistic Fracture Mechanics Calculations						U		69
7 Screening Defect Assessment Calculation for Inspectors					U	U		76
8 Non Destructive Examination	A	A	A	A	U	U	U	85
9 Failure Investigation			A		U	U	A	117
Part III - FFP Help and Worked Examples								
10 Information Checklist			A	A	A	U		121
11 FFP Analysis Checklist			A	A	A	U	A	127
12 Mitigation Checklist			A	A	A	U		156
13 Worked Examples					A	U	A	167

<u>legend</u> A = awareness. This means an understanding of the contents in a section of the Guidelines.
U = user of a section of the Guidelines. The user must always have an understanding of Part I of Guidelines as well as the relevant parts of Parts II and III.

[1] level three according to the Dutch system of accreditation.

The best way to ensure objectivity is to follow procedures and use these Guidelines for participants to cross check information used in an FFP assessment. It is important to realise that each contributor and party to the FFP assessment will have their own role to play and responsibilities. All participants are obliged, at the very least, to understand their own roles and the roles of others in the context of the FFP process. This means that the participants in the FFP process should know a large part of Part I. Note that this is 40 pages of text.

Since the Guidelines were written for a large interest group, it may be sensible to abstract information from the Guidelines for direct use for individual participants in the FFP process. The information abstracted may also be modified to suit a user's specific needs. For example, a company dealing with only one type of equipment or a single field of engineering should be able to significantly simplify the checklists provided.

Table 1 gives the sections, that are of interest to different participants with an indication of whether the reader should be aware of or a user of a particular section.

1.5 Structure of the Guidelines

The Guidelines are divided into three parts.

Part I Overview of FFP

- Section 2 gives a definition of fitness for purpose.
- Section 3 indicates how it can be used in the different phases of the life of a structure from the design through fabrication to the service phases.
- Section 4 gives an introduction to FFP assessments with a schematic impression of the FFP process with its interactions and feedback loops. There are also schematic impressions of the way to refine an analysis, how to deal with defect extension in service and the requirements for a leak before break analysis, which is an alternative to preventing the initiation of defect extension. Finally there is a schematic representation of a probabilistic analysis, which is compared to a deterministic sensitivity analysis where the parameters are varied individually. The way of choosing partial safety factors for the different input parameters is indicated and the link between the factors chosen and the scatter and the consequences of failure. If fitness for purpose is not achieved even after refinement then various possibilities are given for carrying out remedial measures (mitigation). At the end of the section there is some guidance on the quality assurance aspects for a fitness for purpose assessment and some guidance on the costs and benefits of a fitness for purpose assessment.

Part II FFP in more detail

- Section 5 briefly reviews a number of available defect assessment and fitness for purpose methods giving some of the important similarities and differences. Some new and alternative approaches such as the local approach, wide-plate test and crack arrest approaches are also briefly given. Some the latter methods may provide a positive outcome if the more generally applied methods indicate unfit for purpose.
- Section 6 gives more detail on probabilistic calculations.
- Section 7 is a screening defect assessment based on a simplified method in the BS 7910 defect assessment procedure and is intended for use by plant inspectors for screening calculations when defects are found just outside of the good workmanship limits.
- Section 8 is an extensive piece on inspection. The difficulties in executing NDE and their subsequent influence on the performance of NDE are described. The different NDE

methods are explained along with their physical basis and resulting limitations. There are tables and figures, which give a rough guide to the performance of NDE methods.

- Section 9 describes failure investigation and how a different sort of FFP assessment must be used to determine the critical conditions, which caused failure. The information from a failure analysis is treated as an important source of information for the assessment of similar equipment.

Part III FFP help and examples

- Section 10 includes the Information Checklist that can be used to speed up the search for information needed for the assessment. This checklist is to some extent a duplication of the FFP Analysis Checklist. This checklist covers both requests for background information that may give clues to the nature of the problem and input data for the analysis. It differs from the FFP Analysis Checklist in that it is stripped of items analysis items.
- Section 11 includes the FFP Analysis Checklist for guiding an FFP assessment and checking the underlying assumptions, decisions and completeness.
- Section 12 includes the Mitigation Checklist, an aid to carry out remedial measures and check both in advance and in retrospect if the remedial measures result in FFP.
- Section 13 gives worked examples, covering the lifecycle, that illustrate the thinking in an FFP assessment particularly with respect to the link between fracture mechanics and NDE. References are also given on worked examples that demonstrate the mechanics of a defect assessment.
- Section 1 gives references which are divided according to subject and give the background to the current defect assessment codes and information on possible sources on input data.

Part I - Overview of Fitness For Purpose

2 Definition of Fit For Purpose

A structure is *fit for purpose* when it complies with all operational and safety requirements during its planned lifetime.

Fitness for purpose[2] in the Guidelines is mainly restricted to the mechanical integrity of welded structures containing defects; i.e. proof that no mechanical failure with unacceptable consequences for operations or safety occurs within the planned lifetime, considering all possible failure causes and degradation mechanisms which may occur.

AN FFP assessment is a combination of the knowledge of design, fracture mechanics, metallurgy, corrosion, welding and other joining techniques, materials manufacturing processes, fabrication, inspection including non destructive testing and evaluation, installation methods, operations and consequences of failure.

There are other sorts of fitness for purpose, which concern the limit states of operations and have no consequences for the mechanical limit states, e.g. the fouling of a plant. There are also some areas where there is an interaction between mechanical and operational FFP where mechanical integrity may be demonstrated or achieved at the cost of the operations, e.g.:

- an acceptable dent which obstructs flow in a pipeline and prevents the passage of both inspection and cleaning pigs.
- a pressure de-rating, which may result in FFP but may be unacceptable in terms of loss of production.

[2] In the USA the expression fit for service is used.

3 The Need for Fitness For Purpose Assessments

3.1 Deviations from design criteria or criteria from a previous fitness for purpose assessment

A FFP assessment is needed when a significant deviation occurs either from design criteria or criteria developed as a result of a previous FFP assessment and results in a potential threat to the mechanical integrity. For example, a new design based on good workmanship criteria may be considered a deviation because there is little or no operating experience to demonstrate mechanical integrity. Operations may also deviate significantly from the intentions of the original design. Typically up-scaling or de-bottlenecking of a design are activities which may result in significant deviations. The most common deviation is when the defects exceed the good workmanship limits. An overview of typical deviations from design can be made starting from the three inputs for FFP namely:

1 The fracture toughness, or resistance to long term degradation is less than the specified minimum design values or requirements from an FFP assessment.
2 The stress is greater than the maximum specified design stress maximum allowable stress from an FFP assessment. The cycles of stress are greater in magnitude and/or number than allowed for in the design or a previous FFP assessment.
3 The sizes of defect are greater than the limits prescribed by good workmanship criteria or maximum allowable defects based on an FFP assessment.

note 1 unacceptably low fracture toughness or strength may be a result of

- incorrect material specification or a mix up of materials during fabrication;
- damage, degradation and ageing during fabrication or service;
- inappropriate manufacture, fabrication/installation and repair methods e.g. welding and heat treatments. causing microstructures, which are susceptible to cracking or a reduction in strength;
- a higher or lower service temperature than the design temperature;
- the loading in service being dynamic (high strain rate) rather than the assumed static loading.

note 2 the stress is greater than the maximum specified stress because of

- global deviations of geometry e.g. out of roundness;
- local deviations of geometry e.g. weld geometry including excessive weld reinforcement and penetration, mismatch and misalignment at welds;
- inappropriate manufacture, fabrication/installation methods e.g. inappropriate restraint during welding;
- unexpected high loads during service or fabrication e.g. from earthquakes, subsidence etc.

note 3 the number of cycles of stress exceed the maximum number of cycles because

- the design life has been extended;
- the operations have been changed;
- the contribution of part of the cyclic loading was omitted or underestimated in the design.

note 4 defects outside of good workmanship criteria may be caused by

- inappropriate manufacture, fabrication and installation methods;
- defect growth during fabrication or service from acceptable defects;

- the creation of defects in service and subsequent growth; e.g. creation by corrosion, mechanical damage, high temperature damage etc.;
- extension of the design life allowing more time for defect extension.

3.2 Applications of FFP assessments

The methodology is intended for the assessment of defects in (welded) steel structures and pressure containing equipment. Prior to the application of fitness for purpose methods, fabrication defects should be assessed against good workmanship criteria and only if there are sound technical reasons, should FFP methods be applied. The assessment of defects outside GWMS criteria found during fabrication is not the only reason for a defect assessment. The designer may apply FFP methods to assess the sensitivity to defects or the effect of changes to other design input parameters in the presence defects. The operator may wish to check the effects of extending the operational envelope beyond the original design limits. Note that the development of defects in service is not covered by conventional good workmanship criteria and must be assessed using an FFP approach.

The uncertainties in the application of FFP assessments are greatest at the design stage when there is less information available. In theory confidence in the assessments should increase if FFP assessments are consistently carried out in each stage of the lifecycle e.g. in the design, fabrication and in-service phases of the life of the equipment. An idea of the increasing input information for an FFP assessment is given in Figure 1. The subsequent sub-sections go in more detail into the consequences of the increasing information.

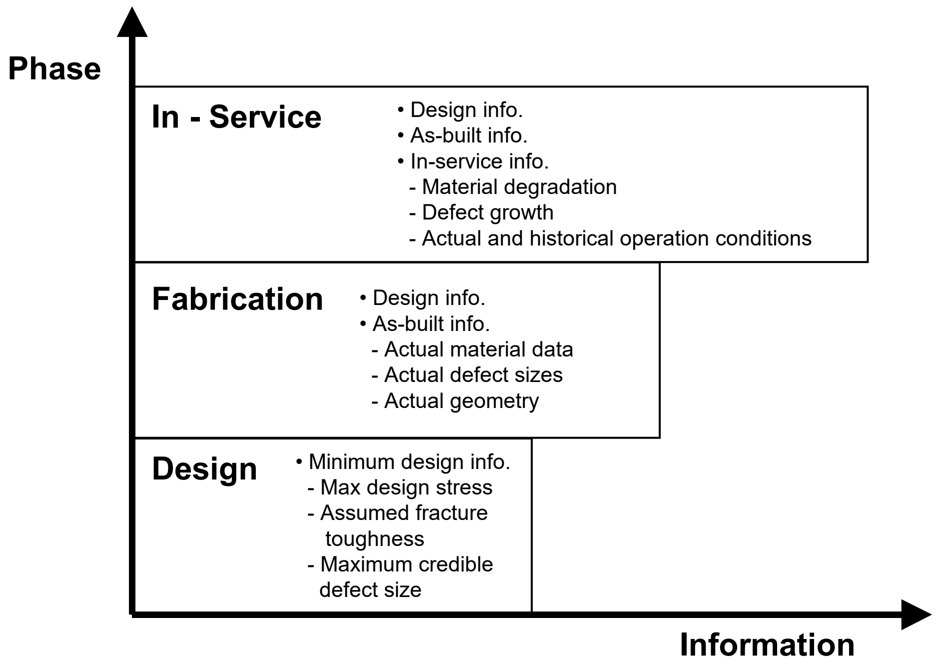


Figure 1 Ideally information for an FFP assessment should increase with progression of the lifecycle

A FFP assessment at the design stage is a sort of insurance, whereas the assessments during the fabrication and service stages are often carried out as a fire-fighting measure after problems have arisen. The lack of both a requirement by design codes to perform an FFP assessment and information at the design stage are the reasons why an FFP assessment is not usually applied at the design stage. When assessments are carried out without prior preparation the pressures on the analysts are very high, as the assessment has to be started from scratch and completed in the shortest possible time to avoid costly delays to fabrication and operations. The Guidelines therefore make a case for a systematic application of FFP assessments throughout all of the stages of the life cycle. This should ensure a more structured and efficient approach and avoid the expensive panics that occur when FFP is has to be applied unexpectedly. The different situations encountered when applying FFP during different stages of the life cycle is discussed in more detail in the subsequent subsections.

The most common form of FFP assessment concerns the assessment of defects that exceed good workmanship criteria. An idea of how the GWMS criteria relate to an FFP assessment are given in Figure 2.

notes

- The margin for a fitness for purpose assessment also includes an allowance for material degradation and crack growth in service.
- The margins and levels given are more for demonstration and in no way represent actual margins and levels, which will vary from case to case.
- The NDE response is tuned so that there is sufficient signal from the defect relative to that from the background noise. In order to avoid the noise, signals representing very small defects are ignored. Generally defects below the good workmanship limits are not recorded (see comments on this in Section 8 in Part II). FFP assessments are applied to defects that fall outside of the GWMS limits. A safety margin dependent on the expected growth of a defect, the consequences of failure and the quality and variability of the input data then ensures that the defect size is limited to a value less than the critical defect size.

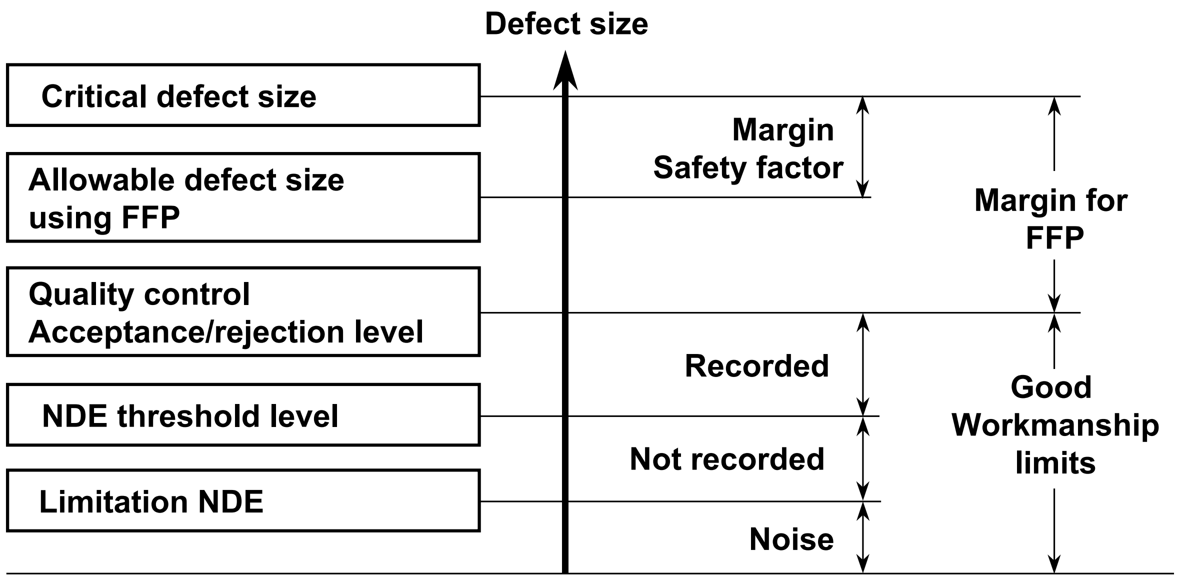


Figure 2 The scope for the application of fitness for purpose relative to good workmanship criteria used to control quality during fabrication. This figure is based on a similar figure in the IIW document, Section 14.2

3.2.1 Application of FFP in the design stage

The level of uncertainty in input data for an FFP assessment is the highest in the design phase. Reliance will be entirely on code guidance, databanks and experience from other in-service equipment. FFP assessments of a design should prescribe good workmanship criteria as the means to achieve quality. The FFP assessment of a design can be used, for example, to check the sensitivity of a design to defects, to specify fracture toughness for a material that is sufficient to cope with defects that have escaped detection, to determine whether the design is amenable to inspection of maximum allowable defect sizes and to indicate future inspection requirements.

The use of Failure Mode and Effect Analysis and Risk Assessment as a part of an FFP assessment at the design stage allows one to obtain more insight into the failure mechanisms and rates of degradation. For example, the selection of regions for FFP assessments in systems experiencing corrosive products will be based on the consideration of the physical and chemical nature of intermediate products formed during the process including the locations and times where they occur. This in turn will enable inspection requirements to be defined early and allow the design to be corrected when accessibility for inspection and maintenance is difficult or impossible or the amount of inspection and maintenance is found to be too costly during fabrication or service. FFP assessments should be used to aid the selection of quantitative NDE methods that are suitable for possible future FFP assessments. Note that the routine NDE methods normally prescribed by the codes are only semi-quantitative and are usually inadequate for an FFP assessment.

A designer could anticipate the need for future FFP assessments during the life cycle by defining a fracture toughness that is sufficiently high to ensure tolerance to the largest credible defect expected, i.e. the defects missed by NDE and growth of defects in service. Note also that the designer may not know which NDT techniques will be used. For example, a designer may wish to define a fracture toughness that can tolerate defects of the order of 10 to 15 mm depth which is the sort of defect depth, which, for example, routine manual ultrasonics should be able to detect with a high probability of detection, see Section 8.4.2. These relatively large defect depths are only applicable to thick walled constructions where the wall thickness is significantly larger than the defect depths mentioned. In spite of the larger tolerance to defects obtained by specifying higher fracture toughness, the designer will additionally require fabrication to be according to the good workmanship criteria specified in the codes.

A new design or new application of a design may have no supporting experience to justify the acceptance of defects on the basis of existing good workmanship criteria. Also, the use of advanced non routine NDE methods, which detect more defects than routine methods will require FFP assessments to justify their use and enable the development of suitable acceptance criteria. In these cases, new good workmanship criteria will probably have to be developed with the aid of an FFP approach. The FFP assessments should then use failure mode and effect analysis and risk assessment to target the analysis.

A summary of possible benefits that can be gained by performing FFP assessments in the design stage are listed below:

- application of new materials such as high strength steels and new welding consumables;
- application of new fabrication methods such as new joining techniques;
- application of new installation techniques (for example when strains experienced during installation temporarily reach levels in excess of those experienced during operation);
- developing a design for a new application;
- designing for areas with incidental severe loading (for example, earthquake areas, offshore where a loading which takes place once in a hundred or thousand year needs to be taken into account);
- upscaling a design (e.g. application of greater thickness);
- de-bottlenecking a design;

- ensuring a design is inspectable and aiding the selection of suitable quantitative NDE methods for future possible FFP assessment;
- avoidance of catastrophic failure (e.g. using crack arrestors, using a modular design where cracks cannot pass from one part of a construction to another, using crack arresting materials).

3.2.2 Application of FFP in the fabrication (installation) stage

The basis for good workmanship standards is routine NDE applied during fabrication, namely radiography, magnetic particle inspection and semi-quantitative ultrasonic NDT methods, see Section 8.3. The aim of GWMS standards is to ensure mechanical integrity through the assurance of quality. Experience has shown that equipment designed according to the codes meeting GWMS standards will be acceptably safe in-service.

There is, however, much evidence of equipment surviving defects larger than those accepted by the GWMS criteria. The question of whether GWMS could be extended by using FFP based acceptance criteria is still hotly debated in some quarters. There is a fear that the use of an FFP assessment during fabrication to justify the acceptance of a defect and avoiding repair would encourage bad workmanship. Nevertheless, in the past there have always been decisions to allow non-compliance with GWMS criteria when a sound, usually a semi-quantitative case could be made. The application of FFP assessments would make the acceptance of non-compliance with code requirements more transparent and rational. The use of FFP assessment is now recommended by some design codes.

The use of an FFP approach is promoted in the Guidelines, because there is much ignorance about the possible applications of FFP methods and their limitations. This does not mean that FFP assessment is being pushed at the cost of GWMS. The FFP approach should be kept in reserve to help in situations where there is sufficient justification for the use of FFP methods. The use of GWMS during fabrication should be kept as the primary means of achieving acceptable quality. When GWMS criteria are not met FFP methods can be considered for the assessment of non-compliance with GWMS criteria. Note that GWMS criteria do not allow cracks. In service, cracks may develop because crack growth is implicit in the design, see Section 3.2.3.1.

A FFP assessment during the fabrication stage comprises of the design FFP assessment if available and the as-built data on dimensions and material properties. The service history, the response of the structure and response of the material in service will be unknown. A FFP assessment made during fabrication will therefore have a level of uncertainty, which is smaller than that of FFP assessments carried out during the design but larger than FFP assessments carried out in-service. Anyone performing FFP assessments during fabrication must be aware of the uncertainty about the service conditions and take due account of the uncertainty in the FFP assessment. It is recommended that advice is obtained on expected operating conditions, consequences of failure, failure mechanisms and future material degradation and defect growth. The data required for an FFP assessment will either be derived from experience from fabrication and operation of similar equipment, materials databases and from laboratory and possibly component tests. Although FFP assessments can be fairly complex, it is often possible for an FFP specialist to define simplified screening procedures to assess defects for inspectors.

It is sensible to avoid surprises during the fabrication, as late changes in materials or procedures generally will result in high costs. Therefore it is prudent to check that the fracture mechanics toughness of materials and their weldments meet the FFP requirements of the designer during early welding (pre-)qualification trials. It is also worth checking if the minimum fracture toughness requirements of the designer do not lead to unrealistically high values of fracture toughness. The increased information available during fabrication may allow a reduction of the requirement.

When structures are large and/or complex (e.g. offshore structure, bridge, pipeline, tank etc.) there will probably be a need to inspect only the most highly stressed areas or areas where defects are most likely to occur during fabrication or develop later in service. The choice of where and how to inspect can be aided by using an FFP assessment, which should ideally have been carried out during the design stage. Inspection planning is discussed in more detail in Sections 3.2.3.1 and 3.2.3.2.

Continuing developments of NDE have resulted in new opportunities; e.g. faster methods, methods with a higher probability of detecting defects and methods that are more accurate. The opportunities provided by these new methods will only be realised if an FFP approach is applied in conjunction with these developments. This is because some of the new methods will detect defects with a far higher probability than that of the routine NDT methods used to establish GWMS. This may lead illogically to a higher repair rate. The small crack-like defects found by the new method that most probably would not have been detected by the routine methods, would be rejected and repaired when GWMS criteria are used. The development of new GWMS criteria by the use of FFP can overcome this dilemma and thereby stimulate the use and development of new NDT techniques, see Section 8.3 and the worked example on NDE on a pipeline lay-barge in Section 13.3.

Quantitative NDE is required for the application of an FFP approach. Since most NDE is routine, the NDE for FFP assessments must be qualified to ensure that the expertise used is sufficient, the methods selected are appropriate for the specific situation and result in the required quantitative information. For a consistent application of the FFP approach, the NDE carried out during fabrication should provide a quantitative initial reference (fingerprint) for in-service inspection. In order to obtain a fingerprint, the NDE used during fabrication should be chosen using an FFP assessment and checked at the same time for suitability as an inspection technique in service. In order to maintain consistency, the same NDE techniques and procedures should be used in-service.

A FFP assessment of rejected defects, for example, can avoid considerable excavation of defects, possible undesirable embrittlement and additional residual stresses when repairs in thick walled or higher strength materials are required. The defects, which are not detected and repaired, because the probability of detection is never 100% can also be analysed by an FFP assessment. A defect assessment calculation for screening defects is given in Section 7.

Post weld heat treatment of thick walled constructions is the usual way of reducing residual stresses. These stresses are an important contribution to the stresses that contribute to the initiation and development of sub-critical crack growth and fracture. The post weld heat treatment besides reducing residual stresses can either improve or degrade the fracture toughness. The repeat of a PWHT after repair welding may result in an extra reduction of fracture toughness or make a microstructure more susceptible to other sorts of cracking. When a construction is too large for a post weld heat treatment in an oven (full PWHT) or if detrimental effects of the PWHT are expected, then the requirement to perform a PWHT may need to be reconsidered. A FFP assessment can then be used to demonstrate whether equipment is FFP if the post weld heat treatment is avoided or just carried out locally.

Equipment produced in large series requires a different FFP approach to the production of individual pieces of equipment. A FFP assessment can be used to target inspection and thereby help justify a reduction of the amount of inspection. A very long, large or complex piece of equipment (e.g. storage tanks, offshore structures, pipelines) where there is a repetition of geometric detail and loading may also be treated similarly. In both cases a tailor-made FFP assessment, which can be re-used each time an assessment is needed, will be sufficient.

Fabrication defects are not the only defects that constitute deviations from design that might impair the mechanical integrity. A FFP assessment could be considered for assessing the geometrical design deviations such as out of roundness, dents, sharp notches, weld geometry including mismatch and misalignment.

If FFP requirements during fabrication are not met then the following remedial actions could be considered; e.g. replacement of materials, selection of more appropriate welding methods or procedures, repair or strengthening, global or local post weld heat treatments, surface treatments or stricter inspection requirements and modified proof stressing. In addition, the FFP analysis may lead to restrictions on operations or more accurate and or frequent inspections in service, see Sections 4.4 and 12.

The process of installation may result in high loads, which occur once in a lifetime. The consequences of the loading on the longer term integrity can be evaluated using an FFP assessment.

A summary of the reasons and opportunities for the application of an FFP assessment for fabrication are listed below:

- to aid the rational choice of a cost effective NDE approach (if not already carried out in the design stage);
- to enable the fabricator to take advantage of modern NDT techniques;
- to gain assurance of integrity in areas where NDE is difficult or impossible because of lack of accessibility;
- to choose NDE techniques that can provide a reference for NDE in service;
- acceptance of a defect or damage as a result of an FFP assessment can avoid costly and possibly detrimental repairs or scrapping equipment and consequent delays;
- to justify the avoidance of an impractical requirement for a post weld heat treatment;
- to assess the effect on long term integrity of incidental high loading, that may, for example, occur during installation;
- to aid the rational choice of the appropriate remedial measure(s) (mitigation) and be used to check whether such measures result in FFP;
- to provide a basis for future assessments in-service.

important points

- Non-experts applying FFP should be aware of the uncertainty about the actual future operating conditions and should seek expert advice on this before proceeding with an FFP assessment of defects or damage.
- It is prudent to check whether the fracture toughness specified by the designer is likely to be achieved in (pre)qualification testing before embarking on the fabrication.
- Qualification of the NDE is required when used in an FFP assessment.

3.2.3 Application of FFP in the in-service phase

This section is divided into a general section and two sub-sections. The latter deal with NDE in service and risk based inspection.

A FFP assessment has to be used to take account of defect growth and degradation of material properties in service. The use of GWMS criteria to judge defects found in service may be over-conservative and unrealistic. The design, in assuming GWMS criteria, is often intended to take account of some degradation and crack growth in service. Unnecessary repairs and possibly scrapping of equipment could be the result if GWMS criteria, which do not allow cracks, are applied. For example, fatigue crack growth can develop from accepted defects in dynamically loaded welded structures, which have been designed using a fatigue design curve rather than being designed to operate below the fatigue endurance limit. A number of design codes now include the possibility of an FFP assessment for these reasons.

The application of FFP assessment during service should in theory be the most complete application of FFP. The design data and design FFP analysis should be available. The as-built material properties, dimensions and defects are known along with the fabrication FFP analysis. The service history may be known from monitoring service conditions and the response of the structure and material. The response of the material is defined in terms of deformations, relaxation of stress, defect growth and material degradation.

It is difficult to determine the degradation of materials using routine NDE methods. One method is to take replicas of the microstructure directly from the material and study the microstructures etc. The microstructures are then correlated with material properties via comparison with databases or by testing similar material, which has been treated to obtain a similar microstructure. An example of this has been given in the worked examples in Section 13.5. Another method is to remove small amounts of material for metallurgical study and mechanical testing. In fairly rare instances, it may be possible to remove a complete section from the wall for full size testing. More frequently a piece of equipment is sacrificed for testing in order to assess the amount of degradation for other similar equipment operating under similar conditions.

Note that the NDE carried out during fabrication can provide a quantitative initial reference (fingerprint) for in-service inspection. In order to obtain a fingerprint, the NDE used during fabrication should be chosen so that the same technique and procedure is used in-service.

Quantitative NDE is required for the application of an FFP approach. Since most NDE is routine, The NDE for FFP assessments must be qualified to ensure that the expertise used is sufficient, the methods selected are appropriate for the specific situation and result in the required quantitative information.

Input data for an unexpected FFP assessment may be difficult to retrieve when there has been no previous FFP assessment in the design and fabrication stages. A consistent application of FFP assessments throughout the design, fabrication and service phases should avoid this.

Future technological developments may require changes to the way NDE and FFP assessments are carried out. Such changes should be registered and FFP analyses used to check the possible influence of a change of procedures.

The results of the in-service FFP analyses can be used for updating the previous design and fabrication FFP analyses. This may result in an updating of the NDE approach, see the next section. FFP assessments in-service can aid decisions on repair, strengthening, replacement and on changing the operating conditions in order to maintain mechanical integrity. For example, changes to the operating conditions that result in the reduction of loading, the increase or decrease in temperature or reduction of the aggressiveness of the corrosive environment could be considered. The results of FFP assessments may also assist in decisions on other measures such as contingencies to limit the consequences of failure. FFP assessments can give useful information on the extent of failure both in terms of leak rates through an opened crack and the extent of a fracture (e.g. leak, fragmentation, and catastrophic failure).

FFP assessments can be used to help decide whether to carry out maintenance or not when there are good reasons not to repair/replace. See also Section 4.4 on mitigation measures. Before a repair is carried out it is worth considering whether a metallurgical or failure investigation would provide relevant input for an FFP assessment (see comments on active and non-active defects in Sections 8 and 9).

FFP procedures are also useful in helping the diagnosis of the cause of failure and in predicting the conditions under which failure occurred. This type of analysis is different from the normal FFP analysis where the emphasis is on failure avoidance. All the safety factors must be removed as far as possible when calculating the conditions of failure. This also means that one should not use lower-bound input values for fracture toughness. In the first instance, average values should be tried in the assessment. If there has been no severe post failure damage (e.g. damage by fire, corrosion, erosion or over-enthusiastic personnel), the defect size at the origin of the failure can be measured accurately on the fracture surfaces. Removal of all safety factors is a problem for all but brittle failures where linear-elastic behaviour occurs. When there is significant plasticity there are implicit safety factors in the analysis that are not easily removed. This means that safety factors need to be estimated.

Operating experiences, failures and FFP analyses in service on similar equipment should be used to back-up the findings of the current FFP analysis. In order to maintain a healthy two-way flow of information, the results of an FFP and failure analyses should be fed back to operators and owners of similar installations in order to prevent similar recurrences of degradation or failure.

FFP analyses can also be used to extend the operating conditions and the lifetime of equipment. Conservatively designed equipment often has much larger safety margins than required because degradation or a certain type of loading assumed in the design does not occur in service. These margins may be decreased if sufficient justification is demonstrated by an FFP assessment.

A summary of the possible opportunities and benefits for the application of FFP assessments in service are listed below.

- to aid the planning of inspection in a rational manner;
- to increase the efficiency of inspection;
- to aid the selection of the most appropriate inspection tools in terms of required accuracy and probability of detection of defects;
- to aid failure diagnosis, see Section 9
- to aid the assessment of the effectiveness of mitigation (remedial) measures;
- to aid the avoidance of unplanned shutdowns;
- to justify the extension of the period between planned shutdowns;
- to help maintain the continued operation of equipment found to contain defects;
- to justify the extension of operating conditions;
- to justify the extension of service beyond the original design lifetime;

Figure 3 gives an idea of the life-cycle application of FFP assessments mentioned in the previous subsections in this section.

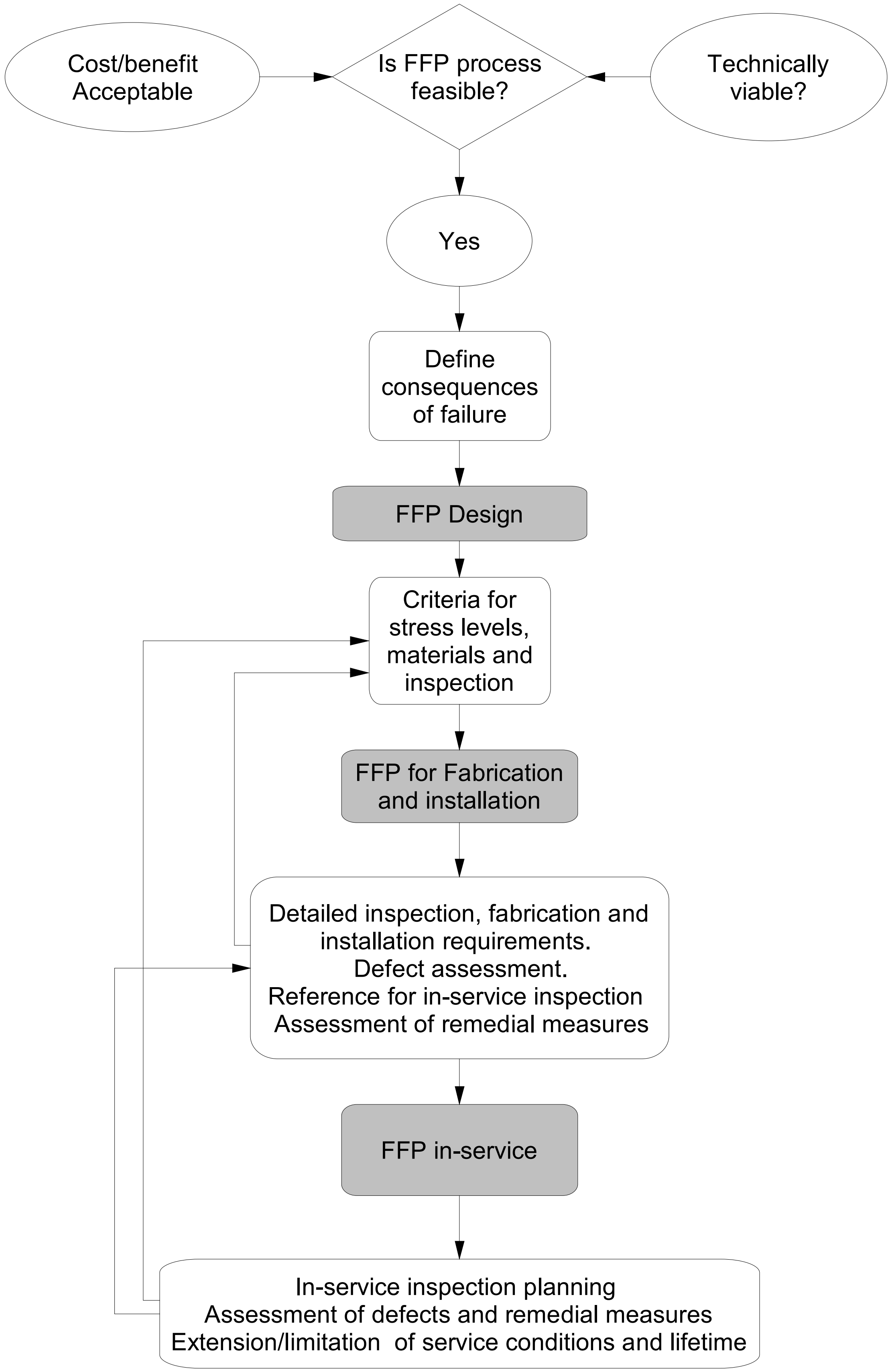


Figure 3 Application of FFP assessments throughout the life-cycle and essential feedback loops

3.2.3.1 inspection and maintenance planning in service

The application of FFP assessments to inspection and maintenance planning have been touched on in the previous sections on design, fabrication and in-service FFP assessments. The links between NDE and fracture mechanics are discussed in more detail in Section 8.3.

Inspection and maintenance is often carried out according to codes or regulations at regular intervals of time within the life of an installation without regard to the actual rate of degradation or defect growth occurring or the parts of the installation most likely to degrade with time. This can result in unnecessarily expensive inspection and maintenance, the wrong choice of NDT being made and cause delay in inspecting the more critical areas of large installations. This undesirable situation can be improved by using the FFP assessment along with failure mode and effect analysis to estimate the risks and the use of risk base inspection described in Section 3.2.3.2.

Application of fracture mechanics in conjunction with knowledge of the relevant defect growth mechanism and a realistic predictive model for defect growth will enable the growth of a defect as a function of time to be determined, see Section 4.2.4.

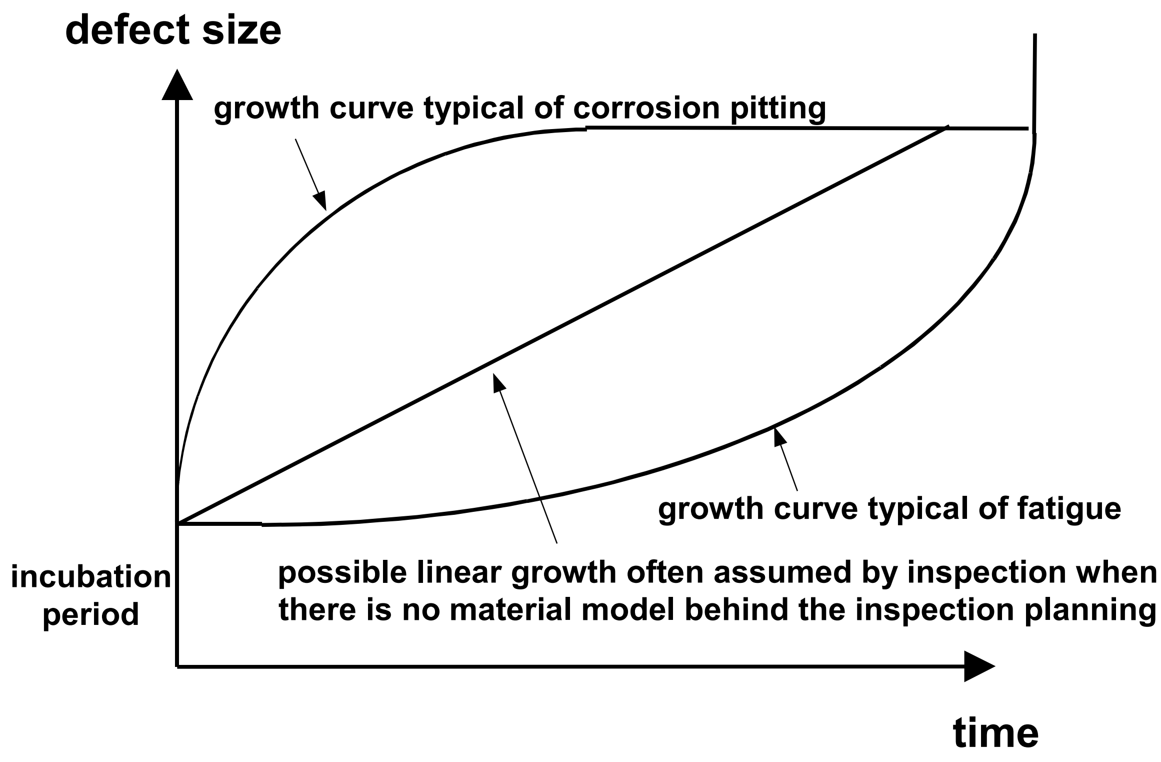


Figure 4 Non-linear defect growth versus inspection after constant interval.

Inspection at fixed constant intervals assuming a linear defect growth model can seriously over or underestimate the non-linear defect growth. In the worst case, the region of fast growth and ensuing failure may be missed completely by the inspection. There is also the possibility of a great deal of unnecessary inspection being carried out.

The models for predicting defect growth may not result in precise predictions of growth but give instead the trend. The uncertainty in the predictive model can be gradually removed by feeding back the results of NDE into the crack growth prediction model allowing the model to be updated in a semi-empirical manner, see Figure 5. The period of so-called incubation before crack growth starts can cause difficulties in predicting defect growth accurately. In many cases there is defect growth but it is at such a low rate that it is not detected by the NDT tool used, see Figures 4 and 5.

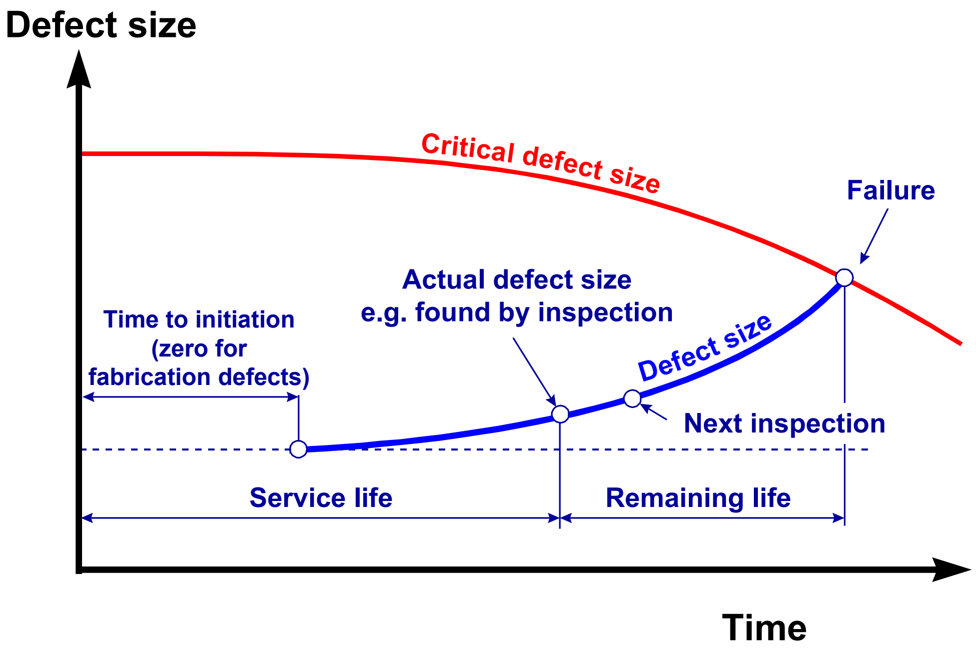


Figure 5 Updating crack growth and inspection periods

The defect growth predictions for planning inspection are started at the detection limit of the NDE or at the size of a known defect. The first inspection should be planned after a detectable amount growth is predicted. If no or less defect growth than the predicted growth is measured at the first inspection, the predicted defect size is reduced to the measured defect size and the growth curve modified to obtain a lower growth rate. This will result in a slower defect growth rate and a longer period before the next inspection. When detected defect is larger than the predicted defect size the growth rate relationship is modified to predict faster growth rates and the period to the next inspection shortened as a result of new predictions of growth, see Figure 5.

There is a possibility of increasing the period between shutdowns by using a combination of FFP assessment to define the requirements for NDE.

FFP can be used to help justify the use of cheaper non-intrusive NDE, i.e. NDE that is carried out externally. Inspection of much refinery and chemical plant is normally carried out internally and requires a shutdown to enable access.

An unplanned shutdown of a plant may occur when significant deviations from the design conditions occur in service. A quantitative FFP assessment may enable the plant inspector to show that inspection and/or repair can be postponed to the next planned shut down.

The choice of suitable cost effective inspection methods or combination of methods can be aided using FFP assessment methods, e.g.:

- If one can demonstrate that defect growth remains non-critical even at large defect sizes and can be repaired without incurring significant unacceptable operational costs then it may be quicker and cheaper to use visual inspection. This is common practice for the inspection of ships during the dry-docking. (e.g. non-critical cracks longer than say 15 centimetres should be visible to the naked eye).

- Note that the probability of detection of all NDT techniques will normally be less than 100%. Very often, routine NDT techniques will have probabilities of detection of less than 50% for typical weld defect sizes less than the height of a weld bead. The use of NDT techniques under difficult circumstances can further decrease the probability of detection. The selection of a method with an adequate probability of detection of the maximum tolerable defect size can be estimated by using a probabilistic FFP assessment. Alternatively, the uncertainty in NDE may be avoided by choosing a technique or combinations of technique that will achieve a relatively high probability of detection (above 90%) of the maximum tolerable defect size, see the table in Section 8.4. The latter approach will allow more scope for accommodating scatter in the stresses or the fracture toughness.
- The estimation of large maximum tolerable defects will allow even routine NDE methods to achieve a relatively a high probability of detection.
- Note that large defects means depths of the order of 15 mm or more for manual UT.
- If surface crack growth can be shown by assessment to be much faster than through-thickness crack growth then NDE methods should concentrate on the easier detection of surface cracks. The measurement of depth is then only necessary once an indication has been detected (e.g. this is common practice when inspecting for fatigue cracks in service in tubular joints in offshore structures).
- NDT in service can be reduced if it can be shown by a combination of fitness for purpose and failure mode and effect analyses that acceptable fabrication defects will not extend, i.e. NDE can be less extensive and carried out less frequently.
- More sophisticated FFP analysis techniques can be used to predict the direction of crack growth and ensure that the NDE is optimised for the direction of growth.
- Fracture mechanics can be used to predict the expected crack opening. This can be used in conjunction with knowledge of the flow of contained fluids to predict leak rates. If limited leak rates are acceptable then the predicted leak rates can be used to design or select leak detection systems, see also Section 4.2.5 on leak before break.

Proof testing can be used in combination with an FFP assessment to estimate the largest size of defects existing within pressurised equipment by calculating the defect sizes that would fail at the proof test. Defects that exceed the critical dimensions should fail. The margin for possible defect growth is the difference between the smaller sizes of critical defect that would cause failure at the proof test pressure and the larger sizes of critical defect that would cause failure at the operating pressure. Note that some smaller defects may grow in a stable manner without becoming critical and eventually cause a leak, which may or may not be acceptable. The pressure test will not give any indication of the size of stable defects that do not become critical. Therefore the growth of assumed stable defects with lengths remaining less than the critical through-thickness length should also be calculated in order to assess the possibility of leakage, see also Section 4.2.5.

3.2.3.2 criticality analysis and risk based inspection

There are a number of developments where attempts are being made to rationalise inspection and ensure that inspection planning takes account of criticality of equipment when determining inspection priorities. The technologies being developed are called ‘risk based inspection’ because of the use of risk to decide on the relative importance of parts of an installation for inspection.

Typically a matrix is developed where the “likelihood of failure” is plotted on the vertical axis and the “consequence of failure” on the horizontal axis. The axes are divided very often into a number of classes. In the example in Figure 6 three classes; high, medium and low have been chosen for simplicity.

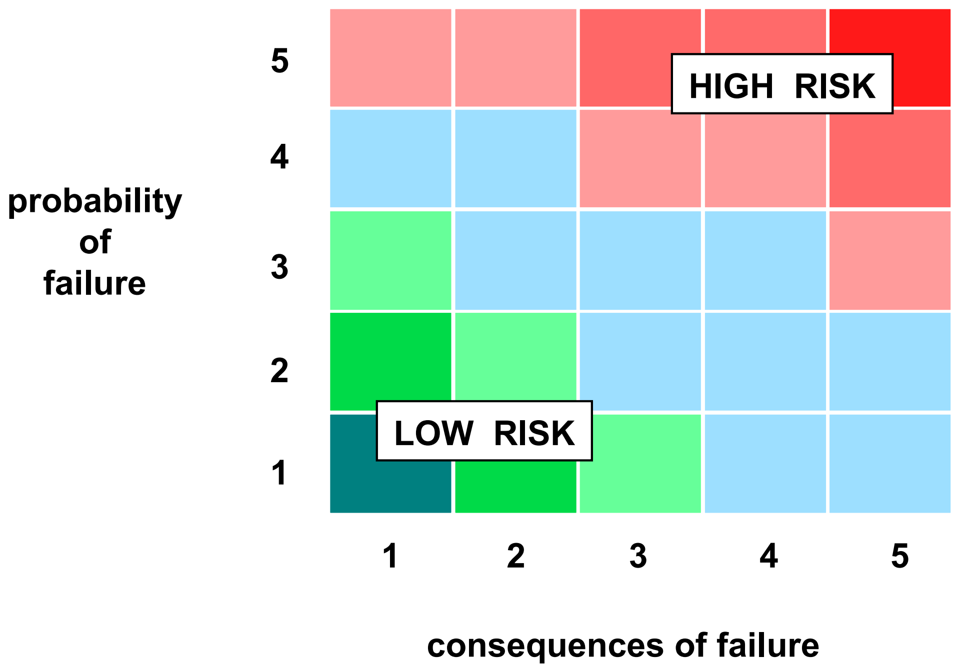


Figure 6 Criticality matrix for the rationalisation of inspection

The basis for deciding where a particular piece of equipment or component falls within the matrix is very often qualitatively based on common sense, insight and experience. The risk based inspection methods mentioned at the end of this section have developed methods of judging the way to rank the likelihood and consequences of failure on the basis of a combination of qualitative and semi-quantitative methods. Such a logical approach can have a significant impact on the planning of inspection and maintenance. It can also define which situations are unacceptable (situations that fall in the high-risk area) and situations that require no or only limited inspection (situations that fall in the low risk area). The rest of the matrix then indicates the situations that require inspection planning. The matrix also allows one to draw lines of constant risk (i.e. risk = consequence x probability of failure; the same risk is for example obtained when high probability of failure coincides with low consequence and when low probability of failure coincides with high consequence). This will give a series of parallel lines with a negative slope.

FFP assessments can be used to estimate the likelihood axis in a more quantitative manner and significantly affect the number of high likelihood cases requiring urgent remedial attention or number of cases requiring an inspection programme.

FFP assessments can also contribute towards defining the consequence axis. The extent of the fracture can be estimated (e.g. partial wall crack, leak, large catastrophic failure) and the opening up of the fracture in the case of a leak so that leak rates can be determined.

As discussed in the previous section, a more quantitative choice of the optimal period between inspections for those items of equipment needing an inspection programme can be aided by FFP assessments.

There are various initiatives to stimulate the risked based analysis approach to plan maintenance and inspection. The KINT in the Netherlands has developed a methodology and in the USA the API is developing similar methodologies, see Section 14.3.

4 The FFP Process

A simplified view of the FFP process is given in Figure 7. It has the form of a feedback loop showing the FFP process to be an iterative process that may have to be repeated several times before a satisfactory conclusion is reached. There is a more complete FFP process scheme reported in Appendix A of the final report of the NIL FFP project 2nd Phase, see Section 14.1.

Once a deviation has been signalled, the asset owner/operator must define the nature of the problem and the consequences of failure (see the diamond at the top of the feedback loop in Figure 7). Multidisciplinary input is needed at this stage to ensure the approach to be taken including assumptions have been properly defined.

The detected or postulated deviation will be an important input for the analysis and will probably relate to relate to one or more of the inputs shown in the analysis triangle; namely the resistance to failure, the loading and geometry and the defect size, see Section 4.1. The combination of defect size, loading and geometry result in the crack driving force, which is determined using fracture mechanics. If this exceeds the fracture toughness (resistance to failure), determined using fracture mechanics testing, then failure will occur. Before a crack reaches a critical size, the crack driving force can cause defects to grow via a number of different mechanisms at a rate, which is dependent on the magnitude of the crack driving force. Rather than estimate the critical conditions for fracture and plastic collapse separately, the analysis methods described in Section 4.2 result in a single assessment point combining the effects of plastic collapse and brittle fracture. After possible refinements to both the analysis and input data have been completed and the multidisciplinary group have checked the outcome, the results and underlying assumptions used in the analysis should be discussed by the group indicated in the next (lower) diamond. The owner/operator decide on fitness for purpose if the results fall within the FAD and are acceptable on the basis of risk of failure (the risk of failure is probability of failure times consequences of failure to meet e.g. safety, environmental, operational and financial requirements). If the result is not FFP, the analysis can be refined using better input data and higher levels of analysis (see Figure 10) or the use of a leak before break analysis (see Figure 13). The signal for the start of an FFP assessment is the occurrence or postulation of a deviation from the design or a previous FFP assessment that may potentially affect the mechanical integrity or operational requirements, see Section 3.1 for a number of possible deviations.

If the results are still not FFP, either an alternative assessment approach can be used, see Section 5.4 or a suitable remedial (mitigation) measure may be selected. There are a number of options for remedial measures. Some of these are given in the in the next block at the bottom left hand side of the feedback loop. The choice of remedial measure should be checked to see if it is practicable and whether FFP is achieved after an assessment the potential remedial measure.

In the next block, the results of the FFP assessment are fed back to the various interested parties to ensure that lessons are learnt and the FFP experience can be applied to the same piece of equipment in the future or other similar equipment or new designs.

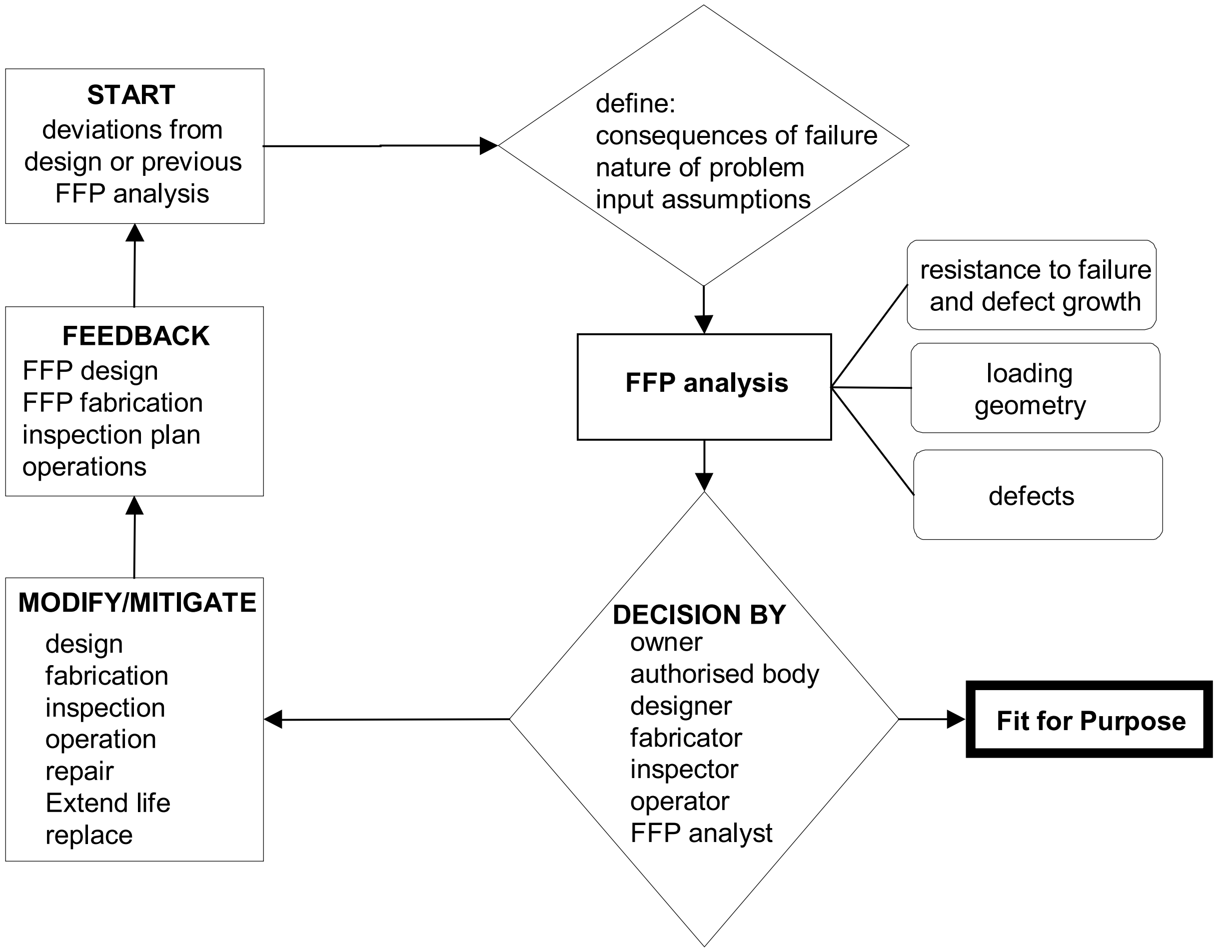


Figure 7 FFP process in the form of a feedback loop

4.1 Input data for the analysis

The input data below is needed to define the two input parameters fracture ratio and load ratio needed for the failure assessment diagram described in Section 4.2 and shown in Figure 8. Input data is required on:

position, orientation, size and shape of defects

The position, orientation, size and shape of defects is required as input for both the fracture mechanics and the plastic limit load solutions. These are in turn needed respectively as inputs to the parameters Kr and Lr in the FAD in Figure 8. The defect size is symbolised in this Figure by a semi-elliptical defect of length "1" and depth "a".

NDE and in some cases destructive metallurgical examination are needed to obtain the required information on defects. The best way to assess and characterise the defect is to use a combination of metallurgical knowledge and information from a combination of NDE methods. This is important for verifying whether the defect is static or whether it is likely to grow due to environmental effects or cyclic loading. The conditions under which NDE is carried out and the method or technique used will strongly influence the outcome in terms of detectability and accuracy of sizing a defect, see Section 8.4. Inspectability (i.e. the conditions which hinder or help inspection) is discussed more fully in Section 8.2.

The commonly used NDE methods are:

- visual inspection
- magnetic particle inspection or MPI, also known as MT (Magnetic Testing), a method for surface crack detection on magnetisable materials such as steel
- liquid penetrant inspection (PT)
- radiography, also known as RT (radiographic testing)
- ultrasonic inspection, also known as UT (ultrasonic testing)
- eddy current inspection, also known as ET, having restricted capabilities on carbon steel
- alternating current field method (ACFM) , mainly used for crack depth measurement

Also different techniques can exist within the methods (i.e. the way the method is implemented). The methods are more fully described in Section 8.3.

When selecting a method or technique, a clear understanding of the physical principles is essential in order to appreciate the possibilities and the shortcomings of the NDE methods. This is of particular importance when using NDE to acquire quantitative input data for an FFP assessment rather than the more semi-quantitative data, which is generated when using NDE to ensure good workmanship. This should ensure that unrealistic FFP criteria are not set, that blind faith in the outcome of NDE is avoided and that there is an awareness that defects will be missed during an inspection. Assistance on the selection of a NDE method or technique is given in Section 8.4. There is no generally preferred method as each method has its merits, and often compromises have to be made and combinations of methods used taking advantage of the different strengths of different techniques and procedures.

fracture mechanics parameter

This is a parameter, which when it exceeds the fracture toughness, causes a cracked body to fracture. The fracture mechanics parameter describes the stress and strain environment around the process zone at the crack tip. Failure starts in the process zone when the fracture mechanics parameter reaches a critical level. Identical fracture mechanics parameters in structures with differing geometry, size and crack size create identical process zones. This means that the crack growth rate or fracture toughness measured in the laboratory using a small specimen can be used to predict the growth rate or condition of fracture initiation in a large structure.

Fracture mechanics relationships between loads, geometry and size of a structure and defect size are needed to calculate the fracture parameters K_I the crack driving force. K_I is the numerator and K_{mat} (the fracture toughness) the denominator of the parameter K_r on the Y-axis of Figure 8. There are other fracture parameters such as the J-integral and the Crack Tip Opening displacement (CTOD). The J-integral and CTOD parameters are used when plasticity occurs at the crack tip but for the sake of simplicity here only the linear elastic stress intensity factor K will be considered. All of these fracture parameters are related and conversion from one to the other is possible. The solutions for the many fracture parameters can be obtained from various handbooks and the appendices of the different defect assessment methods e.g. BS 7910, R6 and API RP 579 methods or supporting documents, see Sections 14.2 and 5.3.

plastic limit load

The plastic limit load is the input parameter for the denominator of the parameter L_r. This can be calculated using special solutions given by the different defect assessment methods. The plastic yield or limit load is the load that causes yielding in the remaining un-cracked ligament when the defect is a surface or embedded defect. This occurs when $L_r = 1$. In the case of a through-thickness defect, it is the global yield strength of the structure containing the defect. Plastic collapse in the cross-section containing the defect is assumed to occur at the maximum allowable value of L_r. The plastic limit load solutions require input data on the material stress-strain behaviour symbolised by the tensile specimen in the Figure 8.

stresses

Loads can be used to calculate stresses, which can in turn be used to calculate the stress intensity factor and the load parameter L_r in Figure 8. The stresses can be obtained from design calculations. When more refined analyses are required then the detailed stresses are often determined via a combination of stress handbook solutions and analytical methods or finite element analyses. They can also be derived from the strains measured on model or actual structures.

materials properties

Material properties include strain hardening behaviour, expansion coefficients, resistance to fracture (fracture toughness), crack growth relationships and corrosion rates. The fracture and crack growth rate properties may have to be obtained on material exposed to relevant corrosive environments. The material properties data can be obtained from recommended lower-bound values, design data (e.g. minimum specified data), the literature, databanks, correlation's between fracture mechanics toughness and Charpy V impact data and by direct measurement using standard fracture toughness tests.

The fracture toughness test is symbolised by the notched test specimen on the vertical axis of Figure 8. It has an artificial crack and is pulled by tensile load until failure. The fracture toughness K_{mat} is calculated from the load at the fracture, the length of artificial crack and the fracture mechanics solution for the test specimen. K_{mat} is the denominator of the parameter K_r in Figure 8.

4.2 The analysis

There are a large number of defect assessment methods available, a number of which have been listed in Section 14.2 and described briefly in Section 5. A preference has been made in the Guidelines for methods, which use a failure assessment diagram. This section gives an impression of how an analysis is carried out. If FFP is not achievable then the possibilities of refinement of the analysis are mentioned in Section 4.2.3. If sub-critical defect growth occurs, caused by processes such as fatigue, see Section 4.2.4, then the tolerable defect size will have to be reduced to allow for the extension of initial defects. If FFP is not achieved when there is sub-critical defect growth for a partial through-wall defect then a leak before break approach can be taken if appropriate. Finally, if FFP is still not achieved then an alternative approach could be considered, see Section 5.4. There is also the possibility of mitigation (remedial action) in Section 4.4.

4.2.1 Failure assessment diagram

The FAD has the general shape of Figure 8 and is an interpolation between the limits of brittle fracture and plastic collapse. Brittle fracture failure at low loads and plastic collapse at high loads bound the curve. The fracture axis therefore determines the proximity to fracture and the load axis the proximity to plastic collapse.

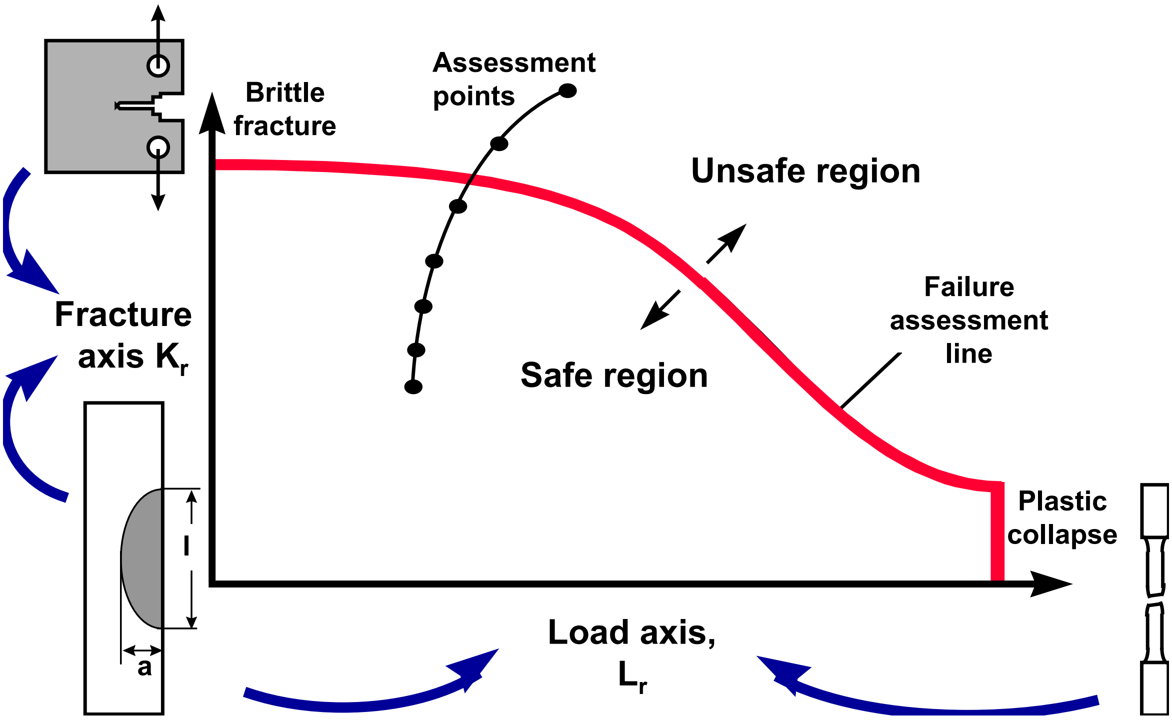


Figure 8 A typical failure assessment diagram

K_r on the fracture axis is defined as the ratio between the stress intensity factor and K_{mat}, the fracture toughness. L_r, is defined as the ratio of the loads that result in the primary stress to the plastic yield load of the structure containing the defect. The result of the failure assessment is a point, which is acceptable if it falls under the curve and unacceptable if it falls above the curve.

4.2.2 Reserve factor and partial safety factor

A *reserve factor* or *partial safety factor* is needed to take account of scatter in the input data, the uncertainty in assumptions taken and the level of seriousness of the consequences of failure. They can be calculated by comparing the result (assessment point) with the failure envelope in Figure 9. This is determined for the simple situation where there are no residual stresses by the ratio OB to OA. See also Section 4.3 and Section 11 item 7.2 in the checklist for FFP assessment.

A *reserve factor* is determined after the analysis. The reserve factor is plotted against each input parameter. If the gradient of the plot is steep then the result is sensitive to the input data. For example, if the reserve factor is very sensitive to the defect size then more effort could be invested in inspection by measuring the defect size more accurately.

A *partial safety factor* on the different input parameters is specified before the analysis. The value of the partial safety factors is decided on the basis of the uncertainty and scatter in the input data. There is some guidance given on this in the BS 7910 defect assessment procedure.

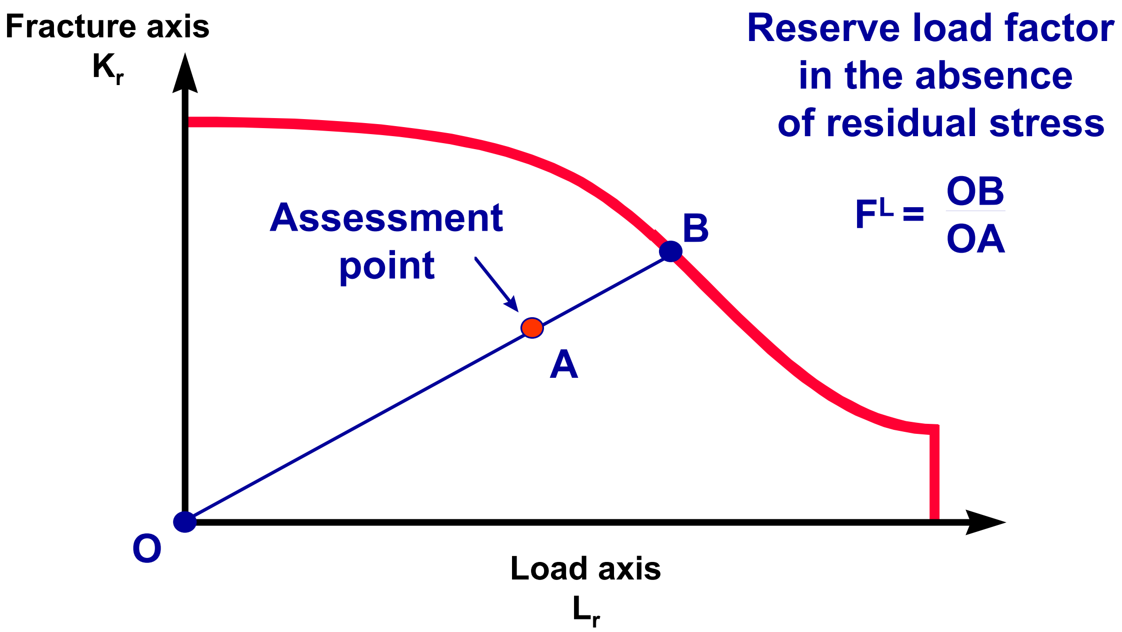


Figure 9 Failure assessment diagram showing how the reserve factor is calculated for a simple situation with no residual stress

4.2.3 Refinement of an FFP assessment

Avoid starting with an expensive analysis with high quality data straight away. A simple screening analysis where hypothetical sets of input data are varied systematically would enable the determination of the sensitivity of the result to different input parameters. The knowledge of the sensitivities can then be used to decide on where to put the most effort; i.e. which data needs to be of high quality and to what level should the analysis be taken. The sensitivity analysis may also show whether FFP is likely to be achieved and whether remedial measures will be required. If the input data is not of good quality, it may only be possible to justify a simple lower bound analysis . Note that a result from a simple screening analysis may be over-conservative and may lead to the unnecessary rejection of a piece of equipment. Further refinement of the assessment can be achieved by improving the quality of the analysis and input data in a series of steps. The loop shown in Figure 10 can be traversed several times and different levels of analysis can be attempted as the data improves. The margin for crack extension is described in Section 4.2.4.

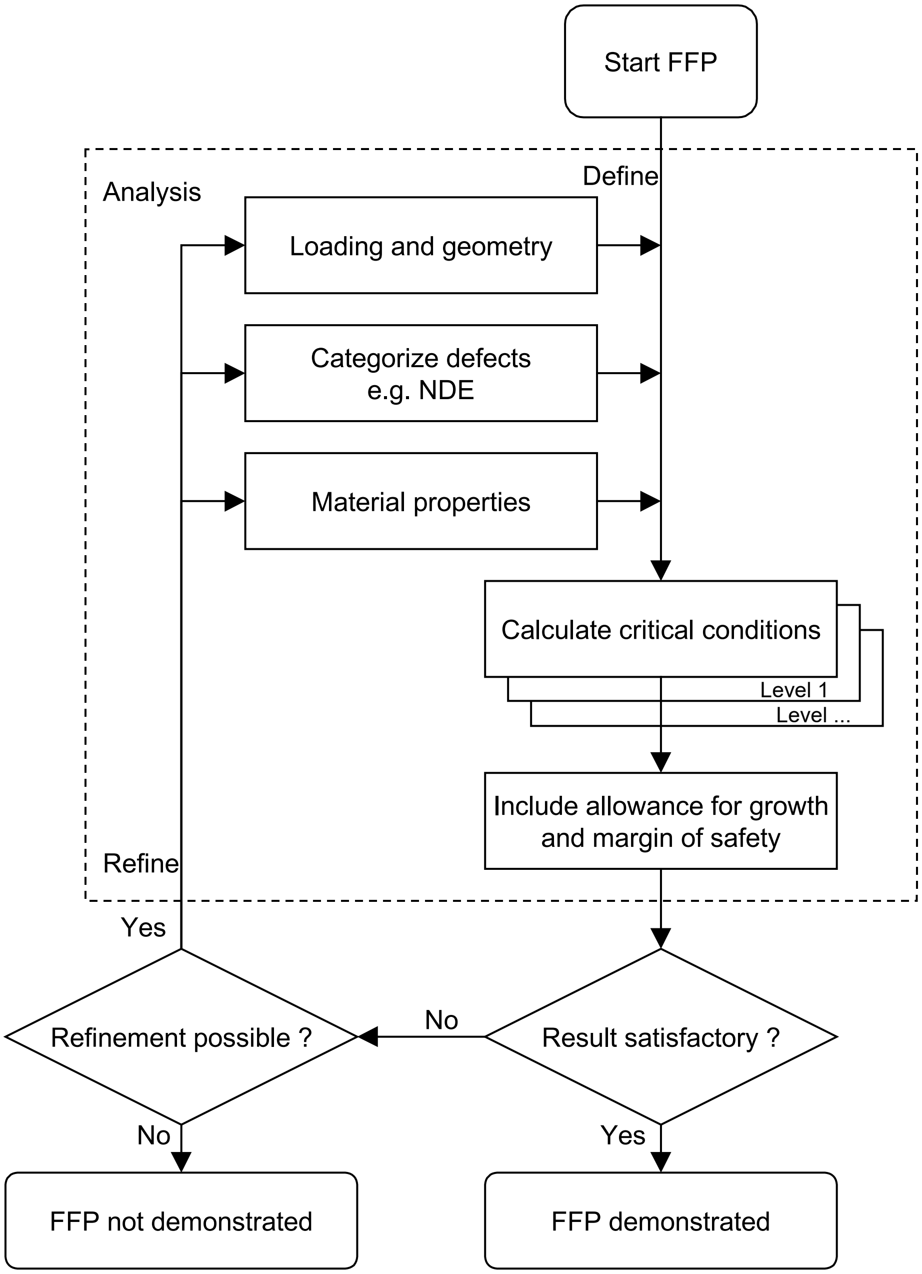


Figure 10 Refinement of an FFP assessment by improving the input data and analysis used

There are three different levels[3] of analysis, each of which has a different FAD. The lowest level is for a more conservative lower-bound analysis when the input data is limited. As the input improves the next level can be used when the FAD is derived from the stress strain behaviour of the material. The highest level of FAD is the most accurate and requires the most detailed input data. This FAD has to be derived for the specific material and the geometry of the cracked component. The higher level assessments can be applied to the cases where defects extend in a sub-critical stable manner by ductile tearing. Extra care must be exercised when using the highest level assessments as the implicit safety factors diminish.

[3] The R6 uses the term "options" for the different "levels", which is the term used in BS 7910. Furthermore, the "options" in R6 are not identical to the "levels" in BS 7910.

More expertise and effort in analysis and measurement of properties is required for a higher level analysis. An example of typical failure assessment diagrams at three different levels is given in Figure 11.

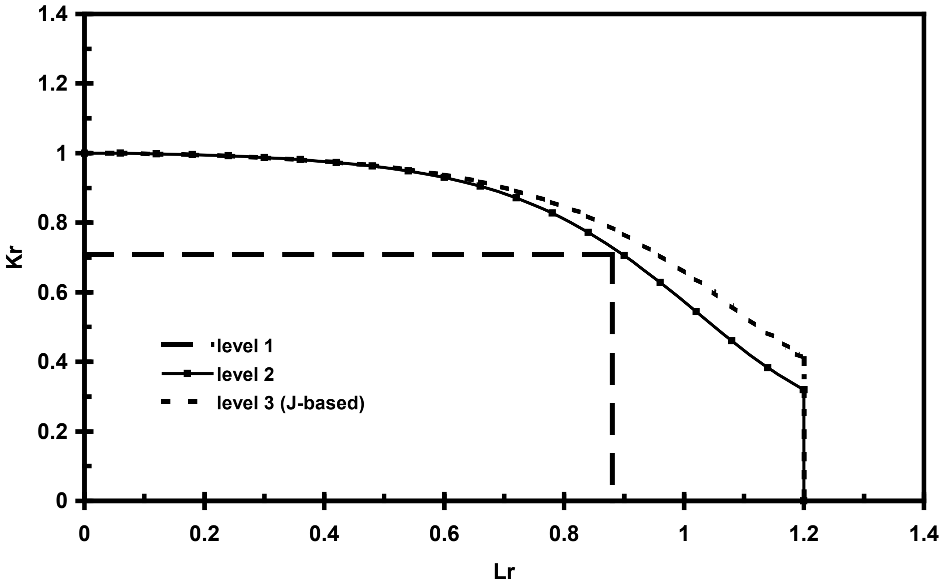


Figure 11 Example of three levels of analysis resulting in three different FADs

The degree of benefit in going from a lower level to a higher level FAD will depend on a number of parameters. In Figure 11 shows "level" 1 is the most conservative. The "levels" 2 and 3 were derived using the actual material tensile properties[4]. The highest "level" 3 also includes the geometry of the cracked body. In some cases there will be a greater benefit than that shown in going from a "level" 2 to a "level" 3 analysis.

4.2.4 Sub-critical defect growth

There are various forms of sub-critical crack growth where a crack grows gradually from an initial defect to the final critical size for failure. The important mechanisms are fatigue crack growth caused by cyclic loading, creep crack growth caused by static loading at high temperatures and environmentally enhanced crack growth caused by fluids (the term fluids includes gases), which react with the material at the crack tip or cause a corrosion pit to develop. As has been previously mentioned in Sections 3.2.3.1 and 3.2.3.2, the different mechanisms of stable sub-critical defect growth can have radically different growth rates. Furthermore different defect growth mechanisms can interact such as creep crack growth and fatigue or stress corrosion cracking and fatigue. The interaction may lead to faster or slower defect growth than that calculated by adding the separate contributions to defect growth from different mechanisms together.

[4] The level 1, 2 and 3 have been derived using relationships published by BS 7910. Normally the level 1 analysis is plotted in BS 7910 with a different X-axis. In this example the level 1 analysis has been transformed so that it can be compared with the other curves. The R6 level 1 curve for example has a similar shape to the higher levels of analysis.

The amount of crack extension by sub-critical crack growth can be calculated using the procedure given in Figure 12. The procedure is a numerical stepwise method, which calculates small increments of defect growth. The critical defect size is calculated using a fracture assessment method. The difference between the critical defect and the current defect size gives the margin for defect growth. As the defect size increases, the stress intensity factor will change and cause the defect to grow at an increased rate. The relationship between stress intensity factor and defect growth rate is used to calculate the amount of future defect extension from the current defect size. This is usually carried out in a stepwise manner allowing only very small increments of defect growth between each calculation step. The extended crack is then checked at each step to see whether it is greater or less than the maximum acceptable defect size. The time to reach the maximum acceptable defect size is the remaining lifetime. Convenient intervals may be chosen for inspection so that inspection takes place when the defect has reached a detectable size and when a measurable amount of growth has occurred. These intervals will differ in duration if the growth rate is non-linear; see Section 3.2.3.1. Alternatively the maximum acceptable defect size could be defined as the deepest repairable defect.

Note that the measurement of sub-critical crack growth laws or relationships is time consuming, costly and generally demands specialised laboratory conditions and equipment. A number of fatigue crack growth relationships are given in Section 14.8. Figure 4 gives an impression of different types of growth rate when different mechanisms are responsible for the defect extension.

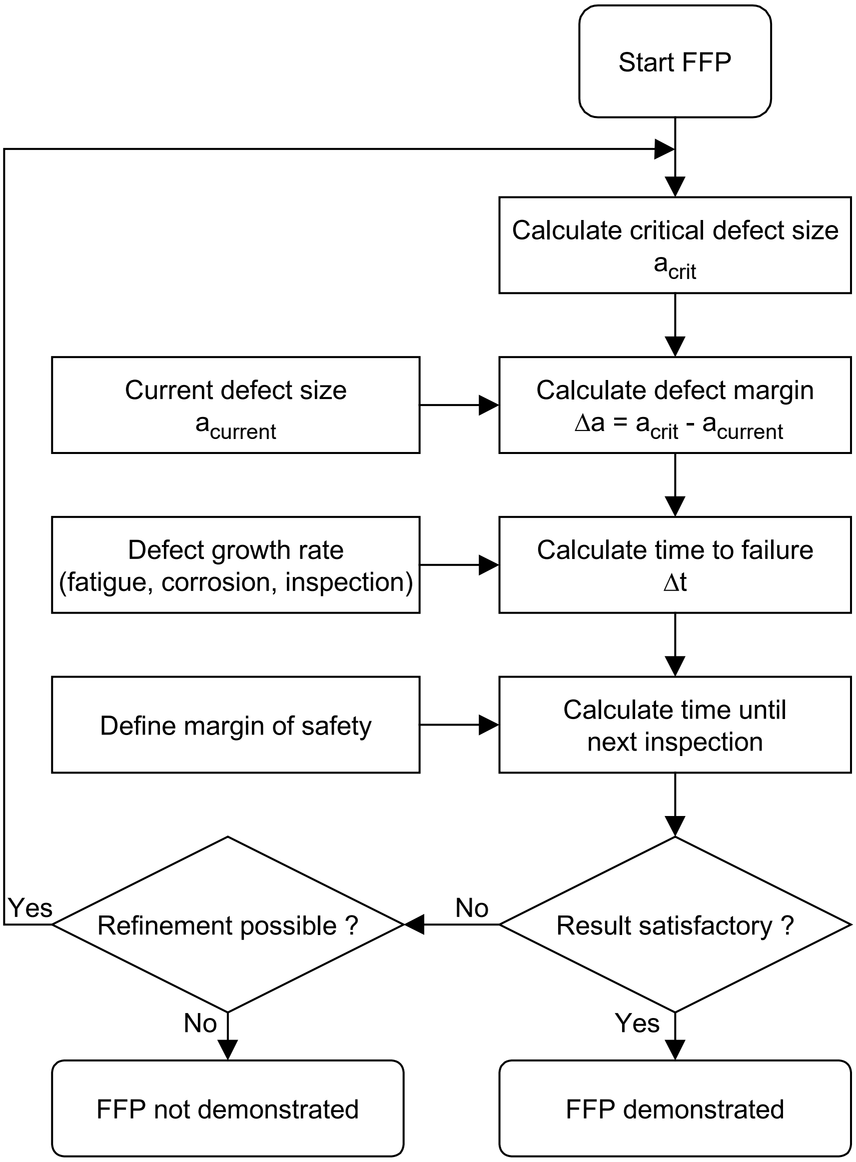


Figure 12 Time dependent failure by defect growth

4.2.5 Leak-before-break

The leak-before-break approach is an alternative method that can be used for pressurised systems. It is mainly applicable to defects in a simple geometry such as pipes when the defect growth through the wall is gradual[5]. Instead of declaring a pressure vessel unfit for purpose as a result of the previously described analyses, it may be possible to accept larger defects that may eventually cause leakage under certain circumstances. Figure 13 gives a number of conditions for applying the leak before break approach. Leak-before-break occurs when a through-thickness crack (leak) develops in a stable manner with a length that is less than the critical penetrated crack length for failure. If the initial crack length is greater than the critical

[5] See the previous Section 4.2.4 on subcritical stable crack growth. If the initial crack growth through the wall is unstable (brittle), the method needs to be combined with a crack arrest approach mentioned in part II Section 5.5. This needs the assistance of an expert. The approach may also be applicable when there are stress concentrations provided the length over which the stress concentration acts is smaller than the critical crack length of a through-thickness leaking crack. Again experts should be involved when stress concentrations are involved.

length for a through-thickness crack, or the development of a critical crack is calculated before penetration of the wall, a stable leak before break situation will not be possible.

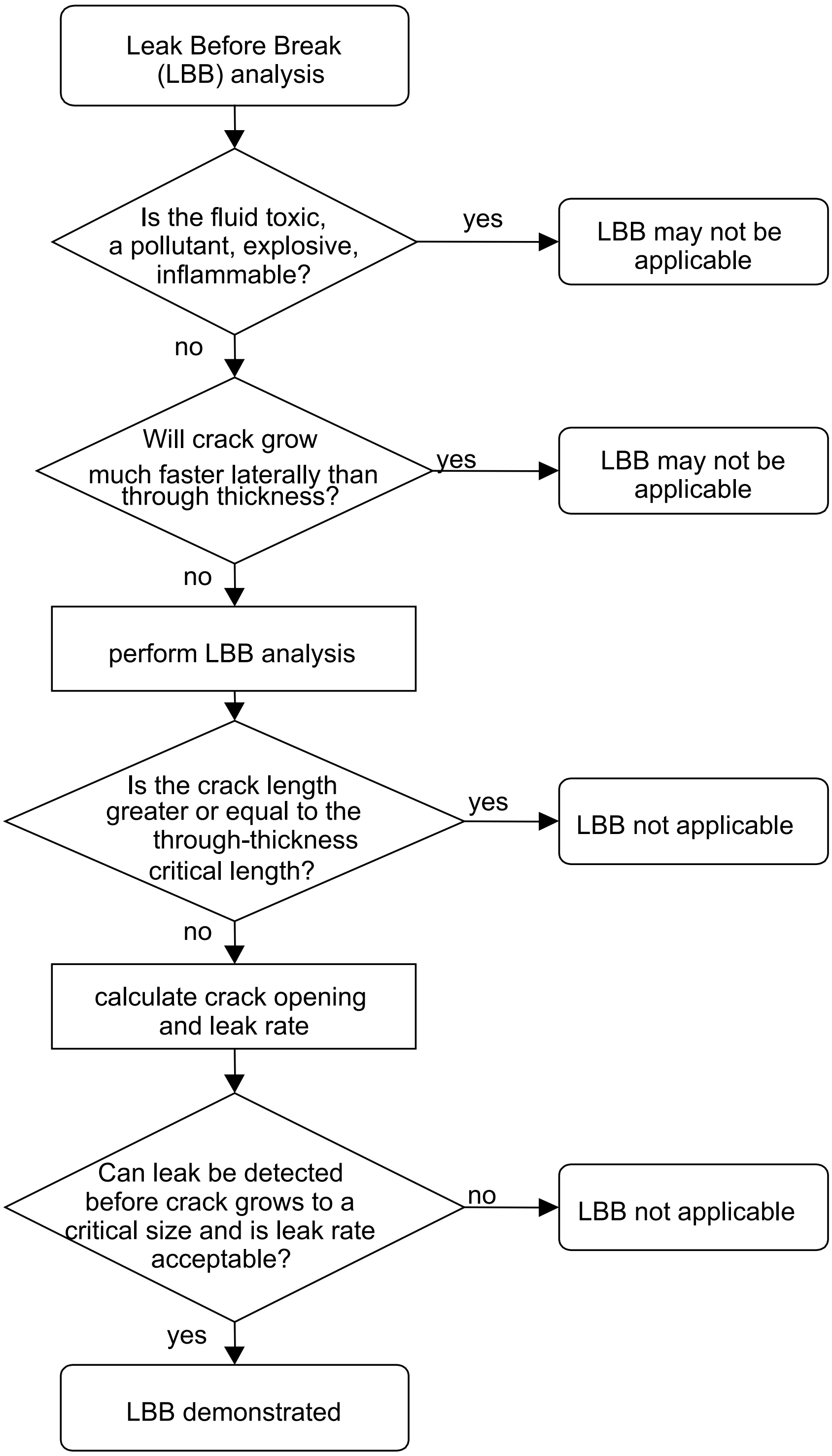


Figure 13 How to judge when leak before break can be used as an alternative to the previous approach of avoiding fracture initiation. The diamonds give the main decisions.

Calculations must be made to determine whether crack growth is faster along the surface in a lateral direction than in the depth direction. If this occurs then the LBB approach is inapplicable. There have been incidences of failures where inexperienced personnel have ignored this aspect. The LBB approach has been incorrectly seen as a panacea for all problems because of its apparent simplicity; i.e. one only has to consider the acceptability of a through-thickness crack instead of a complicated shaped crack in complex local stress fields, while omitting the necessary consideration of subcritical crack growth that may make the approach invalid. There are many reasons why sub-critical lateral crack growth will be faster; e.g. when

- the stresses at the surface are higher due to bending;
- the stresses are magnified by global or surface stress concentration factors, which influence the stress over a distance that is large compared to the critical through-thickness crack length;
- the stresses are raised due to residual welding stresses that act over a distance that is large compared to the critical through-thickness crack length;
- there is a possibility of defects joining up along the surface in some welds due to sub-critical defect growth (e.g. coalescence of fabrication defects via fatigue);
- some forms of stress corrosion cracking occur (note it is difficult to predict stress corrosion crack growth accurately and expert advice should be sought when confronted with stress corrosion cracking).

Lateral crack growth rates can be checked by calculation if the correct sub-critical crack growth laws are used. In some cases the multiple initiation of cracks and their coalescence makes estimates of lateral crack growth rates inaccurate.

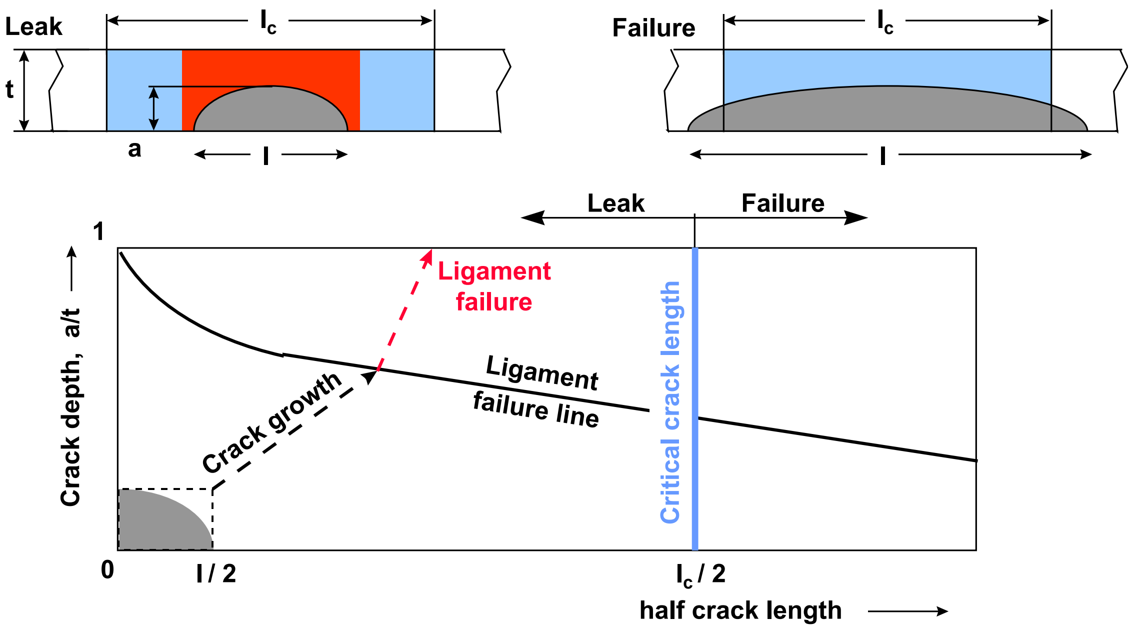


Figure 14 A schematic idea of leak before break (based on a figure in R6)

The top figures give an impression of two surface cracks. The left hand crack, which is far shorter than the critical through-thickness length, will finally penetrate the ligament, provided the critical size is not exceeded during crack extension, and cause a stable leak (ligament failure). The longer surface crack already exceeds the critical crack length for a through-thickness crack and will after sufficient sub-critical crack growth reach the critical size for brittle fracture before the wall is penetrated. The graph underneath gives the crack growth again in 2 dimensions, depth and length with the vertical line giving the critical through-thickness crack length for brittle failure.

A through-thickness crack may also be allowable in structures, if the mechanical integrity of the structure is not endangered. This usually means there must be sufficient redundancy in the structure to share the loads that are no longer supported by the cracked part.

4.3 Dealing with uncertainty

4.3.1 Sources of uncertainty

All input data will suffer from scatter and uncertainties whether it is the dimensions of a structure, the loading, the defect size and the fracture toughness

In general, the largest uncertainties and scatter will be in the fracture toughness, defect size and the residual stresses. When cleavage fracture occurs, the fracture toughness and residual stress will probably be the factors, which have the largest effect on the FFP result. When the failure mode is ductile the defect size will probably become the largest uncertainty. Due to ignorance of the magnitude of residual stress and its distribution, residual stresses are often assumed to have the maximum value of the yield stress of the base or weld material. In some structures loaded by natural forces (e.g. earthquake, wave and wind loading) the loading is not restricted (e.g. like a pressure vessel where the pressure is restricted by a pressure relief valve) and will vary in a random manner. Even a pressure vessel with a safety valve will have some uncertainty in the maximum pressure because the setting of the valve will have a tolerance. Apart from the scatter there is uncertainty because one may be forced, by a lack of data, to use data of a questionable quality. In this case one must remain on the safe side by choosing extra large reserve factors.

When estimating fatigue crack growth and other forms of sub-critical crack growth there will be an extremely high sensitivity to variability in input data because of the non-linear nature of the crack growth laws. The power law relationships (see Figure 4) can mean a sudden growth from a small initial defect to a large defect threatening the structural integrity. This means extra care, taking account of the scatter in input data, is needed for a sub-critical crack growth calculation.

There is also some uncertainty in the accuracy of the models chosen for the assessment. The failure assessment diagram has an unknown amount of safety.

There is also uncertainty in the models used to calculate stress, fracture and plastic collapse. When plasticity develops the stress and fracture models become more complex, increasing the possibility of inaccuracy.

The uncertainty in the data, the assumptions used in the selection of data and models used and reasons for conservatism or lack of conservatism should be made explicit in the reporting.

4.3.2 Analysis of uncertainty

The effects of the uncertainty in the analysis can be investigated by performing a deterministic or a probabilistic sensitivity analysis. Deterministic sensitivity studies to check the effects of uncertainties and variability of data have been described in Section 4.2.3 on the refinement of an FFP analysis (e.g. screening analyses).

4.3.2.1 deterministic sensitivity analysis

The use of safety factors without regard to the possible scatter of input data and the impact of the scatter on the result is not recommended. The problem with safety factors, which are commonly used in design, is illustrated in Figure 15.

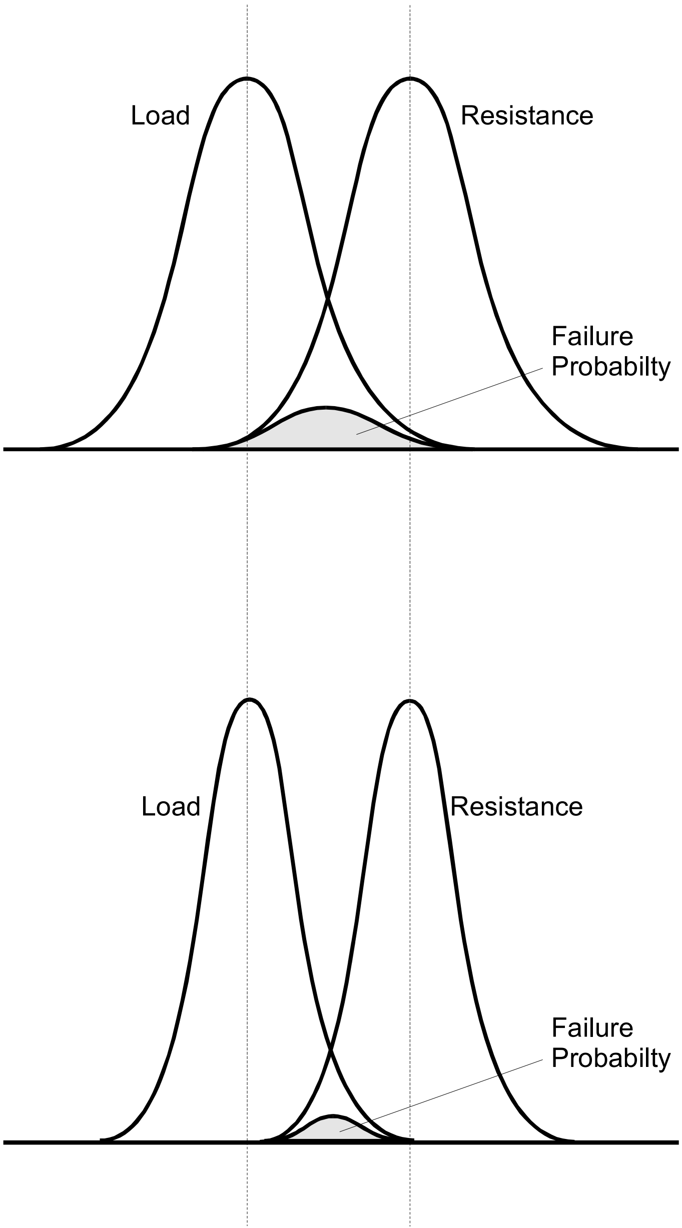


Figure 15 A demonstration of the problem with conventional safety factors

The distributions of load and resistance to load in the two cases in Figure 15 demonstrate that the probability of failure in both cases is significantly different, in spite of having an identical safety margin between the mean material resistance to failure and the mean load on the material. The shaded area under the overlapping curves in Figure 15 represents the probability of failure. In the bottom example, the distributions are narrower (less scatter) causing a smaller overlap of distributions and therefore a lower probability of failure. In the top example, the distributions are broader (greater scatter) and there is a higher probability of failure. In order to avoid this situation one should perform sensitivity studies or probabilistic analyses. Finally an appropriate reserve factor or probability of failure is chosen, on the basis of the sensitivity of the result to the input data and the consequences of failure. The refinement of an analysis depicted in Figure 10 also gives an idea of how a sensitivity analysis should be carried out. The main difference being in refinement one systematically improves the data and models, whereas in a sensitivity analysis one may use input data one does not possess. The possibly hypothetical data and other parameters are varied systematically around the most likely values. This will indicate how sensitive the results are to the input parameters. See Section 4.2 on the analysis and Figure 10. See also Section 11, and Figures 36 to 38.

The BS 7910 method uses pre-selected partial safety factors on each of the input parameters rather than apply a reserve factor as used in R6 that is chosen on the basis of a sensitivity analysis. The concept of a partial safety factor conjures up the idea of a real safety factor whereas there is much implicit safety in the choice of input data and the FAD used. The BS 7910 method gives guidance on the relationship between partial safety factors, scatter and probabilities of failure, see Section 11 item 7 in the FFP analysis checklist).

If FFP is not achievable there is always a possibility of repeating the assessment using a Leak-before-break analysis, see Section 4.2.5.

4.3.2.2 probabilistic analysis

Probabilistic analyses do not give probabilities of failure but rather relative probabilities of failure. In other words there are implicit unknown safety factors in the analysis and input data making it difficult to predict the probability of failure. In many cases, the probabilistic studies are only partial probabilistic studies because of ignorance of the actual distribution of some input parameters.

Probabilistic analysis is for the more skilled analyst. It may be made available to those with less expertise in the form of a special analysis for a problem with given limits where the background work has already been carried out by experts who have developed problem specific robust procedures and software. Figure 16 gives an overview of a probabilistic analysis.

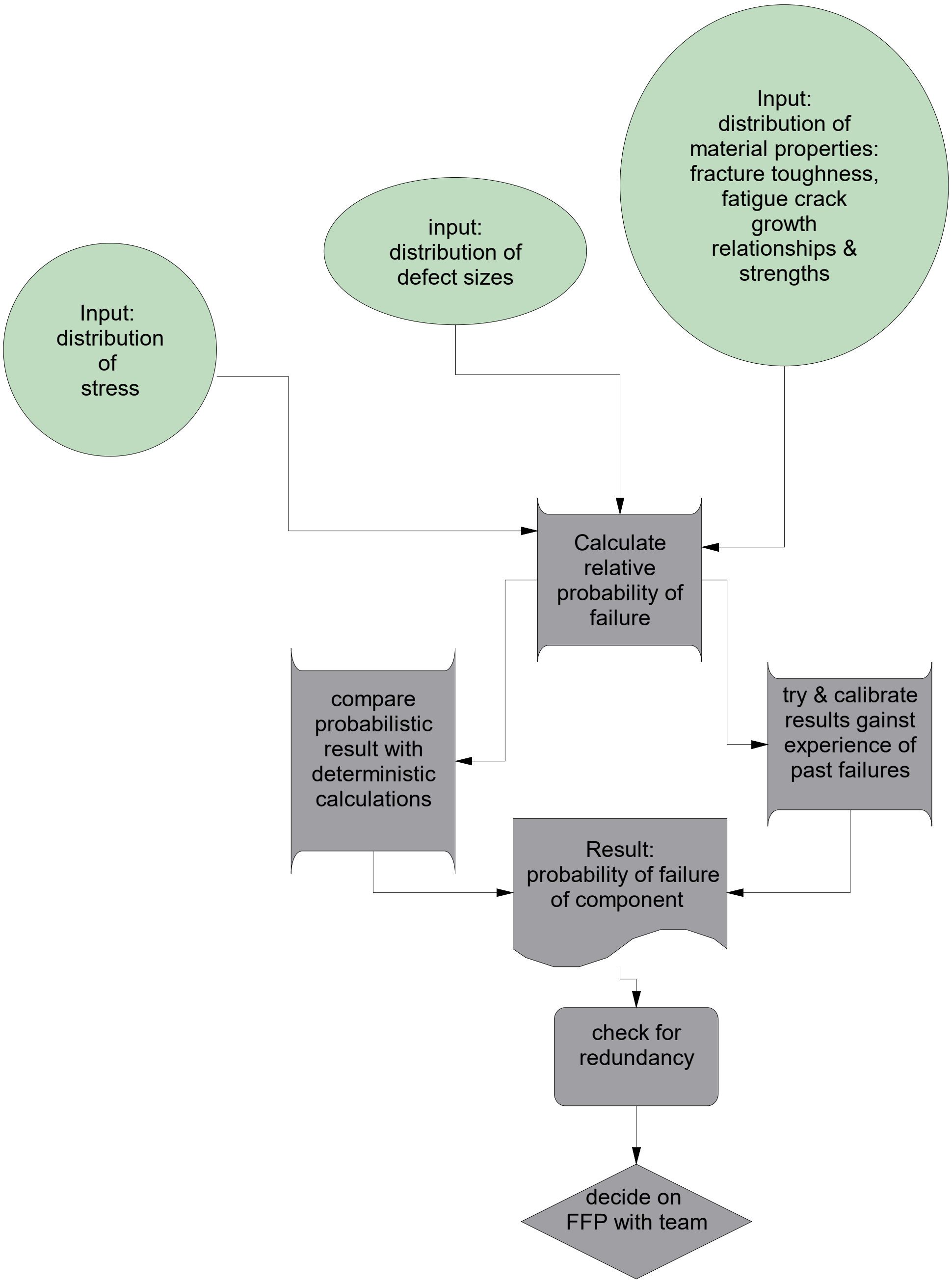


Figure 16 Probabilistic FFP analysis

Probabilistic analysis requires several main inputs in the form of distributions, namely, a distribution of stresses, a distribution of defect sizes, a distribution of fracture toughness and a distribution of sub-critical crack growth rates. The uncertainty in the models used may also be included in a probabilistic analysis. The normal distribution, often used in reliability analysis to obtain distributions of input data, is inappropriate for fracture mechanics analysis. This is because the unrealistic symmetrical nature of a normal distribution and the possibility of predicting impossibly low, high or even negative values with the distribution can cause serious calculation difficulties. See Section 6 on probabilistic analysis methods.

It is important to check a probabilistic analysis for convergence and sensitivity to input data. A check with different analysis methods including a deterministic analysis is recommended. Lastly the results should be compared with the historical probability of failure of installations.

At the bottom of the Figure 16 a check is made for structural redundancy. There is redundancy when sound parts of a structure share the loading of a cracked part of a structure. The shedding of load from the cracked part will decrease the probability of failure. A non-redundant structure where failure of one component would cause immediate failure will have a higher probability of failure. A typical example of a non-redundant structure is a pressure vessel. Relatively insensitive inspection systems that are able to detect component failure sufficiently in advance of structural failure in a redundant structure may be acceptable.

4.4 Mitigation measures as a way of achieving FFP

Mitigation measures, see Figure 7, are remedies that reduce or remove the risk of failure. These remedies will effect the fabrication and operation of equipment. When an FFP assessment gives an unfit for purpose result then refinement of the FFP assessment is usually cheaper than deciding on mitigation measures that may obstruct or delay the future operation of the equipment. If after refinement the equipment is still unfit for purpose, mitigation could be considered. The mitigation measures selected should themselves be subject to an FFP assessment to check whether the hoped for FFP will be achieved. In addition an FFP analysis may help define the consequences of a failure by predicting the extent of failure. See the Mitigation Checklist in Section 12. A few typical examples of mitigation measures are:

- removing superficial defects by grinding or repair, a commonly used technique to delay or prevent the initiation of the growth of fatigue cracks;
- postweld heat treatment to reduce residual stresses and increase fracture toughness;
- de-rating the equipment by reducing the pressure to give an extra safety margin;
- reducing the stresses by clamping;
- removing personnel to ensure safety.

4.5 Reporting, feedback and development of databanks

Definition of the format of reporting and making the reporting a more or less continuous effort right from the start of a project will ensure consistency and quality. The check list for an FFP analysis in Section 11 can also be used to help design a report and ensure completeness.

The R6, BS 7910 and API methods give guidance in reporting results. The fairly complete FFP process scheme reported in appendix A of the final report of the NIL FFP project 2nd Phase in Section 14.1 gives the different points in an FFP process where documentation and reporting is required.

In order to ensure quality can be checked, all data (e.g. raw to processed and interpreted data), assumptions, procedures used and decisions for a particular choice of method or assumption should be reported. This will then be available for feedback for future operation of the equipment and similar equipment, feedback to designers and fabricators of equipment.

Since the FFP analyses will be updated when improved procedures, methods and equipment for fracture testing, fracture analysis and NDE etc. become available, any changes to procedures used in subsequent assessments should be clearly reported.

The electronic retrieval of reports and in particular the retrieval of data from reports is required for the development of a database that can be consulted with a speed that is in keeping with the need in many cases to perform an FFP assessment in the shortest possible time.

Access to a report where the data was generated enables the analyst to judge the quality of input data. See also Section 11 item 3.0 of the FFP Analysis Checklist.

It is sensible to store NDE information on indications of defects, which are below the registration level for the NDE measurements. This is not normally done unless specified. The more recently developed TOFD technique has been developed so that all indications are automatically recorded on a CD-ROM or disk. The reporting of all defects can become important in later assessments because it will give information about extent of defects (defects per metre of weld length and defect populations). This will help probabilistic calculations and the assessment of the possible nature and cause of defects. Such complete defect information will certainly be needed if a significant defect grows during service from an initial defect below the registration level, see Section 8.4.

4.6 Elapsed time and cost/benefit of FFP assessments

No idea of the cost benefit ratios can be given because of the wide variety of situations where FFP may be needed. It is perhaps sufficient to be aware of the costs and time involved and where feasible an indication of these has been given. In many cases the elapsed time from the start to the finish of an FFP activity has been given because the consequences of delays in the FFP assessment can be more expensive than the cost of the FFP assessment.

4.6.1 Benefits

The benefits of FFP for the different stages of application of FFP from design through to service are listed below. A difficult benefit to quantify is the reduction of unplanned failures if a consistent FFP approach is used throughout the lifecycle. Some of the benefits listed below can be accurately defined in financial terms.

- weight-saving: application of new materials such as high strength steels and new welding consumables;
- faster and or cheaper fabrication: application of new fabrication methods such as new joining techniques.;
- new possibilities: developing a design for a new application;
- construction in hostile areas or conditions: designing for areas with incidental severe loading and for aggressive corrosive environments;
- increasing output per unit: upscaling a design (e.g. application of greater thickness);
- de-bottlenecking a design;
- faster or cheaper installation: application of new installation techniques;
- cheaper inspection: ensuring a design is inspectable, the rational choice of a cost effective NDE approach including inspection planning during fabrication and service;
- avoidance of damage to people and plant: Avoidance of catastrophic failure;
- Assurance of integrity: in areas where NDE is difficult or impossible because of lack of accessibility;
- Continuation of operations, avoidance of unplanned shutdowns, avoidance of costly repairs and the scrapping of equipment;
- The rational choice of the appropriate remedial measure(s);
- The extension of operating conditions;
- The extension of service beyond the original design lifetime.

4.6.2 Elapsed time and costs of an FFP assessment

In making the estimates of cost and elapsed time it is assumed that the level of automation and costs are those in 1999. The Euro has been used to estimate costs with rate of exchange with the Euro taken as being approximately 2.2 guilders. Regardless of the actual costs, the estimates give a reasonable idea of the relative costs and time required for the different aspects of FFP assessment. Elapsed time is defined as the time between the start and finish of an activity and not the time to perform the activity.

When an unplanned shutdown of critical equipment for a production process is awaiting the outcome of an FFP assessment time is at a premium. This means that delays caused to assessments by bad planning and organisation, the use of inexpert advice can result in heavy additional costs. When an FFP assessment is developed systematically from the design stage through to the service stage, this type of delay should be minimised. If, for example, a manufacturer builds large series of similar equipment then a single design FFP assessment will make the application of an FFP assessment more economical.

The overall cost will depend on the costs of preparing, attending and reporting meetings with the different parties and disciplines involved, the cost of acquiring input data, the cost of the defect assessment and the costs of reporting.

Elapsed time and cost of input data depends on the scope of an FFP assessment. Typical time consuming activities are:

- the acquisition of relevant design, fabrication and operations information;
- the acquisition of materials data from qualification tests, databases, the literature, collection of materials and the subsequent testing and metallurgical investigation;
- the acquisition of NDT data and its evaluation or re-analysis of existing data;
- the simulation of weld defects in order to determine the cause of a defect and when and to what extent defects are likely to occur (this may be needed if the cause of a fabrication defect is not properly understood).

The acquisition of input data results in the highest costs of the FFP assessment and requires the most time.

The NDE costs will depend on the magnitude of the problem and whether or not automatic techniques can be applied or not, (e.g. length of weld that needs to be Non destructively tested). Prior to NDE, there are logistical aspects in making the site of the defect accessible, transporting NDE personnel to the site and ensuring that methods, procedures and inspector are qualified for a quantitative FFP assessment of the specific problem. Sizing of a previously detected defect may take anything from minutes to several hours. In areas, which are difficult to access, the time required in preparation may be up to a month with qualification trials on mock ups and preparation to overcome logistical problems (e.g. sub-sea NDE). Studies on models, which are used to simulate the actual construction in the laboratory, can cost between Euro 15,000 and 30,000. This cost may increase significantly if actual conditions are simulated as well as the structural geometry and the defect (e.g. underwater inspection). Using recent software developments, which can take account of geometrical complexity, can reduce the costs and delays. The available software is unlikely to take account of other synergistic effects hindering inspection such as the conditions on site, the material variation and effectiveness of the ultrasonic reflector (defect). The paper Wall and Wedgwood gives an idea of the speed, coverage and reliability of NDE techniques and calculates the costs and benefits of NDE in specific cases, see Section 14.3.

The cost of a failure investigation will be somewhere between Euro 2,000 and 20,000 for the majority of failures and take between a few hours and a couple of weeks.

The time for acquiring materials for testing and metallurgical and failure investigations will depend on whether it needs to be ordered from a supplier, storage or removed from failed equipment. A week to four weeks is not unusual depending on the accessibility of the material and whether a visit to the installation is needed for selection of material.

The time needed for most materials testing will be of the order of a few days to two weeks and will be a function of the number of tests. The time for preparation of test specimens will be of the order of a few days to a week.

Long duration tests such as ageing, fatigue, creep and tests under corrosive conditions take days, weeks and months depending on the situation. Some tests can be accelerated to some extent but others cannot. Testing in parallel can reduce the time for such long duration tests. The costs of long term testing will probably be above 30,000 Euro and depend on the duration and complexity of the tests.

4.6.3 Elapsed time and cost of remedies to achieve FFP

This involves the assessment of potential mitigation measures and the implementation of the mitigation measures. The time needed to perform remedial measures will be of less importance if they can coincide with a shutdown. Discrimination should be made between the cost of remedial measures which are continuous such as monitoring, inhibition or de-rating and the cost of other measures which are incidental such as a repair or PWHT.

4.6.4 Overall costs and elapsed time of an FFP assessment

Overall costs and elapsed time of an FFP assessment by experts including reporting but excluding the costs of NDE and mitigation and costs of other participants.

- For a straightforward assessment: Euro 3,000 to 6,000: one or two days.
- For FFP assessment with a refined fracture analysis: Euro 8,000 to 16,000: one or two weeks depending on the availability of data.
- For an FFP assessment needing a metallurgical or failure investigation and or testing and some refined fracture mechanics: Euro 12,000 to 30,000: two weeks to a month.
- FFP assessments with a metallurgical or failure investigation, long duration tests and or large scale tests: Euro 30,000 to 300,000: one month to a year.

4.7 Decision-making

The following should receive special attention in order to arrive at a sound decision by the asset owner/operator:

- decision about the financial viability of an FFP assessment;
- definition of the nature of the problem;
- definition of the consequences of failure;
- check on and decision about the technical viability of an FFP assessment;
- critical review of the FFP assessment;
- decision on whether the structure is FFP, taking account of the consequences of failure;
- decision when unfit for purpose, to refine the FFP analysis, use alternative assessment methods or use remedial measures;
- final decision on FFP after use of alternative methods or taking remedial measures, taking account of the consequences of failure.

step 1 decision about the technical and financial viability of an FFP assessment

This involves:
- the expected cost benefit, see Section 4.6;
- agreement that there are sound technical reasons for carrying out a fitness for purpose assessment. This means checking whether an FFP assessment is permitted and whether repair is preferable to an FFP assessment. The support of the authorised body is needed here.

step 2 definition of the nature of the problem

This will probably require the support of the FFP analyst and the plant inspector.

step 3 definition of the consequences of failure

The consequences of failure will affect the way the result of an FFP assessment is judged. The consequences of failure are usually divided into three to five categories e.g.:

negligible	no significant consequences
moderate	only financial consequences
severe	threat to human life or pollution
very severe	potential threat to multiple life

The consequence categories will be selected according to requirements of local government. The consequences will differ strongly according to location. It is conceivable that the categories listed above need to be refined further in some special cases. The consequences will depend strongly on the nature of the products contained by the installation. Fire, explosion, toxicity and pollution are the typical effects of failure considered and are usually systematically described by contour lines of equal effect. The contours are plotted as a function of distance from the failure in order to determine whether human beings and other infrastructure lie within the contour. Usually but not always the effects decrease with increasing distance. The contours are generally asymmetric and are shaped by the weather conditions and the freedom of gas and liquid streams to develop freely. Note that the contours can be intentionally shaped by making use of barriers to channel flow as a remedial measure forcing the contours in directions where the consequences are minimised.

step 4 check on the technical viability of an FFP assessment

The chance of a successful outcome is not always easy to see in advance and may become clear if a sensitivity study is carried out at the beginning. A lower level analysis using assumed ranges of likely input data is a relatively cheap and quick way to obtain a good idea of the viability of an FFP assessment and defining where accurate input data is required.

step 5 critical review of the FFP assessment

The uncertainty in the analysis and input data and the nature of assumptions made in an FFP analysis will require careful weighing of specialists' advice. The participants in the review process are clearly indicated in an overview of the analysis process given in Figure 7.

step 6 decision on whether the structure is FFP in view of consequences of failure

In order to calculate the risk, the consequences need to be given a numerical value. This value is a function of the severity of the consequences. Cleaning up pollution and financial losses due to lost production, damage to surrounding equipment and replacement of the equipment can be estimated but other consequences are far more difficult to judge. As a result government and local government often have Guidelines giving the acceptable probabilities of failure for different applications in different situations. The acceptable risks will also differ for different countries. Certain financial losses are best determined by the asset holder or owner/operator.

There is probably some inconsistency between different industries. The paper by KFC in Section 14.4 attempts to address this. Voluntary risks are considered to be different to involuntary industrial risks and therefore acceptable probabilities of fatalities will therefore be significantly lower for industrial risks. The calculation of probability of fatality can result in different outcomes depending on the basis of the calculation. For example, the probability of a fatality per kilometre flown is much lower than that for the number of hours of exposure. The hours of exposure may be more relevant when one considers that a life is measured in time and not kilometres. An idea of typical probability of fatalities is given in the next list.

10^{-4}/year: road traffic accidents

10^{-5}/year: accidents at work

10^{-6}/year: fires caused by appliances in home

10^{-7}/year: hit by lightning strikes

An idea of acceptable probabilities of failure, that give an acceptable risk for different consequences of failure, is given in BS 7910, see Section 11 item 7.3 in the FFP checklist. BS 7910 does not consider in its table the threats to the environment or financial consequences but does provide a simple guide. The BS table gives an allowance for redundancy (when there are alternative load paths allowing the re-distribution of stresses acting on a cracked member to other un-cracked members). For the case of a pressure vessel, there is no redundancy.

step 7 decision when unfit for purpose to continue development of the FFP approach

A decision in conjunction with specialists will be required as whether to continue the development of the assessment by refinement, additional inspection methods, remedial measures and the use of alternative methods. This is a decision point since the further development may result in significant costs and there may be practical implications for implementation.

step 8 final decision on FFP in view of consequences of failure

This is basically a repetition of the previous decision step 6.

4.8 Quality management and persons involved in the FFP process

A quality management approach should be followed in the application of FFP. This includes such things as organisation of an FFP assessment, reporting procedures, feedback loops to e.g. design, the shop floor, and operations, ensuring personnel participate with adequate qualifications/experience and that decision-making as described previously is properly documented. For a list of participants see Section 1.4.

Within the assessment itself there are a number of specialists who will be involved to a greater or lesser degree depending on the nature of the problem. An expert with a good overview and experience should be able to decide on the mix of expertise needed in a team for a given problem. Disciplines that will often be involved are fracture mechanics, NDE, stress analysis, welding and fabrication, physical metallurgy and corrosion. There are information, FFP analysis, mitigation check lists in Part III that can be used to achieve an overview of the FFP process and as an aid to requesting information.

There are various levels of expertise needed for FFP assessments. For the setting up of FFP assessments it is advisable to use expert advice in most cases. Skilled engineers should be able with expert[6] advice to carry out most of the procedures. The FFP assessments can be developed for individual applications into straightforward calculation procedures and defect acceptance criteria for application in the field by inspectors.

Screening analyses of the type recommended for an inspector in Section 7 should be checked by skilled FFP assessors.

NDE methods, procedures and inspectors should be qualified for carrying out a quantitative FFP assessment.

It is important to check that institutes etc. carry out FFP assessments and fracture mechanics according to international and/or national procedures. The fact that FFP assessment and ingredients such as fracture mechanics and NDE are under fairly continuous development has resulted in differences between various institutes, some of which use their own procedures. If there is a reason for deviating from procedures because current procedures cannot be applied easily to a particular problem, this should be clearly stated and properly reported with arguments for the deviation.

example of interactions during a defect assessment

A simplified idea of the interactions between senior plant inspector, NDE inspector, FFP analyst and asset holder, fabricator, designer and authorised body is given in a diagram in Figure 17 where the participants are shown by the grey blocks. The situation when a defect outside of good workmanship or FFP limits is discovered is depicted. The top right hand circle marked START indicates the beginning of the interaction. The figure indicates the following steps:

- The NDE inspector (level 2)[7] discovers a defect outside of the acceptance limits provided by the NDE inspector (level 3) in equipment during a shutdown.
- The NDE inspector (level 2) informs the NDE inspector (level 3), who in turn informs the senior plant inspector.
- The latter subsequently warns the owner/operator (asset holder), who involves the authorised body, designer and fabricator.
- If there are good reasons for an FFP assessment the analyst and his team will be involved by the senior plant inspector or the owner.

[6] An expert is defined as someone, who carries out regular FFP assessments and is in close contact with a network of experts. Some years of experience in the field of application is an essential requirement. In view of the continuing developments in FFP, the expert should maintain access to new developments via a network of contacts, recent literature and attendance of relevant conferences. The expert responsible for the overall analysis should have the ability to understand the value of and integrate the different interdisciplinary inputs into the assessment.
Skilled engineers are for example, personnel with a background in structures, mechanical engineering or materials.

[7] The levels indicated are the Dutch SKO levels. Equivalent European or international qualifications are also acceptable.

- The diamond shaped decision box is where the FFP assessment is approved by the asset holder. Any actions such as further refinement of the analysis, additional inspection and remedial measures including repair are decided here.
- Any such additional requirements need the involvement by the asset holder of an analyst for an FFP assessment to determine the effect of the modifications and of a NDE inspector (level 3) and the senior plant inspector to determine the practicality of the modifications.
- The final decision to approve FFP is taken by the asset holder. In many cases approval will also require acceptance by an authorised body.

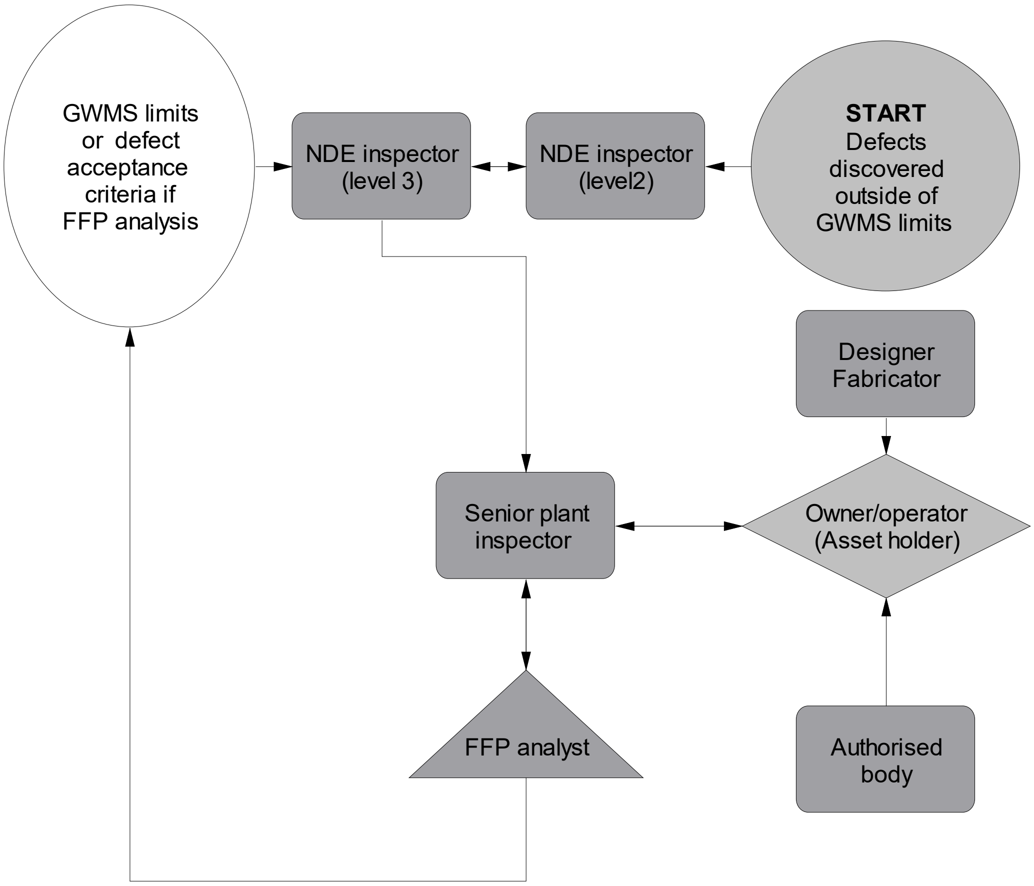


Figure 17 The interactions when a defect outside of GWMS criteria or previous FFP limits is discovered

A FFP assessment may start elsewhere and not at the point in Figure 17 when a defect is discovered outside of good workmanship criteria. The start of the process, for example, will probably be with the fabricator or plant inspector when a material does not meet the specifications during fabrication or has degraded during service. When the stresses are above the acceptable levels the operator or designer may start the process. When FFP assessment is planned in advance of any problems occurring during fabrication or service, the start will most likely be with the asset holder.

Part II - Fitness For Purpose in More Detail

5 Defect Assessment Methods

5.1 Introduction

The purpose of this section is to give a brief overview of the different assessment methods and their historical development. This may help the choice of a particular method. An idea of the differences between three methods can also be seen by comparing the contents of the methods in Section 5.3. The reason for choosing any particular method will depend on how appropriate the method is for a specific problem. In this respect some methods give more attention to corrosion related problems than others. Some methods are more directed to a fitness for purpose approach while others are more suitable for the prediction of critical failure conditions rather than failure avoidance. Some of the methods contain compendia of fracture mechanics solutions and other valuable data that may be useful even use is made of another method. If information from one assessment is used to provide input data for another method, there should be a check on consistency. There is a possibility that a given method has implicit safety factors, which assume that the input data is for example lower-bound or at least conservative. If the assessment methods do not result in an acceptable solution because of the nature of assumptions forced by the method, then one of the listed alternative methods can be used. Some of these methods have been recently included or will be included in future in the appendices of one of the three main assessment methods.

5.2 Overview of defect assessment methods

There are a large number of national and code related defect assessment methods. A limited number of the better known methods have been selected for here namely; R6, BS 7910, API RP 579, EFAM, EPRI, ASME XI and EPRG, see Section 14.2. The R6 method originated in the nuclear and power generation industry. BS 7910 was applied in the past to the offshore and petro-chemical industries. API RP 579 is being developed for the oil and gas and petro-chemical industries, EFAM (also known as ETM) originated at a nuclear research institute, which during the development orientated itself towards other industries. ASME XI was developed for the nuclear industry. EPRI originates from the power generation industry and the EPRG guidelines are purely for pipelines.

The different methods have been validated against numerous large-scale tests (namely wide-plate tests, pressure vessel tests, pipe burst tests and component testing such as tubular joints). In the case of the EPRG wide-plate tests are the basis of the method. In this respect it should be noted that many design codes were originally developed from correlations of Charpy V with both wide-plate tests and service experience. The defect assessment methods were developed initially for ferritic welded steels, but many of them can be applied to non-ferrous metals.

Most of the assessment methods treat the failure modes relevant for the industry for which the method is intended. Most of the methods treat the cleavage, ductile tearing and plastic collapse and fatigue failure modes. The methods developed for the power and petrochemical industries also deal with the prevention of creep failures. There has been a trend of development from industry specific to more generally applicable national assessment methods and more recently in Europe towards European defect assessment procedures. The latter appear to be moving towards the adoption of a form of the BS 7910 and R6 approaches.

In a typical fracture analysis, the crack driving force (fracture mechanics parameter) is compared with the fracture resistance. Failure is determined when the crack driving force exceeds the fracture resistance. A separate calculation is then needed for the determination of the moment of plastic collapse. The EFAM (Germany) and EPRI are typical of this approach and use crack growth resistance curves for the assessment of failure. EPRI is also one of the first codes to develop FADs and stability assessment diagrams and developed a number of J-integral solutions for cylindrical cracked bodies.

The ASME XI uses reference curves, which assist in the use of the selection of the fracture toughness when there is no fracture toughness data available. The defect assessment method is only applicable if the equipment has been built according to the ASME code.

The EPRG (European Pipeline Research Group) method (for European gas transmission pipelines) uses reference curves and tables to determine the limits of an FFP application, which is based on the old PD 6493 (now BS 7910). The EPRG method requires the welding procedure to restrict the weld bead height to 3 mm and thereby limit the typical maximum defect to 3 mm.

The R6 and BS 7910 methods were originally developed separately. Development has been over a period of about 30 years. The R6 method developed three failure assessment diagrams (FAD) in a similar way to the EPRI approach. A FAD represents a continuous transition between brittle fracture and plastic collapse and its use avoids the need to perform separate calculations for the different modes of failure. The R6 approach uses K and J fracture parameter. The different levels of FAD are known as options. Option 1 uses a theoretical strain hardening solution and can be used if there are no stress strain data available. Option 2 allows the use of specific strain hardening data. Option 3 allows the development of a FAD that is based on the J solution of the cracked body of interest and is the most accurate FAD as a result. A ductile tearing analysis is allowed with both the option 2 and option 3 FADs. The BS 7910 method (previous version was known as PD 6493) was initially developed as a method, which in the beginning exclusively used K and CTOD fracture parameters. Gradually, the CTOD approach has converged with the R6 approach and now uses three FADs and includes the J integral fracture parameter. It differs from the R6 approach in that the level 1 has a box shaped FAD rather than a FAD, which interpolates gradually between brittle fracture and plastic collapse. The BS 7910 level 1 FAD is intended for use with lower-bound material properties and upper-bound loading and defect data and has an in-built safety factor unlike the BS 7910 level 2 and 3 FADs and the three FAD options of R6. The BS 7910 level 2 FAD is comparable with the R6 FAD options 1 and 2. The BS 7910 level 3 FAD is comparable with R6 option 3 FAD. Other assessment methods such as that in the API 579 Fitness for Service document are based on R6 and PD 6493:1991.

Since the above methods were derived using similar fracture mechanics approaches, the outcome of calculations should predict the same trends and in many cases give similar results. The approaches which are closest (e.g. FAD based) can be expected to give more or less the same results although there will be differences due to differences in the FADs that are derived. The R6 gives excellent guidance and is probably the most open method and leaves a number of decisions with respect to margins of safety to the analyst. The other FAD methods tend to be more prescriptive. All of the FAD methods have significant appendices, which give a wealth of information.

The BS 7910 method is particularly good on welding aspects and has some specific appendices for applications to offshore structures, pipelines and pressure vessels.

The API 579 gives the most guidance on typical in-service damage and corrosion related problems. It also has a section on assessing FFP of existing equipment on the basis of the equipment remaining above given fracture toughness limits and within given operational envelopes provided the equipment has been designed according to the ASME code.

The EFAM method was developed using the CTOD measured over a gauge length of 5 mm across the crack tip in a CTOD test. This method avoids a number of difficulties encountered when using the conventional method of measuring the crack mouth opening displacement. It avoids the need to extrapolate the mouth opening displacement, measured where the notch meets the edge of the test specimen, to the actual crack opening at the remote crack tip. The test method has been found suitable, for example, for studying the effects of mismatch of the strength between the weld and base metal. Defects located in the heat affected zone where there is mis-match of strength will develop an asymmetrical plastic zone. There is a document EFAM ETM-MM 96 which gives procedures for testing welds with mismatches of strength and has a number of appendices giving local yield solutions, information on local stresses and the transferability of material properties. More recently, the R6 and the BS 7910 have added appendices on the effects of mismatch of the weld strength with that of the parent plate. The EFAM method also has a significant part on stress corrosion cracking testing unlike other methods.

The contents of the appendices of some of the defect assessment codes have been given below. In conclusion, there has been no conclusive demonstration that one method is better than another. Two of the methods, R6 and BS 7910, have undergone a much longer development and are very complete in terms of the defect assessment. Other methods possibly due to a shorter development are incomplete in certain areas. Also where more recent methods are based on R6 and BS 7910 there is a risk that certain aspects may become inconsistent as the new developments add and subtract certain aspects of the original methods. The API 579 document gives more information on how to deal with some of the practical FFP problems that may confront operators of equipment. In addition there is information on how to organise an FFP assessment.

5.3 The contents of the appendices of the defect assessment procedures

The contents of the basic weld defect procedures have been omitted because of their great similarities. This means that only the appendices have been listed for all three methods and in the case of API 579, also parts of the main body of the document have been listed that are not concerned with the basic weld defect assessment procedures. The three procedures all have extensive lists of references so that the origin of information in the documents can be traced along with sources of useful input data and stress and stress intensity factor solutions.

BS 7910 annexes

- A (normative) Evaluation under combined direct and shear stresses or mode I, II and III loads
- B (informative) Assessment procedures for tubular joints in offshore structures
- C (informative) Fracture assessment procedures for pressure vessels and pipelines
- D (normative) Stress due to misalignment
- E (normative) Flaw re-characterisation
- F (informative) A procedure for leak-before-break assessment
- G (normative) The assessment of corrosion in pipes and pressure vessels
- H (normative) Reporting of fracture, fatigue or creep assessments
- I (informative) The significance of weld strength mismatch on the fracture behaviour of welded joints

- J (informative) Use of the results of Charpy V-notch impact tests to indicate fracture toughness levels
- K (normative) Reliability, partial safety factors, number of tests and reserve factors
- L (normative) Fracture toughness determination for welds
- M (normative) Stress intensity factor solutions
- N (normative) Simplified procedures for determining the acceptability of a known flaw or estimating the acceptable flaw size level 1 fracture procedures
- O (informative) Consideration of proof testing and warm prestressing
- P (normative) Calculation of reference stress
- Q (informative) Residual stress distributions in as-welded joints
- R (normative) Determination of plasticity interaction effects with combined primary andsecondary loading
- S (normative) Approximate numerical integration methods for fatigue life estimation
- T (informative) Information for making high temperature crack growth assessments
- U (informative) Worked example to demonstrate high temperature failure assessment procedure

The above is based on the 1999 version. Subsequent extensions and modifications are expected.

R6 rev. 3 appendices

- Determination of fracture toughness values
- Plastic yield load analysis
- Determination of stress intensity factors
- Evaluation of K_r^s
- Computing aids
- Evaluation of fatigue and environmentally assisted crack growth
- Evaluation under Mode I, II and III loads
- Assessment of the integrity of structures made of CMn (Mild) steels
- A procedure for leak-before-break assessment
- Probabilistic fracture mechanics procedure
- Treatment of displacement-controlled loading
- Treatment of weld residual stresses
- Evaluation of load-history effects
- Allowance for constraint effects
- Assessment using crack arrest (not yet issued)
- Allowance for strength mis-match effects
- Guidance on local approach methods
- Guidance on finite element methods
- Validation of R6 revision 3 background to the development of FADs and validation tests.

The above is based on the version with last amendments record no. 10 May 1999. Subsequent extensions and modifications are expected.

API RP 579

Some of the sections, which do not concern the basic defect assessment procedures for flaws, have been included in addition to the appendices.

sections

- Section on organisation, jurisdiction, responsibilities and qualifications.

- Section on a fitness for service Engineering Evaluation procedure. A semi-quantitative approach for equipment to built according to ASME codes.
- Sections on assessment of general metal loss, local metal loss and pitting corrosion
- Section on assessment of blisters and laminations
- Section on assessment of weld misalignment and shell distortions
- Section on assessment of crack-like flaws including sub-critical crack growth.
- Section on assessment of components operating in the creep regime
- Section on assessment of fire damage

appendices
- Thickness and MAWP (Maximum Allowable Working Pressure for the un-cracked component) formulae for a fitness for service assessment
- Stress analysis overview for a fitness for service assessment
- Compendium of stress intensity factors
- Compendium of limit load solutions
- Residual stresses in a fitness for service assessment
- Materials property information used in a fitness for service assessment e.g.: strength parameters, physical constants, fracture toughness (testing, via Charpy V data, in-service degradation of fracture toughness, austenitic stainless steels, probabilistic fracture toughness distributions, sources of fracture data), fatigue crack growth calculations, fatigue crack growth relationships and data, stress corrosion crack growth relationships and data, fatigue S-N curves for smooth and welded bars), creep rupture, creep strain rate, creep fracture strain, creep crack growth data, creep regime fatigue data and stress-strain curves.
- Deterioration and failure modes e.g.: erosion, corrosion-erosion, subsurface cracking, microvoid formation and microfissuring, metallurgical changes.
- Non-destructive Examination Techniques/Information used in a fitness for service assessment is incorporated in the individual sections on assessments.
- Validation of assessment methods for volumetric and crack-like flaws

The above is based on issue 12 September 6, 1999. Subsequent extensions and modifications are expected.

5.4 Alternative approaches

5.4.1 Shallow crack fracture (constraint based fracture mechanics)

Shallow cracks have low plastic constraint because of the easy plastic flow path from the crack tip to the surface. This means that eventual fracture from an initial defect will be at significantly higher loads or deformations. It is therefore conservative to treat such a shallow crack as having fully constrained plasticity as in a normal assessment. This conservatism is implicit in the normal assessments.

There are two ways of reducing the conservatism introduced by using fracture toughness data based on deeply notched fracture mechanics test specimens for the assessment of shallow defects. The first option is to use a modified FAD, see Figure 18. The second option is to use a shallow crack fracture mechanics test specimen with the original three level FAD approach. Care should be taken not to use the shallow crack fracture result with the modified shallow crack FAD as this would result in taking account of the benefit of low constraint twice. See Section 14.13 for references of the shallow crack methods. There are also references in

Section 14.7.3 on shallow fracture testing, which is an empirical way of measuring the apparent increase in fracture toughness due to low plastic constraint in a test specimen.

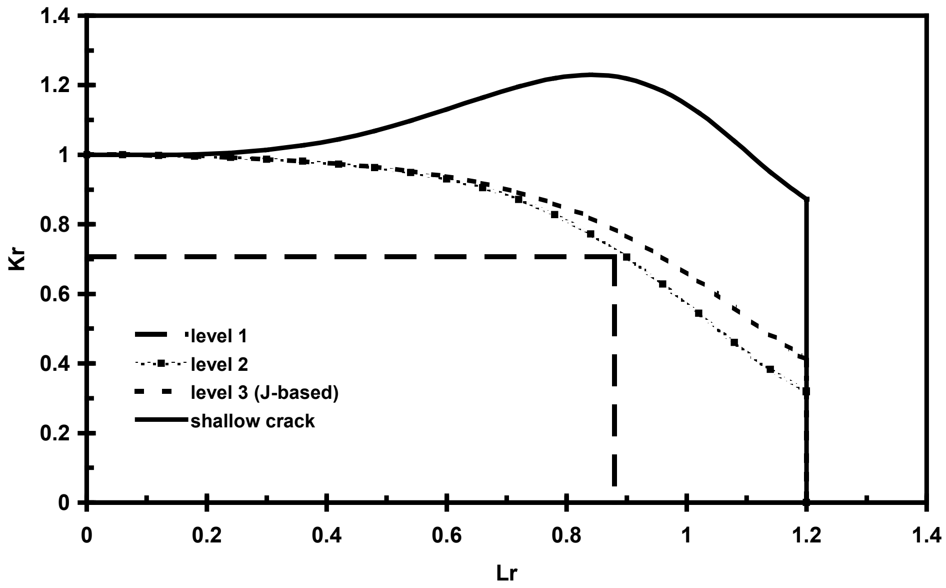


Figure 18 FAD showing the beneficial effect of low constraint

The bump in the shallow crack curve shows that significantly higher K_R values can be tolerated than when full constraint is assumed when levels 1, 2 and 3 are used. The benefit of assuming low constraint will vary depending on the material constants that are used as inputs to derive the curve. There is no advantage from low plastic constraint if the failure is either by brittle(linear elastic) fracture or plastic collapse.

5.4.2 Local approach

The local approach can be applied to cleavage fracture and ductile tearing of ferritic and austenitic steels. For the moment it can be applied to the unwelded condition. Future developments may allow the application to weldments. The local approach consists of micro-mechanical models of failure, in which the failure stress, strain and damage close to a stress concentrator or crack are related to the critical conditions for fracture. The models are calibrated by determining material parameters, which are derived from reference test data, quantitative metallography and finite element analysis. The micromechanical failure models relate for example the slip induced failure of brittle particles near the crack tip to the condition for cleavage fracture. In the case of ductile tearing the voids which develop around particles, grow and finally coalesce to cause crack extension, are the basis of the models. Since the models incorporate the statistical distributions of particles, the results give a distribution of fracture. The methods are very useful for obtaining more fundamental insights into fracture and can be used to complement a defect assessment and provide, for example, distributions of fracture toughness that would not normally be available (see the R6 approach for more information on the local approach).

5.4.3 Wide-plate test

The wide-plate test is a large flat plate (approximately 1 m x 1 m). The welds and defects are made in the plate so that they are oriented in the direction the defect is expected to lie in the actual structure. In practice, this means the defect is nearly always positioned perpendicular to the principal stress, which is the most conservative orientation. The original wide-plate tests had a 10 mm long through-thickness defect. The defect should be as sharp as a the result is to cover the sharpest possible defects. The wide-plate is tensile loaded gradually until failure at the appropriate temperature (usually the minimum design temperature). The material is acceptable if the test meets a given criterion.

There are a number of possible criteria that can be selected, e.g.:

- Full uniform yielding of the plate also known as gross section yielding
- Failure after a minimum overall strain has been reached (0.5% plastic strain has been used in the past as a pass criterion for the wide-plate versus Charpy V correlations that formed a basis with service data for the BS codes for material selection for pressure vessels and tanks);
- Failure after four times the yield strain.

In the past different techniques were used to obtain a defect and resulted in different degrees of sharpness making some of the wide-plate test data difficult to compare. Discussion about the acuity of a defect can be avoided if the defect (notch) is sharpened by extending it by fatigue.

The wide-plate test can also be used as a validation of a fracture mechanics approach, or used directly to accept a defect. In both approaches the largest credible defect or actual defect in a structure are introduced in the wide-plate. The surface notch in most cases is then extended by fatigue until the crack tip reaches the intended (suspect) weld microstructure.

The wide-plate test has the advantages that the actual conditions in a welded structure can be simulated directly without the need to resort to assumptions either in the model used or the input data. For example, a (shallow) defect in a welded plate structure (also thin wall pipes) can be directly simulated. This avoids complications such as; e.g. the assessment of shallow cracks, the need to calculate stress concentrations at weld toes and stress concentrations due to misalignment, the need to use stress intensity factor solutions, the need to take account of the mismatch of strengths between the weld and the base material and the need to estimate residual stresses etc. The stress concentration is simulated conservatively by increasing the overall strains to the yield strain and beyond depending on the stress concentration considered. The residual stresses are contained within the plate since the plate is large enough to avoid their relaxation when preparing the test specimen.

The disadvantage is the relatively high costs of the tests and the large amount of material required for a test. This inevitably results in fewer tests being carried out. This is a weakness because there is usually significant scatter in material properties. If the wide-plate tests are carried out in conjunction with small-scale fracture mechanics tests, the small-scale tests can be used to obtain an idea of the scatter. See Section 14.17. In addition, a complex geometry cannot be simulated in the tests so that the stresses or strains in the actual geometry must be estimated and over-conservatively applied as a tensile stress or strain to the wide plate.

5.5 Crack arrest and dynamic fracture

5.5.1 Arrest of brittle fracture

The use of a crack arrest approach is less common because most analysts are less familiar with the subject. A crack arrest approach can be used as:

- a belt and braces strategy when there is some uncertainty about the scatter in input data and when the resulting reserve factor using a “static” fracture analysis is marginal;
- part of a leak before break approach when unstable fracture instead of stable sub-critical crack growth is possible, see Section 4.2.5;
- a way of avoidance of catastrophic failure if this results in unacceptable consequences.

Brittle crack arrest can be achieved if:

1 the fracture runs out of sufficient stress for crack propagation (i.e. the stress intensity factor is decreased below the arrest value).
2 the fracture runs from a brittle material into a material with adequate toughness to cause an arrest.
3 there is a free-surface preventing the passage of a crack.

note 1

This may occur when stress and stress intensity factor decrease with increasing crack depth or length e.g.:

- When a fracture extends beyond the influence of a stress concentration.
- As a fracture propagates through the thickness in a beam under displacement controlled loading.
- When a crack meets a stiffener aligned in the direction of principal stresses, i.e. perpendicular to it path.
- When there is insufficient loading (or potential energy) to sustain a fracture (e.g. small diameter pipes often have insufficient potential energy to sustain a brittle fracture).

note 2

Crack arrest due to increased toughness can occur

- When a fracture deviates form a weld into tougher plate material. (This is the tendency when a weld metal is overmatching or there is significant scatter in the fracture resistance of different plates in the path of a fracture).
- When a fracture deviates from an embrittled heat affected zone into a tougher weld. (This is the tendency when a lower strength weld is used).
- When a fracture meets a tougher weld in its path, e.g. a weld crossing provided the weld is not too narrow.
- When a fracture in a heterogeneous microstructure meets a microstructure with a high toughness. (This often occurs in fracture tests on welds where the crack jumps several millimetres in the weldment. This is known as a “pop in”.)
- When the fracture propagates into a region at a higher temperature, which will have a higher fracture resistance.
- When the fracture propagates from a high plastic constraint area to a low constraint area. This may happen when a fracture propagates to an area with a thinner wall or when the fracture becomes a through-thickness fracture and shear lips, that cause the fracture to tunnel beneath the plate surface, are developed. A tunnelled fracture will have a lower stress intensity at the crack tip, enhancing the arrest of a fracture.

note 3

- crack arrest can occur
- when a fracture meets a mechanical joint, or hole.

5.5.2 Arrest of ductile fracture

In special circumstances running fractures can occur in ductile materials that are sufficiently tough to arrest brittle fractures but insufficiently tough to stop a ductile fracture. There must be sufficient potential energy to maintain a running ductile fracture. The running ductile fracture usually starts in an area of local embrittlement or because of local damage from external sources. A requirement for running ductile fractures is that the load must be maintained throughout crack propagation. Such fractures may occur in storage tanks where load is maintained while the fracture propagates or because the decompression characteristics of a gas in a gas pipeline are such that the crack propagates faster in a pipe than the pressure can be released through the fracture.

Running ductile fractures can be prevented by selecting material, which has sufficient fracture toughness to prevent such propagation. It is also possible to arrest such fractures in pipelines by constraining the development and movement of the flaps that open up as a crack propagates. This is done by means of mechanical restraint; usually a periodic reinforcement of the pipe. Limiting the pipe diameter and thereby the stored energy is another possibility of avoiding a running ductile fracture. It can also be prevented by controlling the composition of the gas by minimising the concentrations of "rich" volatile components.

selection of materials that give crack arrest in pipelines

There are methods for selecting combinations of toughness and pressure levels that prevent catastrophic brittle or ductile fracture; see Section 14.14. The methods developed for pipelines are semi-empirical because the models have been adapted to give safe lower-bound predictions for actual tests and therefore care must be taken not to extrapolate outside the region of applicability.

5.5.3 Crack arrest tests

There are three types, namely large-scale tests (sort of wide-plate test), small-scale fracture mechanics tests and technological tests.

large scale tests

A temperature gradient can be created along the expected path of the crack as in a Robertson test. A brittle crack is initiated and the temperature at which the crack stops is used as the crack arrest temperature. A temperature margin is added on to the temperature at which the crack arrested in order to define a safe operating temperature.

Alternatively the plate is kept at a constant temperature. A brittle crack is initiated and allowed to propagate through brittle material. Arrest is achieved if the fracture arrests in the target material within a distance of approximately twice the plate thickness before stress waves reflected from the plate boundaries reach the propagating crack. The length of the brittle zone used to obtain a brittle fracture is the length of embrittled "sub-standard" zone that can be tolerated under the conditions of the test.

In a similar way to the previously mentioned wide-plate test, the large-scale tests are able to account for uncertainties such as the effect of residual stresses and effects of weld strength mis-match relative to the parent plate that may affect the prediction of arrest using a dynamic fracture mechanics crack arrest test. The tests have the disadvantage that they are expensive. There is less effect of scatter of material properties, since in crack propagation tests it tends to be the average properties that determine arrest and not the local microstructural heterogeneity that affects wide-plate fracture initiation tests.

small scale tests for arrest of brittle fracture

fracture mechanics tests

The crack is initiated in a brittle manner and allowed to propagate in a special fracture mechanics test where there is sufficient room for a crack to propagate. The specimen and constant displacement loading conditions are chosen so that the stress intensity decreases in the direction of crack propagation. The stress intensity factor at arrest gives the fracture toughness for crack arrest. The analysis takes account of possible dynamic effects, see Section 14.5.1 on testing standards. Note there is also a British Standard for measuring the dynamic initiation toughness given in the same reference list.

technological tests

There are two types of small scale test for assessing the capability of a material to prevent running brittle fractures. There are ASTM testing standards for both tests.

There is a nil ductility test, which has been demonstrated to correlate with crack arrest in large- or full-scale tests for a number of different steels. This test has a small brittle weld deposit on the bottom free surface of a rectangular specimen. A weight is dropped on to the top of the specimen. The nil ductility temperature is estimated from the test, which shows that a crack initiating in the brittle weld stops before it reaches the ends of the bottom specimen surface. In order to determine the allowable minimum operating temperature a margin, which is dependent on the material and the outcome of the correlation with large-scale tests, is added on to the nil ductility temperature. The margin is of the order of 35 °C but this can vary with the material and the thickness. The margin of temperature is obtained from correlations with large or full scale crack arrest tests. If the correlations have not been made in the past for the material in question then a new correlation must be made before the test can be used for material selection.

There is also a drop weight tear test. The fracture is introduced by means of a notch on the bottom surface of a rectangular bend specimen. A weight is dropped from a prescribed height on to the top of the specimen. Usually a transition curve is determined of either the fracture appearance or the energy absorbed in fracture against temperature. Correlations with large or full-scale tests allow a criterion for crack arrest to be developed; e.g. for prevention of brittle fracture in pipelines a 50 to 75% shear fracture is required.

tests for crack arrest of running ductile fracture

In pipelines this type of fracture is controlled by using materials with a high upper shelf Charpy V impact toughness or Drop Weight Tear Test. Note that if dynamic fracture mechanics is needed then consult an expert. See also Section 14.14.

6 Probabilistic Fracture Mechanics Calculations

A guide to probabilistic calculations has been given in the form of an awareness chart. Probabilistic analysis is for the more skilled analyst. It may be made available to those with less expertise in the form of a special analysis for a problem with given limits where the background work has already been carried out. Probabilistic analyses do not give probabilities of failure but rather relative probabilities of failure. In other words there are implicit unknown safety factors in the analysis making predictions conservative.

Probabilistic analysis requires inputs in the form of distributions, namely a distribution of stresses, defect sizes and fracture toughness (see the worked example in Section 13.8). The normal distribution often used in reliability analysis to obtain distributions of input data is inappropriate for fracture mechanics analysis because of the unrealistic symmetrical nature of a normal distribution and the possibility of predicting negative values with the distribution can cause serious calculation difficulties. Weibull or lognormal distributions should be fitted to the inputs of defect size and fracture toughness. They offer the flexibility of allowing fits to asymmetric distributions and the introduction of a maximum (for defect size) or minimum value (threshold value for fracture toughness). Note that the Weibull and other distributions have no physical significance of their own. This is contrary to information in textbooks that appear to give the Weibull distribution a sort of physical significance by calling it the "weak link" model. The distribution is only as good as its fit to the data. Any extrapolation outside of data to estimate, for example, very low values is purely an extrapolation.

The result of probabilistic calculations can be presented as a scatter diagram of points, which fall either in or outside of the failure assessment diagram.

Many calculations are partial probabilistic calculations in that only the input parameters with the largest scatter (e.g. the fracture toughness and the defect size) are treated probabilistically. When the fracture is ductile, the defect size is the largest uncertainty. When the fracture mode is cleavage, the fracture toughness is usually the largest uncertainty. When the loading is random as in the case of loading by natural forces (e.g. wave, wind and earthquake loading) the loading is also included as a distribution.

The residual stresses are normally the biggest source of uncertainty of the stresses. Due to ignorance of their distribution and magnitudes they are often assumed to have the maximum theoretical value of the yield stress of the material containing the defect tip.

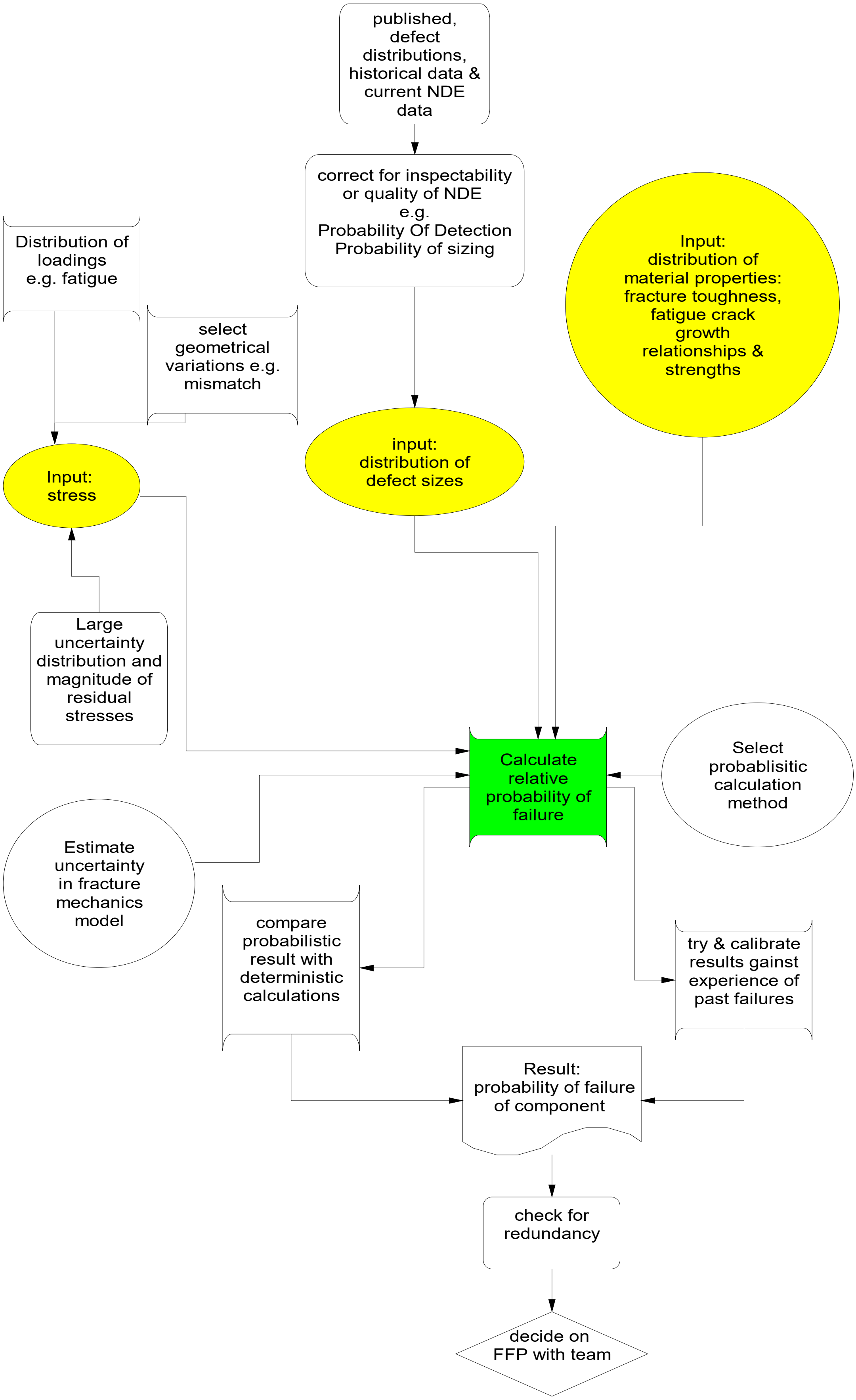


Figure 19 Inputs required for a probabilistic fitness for purpose assessment

A Monte Carlo simulation is probably the least complicated way to perform a probabilistic analysis and is also very flexible. For example, the probability of failure for stationary fabrication defects, which are detected with a certain POD and repaired if they fall outside of GWMS limits is given below. First a number of input data has to be established, such as the defect distribution (height, length, type), probability of detection of the NDE techniques, loading condition and material properties. The principle of the simulation is as follows, see Figure 20:

1 a defect height is sampled from the height distribution;
2 this is followed by samples from the defect type distribution, length distribution, and position in the wall distribution;
3 a defect assessment is carried out on the sampled defect to determine its position in the failure assessment diagram (safe or unsafe region, see Figure 8);
4 the next step is to determine whether the defect is detected. Therefore a POD is sampled and compared with the probability of detection distribution of the POD of the inspection method at the height in the first step;
5 when the defect is detected (N_{det} in the figure), i.e. the sampled POD is less than POD at height, it is sized (length, height, ligament height);
6 then it is checked if the defect dimensions are smaller than the given acceptance criteria. If the defect is rejected (N_{rej} in the figure), the weld is repaired and it does not contribute to the probability of failure. If the defect is accepted, it can be wrongly accepted due to sizing errors. Such a defect contributes to the probability of failure (part of the defects left in the figure);
7 a defect, which is not detected (part of the defects left in the figure) and which results in assessment point outside the failure assessment diagram, also contributes to the probability of failure;
8 steps 1 to 7 are repeated depending on the number of simulations;
9 the probability of failure (POF) is calculated as the number of defects which lead to failure and are not detected or wrongly accepted divided by the total amount of simulations (say 10^7).

The above scheme is based on an analysis presented in a paper by Krom et al. on the assessment of pipeline girth welds, see Section 14.4.2.

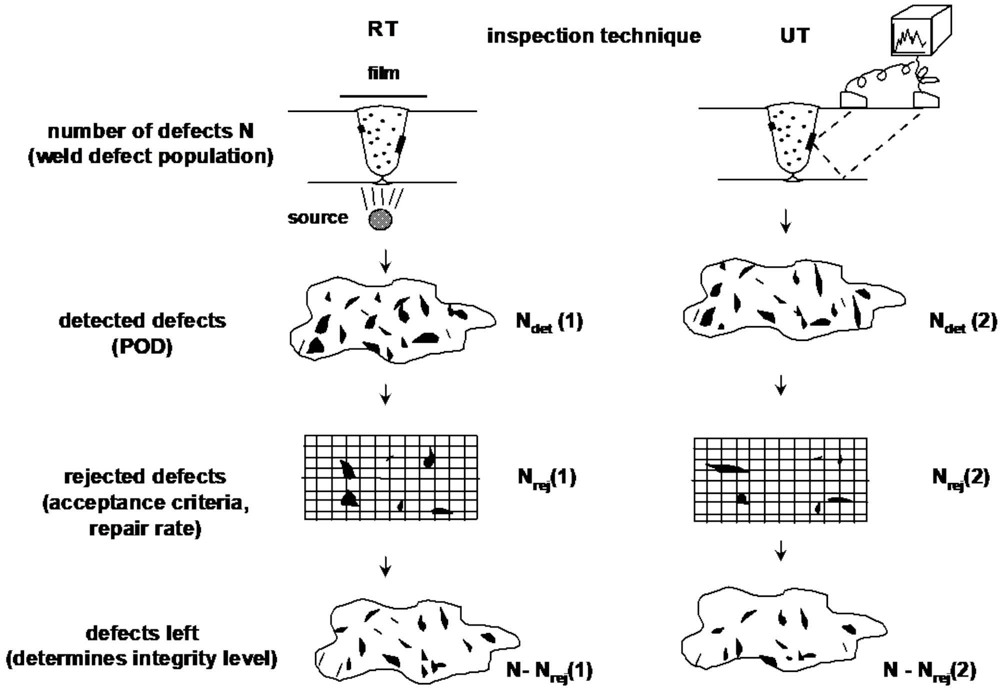


Figure 20 Illustration of the effect of the inspection technique on the repair rate and the integrity level

A number of additional notes relevant for probabilistic analyses are given below.

note 1 defect distribution

The incidence of larger defects is of more importance than the incidence of the larger number of very small often microscopic defects. Therefore, it is less important to fit the lower tail of the defect distribution accurately and most emphasis should be placed on fitting the distribution to the larger defects and determining a maximum defect size (the maximum credible defect or the 100% POD for the distribution). The 100% POD is difficult to achieve as the PODs become gradually assymptotic as the 100% POD is reached. The POD curves are steeper up to about 85% POD.

- most defects are small, less than 1 mm and are truncated by the inability of NDE to detect very small defects or the setting of the NDE threshold level, see Figure 2.
- no single distribution of defects may be satisfactory and one may need to combine results from different references and to look for data including historical inspection data on similar equipment.

The defect distributions given in Section 14.4.1 can be used with discretion when there is no or limited NDE data. Some typical observations that have been gleaned from the references have been given hereafter.

observations relevant for offshore structures

- Structures of a similar type but made by different fabricators have very similar defect distributions.
- Planar defects have different distributions to non-planar defects.
- Average defect rate before repair is 0.7/m and after repair is 0.2/m.
- There is no simple relationship between defect length and height .
- Rate of defects in offshore structures = 0.5 to 1.5/m weld length.

observations relevant to other equipment

0.16 to 0.18 defects /m weld length for large chemical vessels. This is significantly less than the numbers of defects reported for offshore structures. Most common embedded defects are slag and lack of side-wall fusion defects. Embedded slag and lack of side-wall fusion defects are normally confined to one welding pass.

note 2 correction for inspectability

The distributions in terms of mean and upper and lower-bound values should be modified by information about inspectability. The difficult circumstances under which NDE is carried out, see Section 8.2.

note 3 interpretation of the distribution of fabrication defect sizes

Metallurgical and welding knowledge may also be used to assess mean and upper-bound values for defect sizes. e.g. fabrication defect heights are in most cases unlikely to be greater than a weld bead height; see note 1. One could also determine the probability of the chance of adjacent weld beads containing coincident defects, resulting in a defect height greater than a weld bead. For this one needs an idea of the number of defects per weld length and the lengths of defects per weld length.

note 4 distribution of loading

The fatigue crack growth is usually a result of the large number of small cycles in most dynamically loaded structures. If this is the case, the distribution at lower loads usually needs to be fitted carefully. In truly random fatigue processes (e.g. wave loading of offshore welded steel structures) the sequence of loading is normally relatively unimportant and can be ignored.

When predicting fracture the relatively few high loads must be fitted properly to the chosen distribution.

When the fatigue spectrum results in large numbers of low loads that are interspersed by occasional high loads the crack growth due to the low loads will probably be retarded. The overall crack growth will be much less provided the crack growth from the incidental high loads is insignificant relevant to the crack growth that would have been caused by much larger number of small load cycles. The retardation of crack growth will depend on the material, the ratio of small stress ranges to the few large stress ranges and the mean stress level. For more information on this one should consult a specialist.

note 5 short and long range residual stresses

Short range residual stresses from welding and plastic deformation and long range stresses caused by restraint during construction result in a large uncertainty in residual stress. These are often treated as a deterministic input parameter in the probabilistic analysis.

note 6 variations in thickness and geometry including local geometry

Local variations in geometry such as misalignment, mismatch and the profile of a weld contribute significantly to the variations in stress as a function of the position along the length of the weld.

note 7 input of material and fracture toughness properties and separation into failure modes

Separate the modes of failure in the fracture tests into cleavage and ductile types of failure and then fit distributions to the different data sets.

The scatter is greatest in the transition range of fracture toughness. Such scatter in the fracture toughness may cause the fracture toughness input to dominate the uncertainty in defect size in a probabilistic defect assessment.

note 8 fracture toughness distributions

The Wallin method allows the use of Charpy V values in combination with a limited amount of fracture toughness data to generate a fracture toughness distribution. This method is proposed by the BS 7910, R6 and the API 579 documents. See worked example 13.10.

One can also create sufficient data to obtain a distribution by searching existing databases for data on similar materials and mixing the data after checking for compatibility of data from the database with measured data.

Fracture toughness distributions should be truncated at the lower tail. The limits can either be physical limits such as a threshold value of fracture toughness. API 579 assumes the thresholds proposed by Wallin for ferritic steels of 20 MPa $m^{1/2}$. Note one can also treat the threshold as an uncertainty with its own distribution.

note 9 fatigue crack growth distributions

The fatigue crack growth relationship can be described over most of the relevant growth rates by an exponential relationship between the crack growth rate and the range of fluctuation of the stress intensity factor. The exponent of the relationship is “m” and the intercept is “C”. It is usual to keep the exponent “m” constant (approximately 3 for low to medium strength structural steels) and to determine the distribution for the intercept “C”. For limited number of materials (e.g. for materials used offshore) there is large amount of fatigue crack growth data. See Section 15.8 on fatigue crack growth data. The scatter can be deduced in some references. There is most scatter at low crack growth rates near the threshold.

notes 10 uncertainty in the fracture mechanics model

This will to some extent depend on uncertainty in the stress model and the fact that there is some implicit conservatism in the FADs.

note 11 select the probabilistic calculation method

Three ways of calculating the probability of failure are given below:

1 a numerical integration using the three probabilistic main inputs defect size, loading and fracture toughness .
2 the first and second order (FORM & SORM) reliability approaches can be used.
3 a numerical simulation using Monte Carlo simulations.

The numerical integration is very complete and depends on having the required distributions. There are often problems in obtaining convergence and the analyses need the support of mathematicians.

The FORM and SORM methods have been developed into relatively robust computer software. They have the disadvantage of being limited to unrealistic normal distributions of input variables that are not suitable for most fracture toughness or defect distributions. Non linearity of the limit state function can also cause numerical problems.

The Monte Carlo method is the simplest and most flexible calculation method. The calculation is a random draw from the distributions of input data. A defect assessment calculation is performed on each draw. The results, which fall outside of the FAD are failures. The probability of failure is the ratio of the number of draws that fall outside of the FAD to the total number of draws. A large number of computations are required before convergence is obtained. This is not a problem for modern computers. The time needed for calculation increases with decreasing probability of failure. See Section 14.4.2 and the worked example in Section 13.8.

note 12 checking the results against deterministic analyses

Comparison with the trends observed from deterministic calculations where a single variable is varied at a time is recommended because errors in the probabilistic analysis may not be easy to identify. The parameters defining the distributions should also be varied to obtain a feel for the sensitivity of the calculations to input data.

note 13 checking the results by calibration against actual experience

This is difficult for static equipment because unlike reliability assessments, which have been applied to rotating equipment where there is a history of thousands of failures, there are relatively few failures of static equipment. The very low incidence of failures means that failure statistics comprise of the few failures divided by the number of similar (e.g. tank, pipeline, pressure vessel) but in reality different (e.g. different design details, materials and fabrication methods) constructions around the world. Nevertheless, knowledge of actual failures and their special circumstances along with the failure statistics may help one to decide if a probabilistic failure prediction is reasonable or not.

note 14 check for redundancy

Many structures have redundancy such as offshore structures where failure of a node often means a weakening but not failure of the structure. There are rules for assessing redundancy in reliability studies. Redundant structures have significantly lower probabilities of failure than non-redundant structures, see Boppas-Smith in Section 14.4.

note 15 decide with the team whether the probabilities of failure are acceptable and lead to FFP or not

FFP is not judged on the basis of the probabilistic results alone but on risks to safety, the environment and finances. The product of probability of failure and consequences of failure gives the risk. The relative risks can be calculated by using the product of the relative failure probability and the consequences of failure defined by the team. The results of a probabilistic analysis can be used to help determine partial safety factors for deterministic analyses, which can be carried out more easily by non-experts; see item 7 in the FFP Analysis Checklist in Section 11.

7 Screening Defect Assessment Calculation for Inspectors

7.1 Introduction

This section describes a simple tool to show how a plant inspector[8] could carry out a straightforward screening defect assessment. The tool is intended for use by the plant inspector in the first instance to see if there is a possibility of acceptance of defects, which are just outside of good workmanship limits and there are sound technical reasons for avoiding a repair. The use of the tool should help the plant inspector make a rational decision about the feasibility of setting up an FFP assessment. The tool is not intended as the basis for deciding the acceptance of defects and avoiding the need to repair. The reasons for acceptance should be reviewed and approved by an FFP specialist and the owner (asset holder) and will in many cases require the approval of an "authorised body".

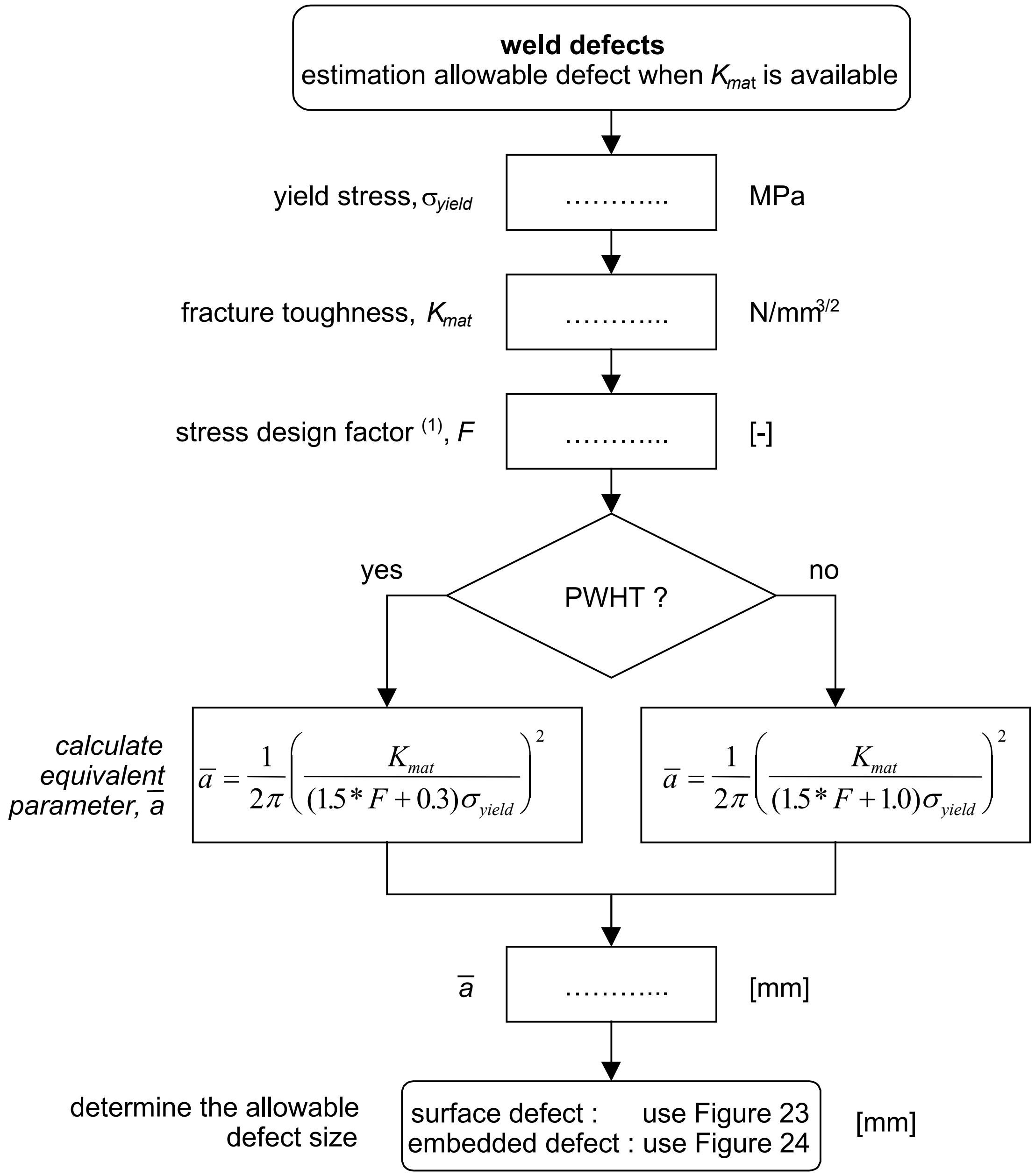
Ideally FFP assessments should provide criteria for NDT before NDT is started. In practice this rarely happens and the inspector is often faced with the dilemma of whether or not to remove defects that fall just outside of the good workmanship criteria. These defects can be relatively frequent and their removal costly, particularly when deeply embedded in thick-walled constructions. The repair may possibly be more detrimental than accepting the defects.

In most cases, there is a tendency to repair because of the pressure of deadlines and the wish not to become involved in lengthy discussions that may lead nowhere. If inspectors become familiar with the calculations recommended in this section, they will gain more insight into the FFP process. A better feeling for FFP should enable a more effective and constructive dialogue with FFP specialists.

If the defect is thought to be active and growing in service an FFP analyst should be involved straight away. Note that if growing defects are repaired without any analysis, then possible warning signs about the health of a structure will be ignored. Since NDT cannot detect defects with a 100% probability of detection there may be other undetected defects (possibly larger) elsewhere, which will continue growing, in spite of the defects that have been repaired.

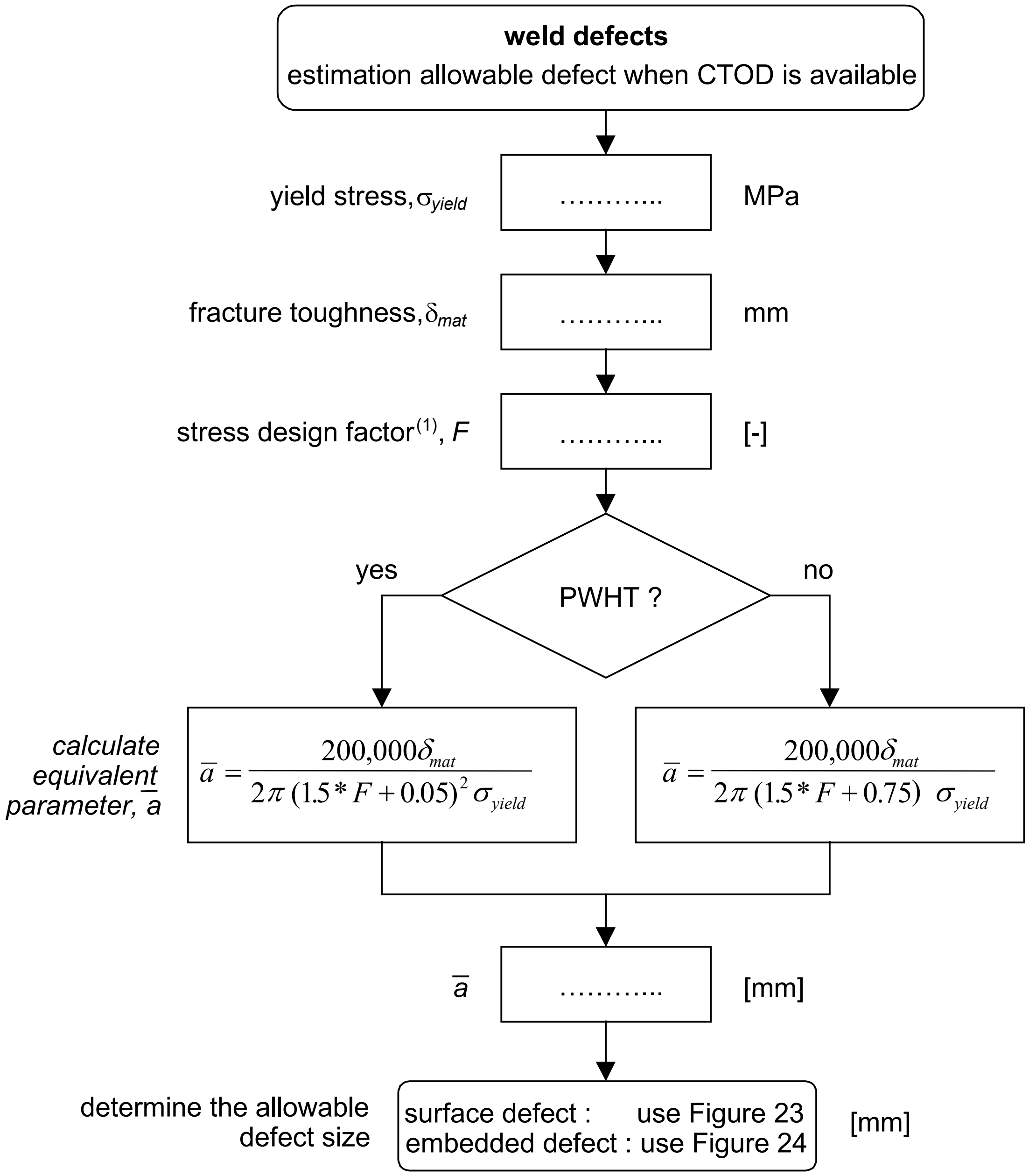
The inspector should report the results of calculations to the asset holder and an FFP specialist. Both the FFP specialist and asset holder should review the analysis and judge whether there is any justification for a more refined analysis of the defects that have been rejected. Thereafter a decision by the asset holder can be made to repair or not to repair. Four manual calculation procedures based on BS 7910 Annex N are given in the following figures. The explanations are given after the figures.

[8] The plant inspector is defined as an inspector with significant experience and a knowledge of the installation, processes and materials and corrosion.



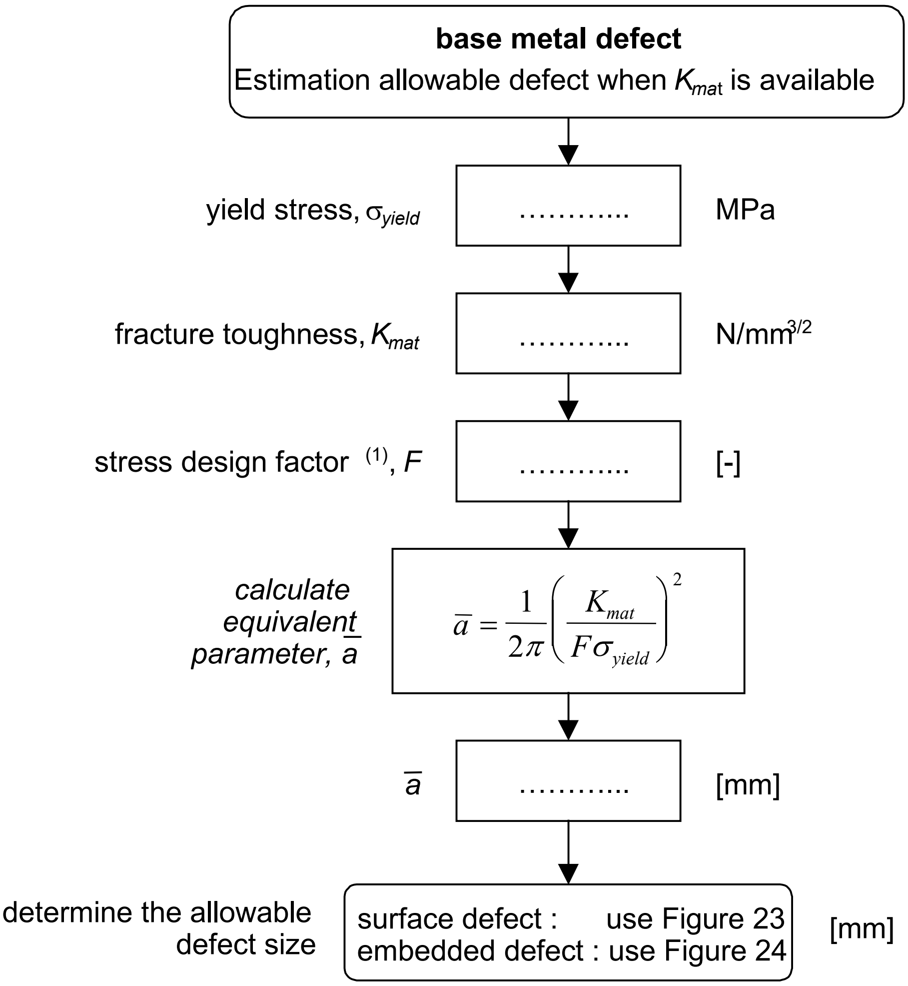
(1) F = design stress / yield stress

Figure 21a Estimation of allowable weld defect when the fracture toughness is known in terms of K



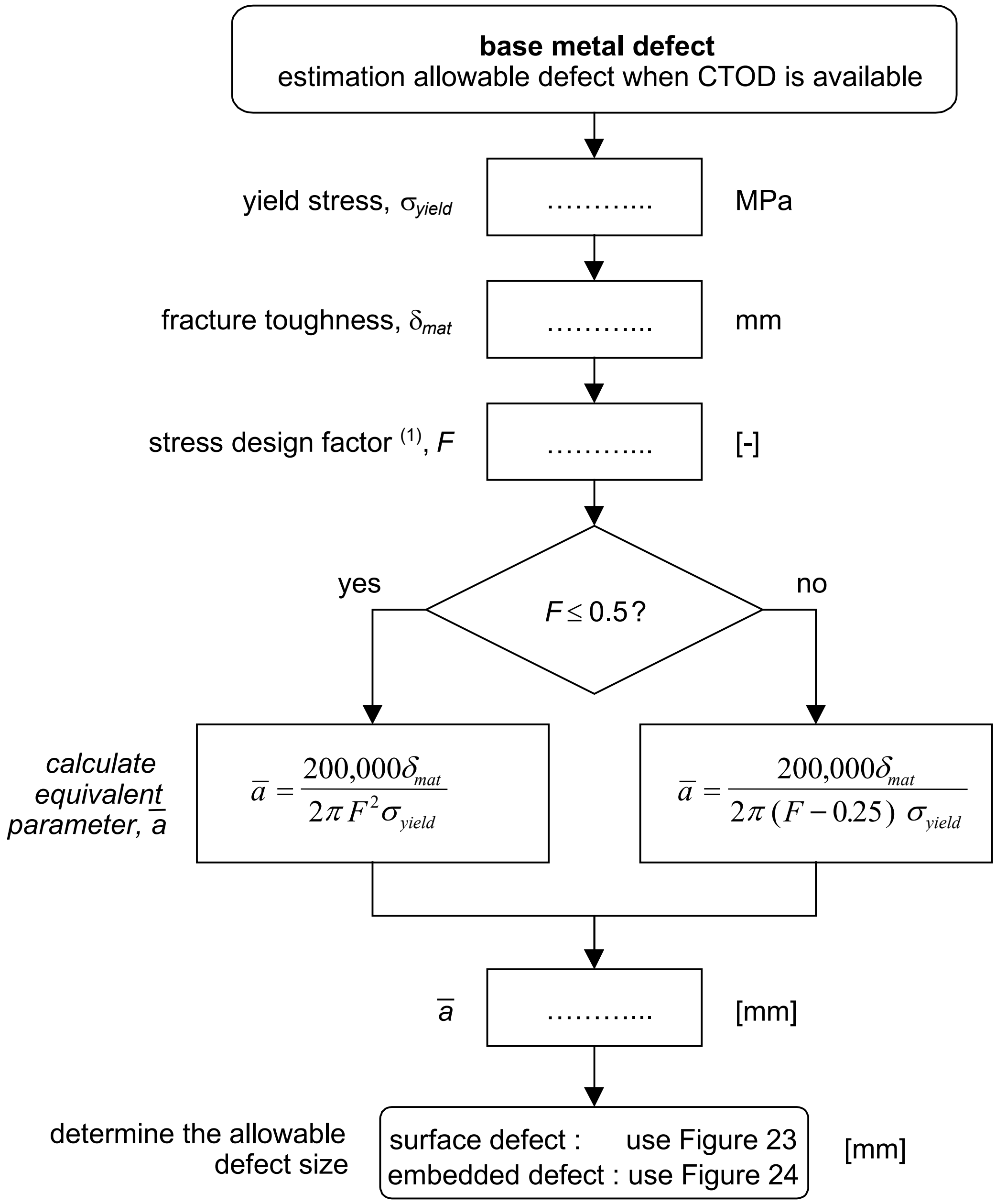
(1) F = design stress / yield stress and must be greater than 0.2

Figure 21b Estimation allowable weld defect size when CTOD toughness is available



(1) F = design stress / yield stress

Figure 21c Estimation of allowable base metal defects when fracture toughness K is available



(1) F = design stress / yield stress

Figure 21d Estimation of allowable base metal defects when CTOD is available

7.2 The calculation procedure

The level 1B assessment in BS 7910 annex N should be used with conservative input data for the fracture calculation. Level 1B is a manual calculation, which does not use a failure assessment diagram. The fracture calculation is followed by a simplified plastic collapse calculation. The defect is then compared with the allowable defect sizes calculated using the fracture and plastic collapse calculations.

The schemes in Figures 21a to d give a step by step approach for defects. Schemes in Figures 21a and b are intended for defects close to or in welds (i.e. close means within a distance of the width of the weld or thickness of the plate, whichever is the greatest, from the weld toe). Figures 21c and d are for defects away from welds in the parent material. The schemes in Figures 21a to d require the calculation of the parameter $\bar{a}$, which is calculated using Figures 23 or 24. The parameter $\bar{a}$ (or a_{equiv}), is the half defect length of a through-thickness defect equivalent to the actual surface, embedded defect or (re-categorised) embedded defect.

The results of the calculation should be presented for review by the asset holder and an FFP specialist. The asset holder should make the decision to repair or not to repair.

7.3 Input for the analysis

Advice is given on the selection of input data for the analysis. To some extent it is a simplification of the recommendations in the BS 7910 standard with a tendency to be more conservative. The input data consist of fracture toughness, stresses and defect size.

yield strength

Assume the minimum specified yield strength of the base material unless actual data are known.

Note that when the fracture toughness CTOD test data are available the actual yield strength will be known.

Note the minimum specified tensile yield strength is often the only information available. To account for the unconservatism of the minimum specified value, this value could be increased by a further 20% to 60% depending on the difference between the yield and tensile strengths.

fracture toughness

Use fracture mechanics test toughness values if they are available. In this case, the choice of a representative value for the calculations may need the advice of an experienced FFP assessor. CTOD values that are equivalent to a value of K_{mat} = 2800 N/mm$^{3/2}$ are in the range of 0.05 to 0.1 mm depending on the yield strength of the base material. If only Charpy V values are available then BS 7910 gives the method of calculating the lower-bound fracture toughness K_{mat} from the Charpy V value. The formula for cleavage fracture is given here (lower shelf and transitional temperature):

$$K_{mat} = (820\sqrt{C_v} - 1420)/B^{1/4} + 630$$

where K_{mat} is the fracture toughness in N/mm$^{3/2}$, C_v the Charpy V energy in J, and B the thickness in mm.

If no Charpy V values are known then the lowest fracture toughness of 1000 N/mm$^{3/2}$ must be assumed. This value is very low and will probably result, when applied and residual stresses are high, in very small acceptable defects, which are only detectable with a low probability and impossible to size accurately. In order to have a reasonable chance of calculating acceptable defects the fracture toughness K_{mat} will need to be in a region above the transition temperature for fracture toughness and have a value of the order of say 2800 N/mm$^{3/2}$ or more when considering low to medium strength structural steels.

The relationship for cleavage fracture gives fracture toughness of the order of 2000 N/mm$^{3/2}$ for Charpy V values of the order of 30 to 50 J and fracture toughness values of the order of 3000 N/mm$^{3/2}$ for Charpy V values above 60 J.

Alternatively, if the equipment is operating well above the transition temperature (temperature at the minimum specified Charpy V value), then BS 7910 shows how a higher level of fracture toughness of K_{mat} = 2800 N/mm$^{3/2}$ can be assumed in the defect assessment calculations. For example:

- for a thickness of up to 25 mm if it operates at 20 °C above the transition temperature.
- for thickness up to 50 mm if it operates at 35 °C above the transition temperature.

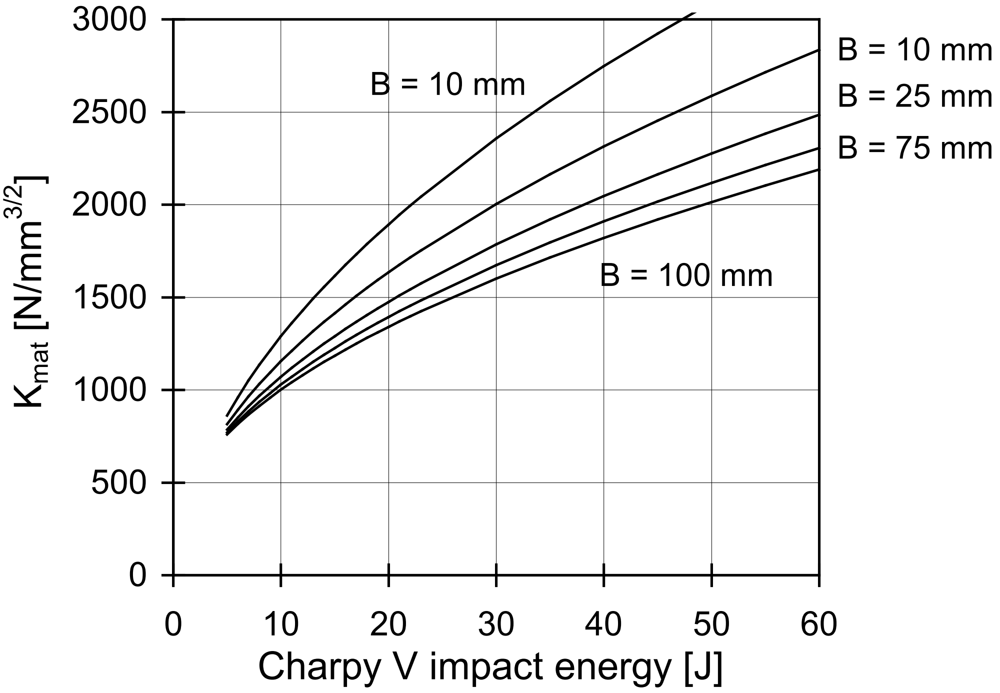


Figure 22 K_{mat} as a function of the Charpy-V impact energy for lower shelf and transitional behaviour

stress design factor

The nominal stresses are often chosen to be 2/3 of the minimum specified yield stress. This would then give a stress design factor F of 2/3.

residual weld stresses

A residual stress equal to the minimum specified yield strength of the base material has been included for defects in a weld that has not been stress relieved or only locally stress relieved.

A residual stress of 30% of the minimum specified yield strength of the base material has been included for defects in a weld that has been post weld heat treated.

This calculation procedure is often unconservative for defects in welds because the actual residual stress can bemuch higher than the assumed specified minimumm yield strength, which is often the only information available.

Defects that are further than the distance of the width of the weld or thickness of the plate from the weld toe, whichever is the greatest, are assumed to be in the base material and free from residual stresses.

stress concentration factors

The maximum value of the stress concentration factor is assumed to be constant over the entire wall thickness, regardless of the actual distribution. Allowable defect sizes at nozzles and other welded joints where there are high stress concentration factors will be small when this simplified procedure is used. The stress concentration factor of a hole is 3. A stress concentration factor of three can also be used as a conservative estimate for a nozzle. A typical stress concentration of 1.5 can be used for a toe of a butt weld, which has been made according to the code requirements. The stress concentration factor at a weld toe of a nozzle will then be 4.5 (i.e. 3*1.5).

7.4 Calculate the allowable defect size and compare with the defect size found using NDE

The length of the defect in pressure containing equipment should be limited to less than twice the wall thickness to avoid approaching lengths of defect where bulging would make the defect calculations unconservative.

The smaller ligament between an embedded defect and the surface is checked first because there is a significant risk of plastic collapse to the nearest free surface when an embedded defect is close to the surface. The calculation of local plastic collapse is complex so a simple rule is used to decide when to recategorise an embedded defect, that is close to a free surface, as a larger surface defect. If the embedded defect is closer than one fifth of the wall thickness to the free surface then the defect is recategorised as a surface defect. The new depth is equal to the distance to the free surface (the smallest defect-free ligament, distance p in Figure 24) plus the original embedded defect height. In other words, recategorise the embedded defect as a surface defect when p in Figure 24 is less than 1/5 x wall thickness).

Next calculate the equivalent defect length. This is then converted to a surface defect depth or an embedded defect height by using graphs N1 and N2 respectively in annex N of BS 7910. For convenience the two curves have been reproduced in the document.

Then compare the calculated allowable defect size with the actual defect size found using NDE (This may be the recategorised embedded defect size for shallow embedded defects rather than the actual defect size). Routine UT, RT and MPI will give lengths of defects but not give an explicit measurement of the depth or height. See Section 8.4 on the Selection of NDT Methods. Find out if the NDT inspector is able to give an estimate of the depth. If there is no or uncertain information on the defect depth or height, it may be possible from a knowledge of the welding process, experience and loading conditions to judge that the defect is a typical fabrication defect, which is lying within a weld bead. If this is the case, then assume that the surface defects are as deep or embedded defects as high as a weld bead height.

plastic collapse part of the calculation

Do not be surprised if the plastic collapse calculation results in smaller allowable defects than the fracture calculation when defects are in thin materials (e.g. less than 10 mm thick). A defect is acceptable when the crack depth ratio $a/B < 1 - F$ where B is the thickness. For example, this would give an allowable defect for plastic collapse of 1/3 of the wall thickness when the design factor is 2/3.

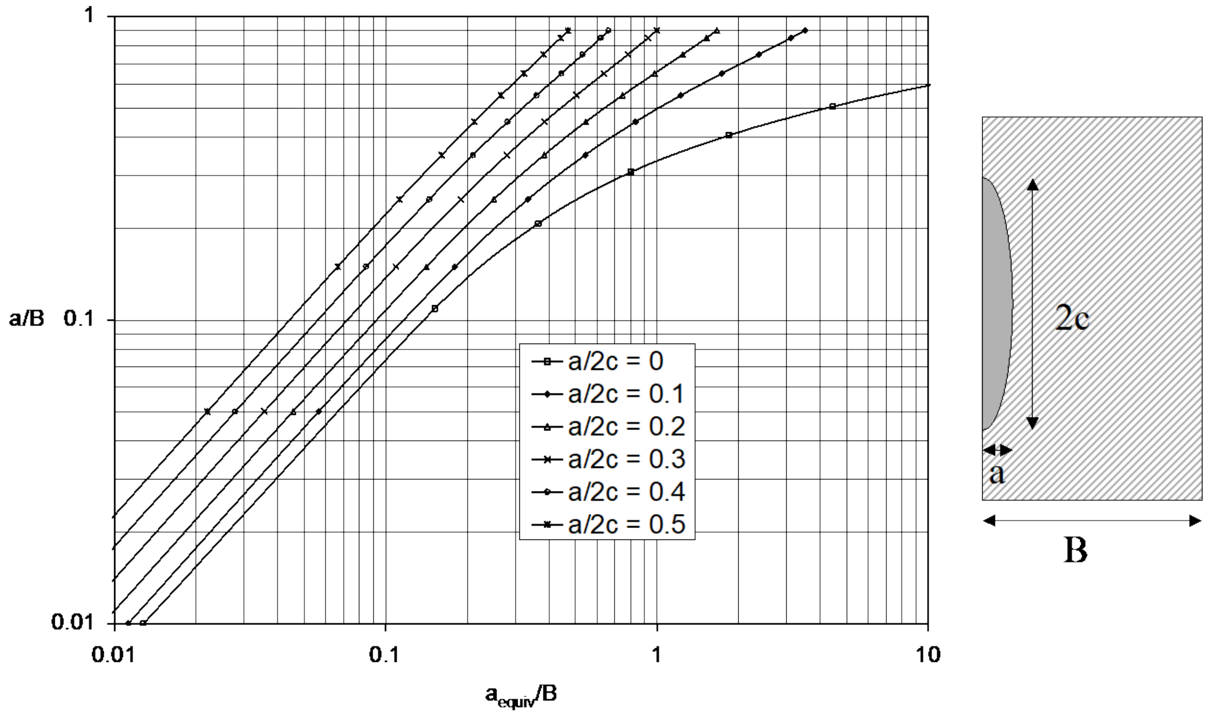


Figure 23 Relationship between actual defect dimensions and the equivalent through-thickness defect length for surface defects

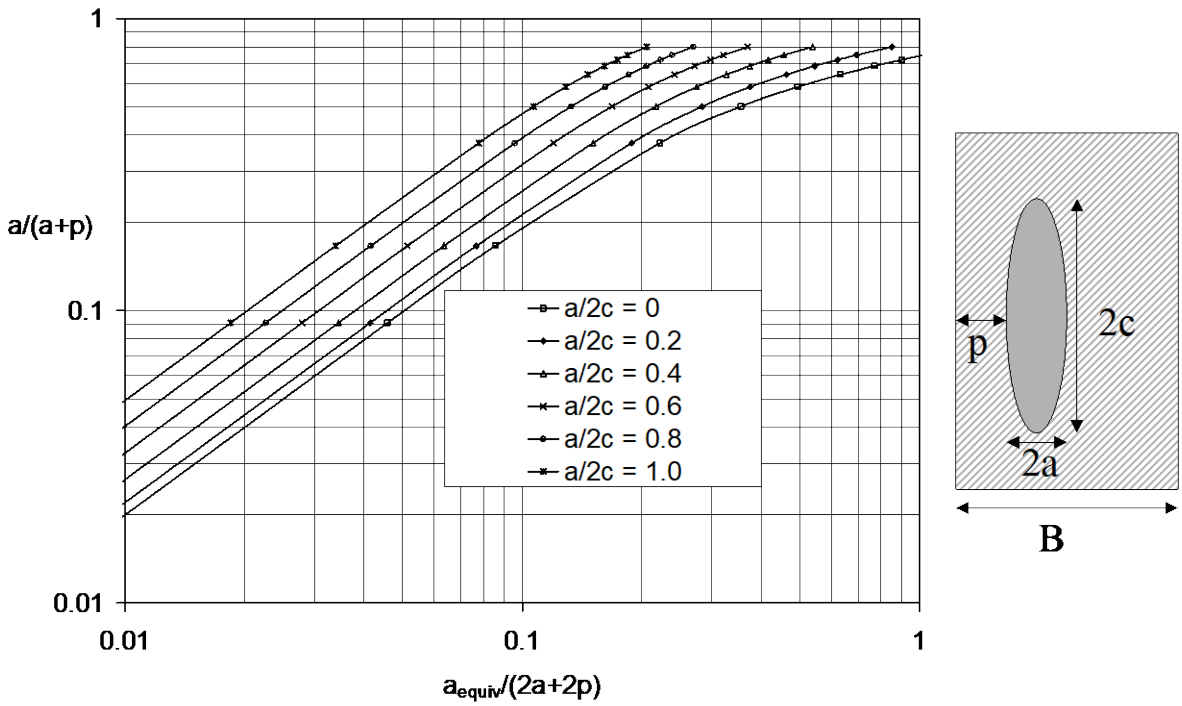


Figure 24 Relationship between actual defect dimensions and and the equivalent through-thickness defect length for embedded defects

8 Non Destructive Examination

8.1 Introduction

The section on NDE starts off introducing the topic of NDE and presents some definitions of expressions related to NDE. This is followed by another introductory section on inspectability, which concerns the difficulties and challenges that confront and NDT operator as the conditions for NDT are rarely optimal (inspectability). The NDT techniques are then explained and finally advice is given on how to select techniques either in isolation or in combination with other techniques.

Non-destructive testing is introduced in Section 4.1 in the section on input data for FFP assessments and also forms an important part of the FFP Information Checklist and FFP Analysis Checklist in Sections 10 and 11.

Non-destructive testing techniques are needed to detect defects and to determine the following defect parameters. No single method, unfortunately, is capable of all these measurements. This means that a careful selection of the NDT method is needed depending on the requirements of an FFP assessment and this will probably lead to a combination of techniques being used where weaknesses are compensated by strengths in other techniques.

- position
- size
- extent
- orientation
- nature

The different commonly used NDT methods are described in Section 8.3 where the method, its application and expected results are given. The physical principles of each method are given to help people who are not well versed in NDE understand the limitations of each method. The limitations of NDT methods are important when deciding how to perform an FFP assessment. A table is given in Section 8.4 on the selection of NDT methods to help both the FFP analyst and the NDT inspector. Some of the ways of enhancing the standard techniques to achieve a better performance is given in the same section. The ways in which methods can be combined to achieve more of the goals listed above for FFP driven Non destructive examination are given in Section 8.4 on the selection of NDE methods. The need to strive for the very best performance will depend on many things such as the technical need, the cost and the time required. Whatever the theoretical optimal performance, the actual conditions under which NDT is carried out will often be the determining factor. This aspect is described in the 8.2 on Inspectability and needs to be kept in mind by the analyst, the plant and the NDT inspector. The two key aspects, the probability of detection and the accuracy of sizing are referred to throughout the text, see also Sections 8.4.2 and 8.4.3. The POD will be the most important factor if there is a significant probability of missing defects. Once all the defects have been detected, the POD ceases to be an issue. Techniques, that have sufficient accuracy, can then be selected to measure the size of a defect.

Definitions

NDE non destructive examination, a combination of different NDT techniques.

NDT non-destructive testing technique or method

quantitative NDE methods methods, which allow the accurate determination of defect height or depth and length.

semi-quantitative NDE methods methods where only the length is determined or the defect height or depth. Methods, which give a signal, that is a mixture of different responses from the various parameters that affect the signal. These methods need either the use of additional quantitative NDT and/or expert knowledge to obtain more quantitative information about a defect.

mechanised NDT Means the component is mechanically scanned either semi-or fully automatically and will produce a record.

automated NDT means that the results of mechanised NDT are automatically interpreted to enable automatic defect acceptance or rejection.

UT ultrasonic testing

MT magnetic particle inspection (MPI) potential drop measurements

PT liquid penetration testing

MFL magnetic flux leakage

PD potential drop

indications

Indications are the response from the interaction of the NDE method with inhomogenities or other features of the item under test. If the indication is outside the acceptance limits for the NDE method used, it is classified as a defect after interpretation and confirmation using e.g. metallurgical insight.

flaw and defect

The terms “flaw” and “defect” are synonymous and represent regions in a material where there is a discontinuity. The term “flaw” is preferred in the USA because the term “defect” gives an impression that the material is defective and therefore unacceptable while the word “flaw” gives the impression of a natural phenomenon that could occur in any material.

extent of defects

This is defined here as the number of defects and their frequency etc. e.g. number per meter. Note that the presence and frequency of defects will probably be similar in similar constructions and in similar design features. Note this is not the size of the defect.

defect type

This is the ability of an NDE to distinguish between different types of defect, e.g. cracks, lack of fusion, slag etc. In general, it can be said that most NDE techniques have difficulties in distinguishing between defect types. In most cases, a differentiation between planar and non planar is all that is possible. However, the classification can be enhanced if the interpretation of indications is made by someone who takes account of the physical metallurgy of the (welded) material, the welding process and -procedure and failure mechanisms. It is important to know the type of defect in that this may help determine the cause and the extent of defects in areas which have not been inspected. The FFP analyst needs to know more specifically if the defects are active or non-active and whether they are planar or non-planar. These aspects are covered immediately after this note.

active and non-active defects

Active defects are defects which are either growing or defects which have grown but which may or may not have been arrested.

Non-active defects are defects such as fabrication defects or for example mechanical damage.

note

The different information on size, shape, acuity (planar or non-planar), orientation, position relative to welds, free surfaces and stress concentration factors, extent of defects and the use of metallurgical knowledge are needed to make assessments of the type of defect. The position relative to welds, free surfaces and stress concentrations will give information that may help interpretation as to whether the defect is a fabrication defect or defect that has grown under the influence of stresses. The orientation of the defect, for example, not only provides information about the type of defect but also gives an idea of the direction of the stresses in the case of active defects.

planar versus non-planar defects

Defects are considered as planar if on the basis of observations it can be concluded that there is inadequate bonding, incomplete root penetration or a crack. All other defects must be regarded as non-planar defects.

note

Defects are generally assumed to be planar by the FFP analyst because of uncertainty about the sharpness of the defect and because fracture mechanics methods, which are needed to obtain quantitative predictions of defect growth and criticality, are normally based on the assumption of sharp planar defects.

Some methods can discriminate between planar and non-planar defects. Since non-planar defects are unlikely to be active growing defects, with the exception of easily identifiable corrosion defects on the surface, these defects can usually be confirmed as fabrication defects. This knowledge helps the analyst who can use the fabrication defect as an initial defect in the calculations and may be able to demonstrate that the fabrication defect will not be extended during the service life. Note that an FFP assessment may also be used to help confirm that a defect is a fabrication defect.

Planar defects present a problem for the FFP analyst, since it is difficult or even impossible to discriminate between dormant fabrication defects or growing defects in service. Usually the analyst will assume the defect has been growing from the beginning of service or even since fabrication. This conclusion may then have significant consequences for the planning of the monitoring of the defect or other mitigation measures. In some cases it may be possible to back-calculate using the FFP analysis and demonstrate that the defect is indeed a non-propagating fabrication defect.

8.2 Inspectability

This section on inspectability is an attempt to put into perspective the relative difficulties/challenges confronting the NDT operator and the types of failure mechanisms that cause defects. The FFP specialist should be **aware** of the effect “inspectability” because it has a significant impact on the POD, accuracy, timing and the costs of NDT particularly when non-standard approaches are needed. Proper awareness of “inspectability ”issues may avoid the definition of absurd defect acceptance criteria and temper over optimistic estimates of

PODs and accuracy. This section thus forms an introduction to NDT methods and Selection of NDT methods. The difficulties/challenges will depend on:

- length of weld in a construction;
- global geometry;
- accessibility;
- conditions and time constraints under which ndt is carried out;
- wall thickness;
- surface roughness, local geometry and type of weld;
- material;
- mode of failure, defect type, size, position and orientation;
- defect interactions.

8.2.1 Length of weld in a construction

Firstly, the weld length to be inspected has an impact on the economics of the methods used, and the probability of detection of defects. For example, the weld lengths in different types of construction can be of the order of 50 kilometres for pipelines, 5 kilometres for tanks, bridges and piping and 100 to 10 metres for spheres and pressure vessels. However, the actual amount of weld inspected in larger structures can be significantly reduced by the use of selective inspection. Typical amounts of weld inspected could be 10% of weld length for tanks where only the weld crossings are inspected. Bridges and offshore structures are usually only inspected in detail in the most highly stressed areas. There is a clear logic in the use of selective inspection because the areas chosen are likely to act as early indicators for the health of the rest of the structure. The additional use of an FFP assessment to target NDT efforts will result in a more rational selection of the weld lengths for inspection, better planning of inspection and the selection of appropriate inspection methods. There will also be a tendency to use of methods with a high probability of detection and possibly low accuracy suited for covering larger areas of material rapidly for an initial inspection. Detected defects could then be examined later with a more accurate technique.

8.2.2 Global geometry

Simple geometry such as a pipe lend itself to mechanised NDT with higher POD, accuracy and reproducibility when defect growth needs to be monitored. The disadvantage of mechanisation is the possibility of systematic errors in detection and sizing if the initial settings of the NDT equipment are incorrect.

Complex geometry often requires manual NDT, which by nature is operator dependent but has less chance of defects being missed because of systematic errors. See also the comments on accessibility in Section 8.4.

8.2.3 Accessibility

There are three types of inaccessibility, namely:

- the equipment may have a difficult geometry and/or limited space to operate NDE probes properly;
- the equipment may be on-stream and inspection may only be possible from the outside;
- the equipment may be situated in an inaccessible environment such as sub-sea, or underground.

Note that ultrasonic inspection methods need a minimum amount of space because of geometric limits imposed by the object being inspected and physical dimensions of the probes preventing the optimum angles of incidence for the ultrasonic beam. Thus each NDE technique requires a minimum amount of space because of the size of the probes and the minimum distance needed between a sensor and the defect to achieve optimum incidence of the waves on the defect. In general, for those areas where access is difficult, it is possible with an increased effort, to improve on the performance of the NDE technique by optimising the method and the access.

Examples are the use of long range ultrasonic techniques, the use of complex geometry software modelling for TOFD and mechanised Pulse Echo techniques for the inspection of the inner corner of nozzles in vessels etc. Pulsed eddy current techniques can be used to detect corrosion without the removal of insulation. Double–walled RT can avoid the need to empty piping in order to place a film on the inside surface of the pipe. A radiographic source is placed on one side of the pipe and a film on the other side of a pipe. Defects are then detected with a lower sensitivity.

Proper development of the NDE at the early design stage along with an FFP approach can limit the adverse effects lack of accessibility on performance.

8.2.4 Conditions and time constraints under which NDE is carried out

Adverse conditions caused by lack of accessibility and discomfort will lead a reduction of working times of personnel. The extremes of sub-sea, cramped space, wind, temperature, moisture and poor lighting, noise and vibrations will not be conducive to high accuracy and PODs and will result in increased costs. Comfortable shop conditions are favourable for NDT. The use of radiographic techniques results in a potential health hazard, which requires measures to protect personnel.

Time constraints in the form of a limited window of opportunity for NDE during a shutdown or between operations may also have a negative effect on the operator.

Proper development of the NDE during the early design stage along with an FFP approach can limit the adverse effects of conditions on performance of NDE and the outcome of an FFP assessment.

8.2.5 Wall thickness

See the issues concerning very thick and very thin wall thickness in Section 8.4.

8.2.6 Surface roughness, local geometry and type of weld

Surface corrosion pitting and the type of welding or joining technique can lead to varying degrees of surface roughness, which can impede the detection and sizing of surface defects. For example most techniques require an intimate contact with the surface. In addition, a defect on the far surface may be obscured when this surface is rough due to for example corrosion.

If the weld cap, undercut and misalignments are within specification then routine NDT should be able to perform to the required levels of POD and accuracy required for GWMS. In spite of acceptability for routine inspections, the presence of a significant weld cap, undercut and misalignment will hinder non routine inspection aimed at obtaining quantitative data for an FFP assessment. This means that there can be significant technical advantages in machining away weld reinforcements and penetrations of weld at the root of the weld.

The fact that the weld geometry is out of specification may become the main reason for an FFP assessment; i.e. because it cannot be inspected properly, the probability of undetected defects is probably higher and the stress levels are higher.

8.2.7 Material

Large grains, micro-cracking and porosity may obscure significant macroscopic defects from an ultrasonic beam. Applicability of MT techniques is limited to homogeneously magnetisable materials. Application to high alloy (magnetisable) materials such as duplex steel is inadvisable, due to the potential occurrence of spurious indications.

8.2.8 Mode of failure, defect type, size, position and orientation

See also Section 9. The remarks made here should help the classification of defects and give the plant and NDT inspectors more of an idea about the concerns of the FFP analyst. The combined knowledge of the physical metallurgy of the (welded) material, the welding process and procedure and failure mechanisms are needed to interpret NDE indications. The FFP analyst will most likely consider volumetric (non-planar) defects outside of GWMS standards as planar defects because the experience of accepting such large defects is limited and there are no tools for assessing the degree of acuity of volumetric defects. It is also known that some volumetric defects can have very sharp tips. The non-planar defects will generally have a higher POD and accuracy of measurement.

Defects close to a surface form one of the most common problems for FFP assessment. Defects are often found close to the surface near areas of highest stress (i.e. higher bending stresses at the surface and local stress concentration effects at the surface near weld toes). Creep waves can be used to detect defects close to the near surface. Pulsed echo UT can be used to detect defects close to the far surface.

Knowledge about the weld bevel will help in making judgements and setting up the mean orientation for the NDT for detecting fabrication defects. Nonetheless defects will not necessarily have a constant orientation relative to the surfaces and NDT procedures have to account for this. For example, focussed UT probes could miss parts of a defect with a varying orientation. Typical average orientations of fusion line defects range for different weld preparations (e.g. V, X and U preparations) from approximately 45°, 60° and 90° to plate surface. Therefore the appropriate UT angle probes are needed.

The fabrication defect depths and heights are often smaller than the height of a weld bead. The height of a fabrication defect is then often assumed to be limited to less than the height of a weld bead if the method used is insufficient to accurately measure the height of such relatively small defects. This means FFP analysts assume defects with depths (or heights for embedded defects) of between 3 to 6 mm, which are typical height of the majority weld beads.

Once the defects start propagating, the defects will tend to grow perpendicular to the principal stress direction, which is usually perpendicular to the plate surface. Cracks can deviate from the perpendicular direction in the presence of complex stress fields. A crack will propagate in both the length and depth directions. The crack growth will be most rapid in the direction where the crack driving force is normally the highest. This often means that propagation will be greatest in the depth direction. There are exceptions when growth may be faster in the length direction. For example, this may occur f there is a high stress concentration at the surface and the surface length is relatively long compared to the depth the crack and particularly if there are a number of surface defects in close proximity, causing the defects to coalesce. The crack driving force acting on a crack through the wall will be increased by the influence of the opposite surface at an early stage unless it is a thick wall. For example, weld defects at the surface with a depth of less than 3 mm in a 30mm or thicker wall (less than one tenth of the wall thickness, the influence of the opposite surface is small). As the crack depth becomes large relative to the distance to the opposite free surface, the crack driving force will tend to increase rapidly, greatly increasing the crack growth rate and the possibility of unstable fracture.

8.2.9 Common modes of failure

A brief description of the different failure modes and possible suitable NDT techniques and consequences for NDE are given in this sub-section. The failure modes considered are:

- fatigue
- brittle fracture
- corrosion
- stress corrosion cracking
- hydrogen induced cracking
- creep

8.2.9.1 fatigue

Fatigue cracks are usually very regular with smooth faces. This makes them ideal reflectors for UT methods. If fatigue crack growth is possible, then NDT must be capable of detecting and sizing relatively small surface defects in the vicinity of geometrical stress concentrations. In less common situations fatigue can begin from a relatively large embedded defect. Fatigue cracks at weld toes have the tendency to propagate rapidly along the surface following stress concentrations such as the stress concentration caused by the toe of the weld. The propagation along the surface is rapid because the propagation is a process of multiple crack initiation often from extremely small defects at the weld toe. This is followed by a rapid linking up these cracks to form a single crack. This results in a long, almost straight-fronted crack that propagates, once it is formed, in the thickness direction. The resulting long shallow crack is generally assumed to be infinitely long by FFP analysts. This means the accurate measurement of length when a crack is greater than 10 times its depth is not important for fatigue crack growth calculations. The initial stage of crack coalescence results in rough crack faces and a poorer reflector for UT. After coalescence the faces become smooth.

If the crack initiates from a single point or defect and there is no crack coalescence at the surface, the elliptical or semi-elliptical shape will usually develop, depending on whether the crack starts respectively within the wall or at the surface. A fatigue crack at the surface is unlikely to be deeper than half its length since it will tend to propagate from an initial semi-elliptical shape to a semi-circular shape. This means that if the length is known a conservative estimate of the depth can be made.

Fatigue crack growth is often exponential. Initially the growth rate will be extremely slow but once a certain depth is reached it can grow very rapidly. The growth rate will increase further when the opposite free-surface starts to influence the crack. MPI techniques are used for detecting and measuring the length of fatigue cracks since fatigue usually starts at the surface. Grinding until the crack is removed is often used to determine the depth of cracking. This information can be used to aid the assessment of other cracks that have not been detected, see the worked example in Section 13.9 . The depth of a fatigue crack can be measured using UT angle probes, TOFD or potential drop techniques. Since it is important to size small surface cracks when fatigue is suspected, cracks at the near surface will probably be measured using PD or TOFD where use is made of the lateral wave. Cracks at the far surface will probably be investigated using pulsed echo UT with focussed probes and TOFD.

8.2.9.2 brittle fracture

If this is the suspected failure mode then NDT must be able to detect and size larger embedded defects or a smaller surface defects usually in the vicinity of geometrical stress concentrations. Fractures often arrest after passing through a small region of embrittlement or after passing out of a region of stress concentration or high residual stresses. The fractures will have a more irregular shape of crack and a rougher surface than a fatigue crack. An arrested fracture can have any size. Visual methods can be used when large through-thickness cracks develop. It is sometimes difficult to see whether a brittle fracture has significantly tunnelled beneath the surface; i.e. the defect resulting from a brittle crack jump may be much larger than it appears. In this case, NDE methods suitable for investigating the bulk material such as UT, must be used to determine the size of a tunnelled fracture. Similar methods to those used to measure the depth of a fatigue crack can be used for measuring the depth of a brittle fracture that has arrested before penetration of the wall . In view of the irregular shape, rough surface and orientation of the fracture, focussed probes could be an advantage in that they give a greater chance of receiving reflected signals than a larger diameter beam.

8.2.9.3 corrosion

This usually results in voluminous surface damage unless material conditions or geometry promote the formation of crevice corrosion which is more or less planar. There are many NDT methods, e.g. UT and MFL for detection and measurement and pulsed eddy current for screening for detecting and measuring the loss of wall thickness and they are given in Table 1 in Section 8.4.

The size of small pits can be less than a millimetre in cross-section. A pit will grow rapidly initially in the depth direction and as it increases its cross-section the rate of growth in the depth direction will decrease significantly, see Figure 4.

8.2.9.4 stress corrosion cracking

NDT must be able to detect and size relatively small surface defects. Since a minimum stress level will be needed, the cracks often form near geometrical surface stress concentrations and welds where there are extra residual stresses. Welding can also make the microstructure sensitive to stress corrosion cracking. If the cracks initiate in an area of uniform stresses then parallel cracks may form. Stress corrosion cracks, similar to fatigue cracks can propagate rapidly along the surface. MPI is again used to detect cracking that starts at the surface. The multiple cracking that may occur from the surface and the fact that cracks will often be branched make this type of crack a poorer reflector of ultrasound than a fatigue crack. Candidate methods are TOFD, PD, and manual UT. FFP assessment of SCC is complex because of the lack of reliable growth rate data and needs expert advice.

8.2.9.5 hydrogen induced cracking

NDT must be able to detect planar laminar defects (defects orientated in a plane parallel to the plate surface). In some cases, these laminar defects will also be connected by a series of linked cracks that propagate in a step-wise manner towards the surface where the corrosive cause of HIC is acting (e.g. the inner surface of a pipe transporting corrosive fluids containing H_2S). The step-wise cracks tend to step to the surface with overall angles varying between

45° and 90°. UT reflections from the stepped cracks will be inferior to those from the laminar crack or a fatigue crack. The step-wise cracks often eventually form parallel pairs of surface-breaking cracks. When the laminar cracks form near the surface or in relatively thin material they form blisters which can be seen visually. Once laminar cracks have been found then a search should be made for surface breaking cracks. At the moment of initiation HIC will have microscopic dimensions. Later HIC may grow to lengths of a plate thickness and more. Small laminar cracks can often be tolerated. The integrity may be impaired when the stepwise cracking develops or large laminar cracks develop. MPI is used to detect the surface-breaking stepwise cracking. A UT 0° probe emitting ultrasonic compression waves (for wall thickness measurement) is used to detect and size the laminar hydrogen induced crack. Angle probes can be used to detect and size the stepwise cracking that is not yet surface breaking. This can help the identification of a crack as HIC rather than a laminar defect created either during steel production or as a result of stresses acting in the thickness direction on weak laminar plane in the steel. Since HIC can occur at different depths there is a possibility that HIC crack may partially obscure another deeper crack.

8.2.9.6 creep

Creep damage and cracking is often at the surface. The damage may consist of voids and at a later stage of cracks or extension of defects by cracking. This can be detected by taking replicas of a polished surface and investigating the replica with a microscope. There are procedures that can be used to interpret the density of voids and the presence of cracks in terms of the amount of creep life used. MPI is often used for the detection of surface cracks. Strain measurements are used to check whether the maximum allowable creep strain has been exceeded. UT can be used to measure crack depths when creep cracks have developed but will often have difficulties in obtaining a reflection from the crack when there are significant numbers of voids and microcracks obscuring the main crack. There is a method of obtaining a measure of creep damage by using the attenuation of the transmission of an ultrasonic signal.

8.2.10 Defect interaction

Defects can interact with each other and with the surface so that two or more smaller single defects or a smaller embedded defect become a larger single defect or surface defect respectively. For more information on defect interaction the BS 7910 guide or the R6 document should be consulted, see Section 14.2. Clearly discrimination between interacting and non-interacting defects can require a fairly high degree of accuracy.

An embedded defect, immediately below the surface will often be treated as a surface defect by FFP analysts with a depth equal to the height of the embedded defect plus the depth of the material between the defect and the surface (remaining ligament). The reasons for the re-categorisation as a surface defect are the limited accuracy of measurement of the remaining ligament and the questionable accuracy of fracture mechanics and plastic collapse solutions when the remaining ligament is small. See Section 7 on a screening FFP assessment for an inspector for an idea of how to assess when defects interact with the surface.

8.3 NDT methods

There are many NDT methods, each with their specific capabilities and limitations. Some methods are only able to measure the length of the defect, while others also have capability to measure height of the defect. The methods also vary in their capacity to characterise a defect, i.e. to determine whether a defect is voluminous, planar, sharp etc. The different physical principals on which the methods depend and the conditions of application cause the differences in performance. Short descriptions of a number of NDT methods including the physical principals and applications are given in this section. The methods are divided into routine semi-empirical methods for ensuring GWMS and non-routine methods, which include quantitative methods for FFP assessments.

8.3.1 Routine NDT

The procedures for application and acceptance criteria for routine NDE for ensuring GWMS are laid down in codes and specifications.

8.3.1.1 visual inspection

description

Visual inspection is the oldest form of inspection. It may be performed by the naked eye or by aid of tools such as magnifying glasses, mirrors and endoscopes. As for any NDT-technique, codes and specifications exist to regulate its use (viewing angle, equipment to be used, illumination conditions etc.), including acceptance criteria for defects.

applications

It is only used for the detection of surface defects, such as cracks, casting defects, corrosion, machining defects etc. Inspection may be performed both from the outside and, with the aid of specialised tools such as endoscopes, from the inside of constructions such as bores and cavities. However, detection is limited to surface-breaking defects and often additional NDT (such as magnetic particle inspection, liquid penetrant testing or eddy current inspection) is required to enhance the probability of detection for expected defects mainly during In Service Inspections, or to comply with the fabrication specifications.

inspection results

Visual inspection shows the shape and extent of surface anomalies. Since only the surface is viewed, in the case of a linear indication of a crack only the indication length can be measured. In the case of non-linear indications, the defect area can also be measured. Note, if the surface is too heavily ground when preparing it for inspection,, material can be smeared over the defect causing its concealment.

8.3.1.2 magnetic techniques

description

There are several techniques, which are used depending on the defects that need to be detected and the sensitivity required.

MT is in principle a surface inspection technique, just like visual inspection. The portion of a defect that is just below the surface also contributes to the signal. The method relies on the distortion of magnetic flux lines by defects present in the material under inspection, causing leakage of the flux outside the material.

In the case of magnetic particle inspection, a powder or liquid containing particles that can be magnetised is spread over the surface of the object. The particles in the fluid concentrate in the region of magnetic flux leakage signalling surface breaking defects. This results in indications of cracks, which may be visually detected. Often contrasting white paint or fluorescent particles are used to increase detectability.

applications

It is used for detection of surface cracks in or close to welds and in forged or moulded steel objects. Applicability is limited to homogeneously magnetisable materials. Application to high alloy (magnetisable) materials such as duplex steel is not advisable, due to the potential occurrence of spurious indications.

inspection results

It is similar to visual inspection, in that only the defect dimensions on the object's surface can be measured such as the length of linear indications and area of non-linear indications. Crack depth cannot be measured. Distinction can be made between linear and non-linear surface breaking indications.

8.3.1.3 liquid penetrant inspection

description

Liquid (or dye) penetrant inspection is a surface inspection method. Defects are detected through capillary accumulation of liquids in cracks. Therefore the crack must be open at the surface in order to be detectable, see also comments made in Section 8.3.1.1. A coloured or fluorescent liquid is applied to the surface and given time to penetrate any cracks. Then the surface is cleaned and a developer is applied which extracts some of the penetrant allowing visual detection of the cracks. Sometimes ultraviolet light is used to enhance detectability.

applications

It is used for the detection of surface cracks and is usually applied on austenitic steel, duplex steel, fully martensitic stainless steel, aluminium or other non-magnetisable construction materials.

inspection results

It is similar to visual inspection, in that only the defect dimensions on the object's surface can be measured such as the length of linear indications. Crack depth cannot be measured. A distinction can be made between linear and non-linear indications. If the surface is too heavily ground, when preparing it for inspection, material can be smeared over the defect causing its concealment. Note that this is generally not a major problem for MT.

8.3.1.4 radiography

description

The object is irradiated with X-rays or gamma-rays. The source is placed on one side of the object under inspection and the film on the other side. In this way, an image of the object is produced. A decrease of the irradiated thickness by the presence of a defect results in a higher density of radiation on the film directly underneath the defect. In this way weld defects, cracks, casting cavities and, to a certain extent, geometrical deviations may be detected. In principle, this technique is only suitable for detecting planar defects more or less aligned with the beam, when they can generate sufficient difference in the density of radiation on the film.

Radiography is one of the most commonly used methods for volumetric inspection. The energy of the source to be used depends on the thickness and type of material to be irradiated.

An increasing wall thickness results in a decreasing defect detectability. Also an appropriate choice of energy source and type of film greatly influences the detection of defects.

applications

It can be used to detect defects in the volume of specimen as well as surface breaking defects, in welds and castings. RT is well suited for detection of voluminous defects such as cavities and porosity, but also linear defects such as cracks, lack of fusion and incomplete penetration may be detected provided they are aligned with the beam of radiation.

inspection results

Radiography is not capable of measuring the through-thickness height of defects with any significant accuracy only the length of a defect can be measured. In addition, radiography is a very powerful tool because it enables the defect to be characterised. The two dimensional picture of the defect gives a direct idea of its shape enabling characterisation.

enhancement of RT

The following possibilities can be considered:

- The removal of weld reinforcement will improve the contrast when defects are encountered near or in a weld, thereby increasing the probability of detection;
- If RT is carried out at different angles there will be more chance of detecting and determining the length of a defect;
- The use of fine grained film will increase the probability of detection;
- Lower energy X-rays will have a higher resolution than the commonly prescribed high energy isotope sources;
- Image analysis of the film or video images will increase the probability of detection and improve the determination of length.

8.3.1.5 manual ultrasonic techniques using pulse echo signals

description

Ultrasonic pulse echo inspection relies on the reflection of ultrasonic waves by imperfections in the material under inspection, such as cavities, cracks and weld defects. Pulses of ultrasonic waves are generally emitted and received by piezoelectric probes. Ultrasonic waves can be transmitted perpendicularly into the material (normal incidence), enabling wall thickness measurement or detection of defects with their main dimensions parallel to the scanning surface, see Figure 25. Ultrasonic waves can also be introduced at an angle, using angle probes placed in the neighbourhood of the weld, to detect weld defects with other orientations e.g. weld defects along the fusion line, see Figure 26.

Pulse echo ultrasonic inspection is a relative method; i.e. results are always related to signals obtained in a known situation (i.e. comparison is made with the signals received from reference reflectors such as holes and notches, a known wall thickness etc.).

The success of the method depends on the probe being accurately placed to receive the mirror-like reflection from the defect. If the orientation of a planar defect is misjudged, then the defect will either not be detected or_misinterpreted due to a smaller reflecting signal. Tightly closed planar defects can also be missed when the sound is transmitted through the defect instead of being reflected. The reflections from non-planar defects are weaker than from planar defects but the chance of missing a non-planar defect is much smaller because of the greater chance of receiving a reflection despite a smaller signal. Thus optimised procedures are needed. This means the careful selection of probe angles to transmit and receive signals.

The emission of ultrasonic wave pulses by a set of probes with different incident angles will enable insonification (irradiation) of the region where defects are expected. To hit these defects perpendicularly, and to allow the receipt of the reflections from the expected defects, sufficient space on either side of a weld is required; see remarks in Section 8.2.3.

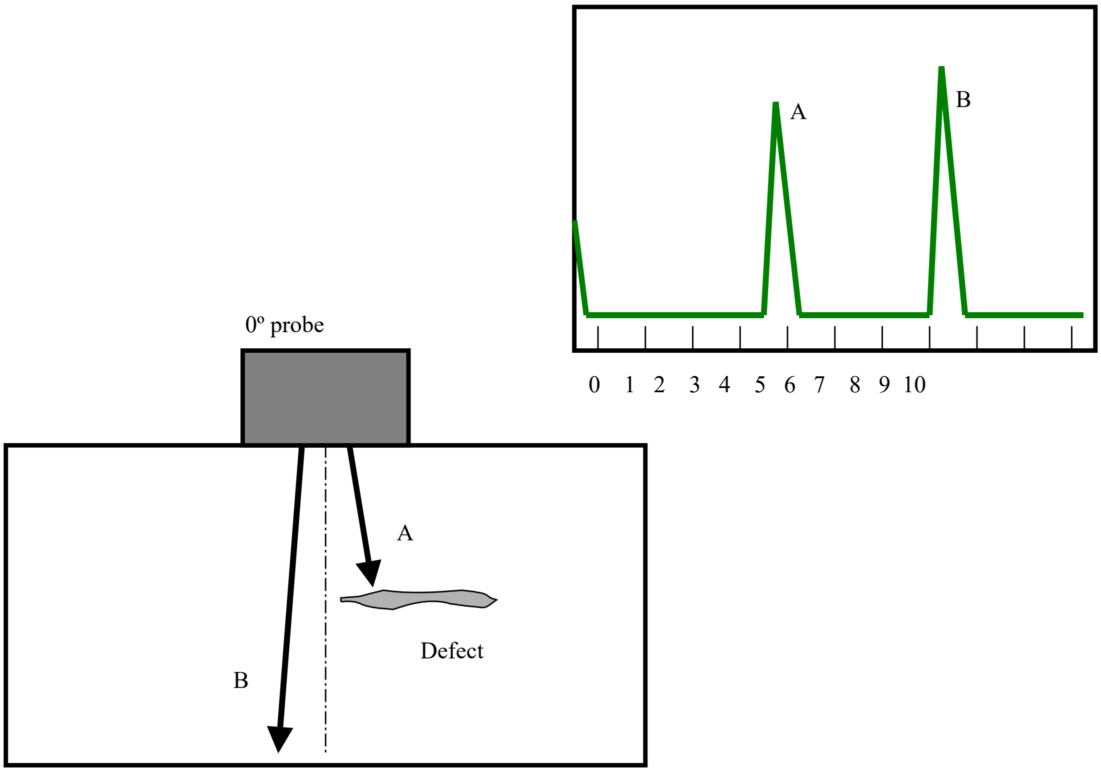


Figure 25 Normal incidence of ultrasonic waves

The portions A and B of the beam from the probe are reflected back to the probe. The peaks A and B give a schematic idea of the response as observed using an oscilloscope. The distance of the peaks from the origin represent for peak A, the depth of the defect and peak B, the thickness of the plate. If the reflector is not specular there will be many additional smaller peaks looking similar to noise caused by the scattered signal. In some cases this can significantly influence the interpretation.

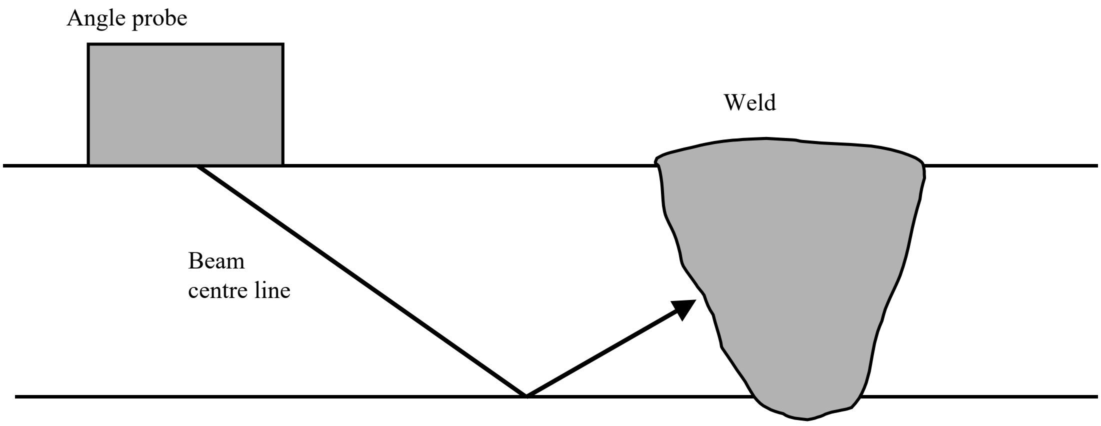


Figure 26 Angle probe for butt weld inspection

The location of the angle probe and selection of the angle of the probe is critical for the insonification (irradiation) of a defect in the fusion line between the weld and plate and its detection via the reflection of the ultrasonic beam. This means that a minimum distance, dependent on the plate thickness and the probe angle, will be needed between the probe and the weld fusion line for the beam to be reflected and detected at the optimal angles. The beam is not a line but will have a certain diameter depending on the type of probe chosen (e.g. 10 mm for non-focussed probes and 2 to 3 mm for focussed probes). The main reflection peak will be accompanied by a number of sub-peaks. In some cases this can hinder the interpretation.

Manual pulse echo ultrasonic inspection, together with radiography, is among the most commonly used methods for volumetric inspection (inspecting the whole volume of material). Normally ultrasonic frequencies between 1 and 10 MHz are used, except in some special applications where much higher frequencies are used to detect and size very small defects. Signals are displayed on an oscilloscope and interpreted directly from the screen.

applications

The main applications of manual ultrasonics are weld inspections and wall thickness measurement. UT is extensively used on steel constructions and piping, vessels, tanks and castings. It is applicable to most construction materials, although some materials may be difficult to inspect due to coarse grain structure or anisotropic behaviour, resulting in high "acoustical noise", damping and beam deflection (e.g. austenitic steel, brass and synthetic materials). Special probes in combination with validated special procedures can often provide a solution in these cases. Specialised UT techniques are available for the detection of surface defects such as small cracks.

inspection results

In an UT inspection any defects that are detected will appear as "peaks" on the screen, which are interpreted by the operator and correlated to possible defects or geometry. The position of the indication on the screen, together with known probe angle and probe position on the material under inspection, provide the operator with information on the location of the defect in the material. Signal amplitude gives a relative measure for defect severity in terms of code requirements, because it is related to the signal of a known reference reflector (e.g. a notch or hole in the material).

The signal amplitude does not supply explicit information about the true height of a defect because the signal amplitude depends on more parameters than defect size alone, such as surface condition, defect type, orientation relative to the ultrasonic incident beam etc.

Defect length can be estimated with a reasonable degree of accuracy from the loss of signal as the probe is moved along the length of a defect. The larger the ultrasonic beam diameter the greater the inaccuracy of the measurement of defect length. Also variation in orientation of the defect will lead to inaccuracy or misinterpretation of the defect length.

The appearance of the signal on the screen provides the operator with some information about the reflector. Correct interpretation of the signal to determine the defect type depends greatly on the experience and skill of the individual operator, as well as his knowledge, not only of the NDE technique, but also on the welding process, construction details etc.

When ultrasonic inspection is used for wall thickness measurement, wall thickness can be derived from the transit time for the ultrasound to travel to the opposite surface of the material under inspection and return to the probe, and the velocity of ultrasound in the material.

enhancement of UT

The following possibilities can be considered:

- removing or reducing surface roughness and/or the weld cap or root by grinding flush with the plate surface can enhance UT;
- mechanisation;
- for vertical defects the use of tandem techniques or TOFD. I.e. so that transmitting and receiver probes are moved in tandem;
- the use of specially built angled probes that are suited to a particular geometry will increase the POD and accuracy;
- rather than just looking at the signal amplitude and transit distance at a given probe position, it can help to record the behaviour of one of them or both during a dynamic scan. Such records are called echo envelope curves, and they can help to reduce the inherent limitations of UT to characterise defects. Another tool, offering more or less similar advantages, is the presentation of digitised C-scan images.
- multiple probes or phased arrays can be used to increase the number of angles at which pulses of ultrasound are transmitted into a body. Phased arrays are capable of dynamic swivelling and focusing of the ultrasonic beam. The number of directions that pulses are sent into an object will increase both POD. It goes without saying that specialised software is needed to analyse the received signals in these more complex arrangements. Note that phased arrays can be used for monitoring defects if the direction of defect growth is uncertain.
- focused probes are used to obtain tip reflections and can be used to increase sensitivity and accuracy, see the worked example in Section 13.7. In the hands of an expert NDT inspector this technique can lead to an accurate estimate of defect height or depth.
- for very thin materials, or in surface layers (up to 1 mm) high frequency probes can be used to detect very small defects such as the initiation of hydrogen cracking. Care should be taken however, because the high frequency probes will be sensitive to a variety of microstructural features which may result in false calls. In very special cases the high frequency probes can be used to detect coarse grained microstructures, which may be suspected as being brittle, see the worked example Section 13.5.

8.3.2 Non-routine NDT

This includes methods, which can provide quantitative information for FFP assessments.

8.3.2.1 mechanised ultrasonic technique using pulse-echo signals

description

The principal difference between manual and mechanised pulse-echo technique is that in mechanised pulse-echo UT both the probe position and the ultrasonic signals are continuously measured and recorded, so that the position of detected defects can be exactly reproduced. It is thus possible to generate images of indications (map, cross-sections etc.) as opposed to only a signal amplitude. Often more than one probe is used simultaneously, dividing the wall thickness in a number of zones, each inspected by a separate probe or a mechanised meandering movement is used by one probe to cover the inspection volume.

Various degrees of mechanisation may be used. In most cases the probe (or probes) is moved over the object by aid of a mechanical scanner, but sometimes the probe is manipulated manually (in which case additional equipment is needed to record probe position and orientation). Processing of the results may be accomplished in various ways, ranging from the numerical display of inspection results (for instance wall thickness readings) to the display of fully coherent colour-coded images. With appropriate computer algorithms it is sometimes possible to automate interpretation and let the equipment make decisions on acceptance or rejection, on the basis of pre-programmed criteria. In the latter case one speaks of automated ultrasonic inspection rather than mechanised.

applications

The range of applications is basically the same as for manual inspection. The reasons for preferring mechanised inspection above manual inspection are:

- the need for a permanent inspection record;
- the need for increased reliability;
- reproducibility (e.g. repetition of in-service inspection);
- inspection in inaccessible locations (radiation, narrow access, high temperature);
- inspection of many welds with the same geometry at high speed (cost-effective).

inspection results

Mechanised ultrasonic inspection can, offer more quantitative results than its manual counterpart, see Table 1 in Section 8.4. This is, on the one hand, due to the fact that it can produce coherent images, showing the amplitude and place of origin of the signals. On the other hand, mechanised ultrasonic inspection allows the possibility of using transducers with sharp focused beams, enabling the inspection of different zones in the material with dedicated transducers. Together with knowledge of the possible defect expected, and using interpretation skills, this can result (to a certain extent) in providing an estimate of the height of any defects present. The defect length can be readily measured as with manual pulse echo ultrasonics.

8.3.2.2 time of flight diffraction

description

The TOFD technique relies on the diffracted signals from the edges of defects rather than specular reflections, see Figure 27. Defects can be detected by transforming these signals into images of the defect, whereby the signal amplitude plays a secondary role. Through-thickness positions and height can be established by measuring the time of flight of the signals, by means of screen observation supported by dedicated software algorithms.

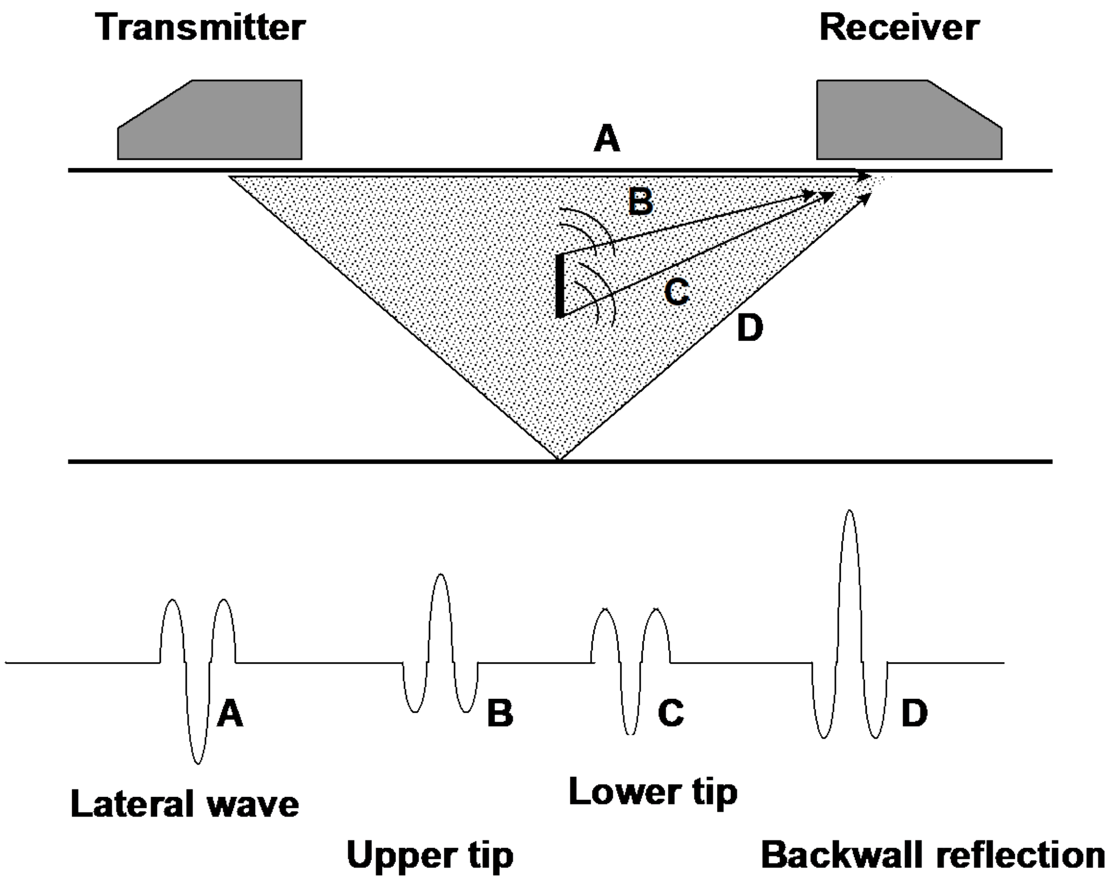


Figure 27 TOFD signals

A TOFD inspection is performed with the aid of two probes (transmitter and receiver) which are, in weld inspection, placed on either side of the weld or in another appropriate configuration if the geometry is more complicated. This probe pair is moved along the weld in a single direction. Signals are recorded by means of a computer and a coherent image is displayed on the computer screen, in gradations of a colour (usually grey) scale. From this image, the positions of defect extremities with respect to a reference (e.g. the object surface) may be determined. The chance of detecting a defect, whether it be planar or non-planar is relatively high (see Table 2 in Section 8.4) because a more diffuse diffracted wave is detected. Close to the scanning surface, the TOFD technique has an inherent “dead zone”. However, this dead zone can be minimised by using high-resolution probes and/or by specialised software algorithms. The extent of this dead zone may vary, dependent on the specific application, between a few tenths of a millimetre and some millimetres. In practical applications, a similar “dead zone” can also occur near the opposite surface, caused by geometry (e.g. hi-lo), causing small surface defects to be screened by the back wall reflection.

In practice this means, that sometimes TOFD must be supplemented by additional surface inspection techniques to obtain full coverage. TOFD is usually applied in a (semi-)mechanised way and provides a permanent record of all produced signals.

The use of a transmitter and a receiver probe for weld inspection means that a certain minimum distance on either side of the weld is needed. This is of the order of three times the plate thickness on either side of the weld. A working space of at least 150 mm is needed above the surface on which the probes are placed.

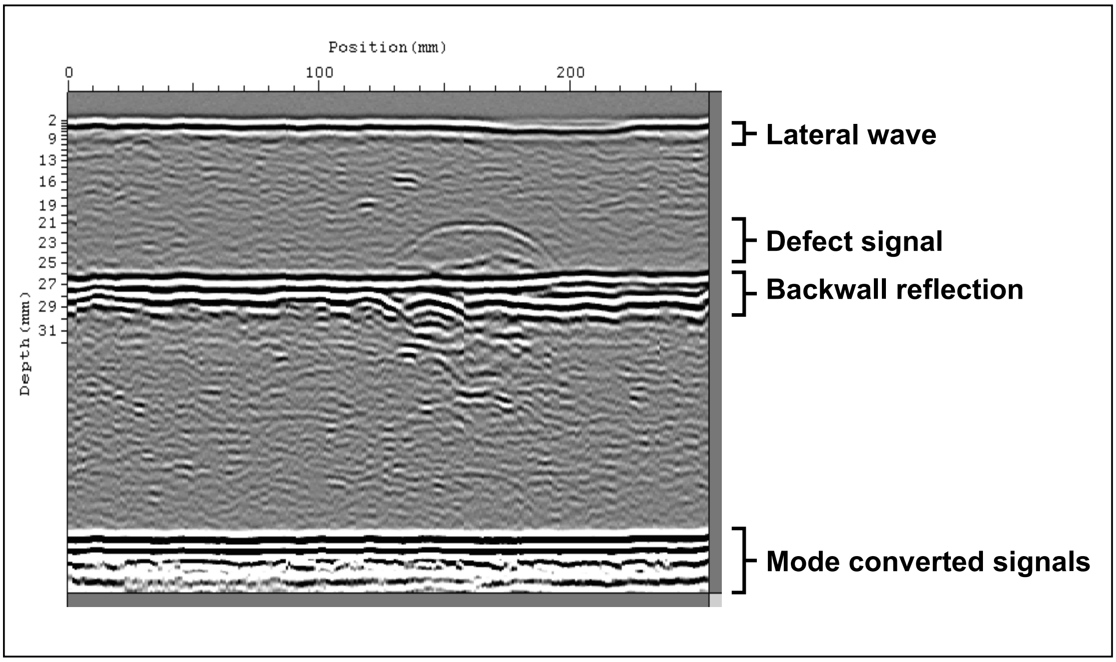


Figure 28 Typical TOFD image

Figure 28 is a typical TOFD image and can be interpreted as follows. The distance from the lateral wave to the semi-circular diffraction pattern of the defect signal represents the distance of the defect to the near surface where the probes are placed. This means that a part of the defect is coincident with the scale that gives 22 mm. Parts of the defect signal indicate that the defect crosses the back-wall reflection. This means that parts of the defect penetrate the wall thickness. The proper shape of the defect cannot be deduced from the figure because the figure represents the transit times of ultrasonic waves and not the physical size of defect. The latter may be obtained by using a transformation algorithm and is performed off-line because of the heavy demand on computing time.

There are in fact two back-wall echoes, namely, the echo of longitudinal waves and the back-wall reflection of transverse waves (mode-converted signals in Figure 27). The lateral wave travels along the surface and can be used to detect and size near surface defects.

Codes for the application of TOFD as well as acceptance criteria for weld defects already exist or are under development, Section 14.3.

applications

TOFD is applied for volumetric inspection, usually in cases where both detection and sizing is required. The same scan is used for both detection and sizing. Other methods usually require different techniques for detection and sizing giving TOFD a potential for being both time and cost efficient. In addition TOFD may be used to size defects initially detected by other techniques. A common application of TOFD is fingerprinting of newly built installations for future reference. The quantitative nature of the results makes the technique very suitable for use in fitness for purpose situations. The defect-sizing capabilities may be used as the basis for fracture mechanics calculations.

inspection results

TOFD inspection results appear in terms of defect position, length, and location in vertical direction and, if defect height is above a certain threshold, also defect height. The threshold for defect height sizing depends on the resolution with which signals from upper and lower tip can be separated, and depends on the ultrasonic frequency (selected on the basis of wall thickness and material properties) and equipment resolution. Typical values for minimum height that can be resolved are 1 to 3 mm.

enhancement of TOFD

The following possibilities can be considered:

- Increasing the frequency to obtain a higher resolution of defects can enhance TOFD. This is only possible if the material's structure is sufficiently fine and not anisotropic.
- Specialised software is needed to analyse the signals diffracted by defects near the surface; e.g. software features for linearisation, straightening, removal of the lateral wave, detection and sizing techniques, etc.
- Additional scans can help to better establish defect position and orientation. Normally only a scan is made along the weld (D-scan). To establish higher accuracy and probability of detection, scanning can be carried out across the weld, although this usually requires grinding the weld cap.
- Because of the flexibility of modern multi-channel computer-based systems for ultrasonic inspection, it may be an advantage to combine ultrasonic techniques such as pulse echo and TOFD inspection. In such a way, full advantage of the merits of both techniques can be taken in terms of defect detection and sizing. With one technique acting as a "safety net" for another, the reliability and quality of the inspection may, in some cases, be enhanced. See Section 8.5 and also worked example in Section 13.3.

8.3.2.3 magnetic flux leakage

description

The magnetic flux leakage or MFL method uses a strong magnetic field, which saturates the steel wall. Anomalies such as metal losses will locally force field lines to leave the material, thus causing flux leakage that can be detected by means of suitable sensors such as Hall sensors. This approach is suitable for wall thickness up to e.g. 12 mm. In practical applications an array of sensors is used, providing full coverage over an extended surface while scanning.

Since the flux leakage signals are, to a certain extent, dependent of the shape of the corroded spot, the amplitude of the signal does not have a defined relationship to the depth or severity of the corrosion. Although modern algorithms have significantly improved this, an accurate estimation of the remaining wall thickness cannot be given. Therefore these techniques are often used as screening techniques to define suspect areas for further inspection with e.g. ultrasonic wall thickness measurement.

Recently a low frequency eddy current technique was developed for the inspection of thicker walls, up to e.g. 35 mm. This also uses magnetic saturation of the steel wall.

applications

MFL techniques have been used in so called intelligent pigs for on-line inspection of long-distance pipelines, to detect corrosion. In more recent years, the technique is used for the detection of corrosion in flat plates such as storage tank floors, whereby magnet and sensors are integrated in dedicated motor-driven scanner that also houses the electronics. Also special (smaller) scanners for the inspection of pipes and vessel wall exist. Although some applications are known, the MFL method is less suitable for the detection of cracks. The low frequency eddy current variant however is suitable to detect cracking.

inspection results

In the simplest approach, the signals of the sensors can be used to trigger visual or audible alarms, warning the operator that a suspect area has been found. Signals can also be used to generate coherent pictures using a computer, whereby corrosion severity is indicated by colours.

enhancement

MFL can be applied using Superconducting Quantum Interference Devices (SQUID) as sensors, resulting in enhanced sensitivity and resolution.

8.3.2.4 long range ultrasonic testing methods

So called long range ultrasonic methods have been developed to detect corrosion pits in areas that are inaccessible for most techniques. Conventional ultrasonic methods for the inspection of large areas, such as vessels or long pipelines are generally time-consuming and costly. In addition, inaccessible regions such as pipe on supports or under clamps generally cannot be inspected unless the entire assembly is dismantled often involving expensive shutdowns and significant effort and cost. The long range methods can be used for the screening of pipe and plate including vessels, tanks etc. and are suitable for an inaccessible geometry such as inspection under clamps, saddles and pipe supports. They are not capable of indicating remaining wall thickness, but are able to indicate defect severity. If defect areas are found, they are inspected in more detail off-stream with quantitative methods for wall thickness measurement such as UT or MFL. This is also mentioned in Section 8.5 on the selection of combinations of methods.

Examples of these techniques are the LORUS method (Long Range UltraSonics), which is based upon the reflections of defects in fully insonified (irradiated) plates, and CHIME (Creeping Headwave Inspection MEthod). Both methods are used to detect defects rather than size them. They therefore require the additional use of a quantitative method to size the defects.

The LORUS method uses bulk waves, generated by an angle probe as shown left in Figure 29. The ultrasonic beam fills the steel component, is able to pass e.g. welded-on obstacles and is reflected by corroded areas. Signals are recorded in coherent colour-coded images indicating the location and extent of the damaged area. The typical range of LORUS is up to 1 metre. The example in the figure is the inspection of a storage tank bottom plate for corrosion. The LORUS probe is positioned on the tank bottom plate which extends beyond the tank wall. This enables the tank to be inspected without the need to empty the tank in the first instance. If significant corrosion is found the tank is emptied and the bottom cleaned so that a quantitative method can be used to measure the loss of wall thickness.

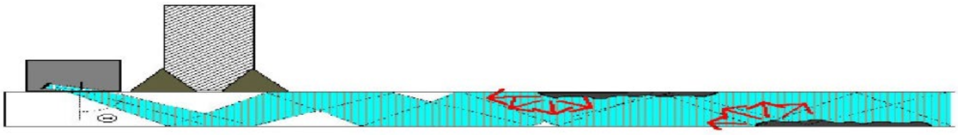


Figure 29 Long range ultrasonic method

Chime is a medium range ultrasonic screening technique which provides full volume coverage between the transmitting and receiving probes which can be separated by up to 1m. Figure 30 shows a sketch of the experimental set-up on a plate and the resulting A-scan signal from good material. Defects or corrosion between the two ultrasonic probes will affect the signal pattern enabling an indication of defect severity to be given.

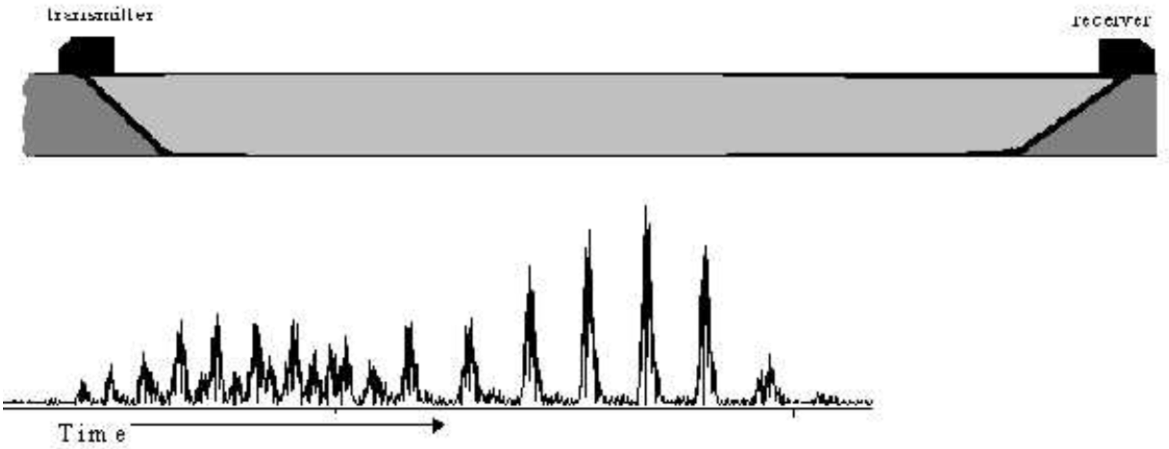


Figure 30 The CHIME technique

8.3.2.5 eddy current technique

description

In eddy current inspection a coil, in which a high radio frequency (RF) current is induced, is brought close to the object under inspection. The material of the object influences the electrical impedance of the coil. Defects are detectable through readily recognisable patterns in the changes of the impedance. Depending on defect type and position, also the phase of the signal is changed. By analysing the phase changes, the effects of lift-off, conductivity, permeability as well as defect type may be separated. Eddy current inspection on magnetisable materials is more difficult than on non-magnetisable materials, because of the reduced penetration depth of the current. Both procedures for application as well as acceptance criteria are laid down in codes and specifications.

applications

The main application is crack detection (at or near the surface) on carbon steel components. On non-magnetisable materials, the main applications are in the aircraft industry and in the inspection of heat exchangers, for corrosion and crack detection, thickness measurement, material characterisation, as well as conductivity and permeability measurements.

inspection results

When applied to detect cracks in carbon steels, the results are semi-quantitative rather than quantitative. Although specialised algorithms for crack depth sizing exist, the accuracy is limited. The results are much more accurate when used to detect corrosion and make wall thickness measurements. On non-magnetisable materials the results can be quantitative. In many cases, defect severity (crack depth, corrosion extent) can be readily measured.

8.3.2.6 pulsed eddy current technique

description

Pulses instead of a harmonic function excite the coil. The material response is measured with a receiver coil. Information on the material for a large range of wall thickness can be obtained by analysis of the response of the signal. As with other eddy current techniques the measurements are influenced by material properties such as conductivity and permeability. The reference measurement is carried out on a representative, undamaged part of the component.

application

Pulsed eddy current is applied for wall thickness measurements of mainly carbon steels and can be used without the need to remove insulation or coatings and when surfaces are rough. Maximum wall thickness is typically approximately 40 mm. Maximum lift-off (distance between the probe and the surface) or coating thickness can be in the order of up to 200 mm, e.g. the wall thickness of pipelines, of up to approximately 200 mm, tanks and vessels can be measured with high accuracy, with a significant lift-off. This enables detection of corrosion under insulation. The system can cope with steel and aluminium jackets that contain the insulation and may be used on-stream. It is not suitable for the detection of local (pitting) corrosion.

inspection results

Inspection results are presented in terms of an absolute value in mm or inches, or a percentage of nominal wall thickness. Procedures for the application and acceptance criteria are under development.

8.3.2.7 potential drop methods

description

DCPD (Direct Current Potential Drop) is a method for sizing of surface breaking defects. A direct current is applied across a surface breaking defect, by means of contact probes. This results in a potential drop. By comparing the potential drop across the defect with the potential drop on a defect-free area, a direct measure of the crack depth is obtained.

ACPD (Alternating Current Potential Drop) is similar to DCPD but in this case an alternating current is used. This method may be more accurate than DCPD, especially when the frequency of the source can be varied and modern electronics is used for analysis of the signal.

ACFM (Alternating Current Field Measurement) is similar to ACPD but in this case an alternating magnetic field is generated through eddy current coils. The probes are the sensors, which measure the magnetic field.

applications

These methods can be used for the sizing of surface breaking cracks, which have been previously detected by other techniques.

inspection results

The inspection result is presented in terms of a measured value for the defect depth. Defect length can be inferred from the measurement positions along the defect where no depth is recorded. Nevertheless, it is more usual to combine the method with a surface method, which is used for detection and the measurement of defect length.

8.4 Selection of NDE

When selecting a NDE method for an FFP analysis, a clear understanding of the principles of the method is essential. In other words when the physics of the method is understood then the shortcomings of the method will be appreciated, see Section 8.3. This will ensure that unrealistic FFP criteria are not set and that blind faith in the outcome of NDT is avoided. See also Section 8.2, which gives a number of the hindrances, that can affect the performance of NDT.

A rough guide to help the selection of routine and some non-routine methods is given in Table 2 on the performance of NDT. The latter represents the consensus of experts in the Netherlands on the state of the art performance of NDT that was reached several years ago, see Section 14.3. A revision of the table can be expected in a future version of the Guidelines. In the meantime, there has been significant technological development in NDE and the FFP analyst should consult NDE experts for the current state of the art performance of NDT if more accurate data are required. The range of POD and mean accuracy for a technique given in the table is in some cases large. The values given can be improved when combinations of methods are used or NDE specialists enhance the methods. The values at the upper end of the ranges quoted will tend to apply to the detection of larger and or more favourable defect types (e.g. planar versus non planar) and location within the wall (e.g. near surface, far surface and embedded).

Note that Table 2 has been slightly modified in order to simplify the table. All NDT methods to different degrees, signal defects which are not real defects. Such signals are known as “false calls”. Generally, the more sensitive the technique or procedure used, the greater the chance of a false call. Nevertheless, if a NDT method signals defects that are not present, then repair or an FFP assessment may be carried out unnecessarily with possible significant impact on the decision to continue operations.

Table 2 Performance of NDT methods used in accordance with existing codes, standards and guidelines

feature		visual inspection	radiography	manual pulse-echo	mechanised UT		MT	PT	ACPD/ DCPD/ ACFM	wall thickness measurement / corrosion detection		
					pulse-echo	TOFD				UT	pulsed eddy current	MFL
defect detection (POD %)		20	45-95	50	65-80	60-85	80	60	n.a.	n.a.	n.a.	n.a.
false call rate in detection (FCR %)		50	10-15	25	10-30	0-20	20	25	n.a.	n.a.	n.a.	n.a.
defect sizing error (mean error) [mm]	length	±5	±6	±10	±5	±5	±3	±3	n.a.	n.a.	n.a.	n.a.
	height	n.a.	n.a.	n.a.	±1	±1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	thickness	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	±0,2#	±0,5	±1
remaining ligament (mean error)	near surface side	n.a.	n.a.	±4	±4	±3	±2 *)	n.a.	n.a.	n.a.	n.a.	n.a.
	far surface side	n.a.	n.a.	±8	±4	±4	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
defect interaction (mean error) [mm]	in length	±5	±10	±5	±2	±2	±3	±3	±5	±3	n.a.	±5
	in depth	n.a.	wt/3	wt/4	±1	±1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	out of plane	±1	±1	±5	±2	n.a. **)	±2	±3	n.a.	n.a.	n.a.	n.a.
correct defect characterisation (%)	planar / non planar	75 / 75 [3]	70-80 / 80-90	70 / 65	25-60 / 15-90	n.a.	75 / 75	75 / 75	n.a.	n.a.	n.a.	n.a.
	defect type classification	80 ***)	75	35%	n.a.	n.a.	80 ***)	80 ***)	n.a.	n.a.	n.a.	n.a.

legend, see next page

legend at Table 2

*) valid if MT is used as an additional method, and the defect has already been detected with another method

**) valid if TOFD is used in the standard scanning mode

***) surface defects only

assumes reference surface is smooth; i.e. unaffected by corrosion pitting or other features which disturb the surface such as an irregular weld profile.

defect type, classification = ability to distinguish between e.g. cracks, lack of fusion, slag etc.

wt	=	wall thickness
DCPD	=	direct current potential drop measurements
UT	=	ultrasonic testing
ACFM	=	alternating current field measurements
MT	=	magnetic particle inspection (MPI)
ACPD	=	alternating current potential drop measurements
PT	=	liquid penetration testing
MFL	=	magnetic flux leakage

notes on Table 2

- This table is a simplified version of, and based upon Table II NDT Performance Overview, Part II: Quantitative, Doc. FF 97 – 58
- The values only apply to the NDE methods being applied according to existing codes and standards
- Values for false call rate represent the number of false alarms divided by the number of false alarms plus correctly reported defects.
- The POD values are for defects with a range of heights or depths between 6 to 15mm.
- The range of POD for RT is low for planar defects and high for non-planar defects.
- The range of POD for Pulse-echo is low non-planar surface defects and high for embedded planar defects.
- The range of POD for TOFD is low for surface planar defects and high for embedded planar defects.

The range of POD and mean accuracy for the techniques in the table are in some cases large. The values given can be improved when combinations of methods are used or NDE specialists enhance the methods. The values at the upper end of the ranges quoted will tend to apply to the detection of larger defects. (See also footnote in Section 8.4.2 on larger defects)

A possible strategy is the selection of a NDE approach that gives an acceptable overall safety margin or probability of failure. The latter is a function of the risk of failure that is acceptable. This may in some cases lead to the choice of NDT techniques that have a relatively low but acceptable POD. An alternative strategy, when uncertain about the outcome of the overall analysis, is to choose a NDE approach that results in a high (say 90 to 95%) probability of detection.

In order to achieve a high probability of detection, one can use two approaches.

1 A defect size can be chosen that is large enough to be detected with a 90 to 95% certainty. In table 2, a rough idea of the size of defect needed to achieve a 90 to 95% POD under favourable conditions is given. On the other hand, if the NDE is performed under adverse conditions, the POD and accuracy will be reduced.

2 Combinations of NDE methods, where the POD will be higher than for a single method alone. This is explained in Section 8.5;see the bar charts in Figures 31 to 33 of POD performance for different combinations of methods. Note that combinations of methods often occur when quantitative NDE for an FFP assessment is carried out after routine NDE for establishing GWMS.

The selection will depend on the inspectability (see Section 8.2). In particular, the selection will depend on accessibility, the conditions under which NDE is carried out, the type of material being investigated, the stage at which NDE is used (e.g. Fabrication or Service (e.g. the type of failure mode being considered)), the purpose of the NDE (e.g. detection, sizing and the determination of position and orientation), and the performance required (speed, extent of application NDE and probability of detection and accuracy of sizing). In the end more than one NDE technique or procedure may be required in order to fulfil the different requirements, since no single technique gives the complete information listed previously in Section 8.2.

8.4.1 Stage of application

NDT during the fabrication stage is aimed at detecting and sizing defects using routine methods unless unacceptable defects are found. The main emphasis is on maintaining quality. If defect growth is expected in service then NDT methods, which give continuity of measurement into the service stage, are to be preferred. The NDT during fabrication then provides a baseline for monitoring for defect growth in service. In service methods used must give reproducible results that make it possible to monitor defect growth either periodically or on-line. This means (semi-) mechanised measurements are preferable. Note that inconsistent application of NDT methods and procedures and the variable performance (especially for techniques such as manual UT) of different operators from one inspection to the next can cause large increases the errors. This may result in interpretations of significant defect growth when there is no growth and in other cases impossible defect shrinkage.

8.4.2 Probability of detection

Typical ranges of POD values given in Table 2. Some of the ranges are large and in some cases are relatively poor. The ranges are related to the physics of the NDT methods and the different physical conditions under which inspection is carried out; e.g. the ranges are a function of inspectability including defect size. In many cases, procedures can be significantly improved; e.g. in radiography one can adapt the beam direction to the weld bevel angle, and in ultrasonic inspection one can adapt probe angles and characteristics to the weld bevel shape and defect size. In such cases, the improvement of the POD resulting from such measures should be validated on real defects.

POD will increase with increasing defect size. An idea of the depth of defect needed to achieve a POD of about 90% is given in the following Table 3 for three different methods and thickness. Also the effect planar versus non-planar defects on POD is given.

Table 3 A rough idea of the defect depths that are needed to achieve about 90% probability of detection under relatively favourable inspection conditions using different NDE techniques.

NDE method	thickness [mm]	minimum planar depth or height of a defect in mm for a POD of 90% to be achieved.		minimum non-planar depth or height of defect in mm for a POD of 90% to be achieved.	
		surface	embedded	surface	embedded
TOFD	7	5	6	5	6
radiography	7	unachievable	unachievable	2	2
manual UT	7	unachievable	unachievable	unachievable	unachievable
TOFD	27	4	6	4	6
radiography	27	unachievable	unachievable	4	4
manual UT	27	15	15	>15	>15
TOFD	150	3	4	3	4
radiography	150	unachievable	unachievable	8	10
manual UT	150	>15	>15	>15	>15

The results in the table were derived from graphs of Liefting, see Section 14.3. The results are slightly different from some of the upper bound figures in Table 2. It is advisable to use the results in Table 2 in the first instance or Figures 31 to 33 for combined NDE techniques when judging the appropriateness of different methods. The results in the tables are indicative and advice should be sought from a NDE expert on the POD for a specific situation. The PODs in the various tables and figures only relate to the depth. In reality, the POD is a function of the area of the defect (i.e. also the length). It is therefore reasonable to assume that the depths implicitly refer to the length of a defect in that deeper defects will generally have relatively longer lengths than shallow defects. Table 3 is intended to show that most techniques can achieve a high POD if the method used is suitable, the conditions are favourable and the defect size is sufficiently large; i.e. the PODs in Table 3 are the PODs at the upper end of the ranges given in Table 2. It also shows the difficulty some techniques have with planar defects as opposed to non-planar defects. Radiography performs well, according to the table, in detecting non-planar defects giving an idea of general weld quality but could miss a large number of planar defects. Note, that planar defects present a higher risk to the integrity than a non-planar defect of the same size. Manual ultrasonic inspection clearly needs large defects to achieve a high POD[9]. Lastly, an idea of the way thin and thick walls reduce the POD of NDT methods is given.

The POD may be more significant than the accuracy of sizing of NDT for an FFP assessment. For example, it is illogical to measure a defect very accurately if there is a relatively high probability of missing larger defects. For this reason 12.5 mm deep defects were assumed in the early days of defect assessments when selecting a weldment, which

[9] There are cases when a large defect may have a lower POD than a smaller defect. In the case of MUT, if the ultrasonic beam does not have perpendicular incidence on a planar defect, a large diameter defect is easier missed than a small one. This is because a large defect reflects a narrower reflected beam that a small defect would do (large defects act as mirrors, small defects reflect energy over a wider angle).
This effect has nothing to do with the beam diameter generated by the probe. It can often be cured by using a lower frequency (e.g. 2 MHz rather than 4 MHz), because a lower frequency causes more beam spread of both the transmitted and reflected beam.

would have sufficient resistance to brittle fracture for an offshore structure. These defects were assumed to be the largest defects missed by NDT.

The investigation of a large amount of material generally requires a fast method that has a higher POD and possibly a lower accuracy. There is always the opportunity to check a selection of the defects found with a more accurate method later.

Highly sensitive NDT methods have a higher POD but with the exception of perhaps TOFD, have in general a tendency to detect defects which are not present (false calls). This can be compensated to some extent by raising the threshold below which defects are not reported.

Note it is sensible to store NDT information on indications of defects, which are below the threshold for the reporting of defects. The storage of information on defects below the threshold for reporting is not normally done unless specified. The TOFD technique has been developed so that **all** indications are automatically recorded on disk or CD-ROM and therefore retrievable. The sub-threshold defects can become important in later assessments because they give information about extent of defects (defects per metre of weld length (defect populations), helping probabilistic calculations and the possible nature and cause of defects. The information will be needed in the event of a defect growing from an initial defect below the threshold.

8.4.3 Sizing

More accurate methods are needed than those used for detection. These may be much slower, but since a smaller number of defects will need accurate sizing, this should not be a problem. The non-routine methods or combinations of methods can increase the accuracy significantly.

The TOFD technique combines detection with a high POD with high accuracy and allows the NDE to be carried out in a single operation.

8.4.4 Orientation and position

The orientation and position are needed for an accurate FFP assessment. For most fracture and fatigue situations, where crack growth occurs in a plane perpendicular to the maximum principal stresses, defects which are not perpendicular to the stress direction have to be projected onto a perpendicular plane before an FFP analysis can be carried out. The position relative to peak stresses near a stress concentration and the distances of the defect edges from other defects and from the free surfaces have to be known. In some cases the orientation can be estimated from a knowledge of the angle of preparation weld bevel, if the defect can be confirmed as lying along the fusion line. The orientation of an active defect can give the FFP analyst information on the directions of the stresses acting on the defect. Usually, with increased effort, it is possible to assess the orientation and position of defects more accurately by, for example, utilising a fully mechanised meander-scanning UT method or TOFD in more directions and/or focussed probes.

8.4.5 Thickness

Both thin and thick walls provide problems for certain methods. See Table 2 for an idea of the effect of thickness. Radiographic techniques for example, become increasingly impractical for very thick walls. The radiation dose will increase, increasing exposure times and the costs, decreasing the sensitivity and increasing the potential health hazard.

Ultrasonic techniques become less accurate and POD decreases for thin walls (see Table 3) which shows only larger defects will be detected with a high probability for a 7 mm thick plate). Below 10 mm thickness the beam width of a standard UT probe becomes a substantial part of the wall thickness, causing geometrical signals to be confused with defect signals. The “dead zone”, just below the surface where no defects are detected, for TOFD will become an increasingly larger part of the wall as thickness decreases.

For all volumetric NDT techniques, the amount of material to be inspected increases as thickness increases, which affects costs significantly at large thickness, although the effect may differ from one technique to another

8.4.6 Defect interactions

Clearly discrimination between interacting and non-interacting defects can require a fairly high degree of accuracy. The re-categorisation of an embedded defect as a surface defect will have a detrimental effect on the result of a defect assessment.

Also an embedded defect, in the weld bead immediately below the weld bead at the surface, will probably because of the limited accuracy of some NDE methods, be declared a surface defect. For example, a defect that is closer to the surface than one fifth of the wall thickness should be assumed to be a surface defect according to the API 579 approach. There is a more complicated procedure for deciding on the re-categorisation of an embedded defect in BS 7910 (see Section 14.2). The re-categorisation will result in a surface defect depth equal to the height of the actual embedded defect and the depth of the material between the embedded defect and the surface (remaining ligament).

8.5 Selections of combination of methods

Combinations of two or three techniques can be selected to compensate for the weaknesses inherent in most techniques and thereby improve the overall performance. Note that techniques often become combined when going from a routine inspection for establishing good workmanship to a quantitative technique for use in an FFP assessment. Combinations can also be created when using a technique, which is suitable for detection with a method for measurement of defect size.

8.5.1 TOFD or UT in combination with RT

TOFD when used in combination with RT will result in an improved assessment of the defect. TOFD is capable of positioning and sizing defects in the through-thickness dimension, but will have difficulty in assessing the nature of a defect, i.e. distinguish between planar and non-planar defects. RT on the other hand will provide better information on the shape of the defect and the position relative to the weld cap, helping the assessment of the type of defect. Similar enhancement can be obtained when combining pulse echo UT with RT.

8.5.2 TOFD in combination with mechanised pulse-echo UT

Both techniques can be used to achieve a relatively high rate of NDE, with high POD. Their combination will result in a higher POD than that achieved by each of the techniques separately. The overall false call rate can be lower, because of the possibility of mutual confirmation of signals detected. Pulse-echo UT is more sensitive for the detection of small root defects on the opposite surface to the probe. Mechanised pulse-echo UT can also provide a more accurate measurement of length, as generally probes are used with smaller beam spreads. Mechanised systems that use a combination of TOFD and mechanised pulsed-echo

UT have been demonstrated and validated extensively. The worked example Section 13.3 makes use of a combination of TOFD and mechanised pulsed-echo UT.

8.5.3 TOFD and UT in combination with MT

When MT is used with very strong magnetic DC fields on ground welds flush with the plate surface, defects of up to 2 or 3 mm below the surface can be detected. This method therefore compliments UT and TOFD by providing information on the presence of defects and their length in the dead zone.

8.5.4 TOFD and UT with PD techniques

The PD methods will provide the information on the depth of all surface-breaking defects including those with tips in the dead zone of TOFD and UT.

8.5.5 Visual inspection, MT and PT in combination with volumetric inspection techniques

Visual inspection, MT and PT will all provide information on the presence of surface breaking defects, defect length and the nature of the surface breaking defects. This is complimentary to information using volumetric methods (e.g. UT or RT). MT and PT are used particularly for detecting fatigue, stress corrosion cracking and creep cracks, all of which have different responses to the surface inspection methods. In addition they are readily applicable close to stress concentrations.

8.5.6 MT in combination with UT to detect HIC and associated stepwise cracking

Small laminar cracks can often be tolerated. The integrity may be impaired when the stepwise cracking develops or very large laminar cracks develop. MT is used to detect the surface breaking stepwise cracking that often extends from a laminar crack to the surface, a 0° probe emitting ultrasonic compression waves is used to detect the laminar hydrogen induced crack and angle probes to detect stepwise cracking that is not yet surface breaking.

8.5.7 On-stream long range UT in combination with off-stream quantitative NDE methods

So called long range ultrasonic methods have been developed to detect corrosion pits in areas that are inaccessible for most techniques. The techniques are screening techniques used to inspect for wall loss by corrosion in inaccessible regions; e.g. such as pipe on supports or underneath pipe clamps and on-stream inspection of the bottom of a storage tank from outside the tank. They are not capable of indicating remaining wall thickness, but are able to indicate defect severity. If defect areas are found, they are inspected in more detail off-stream with quantitative methods for wall thickness measurement such as UT. The long range ultrasonic methods are discussed in more detail in Section 8.3.2.4 on the selection of combinations of methods.

8.5.8 The effect on POD when combinations of methods are used

As stated in Section 8.4.2, one of the ways to achieve a high POD, e.g. 95% POD, is to combine NDE methods. An impression of POD values achievable when NDE methods are combined have been calculated and presented in bar charts, see Figures 31 to 33. The calculated POD values for the different combinations of NDE methods are based on a number of assumptions; e.g. the POD values in Table 1 and the assumed defect distributions (near surface, far surface, embedded). *The bar charts do not give absolute values of POD, but give the trend in improvement of POD when NDE methods are combined.* Only NDE methods have been chosen that are able to detect defects in the entire weld volume. The following abbreviations have been used in the figures:

MUT : manual ultrasonics
AUT : automated ultrasonics
TOFD : time of flight diffraction
RT : radiography

Surface and embedded defect types have been considered and wall thickness ranges of 6 to 15 mm, 15 to 40 and 40 to 100 mm (plus average values). The following remarks apply:

- In the wall thickness range of 6 to 15 mm as well as 15 to 40 mm, the radiographic technique has been assumed to be X-ray. This is the technique that most codes require for this range.
- In the wall thickness range between 40 and 100 mm, the radiographic technique has been assumed to be gamma ray.

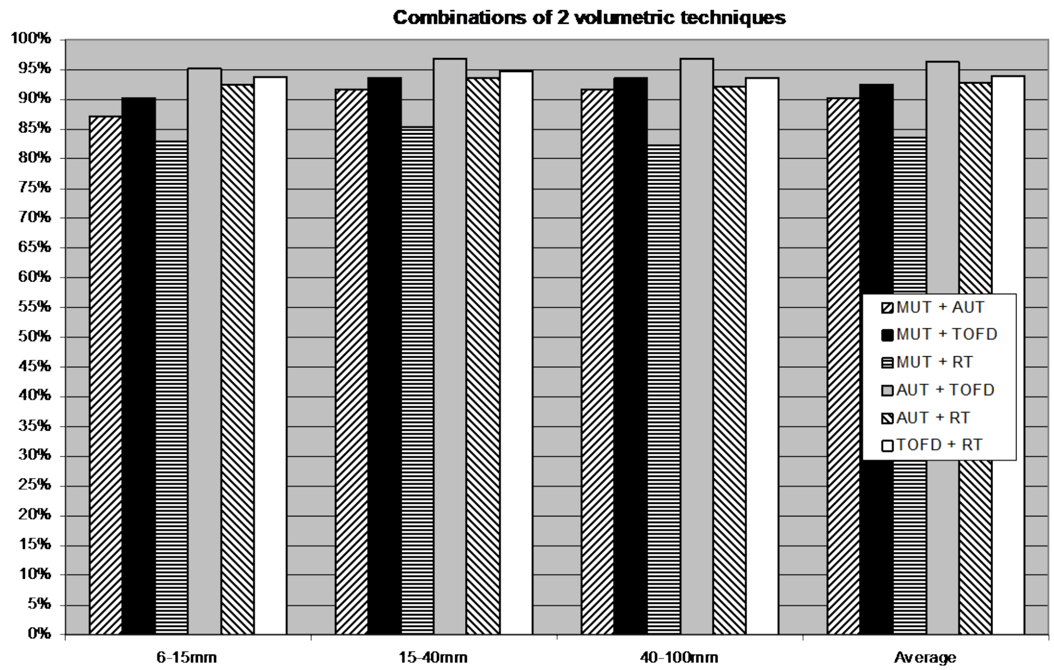


Figure 31 Combinations of 2 volumetric techniques at various thicknessess

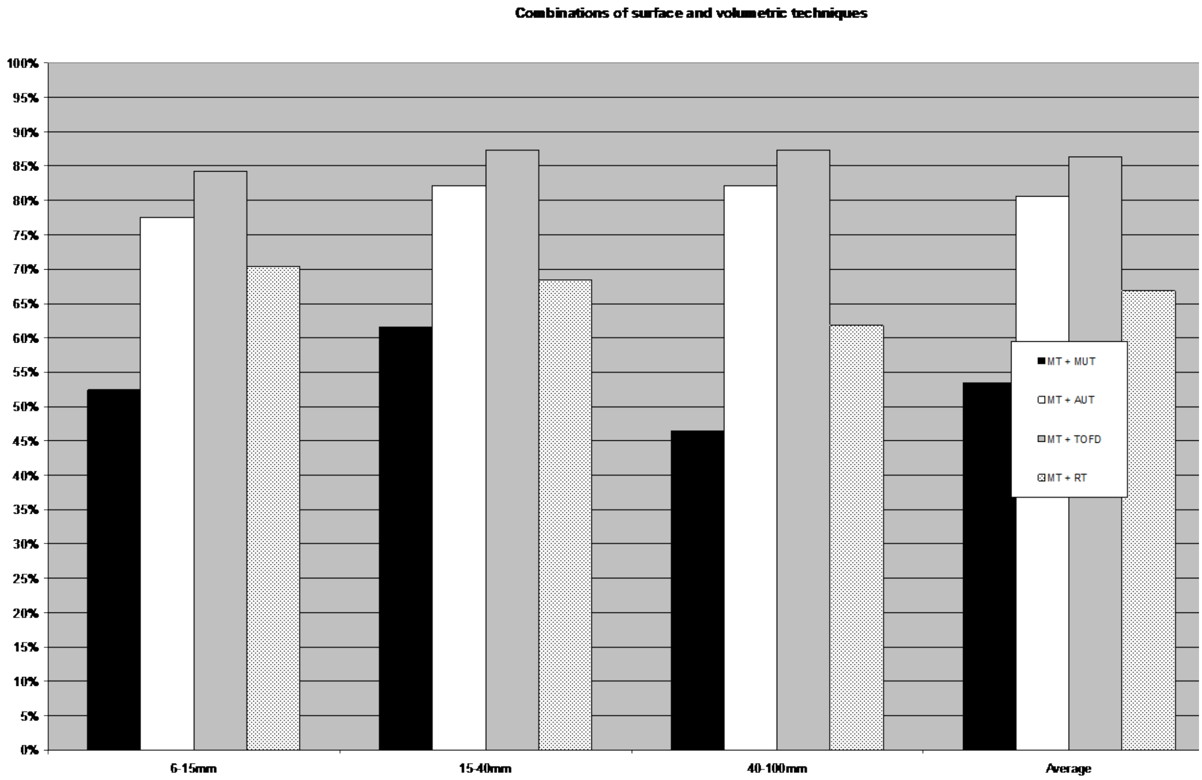


Figure 32 Effect of combinations of a surface and a volume technique on the POD

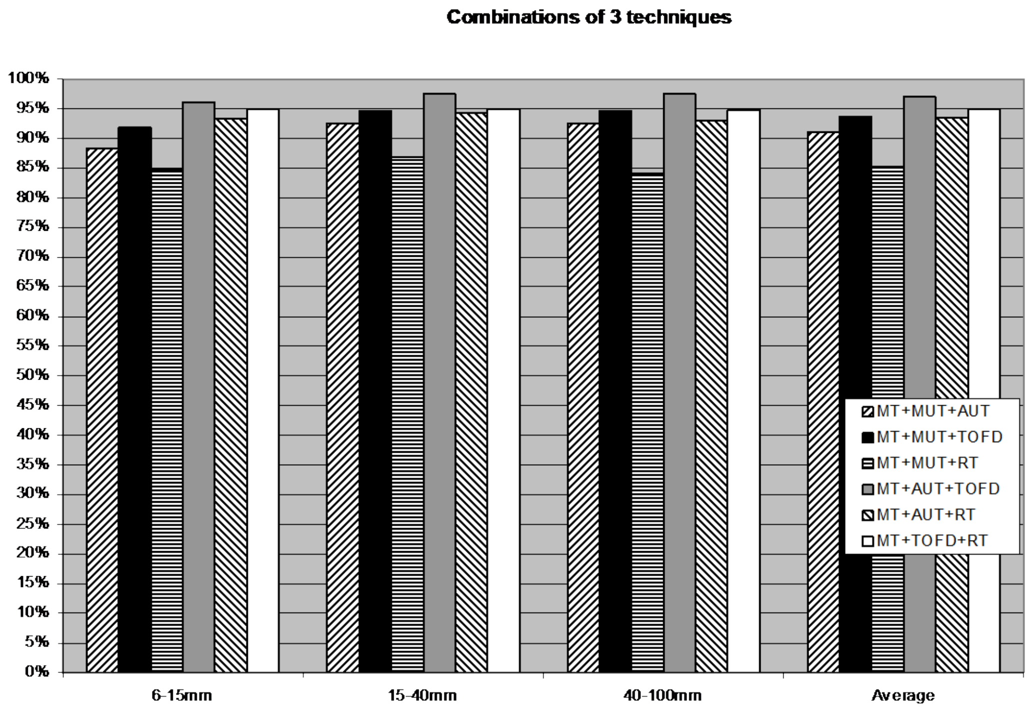


Figure 33 Effect of the combination of three methods on the POD (surface and volume methods)

9 Failure Investigation

9.1 Introduction

Before rushing to remove defects by grinding or other forms of repair, the need for a failure investigation should be considered, see also Section 8.2.8. Apart from revealing much information about the cause and conditions of a failure, an investigation provides important information on whether a defect is static or a growing defect. Removal of material for failure investigation and its conservation should be carried out under the guidance of a failure analysis expert. In some cases it is unnecessary to remove large amounts of material. There are special techniques for the removal of very small samples (often called boat samples). In addition it is also possible to carry out a certain amount of a failure investigation on the actual equipment on site using portable failure analysis equipment.

FFP procedures can be used to help diagnose the cause of failure and to predict the conditions under which failure occurred. This type of analysis is different from the normal FFP analysis where the intention is to prevent failure. In order to ensure fracture control, the normal FFP analyses have to be safe and have to varying degrees, implicit undefined safety factors. When predicting failure, the safety factors must be removed as far as possible and in the first instance the use of lower bound input data in the FFP analysis should be avoided. The defect size is not usually a problem because this can normally be measured on the fracture surfaces provided there has been no destruction of features that provide important clues to the failure.

Metallurgical investigations of the complete failure can reveal much information about the causes, mode of failure, the extent of damage, defects, degradation and defect growth, although the complete range of techniques are not all ways needed because often only a simple confirmation of a straightforward failure mechanism is required.

Note that the results of a failure investigation depend upon carefully planning the investigation and following procedures because there is normally only one opportunity to investigate a unique feature. Intense heat, mechanical deformation, corrosion or mechanical damage to the sample during the removal, transportation and preparation of the sample for investigation may result in the loss of vital evidence. Also a hurried choice of a quick limited investigation, resulting in irreversible changes to the sample, may prevent further more sophisticated investigations that may subsequently be necessary.

The features of the failure, which may be clear for a single mechanism may be ambiguous when the failure mechanism is complex with competing or synergistic mechanisms. The application of fracture mechanics may help resolve such problems. Certain failure mechanisms may be excluded or confirmed when fracture mechanics is used in conjunction with a failure investigation. In addition the fracture mechanics analysis can be used to calculate the failure conditions.

The success of a failure analysis will depend on the use of sound properly defined procedures to remove and conserve samples from the failure. This will need high priority and consideration before the start of any failure investigation.

See Section 14.16 for a failure atlas describing different failure modes under different exposure conditions and for different equipment.

The metallurgical studies comprise typically of the aspects given in the next sections.

9.2 Chemical analysis

Chemical analysis of the material is needed to compare the actual chemical composition with the specified composition. Deviations from specifications may give a clue to potential weldability, corrosion, fracture and strength problems. It is possible with specialised techniques (e.g. electron microscope, Auger techniques etc.) to determine changes in chemical composition locally at grain boundaries for instance or on a fracture surface.

Chemical analysis of the corrosion products on the surface, on the fracture surface, or at the crack tip is needed to determine the corrosive species which may be causing cracking or loss of wall thickness.

9.3 Microstructural investigation

Investigation of the microstructure and form of the cracking on cross-sections taken through the failure area, point of initiation and other relevant areas will give the type of cracking (e.g. fatigue, stress corrosion cracking, brittle fracture and creep), the origin of the failure (e.g. whether it started from a fabrication defect or not) and whether the microstructure has contributed to the failure (e.g. microstructures favourable for stress corrosion cracking or brittle fracture). Microscopic studies of cross-sections can also be used to study the build up of surface layers of different corrosion products in conjunction with the previously mentioned chemical analyses. The investigations are usually carried out with microscopes but in some special circumstances electron microscopes are used to observe the sub-microstructures to obtain additional clues. Bands of plastic deformation can be seen using a microscope. Less severe plastic deformation and very localised plastic deformation (e.g. at a crack tip) is best investigated by observing the sub-microstructure with an electron microscope.

Microstructural investigations can also provide additional quantitative information. E.g. the microstructures can in some cases record mis-operations such as a temperature excursion by registering a change in microstructure. Knowledge of the temperature, at which the change in microstructure takes place, can give an idea of the temperature reached. Fracture surfaces can in certain circumstances reveal the rate or periods of fatigue crack propagation. The periods of crack propagation can be related to plant operations such as start ups and shutdowns or periods of resonance. The rate of crack growth can be determined for a limited range of crack growth using an electron microscope if the cyclic loading is not irregular in amplitude. The crack tip opening displacement can be measured from the fracture surface using an electron microscope. This is type of measurement is used in some fracture mechanics testing procedures to measure CTOD.

9.4 Fractograhpy

Fracture surfaces, which are relatively rough when compared to a polished sample normally, used for microscopy can be studied using microscopes with a relatively large depth of focus, e.g. low power binocular microscopes and scanning electron microscopes at low magnification. Features on the fracture surface can give the direction of fracture. Tracing back from directional features can give the origin of fracture. The features may also give clues to the cracking mechanisms.

9.5 Mechanical testing

The results of tests to measure hardness, mechanical and fracture properties can be compared with specified values and used as input data for a fracture analysis to determine the conditions of failure. Hardness testing can also indicate areas of severe plastic deformation or whether softening has occurred from exposure to too high temperatures. Micro-hardness testing is used in conjunction with (macro-) hardness testing to investigate the presence of hard or soft grains within a heterogeneous microstructure. Hardness testing can also be used to obtain a idea of the tensile properties when a correlation with the tensile properties is used. In some cases, the corrosive medium experienced or rate of loading in service can be simulated in tests in order to measure the effect on fracture and other properties. In special cases, component tests may be used to verify the failure hypothesis.

Part III – FFP Checklists and Worked Examples

Three possible checklists the *Information Checklist*, *FFP Analysis Checklist*, *Mitigation Checklist* are presented in Part III. For the sake of completeness, the checklists contain a certain amount of overlap. It is impossible to cover every possible situation in the checklists and analysts may prefer to distil their own checklist from the ideas presented. The remainder of Part III contains worked examples and a reference section.

10 Information Checklist

10.1 Introduction

The information checklist contains items that only concern information and data needed by an analyst at the start of an assessment. Use of this checklist may shorten the time required to formulate a list of questions when starting up an FFP assessment. The list of questions could be sent to different participants in the FFP process. The overall list of questions could be split up so that the different participants only receive relevant questions. In some cases it may be sensible to send a participant the complete list because individual participants may have more information than the analyst realises. If a complete list of questions is sent, then guidance should be given on the questions where an answer is expected. This will avoid unnecessary, costly searches for information that is more easily retrievable elsewhere. It is often sensible to acquire information in two phases. In the first phase the objective is to find out quickly if someone has the information, in which case a yes or no is all that is required to many of the questions. In the second phase the analyst may then request more detailed information on the most relevant aspects depending on the sort of analysis required and possibly the outcome of some screening analyses.

10.2 List of items in the checklist

The following list gives an overview of the Information Checklist, which is explained in more detail in the section after the list.

item	subject
1	general
1.1	structure/equipment identification
1.2	design code
1.3	environment
1.4	material
1.5	dimensions
1.6	post weld heat treatment
2	loading conditions
2.1	design conditions
2.2	operating conditions
2.3	design stress analysis
2.4	define stresses
3	material properties
4	flaw data and NDE aspects
4.1	flaw type and cause of flaw
4.2	flaw location
4.3	flaw size, and orientation
4.4	basis for flaw data
4.5	defect interaction:
5	destructive investigation
6	in situ (on site) investigations
7	any other relevant observations or data

10.3 Explanation of the checklist

item 1 general

Define:
- the nature of the problem
- the consequences of failure
- the redundancy in the structure
- the urgency required

commentary

The nature of the problem should include the definition of the boundaries of the problem, recent changes to design, fabrication, and operations and theories about the possible cause of the problem. The consequences of failure could be:
- potential risk to human life;
- pollution;
- financial consequences from loss of production, loss of asset(s) and third party infrastructure, loss of customer and claims.

item 1.1 structure/equipment identification
- Supply drawings or diagrams of details where the assessment is required and the relationship of the problem area to the rest of the construction.
- Is the design of this equipment unique (new), e.g. new concept, new material, new fabrication method, new installation method, new operating conditions including environment?
- Have repairs been carried out on this equipment or similar types of equipment?
- Give a reason for repairs; e.g. defect outside of good workmanship limits.
- Are qualification procedures and tests available for the repairs?
- Have previous failures occurred in this equipment or similar types of equipment?
- Give an indication of type of failure; e.g. brittle fracture, rupture, fatigue, creep, corrosion, etc.
- Have previous FFP assessments of this equipment or similar types of equipment been carried out?
- Give an indication of the reason for the assessment; e.g. defect assessment, material not meeting specification, design not meeting specification, degradation, damage, assessment of remedial measures, failure analysis, etc; see also items 5 and 6.

item 1.2 design code (pressure vessel, bridge, offshore, etc.)

State the code used and the design life.

item 1.3 environment (internal and external environments)

Is the environment inert? Indicate the type of environment e.g.:
- external: marine, industrial atmosphere, etc.
- internal: oil, gas, etc.

item 1.4 material

Indicate type of material and if welds are involved; e.g. high, medium or low strength steel, stainless steel, aluminium alloy.

item 1.5 dimensions

State dimensions and tolerances(width, thickness, diameter, etc.).

item 1.6 post weld heat treatment

Has a PWHT been carried out? State the temperature and duration of PWHT.

Has the complete construction or just the weld and its surroundings been post weld heat-treated?

item 2 loading conditions

item 2.1 design conditions

What are the maximum and minimum design conditions and operating conditions? State e.g. temperature, pressure, static, dynamic loading (rates of loading; e.g. impact, and numbers of cycles of loading with corresponding stress ranges).

Are there similar parts of the system that experience the same loading and stress levels?

Was proof testing carried out? State levels of proof testing relative to design and operating stress.

item 2.2 operating conditions

State the operational conditions, temperature, pressure, static/dynamic loading, duration between shutdowns and duration of shutdown and planned operating life.

State the design operational internal and external environmental conditions, e.g. relevant information is needed such as the chemical composition, temperature ranges, pH ranges, expected duration of exposure to corrosive environment, extent of system exposed to corrosive environment, corrosion protection measures.

Are there similar parts of the system that experience the same internal/external corrosive environment?

State the expected corrosion rate in millimetres/year or calculate the rate from the corrosion allowance in millimetres/design life in years.

Is the operational or expected future operational environment different from the design environment? Give the current and expected future and predicted and/or measured corrosion rates.

Have there been modifications to the operations or to the equipment and equipment up and downstream from the equipment? Indicate the changes.

Has re-proof (re-hydro) testing carried out during operations? State the levels of proof testing relative to design and operating stress and frequency and time of testing. Indicate the reasons for proof testing.

item 2.3 design stress analysis

Is there a design stress analysis available?

item 2.4 define stresses

State primary stresses (tension, bending).

Have any detailed stress analyses been carried out on the relevant parts of the equipment?

Give details of the analyses.

item 3 material properties

Give the welding consumable specification, welding method and procedure including a drawing of the relevant weld geometry.

Give the minimum Charpy-V requirements of the base and weld material.

Are there any limitations on the specification of the maximum ultimate strength of the base material? If yes, then indicate requirement, e.g. avoidance of undermatching weld strength.

Give the maximum and minimum weld hardness required for both the heat affected zone and weld.

Give minimum specified yield stress and ultimate strength of the base and weld material.

Give material qualification data and repair qualification data and fabrication test data.

Is there data on the yield strength, ultimate strength, Charpy V impact, drop weight (tear) test, and fracture toughness (e.g. CTOD, K, J, R-curve)?

Indicate the standard used for fracture and drop weight tests and test conditions.

Are the stress-strain curves available for weld and parent metals?

Were fracture and impact data obtained at one temperature or are the full fracture or impact transition temperature curves available?

Indicate if other types of test data that are specific for welds are available; e.g. cross-weld tensile test data.

Give the maximum weld bead height in the capping pass, body of the weld and root pass.

Give the maximum height of the weld reinforcement and weld penetration at the root.

Give the average width of the heat-affected zone.

Give the maximum and minimum hardness for both the base, heat affected zone and weld materials.

Are hardness traverses available?

item 4 flaw data and NDE aspects

Give drawings of defects and locations.

Is the inspection history available? Give the frequency and extent of inspections.

item 4.1 flaw type and cause of flaw

State the type of flaw and cause if known, e.g. fatigue, lack of fusion, planar, volumetric, fabrication, in service, etc. Is the defect a fabrication defect or is it an active growing defect that may or may not be developing from a fabrication defect?

item 4.2 flaw location (at stress concentration, in weld metal, fusion line, etc.)

Give details or refer to item 1.1 if already given.

item 4.3 flaw size, and orientation

State orientation and flaw size.

item 4.4 basis for flaw data

State NDE method(s) used and indicate procedure(s) used. Was the defect size obtained from destructive examination (see item 5)? Indicate if the information has been used to define or interpret NDE findings concerning flaw type, orientation, location, extent and size.

Give the POD if known. Indicate if there are any reasons for a lower than normal POD. E.g. accessibility difficulties, less than 100% coverage of the weld, thickness (very thick or very thin), and operator unfriendly conditions, etc., see Section 8.2 on inspectability.

Give the accuracy if known. Indicate reasons for the choice accuracy; e.g. combinations of method used etc.

Give the extent and distribution of the defects if known. E.g. number of defects per metre, in what part(s) of the weld and part(s) of the equipment, etc.

State estimated defect growth rates (also corrosion rates) from periodic inspections. Give basis for estimates.

item 4.5 defect interaction

State whether there is more than one defect. Give distances between defects as well as defect sizes.

item 5 destructive investigation

Is a failure or metallurgical investigation of the relevant area available? (e.g. examination of cross sections, boat samples containing defects, grinding to remove defects etc.). Indicate the results of the investigation.

item 6 in situ (on-site) non-destructive investigations

State the type in situ investigation and if results are available, e.g. this may comprise of replicas of geometry to aid determining stress concentration factors, microstructures obtained either directly or via replicas, strain gauge results, and hardness via portable hardness meter, etc.

item 7 any other relevant observations or data

Is there any other information, observation or data that may be relevant but not listed in the previous items?

11 FFP Analysis Checklist

11.1 Introduction

The FFP Analysis Checklist is based on the analysis part of the FFP assessment diagram shown schematically in Figure 34. The numbers in the scheme refer to the different items in the checklist. The latter should help the analyst check whether the different aspects have been considered. It should also help others involved in the FFP process to follow the analysis route, and understand the reasons for the decisions and resulting choices. The FFP analyst should also find the checklist a useful guide when making a report. The checklist can be used with any accepted defect procedure. Since it is only an aid, the checklist must not be used instead of an accepted defect assessment procedure. The defect assessment procedures in BS 7910, API 579 and R6 are reflected in the checklist.

When FFP is not established after the analysis and further refinement, then the *mitigation checklist* could be used to provide some ideas on how to proceed.

The FFP Analysis Checklist should be used in conjunction with the Information Checklist, which provides a guide for acquiring input data, see Section 10, and the Mitigation Checklist in Section 12. If the defect assessment after possible refinements does not result in FFP, then either an alternative approach, see Section 5.4, or the Mitigation Checklist, where possible remedies are listed, could be used. The FFP Analysis Checklist is a general checklist applicable to a range of applications and failure modes. If the application is limited the checklist can be simplified. The checklist is divided into 8 items:

- item 1 general background to the problem
- item 2 loading conditions
- item 3 material properties
- item 4 flaw data and NDE aspects
- item 5 analysis option
- item 6 limit load and stress intensity factor solution
- item 7 significance of results
- item 8 conclusion

A more detailed list is given on the next page. An explanation of the items in the checklist is given in the section after the list.

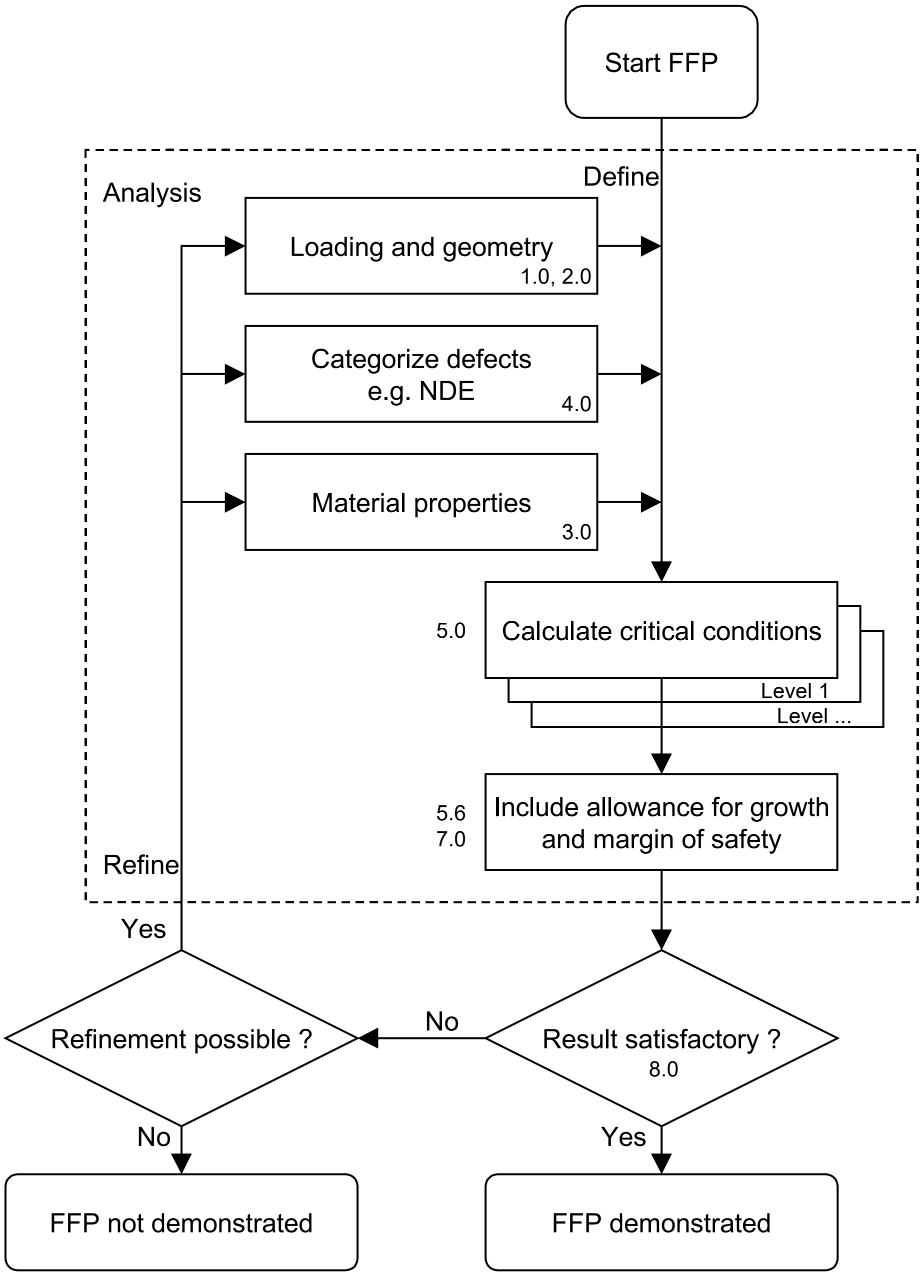


Figure 34 FFP analysis with checklist item numbers in the checklist

11.2 List of items in the checklist

item 1 general (nature of the problem and consequences of failure)

item 1.1 structure/equipment identification (detail)

item 1.2 design code (pressure vessel, bridge, offshore etc.)

item 1.3 environment

item 1.4 material

item 1.5 dimensions (width, thickness, etc.)

item 1.6 post weld heat treatment

item 2 loading conditions

item 2.1 design conditions

item 2.2 operating conditions

item 2.3 design stress analysis available

item 2.4 define stresses (primary, secondary thermal/residual, PWHT, proof testing)

item 2.5 indication of conservatism or unconservatism in the loading conditions

item 3 material properties

item 3.1 material specification (base, weld)

item 3.2 measured tensile and impact Properties (base, weld, weld configuration)

item 3.3 fracture toughness from-Charpy V data, database, materials qualification data

item 3.4 transition temperature

item 3.5 crack growth law (e.g. fatigue), stress corrosion cracking, hydrogen embrittlement

item 3.6 embrittlement, ageing, hydrogen embrittlement.

item 3.7 weld mismatch

item 3.8 modulus of elasticity and Poisson's ratio

item 3.9 indication of conservatism or unconservatism in materials properties

item 4 flaw data and NDE aspects

item 4.1 flaw type and cause

item 4.2 flaw location (weld metal, fusion line etc.)

item 4.3 flaw size and orientation

item 4.4 basis for flaw data (NDE method(s), procedure(s), POD, POS, extent, growth)

item 4.5 defect interaction

item 4.6 indication of conservatism- or unconservatism in defect data

item 5 analysis option

item 5.1 decide if FFP is unnecessary e.g. a superficial repair is possible item 5.2 applied assessment procedure and level of analysis

item 5.3 fracture initiation (brittle fracture, ductile fracture initiation)

item 5.4 applied constraint factor (CTOD-K conversion)

item 5.5 ductile tearing analysis (specify fracture resistance curve)

item 5.6 crack growth (e.g. fatigue)

item 5.7 leak before break

item 5.8 probabilistic analysis (Figure 19)

item 6 limit load and stress intensity factor solution

item 6.1 applied limit load solution (plastic collapse)

item 6.2 applied stress intensity factor solution

item 6.3 indication of conservatism or unconservatism in solutions chosen

item 7 significance of results

item 7.1 results sensitivity analysis

item 7.2 reserve factor as a function of e.g. defect size etc. versus consequences of failure

item 7.3 probability of result falling outside of FAD less than target probability

item 8 conclusion

11.3 Explanation of the checklist

Determine which parts of the list are relevant for the problem. When answering the questions in the list:

- Give an answer yes or no to the questions in the list.
- Give an indication of the reason for choices of assessment, solutions and input data used in the assessment (e.g. scatter, lower and upper bound values, conservative versus unconservative choices).
- Give references to the source of input data and other information (e.g. history) used.
- Indicate the quality of the data and information. The availability of raw data should be indicated as this allows the quality of data to be checked.
- Give references to the report(s) where the FFP analysis and associated work has been performed.

item 1 general

Define:

- the nature of the problem.
- the consequences of failure
- the redundancy in the structure.
- the urgency required

commentary

The nature of the problem should include the definition of the boundaries of the problem, recent changes to design, fabrication, and operations (see checklist) and hypotheses about the possible cause of the problem.

Consequences of failure could be injury or fatality, pollution, and loss of production, loss of asset(s), loss of customer, loss reputation and claims. See also Section 4.7 on decision-making etc. E.g. the consequences could be ranked in the following way (see the list below). The more severe the category of consequence, the lower the required probability of failure or the higher the required partial safety factors and reserve factors (see item 7.0). The proximity of people and other infrastructure, likelihood of explosion, fire, release of toxic materials and pollutants will determine the severity of the consequences. The financial consequences will depend on the previously mentioned consequences, repair and replacement and whether lost production can be recovered using back-up systems.

ranking of consequences of failure

negligible	no significant consequences
moderate	only financial consequences
severe	potential risk to human life or pollution
very severe	potential risk to multiple human lives

item 1.1 structure/equipment identification (detail)

- Obtain drawings of details where the assessment is required and the relationship of the problem area to the rest of the construction.
- Is the design of this equipment unique (new); e.g. new concept, new material, new fabrication method, new installation method, new operating conditions including environment?
- Have significant repairs been carried out on this or similar types of equipment?
- Give a reason for the repairs; e.g. defect outside of good workmanship limits.
- Are qualification procedures and tests available for the repairs? (See also item 3.0)
- Have previous FFP assessments of this equipment or similar types of equipment been carried out?
- Have previous failures occurred in this equipment or similar types of equipment.
- Give an indication of type of failure; e.g. brittle fracture, rupture, fatigue, creep, corrosion etc.
- Give an indication of the reason for the assessment; e.g. defect assessment, material not meeting specification, design not meeting specification, degradation, damage, assessment of remedial measures, failure analysis, etc.

item 1.2 design code (pressure vessel, bridge, offshore etc.)

State the code used if applicable and the design life.

item 1.3 environment

Is the environment inert? Indicate the type of environment:

- external environment, e.g. marine, industrial atmosphere, etc.
- internal environment, e.g. oil, gas, etc.

<u>commentary</u>

If a corrosive environment is present, defect assessments based on materials properties obtained in a non-corrosive environment may be irrelevant. Generally, a corrosive environment will accelerate the defect growth rates. The resistance to brittle fracture may be reduced.

item 1.4 material

Indicate type of material and if welds are involved, e.g. high, medium or low strength steel, stainless steel, aluminium alloy.

item 1.5 dimensions (width, thickness, etc.)

State dimensions and tolerances.

commentary

The conservative dimensions will normally be used, e.g. the minimum wall thickness and the maximum diameter. The tolerances could be used in a probabilistic analysis.

item 1.6 post weld heat treatment

Has the complete construction or just the weld and its surroundings been post weld heat treated? State temperature, duration.

commentary

The PWHT should be checked against the requirements for PWHT for the thickness and material in question to assess whether it has been correctly performed.

Note that there are code requirements to heat treat welded structures above a thickness of 40 mm in order to avoid brittle fracture. Some structures are so large that a global heat treatment is impossible. FFP assessments can be used to demonstrate whether or not the fracture toughness in the as-welded state is sufficient to resist fracture at the larger thickness.

item 2 loading conditions

item 2.1 design conditions

State e.g. temperature, pressure, static, dynamic loading (rates of loading; e.g. impact, or numbers of cycles of loading with corresponding stress ranges)

- Are there similar parts of the system that experience the same loading and stress levels?
- Has proof testing been carried out?
- State levels of proof testing relative to design and operating stress.

item 2.2 operating conditions

State the operational conditions, temperature, pressure, static/dynamic loading, duration between shutdowns and duration of shutdown and planned operating life.

State the levels of proof testing relative to design and operating stress and frequency and time of testing.

State the expected corrosion rate in millimetres/year or calculate the rate from the corrosion allowance in millimetres/design life in years.

State the design operational internal and external environmental conditions, e.g. relevant information is needed such as the chemical composition, temperature ranges, pH ranges, expected duration of exposure to corrosive environment, extent of system exposed to corrosive environment, corrosion protection measures.

- Is the environment inert?
- Are there similar parts of the system that experience the same internal/external corrosive environment?

- Is the operational or expected future operational environment different from the design environment?
- Give the current and expected future and predicted and/or measured corrosion rates.
- Have there been modifications to the operations or to the equipment and equipment up and downstream from the equipment? Indicate the changes.
- Has re-proof (re-hydro) testing carried out during operations?
- Indicate the reasons for proof testing.

<u>commentary</u>

Repairs or modifications, particularly when unforeseen and implemented without qualification procedures, may introduce stress concentrations and have a detrimental effect on both residual stresses and fracture toughness.

item 2.3 design stress analysis available

Is there a stress analysis available?

item 2.4 define stresses

Note the stresses are needed as input for the limit stress and stress intensity factor solutions.

Most defect assessments concern mode I principal stresses, which act in a direction perpendicular to the defect.

When the components of loading in other directions become relatively large compared to the principal stress then other modes of loading become relevant and the direction of crack propagation will change. Special treatments are available for other modes of loading; see the list of appendices of the different defect assessment methods in Section 5.3.

primary stresses (tension, bending)

State the maximum primary principal stresses and maximum stress concentrations in the stress analysis perpendicular to the expected site of a flaw.

<u>commentary</u>

As a first estimate, when calculating the stress intensity factor, the peak primary stresses (e.g. the nominal stress multiplied by the stress concentration factor at the surface) can be assumed to act across the entire plate perpendicular to the defect. (See item 6.2 where the peak stress is mentioned as a way of calculating the stress intensity factor).

The stress concentrations can be calculated using formulae given in handbooks of stress concentration factors [Section 14.10] and the compendia in the appendices of the different defect assessment methods in Section 5.3.

There are two types of stress concentration factor:

- The global stress concentration factor acts across the entire cross-section. Examples are the stress concentration caused by a nozzle and a tubular joint. Nozzles and tubular joints can have different stress concentrations, although a factor of 3 is fairly common for a reasonably well designed nozzle or tubular joint. Note that the BS 7910 gives guidance on stress concentrations for e.g. tubular joints, nozzles in pressure vessels and for pipelines.
- The local stress concentration occurs at a notch or weld toe. These stress concentration factors decay fairly rapidly below the surface of the stress concentration to the nominal stresses (within about 15% of the plate thickness).

Local stress concentrations can also be caused by the additional bending stresses caused by out of roundness and misalignment of welded plates.

The stress distribution can be calculated exactly or assumed to reduce linearly over the cross section providing approximate stress levels for different defect depths. BS 7910 demonstrates how this can be done. The benefits of assuming a stress gradient are significant for the deeper defects, which penetrate beyond the region of the local stress concentration factor.

More accurate solutions can be obtained by calculating accurate stress distributions for a complex (uncracked) geometry by using numerical methods.

Purely elastic analyses may result in unrealistically high stress levels at stress concentrations when the nominal stress levels are relatively high. The stresses may be reduced by a more accurate elastic-plastic analysis.

A reduction of typically 20 to 30% in stress level in regions of stress concentration may be obtained using more refined numerical analyses. This sort of reduction on its own would be significant for fatigue but less significant for the control of fracture. In the latter case, the combination of a number of refinements would probably be needed if FFP were to be demonstrated.

secondary thermal/residual stresses and reduction of residual welding stresses by PWHT and proof testing

State residual welding stress level and distribution used in the analysis.

Have any repairs or modifications relevant for the FFP assessment been carried out on either the equipment containing the defect or similar equipment during fabrication or service? Give the changes.

Have the repairs or modifications been post weld heat treated?

State the calculated thermal stresses.

<u>commentary</u>

residual welding stresses

Repairs or modifications, particularly when unforeseen and implemented without qualification procedures, may have a detrimental effect on both residual stresses and fracture toughness.

Defects located either in a weld or heat affected zone or lying within about a plate thickness of the weld will experience significant weld residual stresses even if the weld is stress relieved. Residual stresses will result in one of the largest contributions to fracture if the fracture toughness is relatively low.

High residual stresses may be assumed as a first approximation to act over the entire cross-section. The BS 7910 document gives guidance on the level of residual stresses that can be assumed. For example, the residual stress is assumed to be equivalent to the lesser of the maximum yield stress of the base material at room temperature for defects parallel to the weld and to the maximum weld metal yield stress for defects across the weld.

When a global post weld heat treatment has been carried out at the proper temperature and for the correct duration then the residual stresses may be significantly reduced. According to BS 7910, the residual stresses across the plate thickness may then be assumed to be reduced to 30% of the yield stress of the base material for defects parallel to the weld and 20% of the yield stress for defects across the weld. A proper global PWHT can have a large beneficial effect on the outcome of the FFP assessment. Note the effect is only large if material is relatively brittle because residual stresses play a relatively insignificant role when the fracture is ductile. The effect of reducing the stresses by post weld heat treatment will increase as yield stress increases.

A post weld heat treatment may also improve the fracture toughness of materials with a low fracture toughness significantly. Fracture toughness may also be reduced by a heat treatment but if the fracture toughness is already low this is less likely. The effect on the calculated allowable defect size can be significantly larger than the effect of the reduction of residual stresses.

When higher levels of analysis are used, a considerable advantage may be obtained if the distribution of residual stresses is taken into account. Usually ignorance of the distribution of complex residual stress fields prevents this, resulting in the previously mentioned conservative assumption that high residual stresses act across the entire cross-section. Local residual stresses are distributed both along a weld and through the plate thickness. The distribution is a result of the residual stresses needing to achieve equilibrium within the welded plate. The residual stress distributions are strongly dependent on the type of fabrication method and procedures and the restraint during welding. Note that weld residual stresses do not only arise from welding but also from the cold forming processes used in fabrication. When the welds are restrained the signs of the residual stresses may be reversed and the distributions become significantly different when compared to unrestrained welds. The degree of restraint is generally unknown. Furthermore, the residual stresses will re-distribute to form a new equilibrium during cracking or repair. The BS 7910 gives some guidance on possible residual stress distributions for given welding procedures. It is also possible to calculate the residual stresses for a given welding procedure using numerical methods provided the restraint is properly modelled. As mentioned in the next paragraph, the knowledge of the sign of the stresses and whether they are low medium or high is often more important than the exact value of residual stress at each point of the distribution. The treatment of residual stresses is an area under development and great care must be taken when using lower levels of residual stress from assumed distributions.

Measurement of the relaxation residual strains can also be obtained by using an X-ray method or strain gauging. The methods require a limited removal of material at the surface (a smooth polished and etched surface for X-ray and a small shallow hole for strain gauge measurements). The careful removal of material is vital in order to avoid the introduction of deformation with accompanying residual stresses. In order to obtain a distribution through the cross-section significant amounts of material must be removed and is therefore in most cases impractical. The measurements do not necessarily need to be highly accurate, as knowledge that the residual stresses are low tensile or compressive in the region where the defect is situated is already of great value.

See Section 14.15 for more information on residual stresses and see also the list of the appendices of BS 7910 and R6 in Section 5.3.

effects of proof testing

This is a concrete demonstration of a safety margin. Proof testing can demonstrate leak tightness and demonstrate a margin of safety by loading to somewhere between 25 and 50% more than the maximum design load.

Proof testing will tend to relax residual stresses if yielding occurs. Both R6 and BS 7910 give methods that take account of this reduction of residual stress. A proof test will create a larger plastic zone at the tip of a defect than the plastic zone created by operational loads. This means that future operational loading will open static defects without causing any further yielding. Proof testing can cause failure during the test. This may be acceptable because equipment with low toughness and large defects are removed from operation. Proof testing may be carried out at temperatures above the fracture transition temperature if there is a fear of failure when the test is performed at ambient temperature. High test temperatures may only be used if the operating temperature is higher than the proof test temperature.

The warm pre-stressing, has a beneficial effect on the fracture toughness. The effect can be calculated using procedures given in the R6 and BS 7910 assessment methods; see appendices of both methods listed in Section 5.3.

The safety margin in stress demonstrated by a proof test can be converted to a safety margin between existing defects in the equipment and the largest defect which could survive the proof test. The margin between the defects gives the room for eventual defect growth. A defect growth calculation will give the number of cycles or time to consume the margin. The time can be used to plan inspections and calculate whether the next shutdown will be reached.

The safety margins estimated from the proof test are irrelevant for defects shorter than the critical length for burst that may eventually grow through the thickness to cause a leak unless the leak is acceptable and the defect does not reach a critical size before penetration of the wall, see leak before break analysis in item 5.7 and in Section 4.2.5.

Proof tests may cause defects extend, particularly if the tests are repeated. Empirical corrections from pipeline test data and calculated amounts of defect tearing can be used to estimate the reduction of the margin of safety. The reduction can be of the order of 10% per proof test for pipelines. Check the pipeline data etc. before choosing a relevant reduction factor.

item 2.5 indication of conservatism or unconservatism in the loading conditions

State the expected over- and unconservatisms.

commentary

possible conservatism in the design

If FFP cannot be demonstrated under the design conditions it may be possible to define and remove some of the conservatisms in the design in the FFP assessment. For example:

- The designer may have assumed a generous corrosion allowance, which is not needed in service because of the absence of corrosion, see item 2.1.1 of the Mitigation Checklist in Section 12;
- The designer of an offshore structure may have assumed extra drag forces due to the growth of marine organisms on the structure. If this growth does not develop to the degree assumed during the service life, then the design will be conservative;
- The lowest temperatures in the design may only occur when the pressure is low and not as often assumed in a design at the maximum design pressure.
- The assumption of peak stresses acting across the entire cross-section.
- The linearisation of a stress distribution.
- The use of a linear-elastic superposition of stresses when there are high stress concentrations and high residual stresses instead of the use of elastic-plastic analyses.
- The use of approximate stress concentration solutions.
- The assumption that high residual stresses act across the entire cross-section instead of a distribution of residual stresses.

possible unconservatism in the design

Note failures are not necessarily a result of an incidental large defect and may be a result of a systematic unconservatism in the design. Failures that have been repaired could be repeated in the future elsewhere in the construction. It is therefore advisable to assess other areas in a construction, particularly where there are similar features and levels of stresses.

possible unconservatisms in the stresses in the FFP assessment

Unconservatism could be caused by forgetting to take account of misalignment. A certain amount of misalignment is allowed by the codes. For example, misalignment may be simply the result of mismatch of two adjoining plates, each with a thickness at the opposite sides of the tolerance band. Misalignment (also angular misalignment) of plates at welds can result in stress concentrations typically of the order of 1.5. BS 7910 gives formulae for calculating the stress concentrating effects of misalignment. This is accounted for in a design code but would cause an unconservatism in the FFP assessment.

item 3 material properties

State the source of materials data when giving data used in the analysis.

- Has a failure investigation been carried out and has the materials information obtained during the investigation been used in the FFP assessment?

commentary

The possible sources of data are:

- design requirements
- mill certificates
- qualification tests for fabrication and repair
- fabrication quality control tests
- estimations from Charpy-V tests
- estimations from databanks
- material acquired and welded for an FFP assessment
- material removed from the construction (in-service)

It will be difficult to check the quality of the data from the literature if the raw data on which the data is based is not available either in the publication or separately from the author.

item 3.1 material specification for base and weld material

State the base material specification. Briefly indicate the welding consumable specification, welding method and procedure (including the weld bevel geometry).

- Give minimum specified yield stress and ultimate strength of the base and weld material.
- Give the maximum height of the weld reinforcement and weld penetration at the root.
- Give the maximum weld bead heights in each pass of the weld (for estimates of max. defect height or depth).
- Are there any limitations on the specification of the maximum yield stress of the base material? If yes, then indicate requirement. (e.g. avoidance of undermatching weld yield stress)
- Give the minimum Charpy-V requirements of the base and weld material.
- Give the average width of the heat affected zone.
- Give the maximum and minimum weld hardnesses required for both the heat affected zone and weld.

item 3.2 measured tensile and impact properties (base, weld), e.g. via qualification testing, etc.

Which data is available? E.g. yield stress, ultimate strength, Charpy-V impact energy.

- Are mill certificates available?
- Have the tests been carried out in the relevant metallurgical condition; e.g. post weld heat treated, embrittled etc.?
- Are hardness traverses available? Is hardness within the specification?

- Indicate if other types of test data that are specific for welds are available; e.g. cross-weld, heat affected zone, tensile test data.
- Are full stress strain curves available? See item 5.2 on Analysis Option.

item 3.3 fracture toughness (weld and base materials)

Measured data (CTOD, K, J, R-curve) e.g. from material qualification testing, etc.

- Is there fracture toughness test data on the following: (e.g. CTOD, K, J, R-curve)?
- Indicate which type of data is used in the analysis. (e.g. for tearing ($\delta_{0.2}$, $J_{0.2}$, $\delta_{0.2/BL}$, $J_{0.2/BL}$, δ_m, J_m) and for brittle fracture (K_{Ic}, K_Q, δ_c, J_c, δ_u, J_u).
- Give the failure mode(s) in the fracture tests?
- Give the standard used for fracture mechanics tests (see standards later on under this item) and test conditions.
- State the minimum values and values used in the analysis if different.
- Have the tests been carried out on material with the relevant metallurgical condition; e.g. Post weld heat treated, embrittled conditions?
- State whether there are sufficient data available for a choice of the input data based on statistics.
- Have the data been obtained from tests that have been carried out under the relevant temperatures, constraint, environmental conditions and loading rates?
- Have the data been measured using test specimens, which are not equal to the full thickness? See the previous comment on constraint.
- Are there suspect brittle microstructures and have they been sampled by the fracture toughness tests?
- Is there is a reason for deviating from standard test procedures because standard procedures cannot be applied easily to a particular problem.

commentary

The value of fracture toughness will depend on procedures and standards used.

See comments on quality of data in the comments on information from databanks in this item.

Material properties can be influenced by the environmental conditions, temperature and loading rate. See items 1.3 and 2.2 in this checklist.

Repairs or modifications, particularly when unforeseen and implemented without qualification procedures, may have a detrimental effect on both residual stresses and fracture toughness.

See also item 5.8 in this checklist on probabilistic assessments.

BS 7910 gives advice on the minimum number of tests.

fracture toughness estimated from Charpy V data and databases

State the values of fracture toughness obtained from a databank.

Have the tests been carried out on material with the relevant metallurgical condition? E.g. post weld heat treated, embrittled conditions

Are there suspect brittle microstructures, if these regions are small it may not be possible to sample them using Charpy V tests?

State the values of Charpy V used and the Charpy V-fracture toughness relationship used with justification of its use.

commentary

estimations from Charpy V data

The use of proper fracture mechanics data should be used whenever possible. If only Charpy V data are available, then Charpy V correlations may be used.

The use of Charpy V correlations with fracture toughness can be used but a penalty in the form of higher reserve factors should be applied to the outcome of the FFP assessment. The application of additional margin in the reserve factor may be needed to cover some of the following comments. See item 7.2 in this checklist.

The Charpy V test is sensitive to the temperature and metallurgical condition e.g. ageing, but not to the environment (e.g. hydrogen embrittlement).

The notch of a Charpy V test specimen cannot measure the fracture toughness in a narrow HAZ or small area of embrittlement if the notch root radius is larger than the HAZ or region of suspected embrittlement.

There are three methods of predicting fracture toughness using Charpy V test results, namely:

1. the Lower Bound Correlation, which should not need the application of extra reserve factors, see BS 7910.
2. "best estimate" Charpy V impact correlations. These give higher values of fracture toughness but may be unconservative. The correlations must not be used outside their range of validity, see Section 14.7.2
3. the Master Curve approach developed by Wallin. This gives a distribution of fracture toughness and can provide information for probabilistic approaches. See also the worked example using this approach in Section 13.10, Section 14.4.2 and appendices of the defect assessment codes in Section 5.3.

fracture toughness estimated from a database

quality of data

Data produced according to accepted national and international standards, where the calculated result can be traced back to the raw data, should be rated as high quality data. It is possible to relate fracture data to other relevant materials property data, e.g. chemical composition, tensile properties, Charpy V data, the material specification and heat of production.

There should be drawings indicating the direction and location of specimen removal from a failure or piece of equipment. A consistent specimen code for all test specimens allowing material to be traced back to the source is needed. If consistent information is not available then this should be indicated and taken account of in the analysis. The accreditation systems now in place help give an indication of whether the provider of data has consistent documentation.

Note that some institutes have their own non-standard fracture test methods. This means that the test method must always be specified. Non-standard test methods may be needed because of the limited amount of material or because component has an awkward geometry for the extraction of test specimens.

sources of data

- material suppliers
- fabricators and component manufacturers
- installation companies
- owners
- test houses

- the national and international (welding) institutes and steel institutes
- national and international standards and data institutes
- universities etc.
- Data suppliers e.g. Engineering Sciences. EDSU data sheets
- R&D programmes (joint industry, national and international). For information on European research programmes see http://www.cordis.lu or contact Senter in the Netherlands. There have been programmes on marine technology and the characterisation of steels in the ECCS (European Community Coal and Steel) programmes and Brite-Euram programmes.
- IIW publications
- conferences e.g. the International Conference of Fracture (ICF), European Conference on Fracture (ECF), TWI conferences, ASTM conferences, major pressure vessel, pipeline and offshore structure conferences, welding and materials conferences
- Leading English language journals such as:

Engineering Fracture Mechanics

Fatigue and Fracture of Engineering Materials and Structures

International Journal of Fatigue

International Journal of Fracture

International Journal of Pressure Vessels and Piping

Journal of Materials Testing

Journal of Strain Analysis

Materials Science and Engineering

NDT & E International

ASTM-STP publications

fracture toughness testing

When a failure assessment diagram is used the fracture ratio is defined as K/K_{mat} (or a similar ratio for J and CTOD). K_{mat} etc. stands for whatever type of fracture toughness that has been determined. The fracture toughness is defined in many different ways and this is denoted by the subscript after the fracture toughness parameter, e.g. for tearing $\delta_{0.2}$, $J_{0.2}$, $\delta_{0.2/BL}$, $J_{0.2/BL}$, δ_m, J_m and for brittle fracture K_c, K_Q, δ_c, J_c, δ_u, J_u.

Since the first moment of tearing (e.g. the separation of the first atoms) cannot be measured, different protocols have been developed for the interpretation of the test. These allow a measurable, but for engineering purposes, an insignificant amount of tearing to take place before the initiation of tearing is defined. The type of initiation of tearing is denoted by a subscript after fracture toughness symbol.

The subscript “0.2 mm” means the initiation of fracture is defined after “0.2 mm” of tearing. When “0.2/BL” is used then initiation is defined as being 0.2 mm from the blunting line. The “0.2 mm” fracture toughness is more conservative than the “0.2/BL” fracture toughness, because the blunting of the crack is included in the measurement of tearing.

The subscript “U” means that some initial tearing occurred before cleavage fracture. In this case, the initiation of fracture is defined when cleavage fracture occurs. This definition will lead to higher fracture toughness with larger scatter than if the initiation of tearing had been taken as the moment of fracture initiation.

The subscript “C” means that the moment of initiation is defined when cleavage fracture occurs without prior tearing.

The subscript “M” means that the initiation of fracture is defined at the achievement of maximum load in the test. This will result in larger values of fracture toughness than the use of the initiation value. No cleavage is allowed to occur in a test before the maximum load is reached. Ductile tearing is allowed and may or may not have occurred before the maximum load. The use of “C” and “M” tests means that the testing is easier to perform because the initiation of tearing does not need to be determined using more complex procedures. The subscript “Q” is used when cleavage occurs after the validity limits of the test in a linear-elastic test.

The highest levels of analysis generally require initiation and the resistance to tearing data or the value at the validity limits of the test. The fracture toughness for the high level analysis is not an individual value but a whole series of values, in the form of a resistance curve to tearing, (the R-curve).

Where possible the full thickness should be tested, because tests on thinner test specimens may prevent the occurrence of cleavage fracture. Tests on ductile materials that are thinner than the material in service will result in lower fracture toughness because the limit of a valid fracture toughness will be reached at a lower value than might otherwise have been achievable if the full thickness had been tested.

It is impossible to achieve maximum plastic constraint if the fracture tests are carried out with a notch in the thickness direction. Such tests are needed when testing in the direction of expected crack propagation and when a particular microstructure is sampled in a weldment. Whether or not the fracture toughness measured is plane strain (i.e. when the plasticity is fully constrained by the specimen thickness) or not is determined after the test and denoted by a subscript I immediately after K, J or CTOD e.g. K_{Ic}. If the subscript is not given then plane strain conditions were not fulfilled and the result is thickness dependent. The best approach is to use the validity criteria to determine the limit of validity in the test and only use fracture toughness values up to this limit.

See Part I, Section 4.6.3 on costs and elapsed time including the planning of testing etc.

testing standards

These are subject to updating so that care must be taken to ensure the last version is used. See the list of standards in Section 14.5.1. In particular there are developments in the testing of welds that have a different strength to the base metal (mis-matched). This means that the correct amount of overmatching must be present in the test. The BS 7910 gives some guidance on this. There are also developments in the testing of shallow cracked specimens that have a similar constraint to a shallow surface defect. Shallow cracks should have a significantly higher fracture toughness because the plasticity is less constrained than in a test where a deep notch is used, see Sections 14.13 and 5.4.1. The most commonly used standards are the BS and ASTM standards.

There are a number of different protocols of dealing with tearing initiation and the tearing resistance. The BS standard gives the most guidance on testing welds. The testing of the relatively narrow heat affected zone is particularly complex. It describes the manufacture of test specimens, giving an excellent flow diagram for preparing test specimens in base material and welds. It also explains how to deal with residual stresses in a test specimen and misalignment and curvature of the test material. There is an important part on the validity and interpretation of test. This includes the investigation of the broken test specimen to see whether the crack tip has sampled enough of the microstructure that has is suspect or targeted as in the case of a HAZ. The investigation of the fracture surface of a broken specimen is recommended in order to assess whether a “pop-in” (small brittle crack jump) occurred in the test and a way of assessing the significance of the “pop-in” is given.

The BS 7910 gives guidance on the number of tests needed. The use of the lowest value in a fracture testing programme of 3 tests is suggested if the fracture behaviour is upper shelf. When the fracture behaviour is in the transition region the scatter will be significant. Guidance is given on the definition of significant scatter. At least 12 tests will be needed for the application of statistics when the scatter is significant. The scatter can be reduced by accurately locating the fatigue crack tip in a specific microstructure.

Note that the ASTM Standards were developed for base metals rather than welds.

item 3.4 transition temperature

Is a full fracture or impact transition temperature curve available?

State the fracture and impact transition temperatures and the way they have been defined.

commentary

A knowledge of transition temperature behaviour in fracture toughness may help the choice of a reserve factor. Differences in the transition temperature within a material are an indication of metallurgical differences and thus a variable quality of material.

item 3.5 crack growth law (e.g. fatigue), stress corrosion cracking, hydrogen embrittlement

State the crack growth relationship used.

commentary

See the references on fatigue crack growth standards in Section 14.5.2 on testing standards.

There is a significant amount of data in the defect assessment procedures on fatigue crack growth rates and fatigue thresholds, below which fatigue cracks do not grow, see Section 14.8.1.

Generally fatigue crack growth data of steels without the influence of corrosive fluids will have similar exponents in the crack growth relationships in spite of different strengths and different microstructures. There is less agreement at low crack growth rates near the threshold where microstructure has a significant influence.

The affect of mildly corroding fluids such as seawater on mild to medium strength steels tends to be a second order affect relative to the influence of the magnitude of the stress variation, see Section 14.8.4.

When conditions are more corrosive (e.g. sour crude oil) the effect of the corrosive fluid on fatigue in steel can be very large. See Vosikovski in Section 14.8.4.

Paradoxically, cathodic protection, which can inhibit the growth of fatigue cracks in steel near the threshold, can increase the crack growth rate at higher growth rates above that measured in freely corroding seawater if there is a degree of over-protection. This means that once fatigue crack growth is detected the possible detrimental affect of cathodic protection must be checked and if present accounted for in the crack growth predictions.

There is much less data on the rate of stress corrosion cracking and hydrogen embrittlement of steels. There is only one defect acceptance procedure that is seriously developing a stress corrosion cracking test and hydrogen embrittlement methods that are suitable for FFP. This is the EFAM procedure mentioned in Section 5 on different defect assessment procedures.

There is a stress corrosion cracking test method, which uses a cantilever beam specimen to determine the moment of arrest of stress corrosion cracking in the specimen. See Section 14.5

on stress corrosion cracking standards. This specimen cannot be used to test in through-thickness direction or give values of stress corrosion cracking resistance above the arrest value.

item 3.6 embrittlement - ageing (strain ageing, irradiation embrittlement, temper embrittlement, hydrogen embrittlement)

State type of actual or expected embrittlement and the assumed or measured deterioration of properties with time or corrosion conditions.

commentary

When embrittlement occurs gradually during service either test blocks of the same material, which have been exposed during service must be tested or the ageing must be simulated. Simulation usually means artificially accelerating the ageing. Hydrogen embrittlement of steels is dependent on for example the corrosion rate and the absorption of atomic hydrogen and the gradients of hydrogen within the steel. Calculations and careful experimental simulation are needed before reliable fracture toughness values can be determined.

item 3.7 weld mismatch

State the degree of undermatching, matching or overmatching of the weld relative to the yield strength of the plate material.

commentary

Some material specifications may result in overmatching welds with a small probability of undermatching occurring. If undermatching happens, then strain will tend to be concentrated in the weld particularly around any defects at the higher stress levels. The plastic strain the defect experiences will depend on the size of the defect relative to the width of the weld and the plate thickness and the degree of undermatching.

There will be implicit safety margins as a result of overmatched welds being used in the validation tests for the FADs. Therefore some of the margin of safety may be lost in undermatching welds. R6 and BS 7910 gives some guidance on this in the appendices. The EFAM (ETM) procedures in Section 5 were the first to develop an approach to deal with mismatch. See also comments in the commentary on testing standards in item 3.3.

item 3.8 modulus of elasticity and Poisson's ratio

State the values used.

commentary

These values are only needed if a conversion is made from CTOD or J to K.

These properties will not vary significantly for many steels and are usually assumed to be the same e.g. values of 205 GPa and 0.3 respectively. significant differences in Young's modulus will occur when going to different materials such as aluminium alloys or in steels when there are effects from texture.

item 3.9 indication of conservatism or unconservatism in materials properties

State the expected conservatisms and unconservatisms.

commentary

conservatisms

1. the lower-bound Charpy V correlations are used.

2. the initiation value of fracture toughness is used instead of the R-curve in the uppershelf region of fracture behaviour.
3. a deeply notched full thickness test specimen is used instead of a shallow crack specimen.
4. the limit of validity is reached before the achievable fracture toughness can be measured in a specimen, which is thinner than the material in service.

unconservatisms

1. "best estimate" Charpy V correlations may result in unconservatisms.
2. when the suspected embrittled area is missed.
3. when the full material thickness is not used in the fracture test so that test conditions for possible cleavage fracture are not achieved.
4. when fracture toughness with the subscript U is used instead of ductile tearing initiation values when measuring fracture toughness in a heterogeneous material.

item 4 flaw data and NDE aspects

Is the inspection history available? Give the frequency and extent of inspections.

Has a failure investigation been carried out and has the information obtained on defect sizes during the investigation been used in the FFP assessment?

commentary

Note that an FFP analysis can be used to help achieve optimal inspection by defining requirements for NDE.

See Section 8 on Inspection. This includes a description of NDE methods, inspectability (the effect of different parameters and conditions on the performance of NDE) and the selection of NDE methods.

item 4.1 flaw type and cause (fatigue, lack of fusion, planar, volumetric, fabrication, in service etc.)

State the type of flaw and cause.

commentary

The main issue is to determine whether the defect is a fabrication defect or is an active growing defect, which may or may not be developing from a fabrication defect.

item 4.2 flaw location (weld metal, fusion line etc.)

Give drawings of defects and locations (see item 1.1 and refer to this item if the information is already given).

item 4.3 flaw size and orientation

State orientation, flaw size and whether supporting metallurgical information has been used in the assessment of the defect.

Note the possibility of assessing the margin between the current flaw size and the critical flaw size in the commentary on item 2.4 under secondary thermal/residual stresses and reduction of residual welding stresses by PWHT and proof testing.

commentary

Information on the welding method and procedure used should be used to support the findings of NDE. E.g. the weld bevel will help give the orientation of fusion line defects and the weld bead height will help in sizing the defects.

A brief description of a number of failure modes is given in Section 8.2 on Inspectability.

item 4.4 basis for flaw data (NDE method)

State NDE method(s) used and indicate procedure(s) used; see Section 8.3. on NDE methods.

An idea of the ranges of POD and accuracy for commonly used NDE methods and are given in the selection of NDE methods in Section 8.4. Nevertheless it is advisable to consult a specialist for the appropriate values for the specific FFP case.

probability of detection

Give the POD. Indicate if there are any reasons for a lower than normal POD, e.g. accessibility difficulties, less than 100% coverage of the weld, thickness (very thick or very thin), and operator unfriendly conditions, etc.

commentary

Note that information on structural and process similarities elsewhere in a system (system analysis), the welding method and procedure etc. and on possible failure modes with supporting FFP analyses, can help define the extent of defects or cracking throughout a system. This should be used together with the POD data. See also Risk Based Inspection in Section 3.2.3.2.

defect accuracy

Give the accuracy. Indicate if there are any reasons for a lower than normal accuracy such as those in under POD.

commentary

High accuracy is less relevant than the POD if defects have been missed.

There are several strategies or combinations of strategies possible; e.g.

- use a high POD, e.g. 90 to 95% POD if there is uncertainty about the outcome of an an FFP assessment;
- accept a lower POD and assess its effect by performing a probabilistic calculation, see Section 6;
- combine metallurgical and welding information to obtain a credible defect size (This only works for fabrication defects).

extent of defects

Give the distribution of the defects if known, e.g. number of defects per metre, in what part(s) of the weld and part(s) of the equipment, etc.

defect growth rates

State estimated defect growth rates (also corrosion rates) from periodic inspections.

item 4.5 defect interaction evaluation and recategorisation

State whether this has been considered.

commentary

There are a number of simple rules in the defect assessment procedures for deciding when defects interact (see the BS 7910, R6 and API 579 documents).

Due to variations in orientation, parts of a defect might be missed. The defect will then be interpreted as a number of separate defects.

Embedded defects must be checked to see whether they will extend to the nearest surface by plastic collapse of the smallest ligament of material. Advice is given on this in the various defect assessment codes. API 579 says that a plastic collapse assessment of a small ligament is likely to be very inaccurate and therefore recommends recategorisation. According to API 579, all embedded defects within 20% of the wall thickness from a free surface should be considered as a surface defect with a new depth equal to the distance to the free surface and the original embedded defect height. This means embedded defects in the weld beads at the surface or in the root of the weld will probably have to be recategorised as surface defects.

item 4.6 indication of conservatism or unconservatism in defect data

State the expected conservatism and unconservatism.

commentary

conservatisms

E.g. measuring a number of small non-interacting defects as a single large defect.

E.g. the application of large partial safety factors or reserve factors in an FFP assessment when there is uncertainty about the maximum defect size.

unconservatisms

E.g. incorrect definition of an active crack as an inactive fabrication defect. See also the NDE sections 8 1 for the definition of active and non-active defects, Section 8.2.8 and Section 9 on Failure Investigation.

E.g. no consideration of the missed defect in an FFP assessment when an NDE method with a low POD is used or when only a limited length or amount of weldment is investigated.

E.g. improper application of a NDE method or use of a method with inappropriate POD and accuracy. A FFP analysis should be used to help choose a NDE method with suitable performance.

item 5 analysis option

item 5.1 decide if a superficial repair is possible

State if the option of repair has been considered. If a repair is chosen has an FFP assessment been carried out for the undetected defects, which have not been repaired?

commentary

Shallow surface defects, which are easily accessible, will probably be repaired.

Care should be taken to ensure that the nature of the defect is determined when defects are repaired in service because there may be larger growing defects, which have been missed as a result of a low POD or the limited amount of inspection. These hypothetical larger growing defects must be assessed. See both the Mitigation Checklist in Section 12 and item 5.6 of this checklist.

A conservative simplified calculation procedure in Section 7 is presented as a way to help the inspector decide whether or not to request an FFP analysis. This will hopefully lead to the inspector to consider the pros and cons of an FFP analysis before deciding to repair.

item 5.2 applied assessment procedure and level of analysis

State which procedure has been used. Note that the procedures are subject to updating so that care must be taken to ensure the last version is used.

If there is a reason for deviating from procedures because current procedures cannot be applied easily to a particular problem, this should be clearly stated and properly reported with arguments for the deviation.

commentary

The BS 7910, R6 rev 3 and API 579 methods are general methods of assessment. The defect methods are similar but can give different results. The defect assessment approaches are fracture control methods and are therefore intended to prevent rather than predict failure. The methods all use FADs, see Section 5.

BS 7910 recommends the application of partial safety factors to each input parameter to ensure that there is a margin between calculated result and the FAD. These are not true safety factors because there are implicit safety factors in the FADs and in some of the inputs used. When FADs are developed for a specific material and cracked geometry and all conservatisms have been removed from the input data there will be no implicit safety factors. R6 uses reserve factors, which are determined after the sensitivity of the result of the analysis to input data has been determined.

The different FFP assessment methods generally have a number of “levels’ of analysis. The different “levels” and “options” lead to different failure assessment diagrams and increasing requirements for the type and quality of data as the analyses become more refined. The major FFP assessment methods have accompanying software for the generation of the failure assessment diagrams and the generation of the fracture and loading ratio inputs.

E.g. BS 7910 has three “levels” of analysis and each ‘level” has a number of options. The sort of data needed for the different “levels” and the consequences of using the data is given in the previous items in this checklist on input data. The size of the allowable defect, for example, should increase as the “level” of analysis increases as with the “option” increases within a “level”. Note that R6 calls the “levels” “options” and the “options” “categories”.

1. Level 1 in BS7910 has a built in safety. E.g. a factor 2 on defect size, 1.4 on stress and 1.25 on plastic collapse.
2. Level 2 is regarded as the normal level analysis and should be used if possible. It gives the possibility of using refined more accurate data and a material specific failure assessment diagram. Partial safety factors on the input data or reserve factors must be used in the analysis. In R6 the partial safety factors are optional. As mentioned previously The R6 approach uses a reserve factor, which is chosen after the sensitivity of the assessment result to the variation of each input parameter has been assessed.
3. Level 3 can be used instead of level 2 if the failure mode is ductile tearing. For level 3 option B a full stress-strain curve is needed to define the failure assessment diagram. Partial safety factors or reserve factors (R6) must be used.

The different levels of a BS 7910 have been plotted in the same graph in Figure 35 in order to enable a comparison to be made. Note the level 1 FAD normally is plotted on a different X-axis. The relative position of the levels 2 and 3 FADs to each other and to their relative position to the level 1 FAD will depend on the material properties used in constructing the level 2 and 3 curves and the incorporation of the actual cracked geometry in level 3.

Note that there is a region around the top right hand corner of the box-like FAD where the margin between the level 1 FAD and the level 2 and 3 FADs is much less than for the rest of the level 1 FAD. This means that care is needed when results fall in this region when using the level 1 FAD. See the next figure.

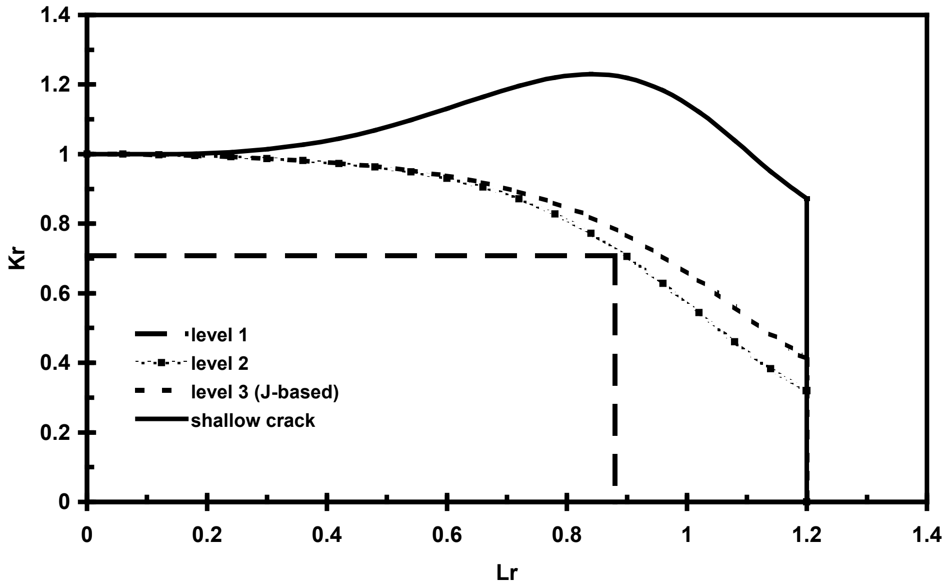


Figure 35 Showing that the margin between the top right hand corner of level 1 and level 2 is much smaller than for the rest of the level FAD.

item 5.3 fracture initiation (brittle fracture, ductile fracture initiation)

State mode of failure.

<u>commentary</u>

If cleavage fracture occurs then the tearing analyses using R-curves are not relevant.

If stress corrosion cracking occurs the assessment procedures are not applicable and special procedures will be needed.

If fatigue occurs see item 5.6.

item 5.4 applied constraint factor (CTOD-K conversion)

State constraint factor used in the conversion.

<u>commentary</u>

There are relatively few CTOD solutions compared to K and J solutions, whereas most of the fracture toughness data available on welds is in the form of CTOD data. This means there may be a need to convert from CTOD to K or J.

The K and J fracture toughness can be converted from one to the other without the need to make corrections via a constraint factor.

Correction via the constraint factor is needed when converting CTOD to K and J or vice versa. If this is not known it is pessimistically assumed to be one, underestimating the K fracture toughness. This pessimism can be avoided if the appropriate plastic constraint factor can be derived from the raw data available from the fracture toughness test. Typical values of constraint lie between 1 and 3. E.g. for deeply notched bend specimens the constraint factor is between 1.5 and 2.0.

item 5.5 ductile tearing analysis

Specify the fracture resistance curve used.

commentary

In a level 3 analysis, the use of the fracture toughness at initiation of tearing may cause the result to fall outside of the FAD. This is not necessarily unacceptable. The results of subsequent calculations using higher values of fracture toughness from the R-curve may eventually fall below the FAD. At this point the initiated tearing is predicted to have arrested and the result is acceptable if there is a sufficient reserve factor. If the results remain outside of the FAD, the arrest of tearing is not predicted and the result is unacceptable.

item 5.6 crack growth (e.g. fatigue)

State the result and indicate significance for the FFP assessment. This may be used to support observations of active versus non-active defects.

commentary

Figure 12 in Section 4.2.4 on subcritical crack growth shows how crack growth can be calculated in a step by step manner.

There is commercially available software for performing fatigue crack growth calculations.

Defect growth is perpendicular to the principal stress direction. This will usually result in defects near the fusion line growing into the tougher base material provided the weld is not a steep sided weld as in a “U” preparation. This may increase the critical crack size, which may become controlled by plastic collapse in the base material rather than controlled by fracture toughness in the heat affected zone and weld metal.

Note, if may be possible to avoid the need to perform fatigue crack growth calculations by a simple calculation using the fatigue threshold and cyclic stresses in the stress intensity factor formula to show that there is no fatigue crack growth. I.e. the cyclic stresses do not cause the range of stress intensity factor, calculated using an assumed defect size, to exceed the threshold for fatigue crack growth.

item 5.7 leak before break

State whether leak before break and has been considered and whether it is relevant.

commentary

When the assessment point for a fluid containment system is unacceptable even after various refinements to the analysis and input data, then the leak before break (LBB) approach method may be taken. See Part I Section 4.2.5, Figure 13 gives a way of checking whether the application of the approach is acceptable or not. The method ends when the leak or through thickness crack is compared with the critical crack length for failure using the failure assessment diagram. See Figures 8 and 14 in Part I.

The LBB approach is probably inapplicable when crack growth along the surface is predicted to be faster than in a lateral direction than in the depth direction. Lateral crack growth rates can be calculated using an appropriate sub-critical crack growth relationship.

Note, that stable sub-critical crack growth is required for the LBB approach. If the crack growth through the wall is unstable (brittle) then the method needs to be combined with a crack arrest approach mentioned in Section 5.5.

item 5.8 probabilistic analysis

State whether there are sufficient data for a probabilistic analysis.

State if the distribution has been assumed or obtained from actual data.

State whether the probabilistic analysis is a full probabilistic analysis or a partial probabilistic analysis.

If the analysis is partial then state which parameters have been treated probabilistically.

State assumptions about truncation of the distributions related to the input and give or refer to reasons.

commentary

See Probabilistic assessments in Section 6, Figure 19. If there are relatively few data then

1. the fracture toughness values measured can be mixed with data from the literature provided the data has been obtained from similar materials tested under similar conditions.
2. the method of Wallin can be used. See worked example in Section 13.10 on the Master Curve Approach for determining fracture toughness.

applied method

Define the method used.

commentary

E.g. 1st or 2nd order reliability methods, Monte Carlo simulation or a full integration of the different input distributions.

applied distributions

Define the distributions used for each of the input parameters.

commentary

Avoid mixing distributions of different modes of failure and of values of fracture toughness obtained on different materials (e.g. weld, heat affected zone, base material and different microstructures within a weld and heat affected zone). Defect distributions in Section 14.4.1 can be used when there is limited data.

item 5.9 over and unconservatism in the analysis

State the expected over and unconservatisms.

commentary

Assumptions about the truncation of distributions of the input parameters may lead to unconservatism or conservatism depending on assumptions and values used.

item 6 limit load and stress intensity factor solution

State which solutions have been used and how they were obtained. See part I Section 4.2 for a definition.

item 6.1 applied limit load solution (plastic collapse)

State the solution used and any assumptions.

commentary

The limit load solution is the numerator in the plastic collapse ratio.

The simplest calculation is to assume the maximum primary stresses act across the remaining uncracked ligament.

A large number of less conservative solutions are given in R6, BS 7910 and the API RP 579 method for a range of different cracked geometries, see Section 14.2.

The limit load analysis can be further improved by performing a numerical analysis for the specific material and cracked geometry in question. Care must be taken to choose the appropriate solution. E.g. whether or not rotation is restrained.

The flow stress is defined as the average of the yield strength and ultimate strength. This is used to define the maximum value the load ratio L_r. The minimum specified material properties should be used unless the actual values are known or a probabilistic approach is taken.

Some other defect assessment procedures (e.g. API 579) use the yield stress plus an increment. This can be unconservative because the flow stress of a low work hardening material may be overestimated.

item 6.2 applied stress intensity factor solution

State the solution used and any assumptions.

commentary

This is the numerator in the fracture ratio input to the FAD.

If a crack exceeds a certain length relative to the thickness and diameter of the pressurised equipment then a bulging factor must be applied. The factor will increase the stress intensity factor.

BS 7910, R6 and API 579 have compendia of fracture mechanics solutions, see also Section 14.11.

There are far more fracture solutions for K than for J or CTOD.

There are relatively more J than CTOD solutions.

A complete elastic or elastic-plastic numerical analysis can be made for the stress intensity factor when no suitable solutions are available.

item 6.3 indication of conservatism or unconservatism

State conservatism or unconservatism in solutions chosen, e.g. the use of elastic instead of elastic-plastic solutions.

Item 7 significance of results

Item 7.1 results sensitivity analysis

Has a sensitivity analysis been performed?

Give the ranges over which the input parameters have been varied.

commentary

Each of the input parameters (e.g. defect size and stress, or combination in terms of K and fracture toughness) should be varied outside values that form the basis of the calculations.

item 7.2 reserve factor as a function of e.g. defect size, fracture toughness etc.

Which input data is of a high, medium or low quality?

State the reserve factor chosen and reasons for choosing it based on the plots of reserve factor against the input parameter. E.g. the assumptions used, uncertainty and scatter in certain input data (see Section 8.4 on Inspection and the questions in item 3.3 of this checklist) and the uncertainty in the analysis used.

Have the consequences of failure and the redundancy[10] in the structure been considered when choosing the reserve factor? See item 7.3 in the checklist.

commentary

The reserve factor is determined for the simple situation where there are no residual stresses by the ratio OA to OB in Figures 36, and 37.

The method of determining reserve factors is more complicated when there are residual stresses (see assessment method R6). The reserve factor is plotted against each of the input parameters, see Figures 36, 37 and 38. Shallow gradients in reserve factor are preferred to steep gradients. If the gradient is steep a higher reserve factor, refinement or remedial action will be required. See also item 7.3.

Both fracture toughness and defect size tend to be the most scattered or inaccurate input parameters and therefore usually require extra attention when selecting reserve factors, e.g. the fracture toughness can change very rapidly with temperature in the transition region. See the various input data sections on stress, defect, stress intensity factor and limit load in order to judge the quality of the data [item 3.3].

[10] redundancy is the possibility of structural integrity being maintained by redistribution of the load on the cracked member to other sound members.

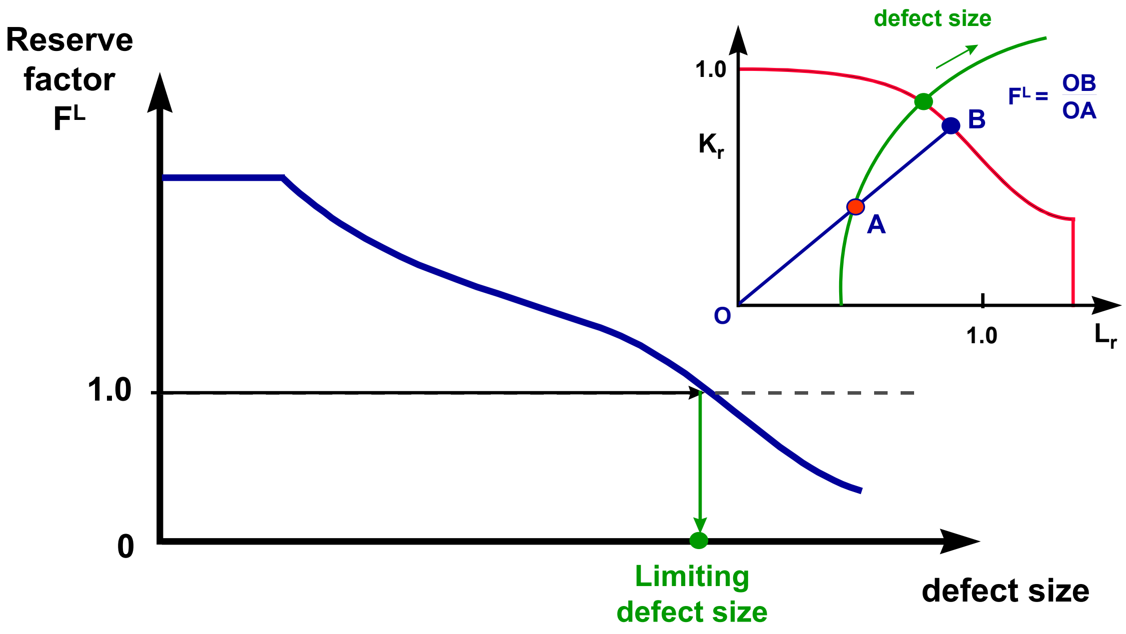


Figure 36 Plot of reserve factors for defect size to aid the choice of appropriate reserve factor on defect size.

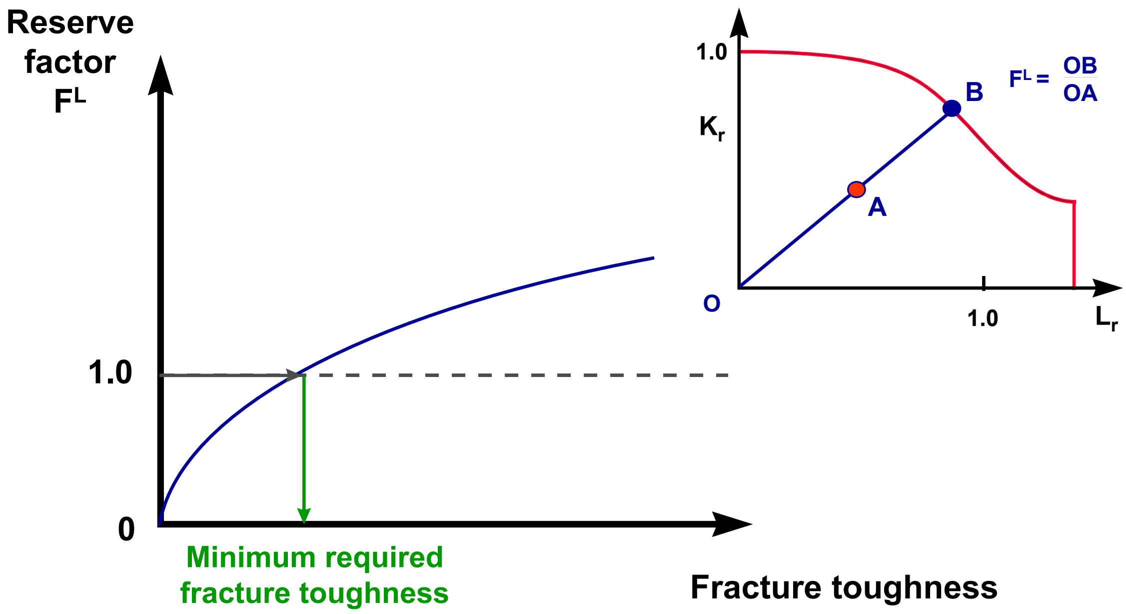


Figure 37 Plot of reserve factors for fracture toughness to aid the choice of appropriate reserve factor on fracture toughness

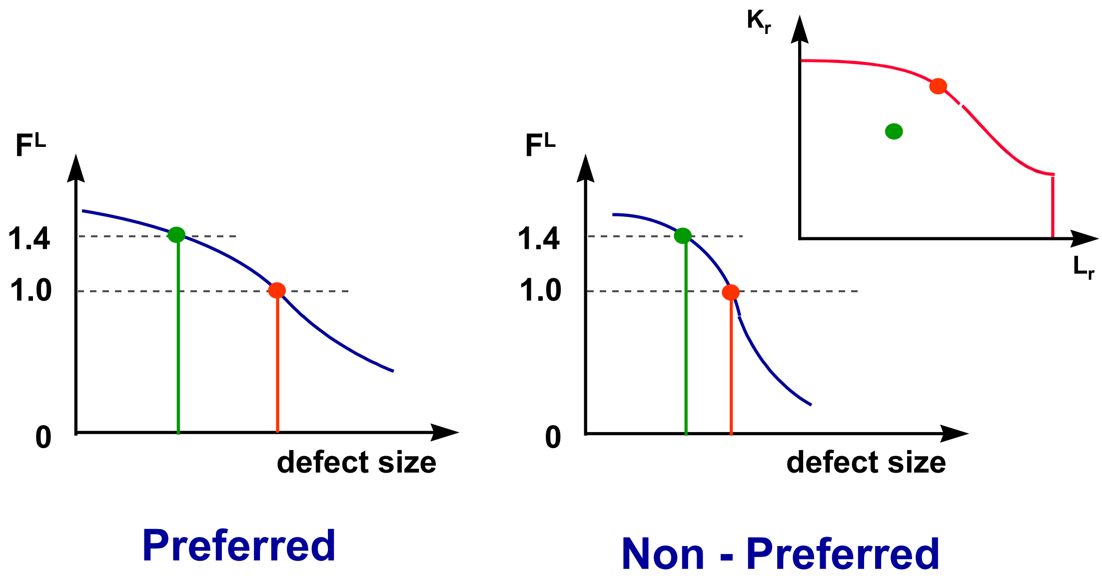


Figure 38 These plots show that a relatively gradual change in reserve factor is preferred. If the change is rapid then this should lead to an extra margin being required.

Item 7.3 probability of result falling outside of FAD less than target probability values

State the result versus target probability values.

State the reason for selection of target values. e.g. the assumptions used , uncertainty and scatter in input data (see Sections 8.2, 8.4.2 and 8.4.3 on NDE and the questions in item 3.3 of this check list) and the uncertainty in the analysis used.

Have the consequences of failure and the redundancy in the component and structure been considered when choosing the target probability values? See the Probabilistic Analysis in Section 6 and the Mitigation Check List in Section 12.

commentary

Note that the probabilities of failure are not true probabilities of failure because of the implicit safety margins in fracture toughness and the FAD.

An idea of acceptable probabilities of failure for different consequences of failure to give an acceptable risk are tabulated in BS 7910 (see the table in this item). The BS table gives an allowance for redundancy (when there are alternative load paths allowing the re-distribution of loads acting on a cracked member to other uncracked members). For the case of a pressure vessel, for example, there is no redundancy. Note that there are less levels of consequence than in the list of consequences given earlier in item 1 of this checklist where an extra level negligible has been added. The consequences in item 1 of this checklist give other additional consequences aspects such as pollution and financial consequences.

failure consequences	**redundant component**	**non-redundant component**
moderate	2.3×10^{-1}	10^{-3}
severe	10^{-3}	7×10^{-5}
very severe	7×10^{-5}	10^{-5}

moderate consequences = plastic collapse and only potential financial consequences without threat to human life

severe consequences	=	brittle failure or potential threat to human life
very severe consequences	=	brittle failure and potential threat to multiple human lives

item 8 conclusion

If not fit for purpose then consider:
- whether input parameters should be further refined;
- non destructive monitoring of defect growth;
- possible alternative assessment methods, see Section 5.4;
- remedial measures, see the mitigation checklist in Section 12.

Do the results conflict with previous operating and defect assessment experiences with similar equipment? If so, re-check the basis for the assessment.

Has a failure investigation been carried out and has the FFP assessment been compared with the results of the failure investigation? Note that in contrast to fracture control approaches, such as BS 7910, R6 and API RP 579, the safety and reserve factors must be removed and mean rather than extreme values of input data used in order to predict failure.

12 Mitigation Checklist

12.1 Introduction

Mitigation measures form part of the FFP process, see Section 4.4 on the FFP process, and are remedies that reduce or remove the risk of failure. The remedies may effect either or both the fabrication and operation of equipment.

When an FFP assessment gives an unfit for purpose result, then refinement of the FFP assessment is usually cheaper than deciding on mitigation measures that may obstruct or delay the fabrication or operation of the equipment. If after refinement the equipment is still unfit for purpose then mitigation could be considered. There are exceptions when for example a proof test or re-proof test or a post weld heat treatment are already planned or have been carried out. In this case the benefits from such actions do not result in any consequences for fabrication or operations.

Maintenance and inspection personnel will be familiar with some of the mitigation measures mentioned in this checklist. They will be less familiar with the possibilities of quantitatively estimating the benefits of mitigation using FFP assessments. Other participants in the FFP process may be less familiar with mitigation possibilities of solving an FFP problem, see Figure 7.

The Mitigation Checklist is divided into two parts. The first part called **Failure Mitigation** is concerned with practical ways of reducing the probability of failure. Here measures are suggested which enable the reduction of the stress intensity factor ratio, the loading ratio (checklist items 1 and 2) or further crack growth (checklist item 3). The second part is called **Consequence Mitigation** and deals with the possibility of accepting a higher risk of failure but taking mitigation actions to reduce or avoid the consequences of failure. It should be noted that consequences can be assessed better if the extent of a failure can be predicted e.g. whether a failure is a small leak or a complete fragmentation. A qualitative idea of risk, can be obtained from the plot of probability of failure against consequence of failure is given in Figure 39, which is a repetition of the figure in Section 3.2.3.2.

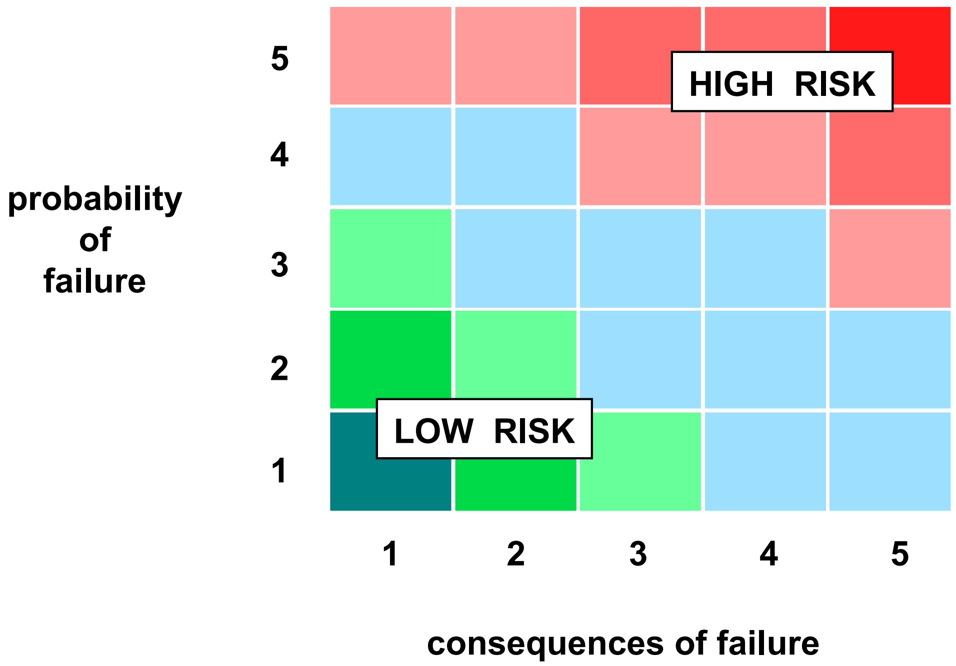


Figure 39 The likelihood of failure versus the consequences of failure

The **Mitigation Checklist** contains some duplication of the FFP Analysis Checklist in Section 11. This is intentional because mitigation checklist is driven by the need to make modifications to the plant or operations in order to achieve FFP, whereas the FFP checklist is aimed at the analysis and refinements in the analysis.

The effect of most of the failure mitigation measures can be calculated. The fracture ratio and or the loading ratios can be decreased if the mitigation measures are successful. Calculation can then demonstrate the reserve factor achieved by the mitigation of fracture. The effect of reduction of the input parameters on defect growth, which may be slowed or arrested when there is a positive effect of mitigation, can also be estimated.

The severity of the consequences of failure can be estimated in part by using fracture mechanics methods to determine the extent of failure. For example, it may be possible to estimate the length of a fracture before arrest. This should indicate whether the failure will cause fragmentation, a large loss of fluids or a small leak.

Since the number of possible mitigation methods is large, it is sensible to review the Mitigation Checklist to see whether there are any attractive methods or whether the list triggers other ideas, which are not listed. The mitigation measures should be subject to an FFP assessment in order to select the most appropriate method and to determine whether FFP is achieved. The technical benefits mentioned are only indicative so that a proper demonstration of the actual benefit will be needed in most cases.

12.2 Explanation of the checklist

Failure Mitigation

item 1 reducing the loads to decrease K or the possibility or plastic collapse by

item 1.1 de-rating

item 1.2 introducing alternative load paths item 1.3 reducing long range restraint

item 2 reducing K by

item 2.1 reducing stress by lowering corrosion rates and taking advantage of corrosion allowance

item 2.2 reducing residual and thermal stresses by

item 2.2.1 global post weld heat treatment

item 2.2.2 proof testing or warm pre-stressing

item 2.2.3 reducing thermal transients

item 2.2.4 other methods

item 2.3 reducing local stress concentrations by

item 2.3.1 grinding, and

item 2.3.2 re-profiling welds

item 2.4 reducing the opening of crack by

item 2.4.1 jacking the crack closed

item 2.4.2 reducing internal pressure in blisters (e.g. HIC)

item 2.5 reducing, removing or modifying the defect size and or the defect by-

item 2.5.1 grinding

item 2.5.2 grinding and re-welding

item 2.5.3 welding a patch

item 2.5.4 reducing or removing acuity of a defect

item 2.6 preventing extra defect growth

item 2.6.1 reducing the number of cycles of loading

item 2.6.2 prevention of a corrosive environment reaching the defect tip

item 2.6.3 reducing the range of the fluctuation in stress intensity factor ΔK

item 2.6.4 pre-stressing to reduce the effective ΔK in fatigue

item 2.6.5 reducing the R-ratio for fatigue crack growth

item 2.6.6 arresting crack growth

item 3 increasing resistance to fracture by

item 3.1 global or local PWHT

item 3.2 heat treatment to remove embrittlement item 3.3 increasing the operating temperature above the brittle-ductile transition temperature

item 3.4 removing dissolved hydrogen

item 3.5 preventing or reducing the access of corrosive species to the crack tip (also for reducing crack growth)

item 3.6 decreasing the temperature to reduce corrosion effects

item 3.7 removing embrittled material

Consequence Mitigation

item 4 avoidance of catastrophic failure

item 5 safety by

item 5.1 removal of personnel

item 5.2 isolation of equipment

item 5.3 removal of ignition sources
item 6 maintaining operations by

item 6.1 ensuring spare capacity
item 7 fit for purpose

item 7.1 unfit for purpose?

The following gives more information about the different aspects in the checklist.

Failure Mitigation Check List

item 1 reducing the loads to decrease K or the possibility or plastic collapse by

item 1.1 de-rating

One of the most straightforward actions is to de-rate the operation by reducing loads. This can be an attractive outcome in times when production is low but is otherwise very expensive in the long term. The effects on the fracture ratio and loading ratio inputs to the FAD can be calculated by an assessment.

item 1.2 introducing alternative load paths

This can be done for example by grouting, stiffening, and the addition of extra members. The effects on the fracture ratio and loading ratio can be calculated using stress analysis.

<u>commentary</u>

This would require expensive modifications being made to equipment. The stress concentrations caused by dents in pipes for example are very high and can cause both fatigue and fracture. Placing a reinforcement plate across the dent to carry the loads can reduce the stress concentration. If a dent containing a defect is unstable this will be insufficient. Grouting will then be needed under the reinforcement plate to stop the dent moving outwards when the pipe is re-pressurised.

item 1.3 reducing long range restraint by

Increasing the flexibility of a construction.

commentary

This is not usually a practical option.

item 2.0 reducing K_r and L_r by

item 2.1 reducing stress by reducing the corrosion rate and taking advantage of corrosion allowance

If there is corrosion, the corrosion rates must be reduced to acceptable levels by either changing the operating conditions or using corrosion control methods (see item 3 of the mitigation list). These options can be costly because they are continuous measures. See also item 3.6.

commentary

In many structures the maximum stresses are far lower than the design stresses because of the generous corrosion allowance. The benefit will, depending on the generosity of the corrosion allowance, be of the order of a 10% reduction of stress.

Measurements of wall thickness must demonstrate that there is no corrosion or that the corrosion rates are significantly less than anticipated in the design.

Expected future corrosive conditions should not become more severe.

item 2.2 reducing residual weld and thermal stresses

The effect of reducing the residual stresses can be determined from the reduction in the stress intensity factor.

commentary

The effect of reducing residual stress is only significant in the case of cleavage fracture (see also item 3.0 of the failure mitigation check list).

Post weld heat treatment will probably provide the largest reduction in residual stresses. Normally, a global post weld heat treatment carried out at the appropriate temperature and period of time will reduce residual stresses significantly without detrimentally affecting the material properties. A global post weld heat treatment is a heat treatment where the whole component is heat treated. Some steels (often special or high strength steels) can be sensitive to heat treatment.

The residual stresses are assumed to be reduced in defect assessment calculations to 20% of the base material's actual yield stress for defects parallel to the weld and 30% of the actual yield stress of the weld for defects across the weld. See also Failure Mitigation item 3.1.

item 2.2.2 proof testing or warm pre-stressing

Proof testing and warm pre-stressing can reduce the residual stresses. These effects can be estimated using the BS 7910 or R6 documents. This reduction of residual stresses is achieved by increasing the stress by a significant factor above the design stress. Note that proof testing is usually carried out at ambient temperature. Warm pre-stressing is carried out at a temperature above the brittle-ductile fracture transition temperature.

The factor by which stress is raised above the design stress is usually in a range between 1.25 and 1.5. The reduction in residual stress levels will be significantly less than a post weld heat treatment.

There may be no extra costs if say a proof test was already planned as is the case with commissioning of equipment and when periodic re-testing is required. Warm pre-stressing may result in extra costs if temperatures have to be raised significantly using steam heating. Note that proof tests at ambient temperature of cryogenic equipment are the equivalent to a warm pre-stress test.

See also item 3 for additional advantages of proof testing and warm pre-stressing.

item 2.2.3 reducing thermal transients by

Reducing e.g. the rate of cooling and heating cycles during operations. This results in recurring operational costs because heat-up and cool-down cycles become longer. The effects of cooling rate on the fracture and load ratios can be calculated using an FFP assessment.

item 2.2.4 other methods

Compressive residual stresses at the surface can be introduced by shot peening to prevent or delay the initiation of fatigue cracks.

The depth of compressive residual stresses will be superficial and depends on the severity of the shot peening. The shot peening is used to obtain longer fatigue lives. It will not work if the fatigue crack has penetrated past the surface compressive stress layer. There are papers showing the effects of shot peening on fatigue life in Developments of marine technology edited by Noordhoek and de Back in Section 14.8.6.

Vibratory stress relief is claimed by some to reduce residual stresses throughout the wall thickness while others believe the method to be ineffective. No quantitative benefit can be calculated.

item 2.3 reducing local stress concentrations by

item 2.3.1 grinding

Local stress concentrations can be removed or reduced by grinding (e.g. weld toes, notches, corners etc. can be smoothed or made less sharp). Surface stress concentrations usually decay rapidly with distance from the surface (i.e. over a range of approximately 15% depth of the wall thickness). When the surface profile becomes less sharp the stress concentration factor decreases but the depth of penetration of the stress concentration increases.

The benefits can be determined quantitatively. The effect of reducing a surface stress concentration is highest for shallow defects, which reside or propagate within the field of stress concentration. Note that fatigue crack growth is highly sensitive to the level of stress because a crack will propagate at a rate, which is related to the cube[11] of the stress range. For example, a factor 2 reduction in local stress could result in a factor 8 reduction in growth rate.

item 2.3.2 modifying the profile of a weld

The profile of a weld can be modified by adding more weld beads to the existing weld making the weld larger or by reducing the weld by grinding. Weld profiling can help achieve a better transfer of stresses and therefore ultimately a lower stress concentration. For example, the stresses at a weld toe, where fatigue cracks may initiate, can be reduced if the weld toe is extended so that it is further away from a structural discontinuity (e.g. nozzle, tubular joint).

[11] for structural steels

item 2.4 reducing the opening of the crack by

item 2.4.1 jacking the crack closed

Jacking the crack closed is not a commonly encountered mitigation method. It can provide a defence against the further extension of a long through-thickness crack either as a temporary or permanent measure. The effect of crack closure or crack opening restraint on the integrity can be calculated.

item 2.4.2 reducing internal pressure in blisters

Drilling holes in blisters will release the pressure of hydrogen, which is the driving force extending hydrogen induced cracks. This is a measure, which is often used in the petrochemical industry and is described in the API 579 document, see Section 14.2. The method should be carried out under close supervision by experienced personnel. Possible effects of the hole drilling on future integrity should be assessed. Once the pressure has been released the crack will cease growing.

item 2.5 reducing, removing or modifying the defect size and or the defect by-
items 2.5.1 to 2.5.3 grinding and re-welding

Shallow defects are invariably repaired by grinding. The idea is to remove the defect by grinding without if possible, the need for further repair of the ground area. Grinding, if the defect is accessible, can be much cheaper option than an FFP assessment. Nevertheless, an FFP assessment may be needed for the case where there is a possibility of larger undetected defects remaining in a structure after repair. The depth of the grinding needed to remove the defects will give some idea of the depth of defects. Back calculation from the defect depth using a crack growth relationship can also give an idea the size of defect, which caused the crack, and whether the defect is an active growing crack or a dormant fabrication defect.

If the depth of grinding exceeds the undercut allowances normally permitted then an FFP assessment will be needed to justify the extra loss of material. The superficial loss of material for structures with thick walls will be easier to accept, particularly if there is also a generous corrosion allowance**.** The procedure for grinding must include careful inspection to check whether the entire defect has been removed. It is probably impossible to be absolutely sure of the removal of the defect. For example, in a cyclic loaded structure, a fatigue crack growth calculation could be performed using a fictitious small crack (of say between 0.1mm and 0.5mm depth emanating from the repair). The size of initial defect in the calculation will depend on the accuracy of the inspection method used.

Note that grinding tends to smear material over the cracks hiding them from visual observation methods. Furthermore, removal of defects by grinding can destroy the evidence a failure investigator needs to identify the nature of a defect. If the defect is removed by taking a small boat shaped sample the investigator can determine whether it is an active or fabrication defect; see remarks in Section 9 on failure investigation.

Grinding must be carried out according to accepted procedures that must be designed to minimise the possibility of further defect extension or fracture.

Repair welding will be under highly restrained conditions if it is needed to fill deep grooves caused by grinding or if a patch of material is inserted. This in turn can result in high residual stresses. The large heat sink of material relative to the small size of the repair and the restraint can promote embrittlement and cracking. These affects can be reduced by the use of appropriate welding procedures. A FFP assessment in conjunction with repair welding trials is advisable.

item 2.5.4 reducing or removing the acuity of a defect

Drilling holes at the tips of through-thickness cracks can be an effective method for removing a crack tip and reducing the probability of further fatigue crack extension. The hole should be inspected to check that there are no remnants of the crack penetrating the hole. Even if there is no remnant crack, it is sensible to check for possible re-initiation of cracking by fatigue. This can be done for example, by performing a crack growth calculation by assuming an initial fictitious crack to exist at the hole; see the previous item. The method is cheap if the crack is accessible and is most applicable for through-thickness cracks in thin walled constructions.

item 2.6 preventing extra defect growth by

item 2.6.1 reducing the number of load or thermal cycles

Reducing the number of load or thermal cycles is an obvious way to reduce fatigue crack growth rates. This can be achieved by altering operations or modifying equipment so that pressure fluctuations are reduced. This may be costly if production rates have to be reduced. A fatigue crack growth calculation with a reduced number of cycles can be used to estimate the effect.

item 2.6.2 prevention of a corrosive environment reaching the defect tip

This increases the resistance to fatigue or other sub-critical forms of defect growth. The effect can be estimated if defect growth data for the material and environment in question are known; see also item 3.5.

item 2.6.3 reducing the range of the fluctuation in stress intensity factor

The reduction in loading is a direct way of achieving this and has the largest effect on reducing fatigue crack growth. See items 1 and 2.

item 2.6.4 pre-stressing to reduce the effective ΔK in fatigue

The application of a large stress cycle relative to the cyclic loading can retard fatigue crack growth significantly. The benefit will depend on the material and the ratio of the range of cyclic stresses to the range of the single large cycle and the R-ratio[12] The benefit must be demonstrated using an FFP assessment and will probably require testing. Sometimes such incidental high loads occur as part of the operations. The periodic application of an over-pressurisation, known as autofrettage, is sometimes carried out to prevent rapid fatigue crack growth in pressurised pipes.

item 2.6.5 reducing the R-ratio for fatigue crack growth

There are also other possibilities, which induce the crack to close prematurely and thereby reduce the range of stress intensity factor.

[12] R is the ratio of minimum to maximum stress in a cycle of load; e.g. if R = 0.5 and above then the mean stress is high, if R = 0 the minimum part of the cycle is zero and if R = -1 the mean stress is zero and when R is negative part of the cycle is compressive.

This can be achieved by reducing the mean primary stress and secondary residual stress. This will reduce the R-ratio[13]. When the R-ratio is low (approaching zero) the threshold value for fatigue crack growth will be much higher. A significant increase in the fatigue threshold as the R-ratio approaches zero is possible (the threshold could be doubled or trebled). See BS 7910 for conservative values for the fatigue threshold. The resulting higher threshold will remove a large number of the smaller cycles from the calculation so that less crack growth will be predicted. The effect is significant if most of the fatigue damage is caused by small ranges of stress.

item 2.6.6 arresting crack growth

There are several methods that can be used to arrest propagating cracks, be it a fast propagating brittle fracture or a growing fatigue crack; see Section 5.4. Crack growth can be effectively reduced and even arrested by the action of extra stiffeners across the expected path of a crack, see also item 1.2. Crack growth can be significantly reduced or arrested by reducing the stresses significantly; e.g. reduction of pressure or pressure cycles in a pipe.

Large holes tre-panned ahead of the crack will also ensure the crack is arrested. This is only suitable for relatively thin-walled materials. The large hole is positioned just ahead of the crack without disturbing the stress field significantly. The hole is sufficiently large to attract any propagating crack. Arrest occurs because the crack on meeting the hole becomes blunted.

As previously mentioned in item 2.5, the crack tips can be removed. This must be carried out with care because the fracture may have tunnelled beneath the surface.

The possibility of a running ductile crack in a pipeline can be prevented by crack arresters, which constrain the development of flaps, which form as the pipe opens up during the propagation of fracture. If the flap formation is stopped the fracture will arrest.

Note that crack arrest options can also be built in at the design stage, see Section 5.4.

item 3 increasing resistance to fracture by

item 3.1 global or local post weld heat treatments

Global or local post weld heat treatments can increase the fracture toughness. The improvement in fracture toughness as a result of PWHT must be demonstrated by fracture tests on the post weld heat treated material because the fracture toughness can under some conditions be reduced by a PWHT. Increases in fracture toughness by as much as a factor of 10 have been found for low toughness materials as a result of PWHT. Note that large improvements are possible when the original fracture toughness is very low. A material, which is already tough, exhibiting ductile fracture behaviour, cannot be improved by a PWHT.

item 3.2 heat treatment to remove embrittlement due to effects of metallurgical changes

Metallurgical changes causing embrittlement occur at high temperatures due to an incorrect heat treatment during fabrication, due to a fire or a temperature excursion during a mis-operation or due to gradual metallurgical changes (ageing) when some materials are exposed to certain high operating temperatures. If the appropriate temperature and time is used for a heat treatment the effects of ageing can be reduced.

A factor of 10 increase in toughness (see item 3.1) may be possible. The improvement of fracture toughness should be demonstrated by testing. The improvement may be temporary if nothing is done to change the conditions, which caused the ageing. The FFP approach should also contain a NDE check to ensure that there are no defects, which can become critical due to the possibility of future ageing causing a drop in fracture toughness.

Embrittlement can occur when ductility is partially or completely exhausted. For example, the straining caused by mechanical damage that results in bulging or denting can significantly reduce the fracture toughness. Tests on similar material, which has undergone similar amounts of plastic strain, can be used to estimate the reduction in toughness caused by plastic straining.

Proof testing and warm pre-stressing can enhance the fracture toughness. These effects can be estimated using the BS 7910 or R6 documents.

item 3.3 increasing the operating temperature

The increase in operating temperature by insulating or heating can increase the fracture toughness significantly and the tolerance to defects. A factor of 10 increase in toughness (see item 3.1) may be possible. As mentioned previously, the improvement in fracture toughness must be demonstrated before it is used in the calculations for FFP. Note that this only works for low toughness materials close to the transition temperature. The fracture toughness of materials on the upper shelf of their fracture toughness, will decrease gradually with increasing temperature.

item 3.4 removing dissolved hydrogen

If atomic hydrogen is dissolved in ferritic steels, then the ductility will be reduced causing embrittlement or reduced resistance to ductile tearing. A factor of 5 - 10 increase in toughness (see item 3.1) may be possible. The improvement will only be temporary if the source of hydrogen charging of the material (usually corrosion) is not diminished or removed. See subsequent items 3.5and 3.6. If the temperature of ferritic steel is raised to temperatures of the order of e.g. 65 to 100°C for a short period, then the hydrogen can be driven out and the steel returned to its original fracture toughness. If the charging of the steel continues then heat tracing may be considered to provide a continuous protection.

Raising the temperature moderately will not reduce the internal hydrogen pressure inside hydrogen induced cracks in steel where the hydrogen is trapped as molecules, which are too large too escape from the internal crack through the lattice of a material. If the temperature is raised to the order of say 500°C then the hydrogen will dissociate and will then be able to escape.

The loss of fracture toughness (tearing resistance) cannot be detected by a dynamic test, such as a Charpy V test, because the hydrogen will not have enough time to diffuse to the propagating crack.

item 3.5 preventing or reducing the access of corrosive species reaching the crack tip (also for reducing crack growth)

Fracture toughness can be increased and crack growth can be reduced significantly if the access of corrosive species (e.g. oxygen ions , chloride ions , water etc.) is prevented from reaching a crack tip by using e.g. inhibition, scavengers, liners, coatings and cladding.

Note that a coating over a surface crack will suffer large strains as the crack opens and will eventually fail.

item 3.6 decreasing the temperature to decrease the rate of a corrosion process (also for reducing crack growth)

A 10 °C drop in temperature can reduce corrosion rates in ferritic steels in some corrosive systems by a factor of about 2 for example.

Note that reducing the temperature may not work when hydrogen embrittlement occurs. Expert advice is needed in order to decide on the best way of achieving mitigation. Again the effect must be verified.

item 3.7 removing embrittled material

Unlike the incidental occurrence of defects, embrittlement can be far more pervasive occurring throughout the entire construction. The embrittlement may occur locally in just the heat affected zone. For such pervasive embrittlement removal of material is usually impractical and other more comprehensive methods such as a heat treatment are needed. See a previous item 3.2.

Consequence Mitigation

item 4 severity of consequences and avoidance of catastrophic failure

The severity of the consequences of failure can be estimated in part by using fracture mechanics methods to determine the extent of failure. For example, it may be possible to estimate the length of a fracture before arrest. This should indicate whether the failure will cause fragmentation, a large loss of fluids or a small leak.

item 5 (item 5.1 to 5.3) safety by

removal of personnel and ignition sources and isolation of equipment

commentary

Isolating equipment with a high severity of consequence of failure so that the consequences of failure are limited or cannot spread beyond the immediate vicinity of the failure, e.g. contain the fracture and any fragmentation, the release of polluting, toxic and inflammable fluids. Isolation of equipment or containment of consequences, may already be implemented in the design, e.g. a bund around a storage tank to contain fluids escaping from a leak. If so then a check should be made to see if the containment is sufficient for catastrophic failure. Note the BS 7910 gives methods to estimate crack openings and leak rates.

E.g. crack arresters could be used to contain a fracture, see Section 5.5.

item 6 maintaining operations by

Item 6.1 ensuring that there is spare capacity for production, storage or transport

item 7 fitness for purpose

item 7.1

Unfit for purpose? If unfit for purpose, after attempts to mitigate, consider alternative methods of assessment or scrap etc.

13 Worked Examples

13.1 Introduction

Eight worked examples have been included in this section. Worked example 13.10 shows how statistical information of fracture can be derived from limited data. The examples with the exception of worked example 13.10, are all intended to show how FFP assessments are carried out without going into the detail of the calculations. In order to convey some of the feeling for the FFP process, examples have been selected for the different stages of the life of a construction; e.g. design, fabrication and in-service. The link with NDE has received special attention in these examples. Table 2 in Section 8.4 and the POD of combinations of techniques in Section 8.5 have been used to estimate the accuracy and probability of detection of the NDE method used. The BS 7910 procedure has been used in several examples. In one case the PD 6493 defect assessment method was used. This is not a problem since the results will not be significantly different to those obtained using the BS 7910 procedure and because the purpose of the exercise is to demonstrate the steps in the assessment and the thinking behind the choices made. Although some of the worked examples are based on past FFP assessments, they have been simplified in order to clarify both the FFP process and the points being made in the example. This means that the input data and calculations are partly or wholly fictitious. *The results in the worked examples must not be used to justify fitness for purpose for similar cases that are encountered by the user of the Guidelines.*

An overview of the worked examples is in this Section is given in Table 4. With the exception of worked example 13.10 the table gives the type of equipment in the first column, the phase of application in the second column and a third comments column giving an idea of the scope of the worked example.

A number of worked examples available in the literature have been listed below. These examples show the actual mechanics of a defect assessment. Prior to the phase 3 of the NIL fracture programme for developing guidelines for FFP, there have been two previous phases, which give examples of fracture mechanics calculations and case studies, see Section 14.1.

IIW case study edited by J.G. Blauel, see Section 14.12

The list of worked examples given below does not include service failures. IIW expects these worked examples to be extended in the future.

	case description	type of case study
1	wide plate with longitudinal weld	model
2	aluminium alloy wide-plate with transverse weld	laboratory
3	ammonia storage tank	FFP
4	wide-plate with longitudinal stiffeners	laboratory
5	austenitic steel pipe	laboratory
6	low temperature aluminium alloy pressure vessel	FFP
7	large scale tension specimen with HAZ crack	laboratory
8	continuous I beam welded on site	model
9	tubular Y-node	laboratory
10	tubular joint	laboratory
11	spherical vessel with equatorial SA weld	laboratory
12	petrochemical vessel	FFP
13	bimetallic weld with crack parallel to the interface	model

14 PWR vessel with in defect in the cladding FFP

R6 rev 3 validation cases [Sections 5.3 and 14.2]

- A1 to A3 and A7 4 pressure vessel burst tests
- A4 to A6 burst tests of pipes (ferrous and stainless steel)
- A8 wide-plate shear tests (mixed mode loading tests)

Table 4 Overview of worked examples in the Guidelines

section	worked example	type of FFP assessment	comments
13.2	pressure vessel	design	95% POD of detection of defects chosen as an inspection criterion, thick walled vessel
13.3	acceptance criteria in girth welds	installation	combination of NDE methods
13.4	flat plate	in-service	conservative approach for inspector
13.5	sea barrier	fabrication	large complex FFP
13.6	pipeline corrosion	in-service	internal intelligent pig inspection, mitigation via de-rating and additional NDE
13.7	heat exchanger	in-service and post mortem	fabrication defects, non-routine NDE, example of post mortem probabilistic calculations, comparison of calculations with burst test result
13.8	heat exchanger	probabilistic analysis	
13.9	separator	in-service	fatigue, NDE, grinding as an inspection and repair method
13.10	using Master Curve	input data for FFP assessment	determination of a distribution of fracture toughness

13.2 Pressure vessel

objective

To demonstrate the application of FFP during design

background

This example shows the use of FFP during the design stage of a thick walled pressure vessel. The vessel is to be fabricated according to the design code and good workmanship criteria. The thickness of the vessel and the higher strength than is commonly used for the fabrication of separator vessels gave cause for concern about the possible detrimental effects of repairs of defects found just outside the GWMS limits and the validity of these GWMS limits (i.e. whether or not the limits were unconservative). In practice, small defects just outside of GWMS limits can be fairly frequent and lead to a large number of repairs. The minimum required fracture toughness for typical tolerable defect sizes that could be missed by inspection and that are just outside the current GWMS limits have been determined. There is no corrosive influence and the number of pressure cycles and their range is limited. The dimensions and material properties are summarised as follows:

- mean diameter = 5100 mm
- wall thickness cylindrical section = 176 mm
- wall thickness spherical head = 91 mm
- material Tst E 355 (DIN17102)
- thickness 176 mm, yield stress = 295 MPa, tensile strength = 450 MPa
- thickness 91 mm, yield stress = 315 MPa, tensile strength = 470 MPa

FFP analysis

A FFP assessment was carried out using level 2 of the PD6493:1991 procedure. The vessel has a top head nozzle and nozzles in the cylindrical section. Finite element stress analyses were performed to determine the stresses at the nozzles. The stresses are the highest at the location of the top head nozzle and are a result of the internal pressure, 11.0 MPa (110 bar) and external loads acting on the nozzle. Two surface breaking defect sizes have been analysed:

- depth = 2.8 mm with length =3.6 mm (i);
- depth = 5 mm with length = 25 mm (ii).

The vessel will be post weld heat treated.

result

The calculated required CTOD fracture toughness is 0.05 mm for defect (i) and CTOD = 0.18 mm for defect (ii). In the analysis partial safety factors have been applied for both load and fracture toughness. Fatigue analysis showed that fatigue is not an issue due to the limited number of start-up and shut-down cycles.

As a result of the analysis, two requirements were defined. Namely, a minimum required fracture toughness (CTOD = 0.18 mm) and the inspection requirements. Due to the fact that application experience of thick walled vessels of this material is limited it was decided that the maximum allowable defect should be detected with a probability of 85%. Therefore, the TOFD method has been selected for the full inspection of all welds in the vessel, see Section 8.4. Taking into account of the inaccuracy of the TOFD method it was decided set the maximum allowable depth for inspection equal to 4 mm and length equal to 20 mm.

conclusion

No significant extension due to fatigue or corrosion was predicted. A minimum required fracture toughness equal to a CTOD of 0.18 mm is required in order to tolerate defects with a size which will ensure an 85% probability of detection.

Checklist for FFP assessments	
item	**input/results/comments**
1 General (also see Information Check List)	
1.1 Structure/equipment identification (detail)	Adsorber vessel
1.2 Design code (pressure vessel, bridge, offshore etc.)	RTOD (Regels voor toestellen onder druk)
1.3 Environment	Liquid / gas
1.4 Material	TstE355 (DIN17102)
1.5 Dimensions (width, thickness, etc)	Inside diameter = 4923 mm Wall thickness heads = 91 mm Wall thickness cylinder = 176 mm
Post weld heat treatment	yes
1.7 Consequences of failure:	
1.7.1 Brittle fracture (yes or no)	
1.7.2 Potential risk to a person (yes or no)	yes
1.7.3 Potential risk to personnel (yes or no)	yes
1.7.4 Potential risk to the environment (yes or no)	yes
1.7.5 Potential financial consequences (yes or no)	yes, (unplanned) repair loss of production and costs (volume per day during shutdown plus any delivery penalties)
1.7.6 Target reserve factor or probability of failure	1.4 on stress level. See also item 7 where account is also taken of inaccuracy of NDE
2 Loading conditions	
2.1 Design conditions e.g. temperature, pressure, static/dynamic loading, proof testing, design life, etc.	Maximum allowable operating pressure = 84 bar Design pressure = 110 bar
2.2 Operating conditions e.g. temperature, environment, pressure, static/dynamic loading, re-hydrotesting, period to shutdown, etc.	Maximum allowable operating pressure = 84 bar
2.3 Design stress analysis available	Yes, Finite Element analysis
2.4 Define stresses	-
Primary stresses (tension, bending)	Yes from FE analysis.
Secondary thermal/residual stresses (post weld heat treatment)	Residual weld stresses after PWHT equal to 30% of the yield stress
Proof testing (level of stress and temperature)	Yes
2.5 Indication of over- or unconservatism in the loading conditions	Accurate. Due to pressure relief valves. The applied membrane and bending stress is a conservative linearisation of the calculated stress distribution obtain from detailed finite element analyses.
3 Material properties	
3.1 Material specification (base, weld) (Minimum requirements for tensile and impact properties)	TstE355 (DIN17102) SMYS = 295 MPa and UTS = 470MPa
3.2 Measured tensile and impact properties (base, weld)	Unavailable
Tensile Properties	
Impact Properties	
Full stress strain curve	
Weld Configuration (max. weld bead heights, bevel angles, width of weld and HAZ, etc.)	Narrow welds. U-profile welds, weld bead height is nominally 3 mm. Insert Nozzles
3.3 Fracture toughness	To be determined. (Objective of assessment).

	Estimated from Charpy data	Unavailable
	Estimated from a fracture toughness database	- Unavailable
	Material qualification data (CTOD, K, J, R-curve)	- Unavailable at time of assessment. Will become available later.
3.4	Transition temperature	< -20°C
3.5	Crack growth law (e.g. fatigue), stress corrosion cracking, hydrogen embrittlement	No corrosion. Fatigue analysis using a conservative relationship in BS 7910 to check crack extension
3.6	Embrittlement, ageing (temper embrittlement, irradiation embrittlement), hydrogen embrittlement.	Inapplicable.
3.7	Weld mismatch	Overmatched
3.8	Modulus of elasticity and Poisson's ratio	E = 199000 MPa,
3.9	Indication of over- or unconservatism in materials properties	Sensitivity analysis performed to support the required toughness. I.e. defect size and yield stress varied.
4	**Flaw data and NDE aspects** **Inspection history (frequency and extent of inspections)**	
4.1	Flaw type and cause (fatigue, lack of fusion, planar, volumetric, fabrication, in service etc.)	Assumed fabrication defect
4.2	Flaw location (weld metal, fusion line etc.)	Welds and fusion line
4.3	Flaw size and orientation	Assumed 5 x 25 mm
4.4	Basis for flaw data (NDE method) (NDE method(s) used and indicate procedure(s) used)	high POD required.
	Probability of detection (influences-accessibility difficulties, less than 100% coverage)	85%
	Defect accuracy (influences-accessibility difficulties, conditions)	Depth +/- 1 mm, Length = +/- 12 mm. Shop inspection with favourable conditions.
	Extent of defects e.g. distribution of the defects, number of defects per metre, part(s) of the weld and part(s) of the equipment, etc.	Isolated defects.
	Defect growth rates (estimated defect growth rates (also corrosion rates) from periodic inspections)	Upperbound fatigue analysis used. No significant growth calculated.
4.5	Defect interaction (evaluation (including the recategorisation of subsurface to surface defects)	No interaction
4.6	Indication of over- or unconservatism in defect data	Crack-like defects and a relatively large fabrication defect size greater than a weld bead height are assumed.
5	**Analysis option**	
5.1	Decide if FFP is unnecessary e.g. a superficial repair is possible	Repairs to be avoided if possible because of concerns about detrimental effects. See FFP inspection requirements
5.2	Applied assessment procedure and level of analysis	PD6493:1991 level 2.
5.3	Fracture initiation (brittle fracture, ductile fracture initiation)	Brittle fracture assessment.
5.4	Applied constraint factor (CTOD-K conversion)	Conservatively taken as 1.0
5.5	Ductile tearing analysis (specify fracture resistance curve)	
5.6	Crack growth (e.g. fatigue), (See part I Figure 12)	Fatigue checked.
5.7	Leak before break (See part I Figure 13) or redundancy	Since subcritical crack growth is insignificant there is no reason to perform a leak before break analysis.
5.8	Probabilistic analysis (See part I Figure 19)	Analysis was deterministic
	Applied method	
	Applied distributions	
6	**Limit load and stress intensity factor solution**	
6.1	Applied limit load solution (plastic collapse)	PD6493:1991 for sphere and cylinder. Note that plastic collapse is not a failure mode for small defect in thick walled vessels.
	definition of flow stress	As defined in PD6493:1991

6.2 Applied stress intensity factor solution	PD6493:1991
stress concentration factor	Sensitivity analysis performed
6.3 Indication of conservatism or unconservatism in solutions chosen	Used conservative stress distributions. The applied membrane and bending stress is a conservative linearisation of the calculated stress distribution obtain from detailed finite element analyses.
7 Significance of results	
7.1 Results sensitivity analysis	Complete sensitivity analysis performed on e.g. yield stress, defect sizes and stress distributions.
Reserve factor as a function of e.g. defect size, fracture toughness etc. versus consequences of failure (Check against item 1.7)	A partial safety factor equal to 1.4 on fracture toughness. (The calculated toughness has been multiplied by 1.4 to account for scatter in fracture toughness data). Inspection accuracy taken into account in defining inspection requirements.
7.3 Probability of result falling outside of FAD being less than target probability values versus consequences of failure.	Probabilistic analysis not carried out.
8 Conclusion	
If not fit for purpose then recommend which input parameters should be further refined, including monitoring with NDE and/or refer to mitigation check list.	Minimum required fracture toughness CTOD = 0.18 mm. TOFD: defect depth 4 mm and length 20 mm.

13.3 Acceptance criteria for mechanised ultrasonic inspection of girth welds in pipelines

objective

To show how new acceptance criteria (AC) could be developed when a new inspection technique is used.

background

Offshore pipelines (trunkline) were welded using a mechanised welding process in combination with a narrow gap weld geometry (steep bevel) in order to save time. The typical defects of this welding process are lack of side-wall fusion (LOSF) defects. Mechanised ultrasonic evaluation was selected instead of ultrasonic evaluation and radiography because manual ultrasonic evaluation has a low probability of detection and radiography is time-consuming and has a health and safety risk. Due to the higher probability of detection using mechanised UT, the repair rate would increase when the good workmanship criteria for manual ultrasonic inspection are used. This could be avoided by using an FFP based AC allowing larger defects than GWMS. The application of FFP based defect criteria may reduce the costs of the pipe laying without compromising the integrity of the pipeline.

defect type, position, and geometry

The majority of defects are lack of side-wall fusion defects. In view of the loading during the pipe laying these defects are the most detrimental defects. Because the LOSF defect is sited at the interface of the heat affected zone (HAZ) and weld, the yield stress and fracture toughness, of the pipeline material and the fracture toughness of the HAZ respectively are used. The flat plate model is assumed because the ratio of the pipe radius R to the wall thickness "t" is sufficiently high ($R/t > 10$). The width of the plate is taken equal to the pipe circumference (2872 mm) and the thickness to the pipe thickness (19 mm). This is effectively an infinitely large flat plate.

loading condition

The highest stresses will occur during the pipe laying process in the axial direction. The highest stress allowed is 410 MPa. This includes bending stresses and a safety factor. The in-service loading conditions for the type and size of girth weld defects considered in this example are insignificant.

defect sizing-NDE method

The economics of the pipe laying process demands a fast NDE technique. Furthermore height (depth) and length sizing are necessary if FFP based AC are to be used. A suitable NDE technique is a mechanised ultrasonic technique in which pulse echo (PE) is combined with TOFD. The combination of techniques results in a high probability of detection. PE is more accurate for determining the length of defects while TOFD is more accurate for determining the height of defects.

FFP analysis

A normal FFP analysis (BS 7910 level 2A) was carried out. No partial safety factors were required since the failure consequences (no loss of human life and no pollution of the environment) during the pipe laying process are considered as less than moderate. In addition, worst case values are taken for the material properties and loading conditions. In the FFP analysis, the critical defect sizes were determined. The critical sizes of surface defects and embedded defects, having a distance to the surface (ligament height) of 3 mm, are shown in the Figure 40. For practical reasons the ligament was not varied. Using the pulse echo technique the wall thickness is divided in zones of about the weld bead height i.e. 3 mm. The defects laying in the zones adjacent to the surface are considered as surface defects. In addition it is very difficult to distinguish them from a surface defect.

conclusion

A simple proposal for the mechanised ultrasonic acceptance criteria is shown in Figure 40. The maximum allowable defect has a height of 3 mm and a length of 50 mm. The height is typical the height of one weld bead. This is a suitable AC for the pipeline girth weld, taking into account the inaccuracies of the NDE-techniques.

The FFP-based AC reduced the number of repairs. Nevertheless the new AC allows defects larger than GWMS and this could lead to a lowering of the weld workmanship. In order to ensure that GWMS does not slip, a penalty can be introduced if defects exceeding GWMS AC but acceptable to the FFP-based AC are consistently found. The GWMS criteria must be used if for example five out of ten consecutive welds were rejected according to the GWMS criteria but were accepted according to the FFP-based criteria. When ten consecutive welds are accepted according to the GWMS criteria the FFP-based criteria can be used again. In this way bad quality is punished and good quality rewarded .

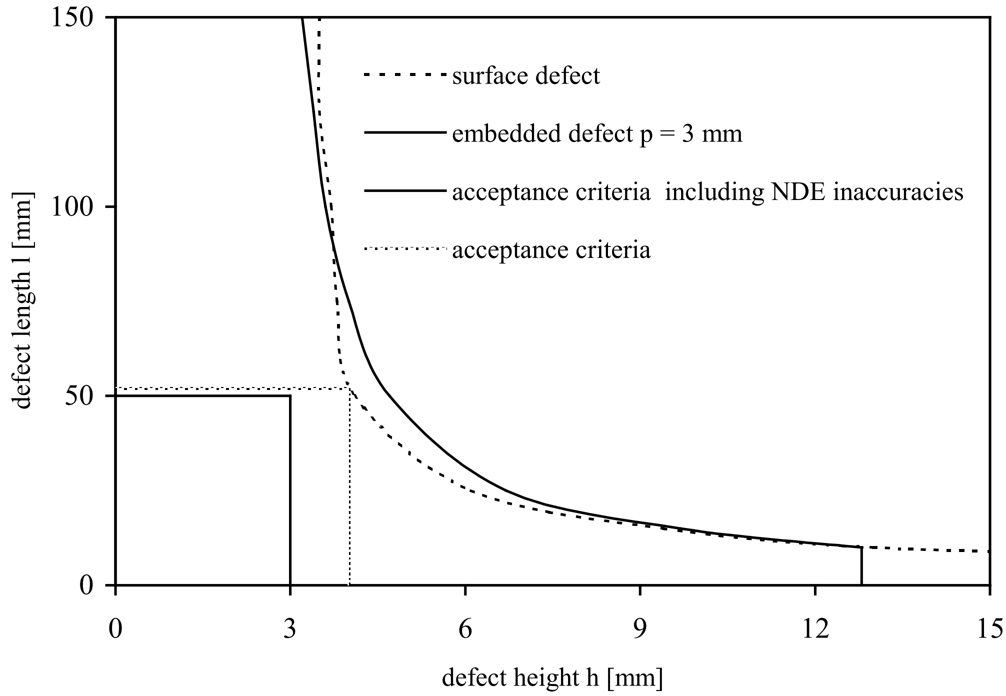


Figure 40 Critical defect length versus defect height and acceptance criteria derived from the FFP analysis including underestimation of the NDE techniques used

Check list for FFP assessments	
item	**input/results/comments**
1 General (also see Information Check List)	
1.1 Structure/equipment identification (detail)	pipeline girth weld
1.2 Design code (pressure vessel, bridge, offshore etc.)	offshore pipeline NEN 3650
1.3 Environment	offshore: sea water
1.4 Material	welded steel
1.5 Dimensions (width, thickness, etc)	wall thickness is 19 mm and the diameter is 36 inch
1.6 Post weld heat treatment	not applied
1.7 Consequences of failure	
1.7.1 Brittle fracture	no ductile fracture, see item 5.3
1.7.2 Potential risk to a person	no
1.7.3 Potential risk to personnel	no
1.7.4 Potential risk too the environment	no
1.7.5 Potential financial consequences	yes, purpose of assessment
1.7.6 Target reserve factor or probability of failure	see item 7
2 Loading conditions	
2.1 Design conditions e.g. temperature, pressure, static/dynamic loading, proof testing, design life, etc.	lay barge load, in service pressure
2.2 Operating conditions e.g. temperature, environment, pressure, static/dynamic loading, re-hydrotesting, period to shutdown, time years in service, etc.	-10 ºC during laying conditions 4 ºC on sea bottom, dynamic loading, small number of cycles.
2.3 Design stress analysis available	yes
2.4 Define stresses	maximum allowable stress during laying
Primary stresses (tension, bending)	410 MPa (=85% of SMYS)
Secondary thermal/residual stresses (post weld heat treatment)	residual weld stress, relaxed according to BS 7910
Proof testing (level of stress and temperature)	not a significant loading for the girth welds compared to the lay barge loads.
2.5 Indication of over- or unconservatism in the loading conditions	axial bending stress included in primary stress
3 Material properties	API X70
3.1 Material specification (base, weld) (Minimum requirements for tensile and impact properties)	minimum specified yield is 482 MPa, minimum tensile strength is 565 MPa (base)
3.2 Measured tensile and impact properties (base, weld)	
Tensile Properties	base: yield strength is 503 MPa, tensile strength is 615 MPa base: yield strength is 600 MPa, tensile strength is 665 MPa
Impact Properties	HAZ: 200 J average of three at -20 ºC weld: 91 J average of three at -20 ºC
Full stress strain curve	not available
Weld Configuration (max. weld bead heights, bevel angles, width of weld and HAZ, etc.)	3 mm bead height, steep U-shaped bevel
3.3 Fracture toughness	
Estimated from Charpy V data	not used because CTOD data available
Estimated from a fracture toughness database	not used because CTOD data available
Material qualification data (CTOD, K, J, R-curve)	0.22 mm, maximum load CTOD of the HAZ minimum of three tests at –20 ºC (BS 7448)
3.4 Transition temperature	below -20 ºC
3.5 Crack growth law (e.g. fatigue), stress corrosion cracking, hydrogen embrittlement	not applicable no fatigue during installation and in service
3.6 Embrittlement, ageing (temper embrittlement, irradiation embrittlement), hydrogen embrittlement.	not applicable, in service clean gas is transported hence corrosion does not occur and there is external protection from coating and cathodic

		protection.
3.7	Weld mismatch	assume overmatched
3.8	Modulus of elasticity and Poisson's ratio	assume 205 GPa and 0.3
3.9	Indication of over- or unconservatism in materials properties	minimum required yield and ultimate tensile stress -20 °C CTOD testing temperature instead of -10 °C
4	**Flaw data and NDE aspects** **Inspection history (frequency and extent of inspections)**	all welds are inspected during installation of the pipe
4.1	Flaw type and cause (fatigue, lack of fusion, planar, volumetric, fabrication, in service etc.)	assume all types of weld defects but analysis concentrates on lack of fusion defects (planar, fabrication). all defects are treated as planar because it is difficult to distinguish them from non-planar with ultrasonic testing.
4.2	Flaw location (weld metal, fusion line etc.)	assume defects in the HAZ
4.3	Flaw size and orientation	assume due to the steep bevel of the weld, the defects will be perpendicular to the primary membrane stress
4.4	Basis for flaw data (NDE method) (NDE method(s) used and indicate procedure(s) used)	mechanised ultrasonic testing a combination of pulse echo (PE) and time of flight diffraction (TOFD)
	Probability of detection (influences-accessibility difficulties, less than 100% coverage)	PE: 60-85 % TOFD: 55-85% at tolerable defect height POD is about 85% combined: approximately 95 % (see table 1 and Figures 31-33 in section 8.4 and 8.5 respectively)
	Defect accuracy (influences-accessibility difficulties, conditions)	PE length + 2 mm TOFD height + 1 mm On a lay barge there is a high time constraint inaccuracies given are based on inaccuracy of the technique, see table 1 in Section 8.3. When rates of NDE are high, human error can be reduced by automatic interpretation of the results.
	Extent of defects e.g. distribution of the defects, number of defects per metre, part(s) of the weld and part(s) of the equipment, etc.	Unknown as analysis is prior to fabrication
	Defect growth rates (estimated defect growth rates (also corrosion rates) from periodic inspections)	not applicable, see item 3.5
4.5	Defect interaction (evaluation (including the recategorisation of subsurface to surface defects)	will be treated in accordance with BS 7910
4.6	Indication of over- or unconservatism in defect data	The use of a combination of techniques should also enhance both detection and accuracy
5	**Analysis option**	
5.1	Decide if FFP is unnecessary e.g. a superficial repair is possible	repair is a part of the normal procedure, see the bonus for GWMS versus FFP in the conclusions.
5.2	Applied assessment procedure and level of analysis	BS 7910 level 2A was used because no stress-strain curve and no tearing data were available
5.3	Fracture initiation (brittle fracture, ductile fracture initiation)	only ductile tearing in CTOD test, therefore assumed failure will be by ductile tearing
5.4	Applied constraint factor (CTOD-K conversion)	use one as factor (conservative)
5.5	Ductile tearing analysis (specify fracture resistance curve)	not used, only maximum load CTOD available
5.6	Crack growth (e.g. fatigue), (See Part I Figure 12)	inapplicable fatigue insignificant during laying because of small number of cycles in-service fatigue insignificant because fatigue loading is below threshold
5.7	Leak before break (See Part I Figure 13) or redundancy	inapplicable during pipe laying since no fatigue growth in service, no need to apply

		LBB analysis
5.8	Probabilistic analysis (See Part I Figure 19)	not applied, too few data available
	Applied method	inapplicable
	Applied distributions	inapplicable
6	**Limit load and stress intensity factor solution**	The radius of the pipe is large enough to use flat plate solutions
6.1	Applied limit load solution (plastic collapse)	normal bending restraint solution used for the surface defect, free rotation solution used for the embedded defect (BS 7910)
	definition of flow stress	average of yield stress and ultimate tensile stress
6.2	Applied stress intensity factor solution	BS 7910
	stress concentration factor	no SCF used for weld bevel since bevel is almost flush with parent plate
6.3	Indication of over- or unconservatism in solutions chosen	flat plate solutions are considered as conservative when applied to a cylindrical geometry with a large radius.
7	**Significance of results**	
7.1	Results sensitivity analysis	proposed acceptance criteria is still valid when a CTOD of 0.15 mm is used or the actual base metal yield strength this used instead of the minimum specified yield strength for API X-70 material.
7.2	Reserve factor as a function of e.g. defect size, fracture toughness etc. versus consequences of failure (Check against 1.7)	proposed acceptance criteria is still valid when inaccuracies of NDE method are included. -20 °C CTOD testing temperature instead of –10 °C. Maximum possible stress assumed. The reserve factor for defect size is 1.4. In view of the consequences of failure the reserve factor is considered to be adequate.
7.3	Probability of result falling outside of FAD less than target probability values versus consequences of failure.	not applied because of too few data
8	**Conclusion**	
	If not fit for purpose then recommend which input parameters should be further refined, including monitoring with NDE and/or refer to mitigation check list.	if a defect is rejected, the weld is repaired. see conclusions for more details

13.4 In-service defect in a flat plate

objective

To show

- the use of BS 7910 level 1B assessment for use for inspectors (see Section 7)
- the effect of residual stresses
- the effect of assumed defect size
- the effect of assumed fracture toughness

background

During a periodic inspection of a construction a defect was reported at a weld close to the inner surface. The length of the defect was measured using routine manual UT. The large structure was composed of large plates (e.g. width W > 1000 mm and thickness B = 25 mm) was subjected to a uniform tensile stress of 100 MPa (1/3 of 300 MPa, the minimum specified yield stress). Only the minimum specified yield stress of the steel was known (300 MPa). The construction was used in a non-aggressive environment at ambient temperatures. A post weld heat treatment (PWHT) had not been carried out. There were no stress concentrations in the vicinity of the defect.

FFP analysis

The analyses were all carried out using a BS 7910 level 1B analysis following the approach outlined in Section 7. This type of analysis is normally used when there is minimum input data. Conservative values for input data are assumed and extra conservatism is provided by the analysis itself.

The first step is to calculate the through-thickness defect size that is equivalent to the reported surface defect. The 15 mm long defect was assumed to have a depth of 6 mm. This is equivalent to a depth of two weld bead heights. This was felt to be a relatively conservative estimate of the depth since the defects were expected to be less than a weld bead height in depth. Using the diagrams in the BS 7910 figures N1 (see Figure 23a in Section 7) the equivalent through-thickness to the 6x15 mm defect is 3.5 mm, see Table 5.

Table 5 Equivalent defect size a,¯ of the reported surface defect:

defect	a/B	a/2c	a,¯/B	a,¯ [mm]
surface	0.24	0.4	0.14	3.5

The second step is to calculate the allowable defect size. Because the exact position of the defect is unknown (base, heat affected zone or weld), and there is minimal materials data, the lower bound material properties were used and the maximum level of residual stresses assumed and used in a conservative level 1 analysis as mentioned above. Initially a very conservative fracture toughness Kmat of 1000 $N/mm^{3/2}$ was assumed, implying that the defect lies in a brittle material.

Table 6 Maximum allowable equivalent defect with residual stresses up to the yield stress (as welded) and up to 30% of the yield stress (PWHT)). Kmat = 1000 $N/mm^{3/2}$

welding condition	loading [MPa]	residual stress [MPa]	total stress [MPa]	$\bar{a}_m$ [mm]
as welded	100	300	400	1.0
post weld heat treated	100	90	190	4.4

The maximum allowable equivalent size calculated was 1 mm (Table 6) using the figures given in Section 7. Note that a stress concentration of unity was assumed for the welds, because they had been ground flush. The assumed surface defect of 6x15 mm is unacceptable,. because the equivalent defect size of 3.5 mm of this defect is larger than the allowable defect size.

A post weld heat treatment PWHT reduces the residual stresses. The BS 7910 allows a reduction to 30% of the yield stress of the base material. Using the figures in Section 7, the allowable equivalent through-thickness defect length was calculated to be 4.4 mm, see Table 2. The equivalent through-thickness length is now larger than the assumed equivalent defect of 3.5 mm so the defect is therefore acceptable.

FFP analysis showing effect of an improved inspection

If it is assumed that the surface defect is re-inspected using an accurate NDE method for example the defect is reduced to a defect with a depth of 1.5 mm and a length of 15 mm, the equivalent through-thickness size is now 1.7 mm, see Table 7. Although this length is smaller, it is still longer than the allowable equivalent defect length of 1mm for the as-welded condition and the defect is still unacceptable in the as welded condition.

Table 7 Equivalent defect size $\bar{a}$, of the reassessed surface defect: height a = 1.5 mm, length 2c = 15 mm, B = 25 mm

defect	a/B	a/2c	$\bar{a}$/B	$\bar{a}$ [mm]
surface	0.06	0.1	0.066	1.7

FFP analysis showing the effect of a higher fracture toughness

A higher fracture toughness can be assumed if high Charpy V values are reported in the welding qualification procedure. It is extremely unlikely that the toughness of a brittle material will be further reduced by a PWHT and there is a reasonable probability that the fracture toughness will be increased even if the flat plate is not fully but locally post weld heat treated. For example when the fracture toughness is 2000 $N/mm^{3/2}$, the allowable equivalent defect length is 4 mm in the locally PWHT condition and 17.6 mm in the fully PWHT condition, see Table 6. The defect of 6x15 mm is now acceptable because its equivalent length before accurate NDE of 3.5 mm is smaller than the maximum allowable length of 4.0 mm.

Table 8 Maximum allowable equivalent defect length with residual stresses up to 30% of the yield stress and up to the yield stress. Kmat = 2000 $N/mm^{3/2}$

loading [MPa]	residual stress [MPa]	total stress [MPa]	$\bar{a}$, [mm]
100	300	400	4.0
100	90	190	17.6

conclusion

In this example, improved inspection is shown to be insufficient by itself to achieve FFP. A full post weld heat treatment that reduces the residual stresses significantly is sufficient to achieve fitness for purpose. If a higher fracture toughness is assumed (as a result of better information or a local or full post weld heat treatment) then FFP can also be achieved.

The results of such a simplified analysis give an indication of whether an FFP assessment is likely to be fruitful. An indication of the effect of remedial measures and improvements such as post weld heat treatment and improved inspection can also be obtained.

Check list for FFP assessments	
item	input/results/comments
1 General (also see Information Check List)	
1.1 Structure/equipment identification (detail)	welded steel plate in a construction
1.2 Design code (pressure vessel, bridge, offshore etc.)	not applicable
1.3 Environment	non corrosive environment, ambient temperatures
1.4 Material	steel
1.5 Dimensions (width, thickness, etc)	width is 1 m , thickness is 25 mm
1.6 Post weld heat treatment	no
1.7 Consequences of failure	
1.7.1 Brittle fracture	no
1.7.2 Potential risk to a person	no
1.7.3 Potential risk to personnel	no
1.7.4 Potential risk too the environment	no
1.7.5 Potential financial consequences	yes
1.7.6 Target reserve factor or probability of failure	inapplicable because of level 1 analysis, implicit reserve factor on stress and defect size moderate consequences, non-redundant structure acceptable probability of failure of 10^{-3}
2 Loading conditions	
2.1 Design conditions e.g. temperature, pressure, static/dynamic loading, proof testing, design life, etc.	ambient temperatures, static loading
2.2 Operating conditions e.g. temperature, environment, pressure, static/dynamic loading, re-hydrotesting, period to shutdown, years in service, etc.	ambient temperatures, non corrosive, no cyclic loading
2.3 Design stress analysis available	100 MPa (1/3 of minimum yield stress)
2.4 Define stresses	
Primary stresses (tension, bending)	100 MPa in tension, no stress concentrations
Secondary thermal/residual stresses (post weld heat treatment)	equal to 300 MPa in the as welded condition equal to 30% of the yield stress in PWHT condition
Proof testing (level of stress and temperature)	no
2.5 Indication of over- or unconservatism in the loading conditions	residual stresses uniform over full thickness

3 Material properties	
3.1 Material specification (base, weld) (Minimum requirements for tensile and impact properties)	minimum yield stress of the base is 300 MPa
3.2 Measured tensile and impact properties (base, weld)	
Tensile properties	
Impact properties	
Full stress strain curve	unavailable
Weld configuration (max. weld bead heights, bevel angles, width of weld and HAZ, etc.)	butt weld V-shaped, bead height equals 3 mm
3.3 Fracture toughness	assumed 1000 $N/mm^{3/2}$ (brittle material)
Estimated from Charpy V	inapplicable
Estimated from a fracture toughness database	inapplicable
Material qualification data (CTOD, K, J, R-curve)	unavailable
3.4 Transition temperature	
3.5 Crack growth law (e.g. fatigue), stress corrosion cracking, hydrogen embrittlement	inapplicable, see item 2.2
3.6 Embrittlement, ageing (temper embrittlement, irradiation embrittlement), hydrogen embrittlement.	inapplicable
3.7 Weld mismatch	assumed overmatched
3.8 Modulus of elasticity and Poisson's ratio	unnecessary
3.9 Indication of over- or unconservatism in materials properties	lower bound toughness used assumes brittle fracture
4 Flaw data and NDE aspects **Inspection history (frequency and extent of inspections)**	
4.1 Flaw type and cause (fatigue, lack of fusion, planar, volumetric, fabrication, in service etc.)	Planar, fabrication defect larger than the GWMS criteria found in service
4.2 Flaw location (weld metal, fusion line etc.)	near or in the weldment
4.3 Flaw size and orientation	6x15 mm height is assumed to be twice the weld bead height
4.4 Basis for flaw data (NDE method) (NDE method(s) used and indicate procedure(s) used)	routine manual ultrasonic inspection
Probability of detection (influences-accessibility difficulties, less than 100% coverage)	inapplicable for given defect as detected but for other defects POD approx. 50%, accessibility good.
Defect accuracy (influences-accessibility difficulties, conditions)	If you use level I, you do not have to take account of the uncertainty in defect size as this is included in the assessment. depth is inaccurate
Extent of defects e.g. distribution of the defects, number of defects per metre, part(s) of the weld and part(s) of the equipment, etc.	single defect suspected as no other defects detected during NDE of a large construction.
Defect growth rates (estimated defect growth rates (also corrosion rates) from periodic inspections)	in applicable as there is no mechanism for growth
4.5 Defect interaction (evaluation (including the recategorisation of subsurface to surface defects)	only a single defect was detected.
4.6 Indication of over- or unconservatism in defect data	The defect size is conservative. The defect has probably the same height as a weld bead (3 mm).
5 Analysis option	
5.1 Decide if FFP is unnecessary e.g. a superficial repair is possible	Repair before the next maintenance schedule is impractical.
5.2 Applied assessment procedure and level of analysis	BS 7910 level 1B
5.3 Fracture initiation (brittle fracture, ductile fracture initiation)	brittle
5.4 Applied constraint factor (CTOD-K conversion)	K_{Ic} used

5.5	Ductile tearing analysis (specify fracture resistance curve)	inapplicable
5.6	Crack growth (e.g. fatigue), (See Part I Figure 12)	inapplicable
5.7	Leak before break (See Part I Figure 13) or redundancy	inapplicable
5.8	Probabilistic analysis (See Part I Figure 19)	insufficient data
	Applied method	inapplicable
	Applied distributions	inapplicable
6	**Limit load and stress intensity factor solution**	
6.1	Applied limit load solution (plastic collapse)	simple procedure for plastic collapse in Section 7.
	Definition of flow stress	average of yield and ultimate tensile stress
6.2	Applied stress intensity factor solution	infinite flat plate solution
	Stress concentration factor	inapplicable because the flat plate with flush ground welds does not have a stress concentration factor
6.3	Indication of over- or unconservatism in solutions chosen	weld has been assumed to be ground flush with no weld toe stress concentration. This may be slightly unconservative
7	**Significance of results**	
7.1	Results sensitivity analysis	-Not FFP in as –welded condition, if upper bound defect size assumed or even a smaller defect size determined via NDE -FFP if . PWHT -FFP with full residual stresses if a higher level of fracture toughness assumed
7.2	Reserve factor as a function of e.g. defect size, fracture toughness etc. versus consequences of failure (check against item 1.7)	built in reserve factor in level 1 in BS 7910 conservative low level of fracture toughness assumed weld defect depth assumed to be much deeper than most expected weld defects. failure probability of the order 10^{-3} expected (see BS 7910)
7.3	Probability of result falling outside of FAD less than target probability values versus consequences of failure.	inapplicable
8	**Conclusion**	
	If not fit for purpose then recommend which input parameters should be further refined, including monitoring with NDE and/or refer to mitigation check list.	-not FFP for the assumed conservative defect size in the as-welded condition. -FFP when a post weld heat treatment applied -FFP when a higher fracture toughness assumed -it is therefore worthwhile measuring the fracture toughness and if necessary performing a post weld heat treatment

13.5 Advanced FFP on a storm surge barrier

objective

To show how one deals with a complex FFP where large scale testing is needed to verify the approach.

background

An assessment was needed for a storm surge barrier that consisted of concrete piers and steel sliding doors. The loading from the water (tidal and wave loads) is carried to the piers by three horizontal tubular truss girders. During the inspection of the welds in the truss girders it was found that the ultrasonic response in the base material was very low. This was then thought to be caused by a coarse grain structure, which could cause a lower fracture toughness. Some unused material of the tubes was metallurgically investigated and the material was found to have a coarse grained microstructure with a yield stress that was less than the specified strength. The Charpy V impact values were also lower than the minimum specified value confirming the suspected problem with fracture toughness. As a result it was decided to stop further installation and perform an FFP assessment. The replacement of the tubulars in the structure already in place would have caused significant delays and enormous additional costs. There was also considerable pressure to complete the FFP assessment within a limited time because of the delay to installation.

problem definition and extent

Eventually only the hot-rolled tubes were found to be embrittled. It was discovered that the manufacturer had changed the process from cold rolling to hot rolling during production while the material had only been qualified for cold rolling. Because only the hot-rolled tubes suffered this problem, the manufacturing and installation of truss girders consisting of cold-rolled tubes was continued. After installation of the cold rolled tubes was re-started, the FFP of the installed hot-rolled tubes was determined by investigating the hot-rolled tubes that had not yet been welded

FFP approach

A non-destructive technique for investigating the grain size of the hot-rolled tubes was first sought. Then the relationship between the grain size and the fracture toughness was developed. Rejection criteria were then established for the grain size.

NDE

After identifying hot rolled tubes with a large grain size indicating a potential brittle fracture problem using manual UT, replicas were taken of the microstructure. The grain size was determined from the replicas. In all, some 20.000 replicas were made from the 3.5 km length of tubes that had to be inspected.

FFP analysis

A FFP assessment based on the BS 7910 level 1B (PD 6493 (1981) was used to established a safe CTOD value. Because the fracture toughness was not specified for the original design in terms of CTOD, a large number of full-scale tests on tubular joints and tubes were conducted and analysed in order to check the failure mechanism and the outcome of the FFP assessment. Initial defects were created by fatigue loading. The most likely site of defects is in the welds.

However, it is was expected and demonstrated by testing that the fatigue could extend the weld fabrication defects into the embrittled hot rolled base material.

Table 9 shows the length of tube, which had to be replaced initially before installation and during the progress of the FFP analysis. When in doubt a CTOD specimen was taken from the tube.

Table 9 Rejection criteria based on grain size versus replaced tube length

tube grain size*	length [m]	percentage [%]
hot rolled	3500	100
< 8.5	1765	50
< 8	1325	38
< 6.8	1085	31
< 6.8 + acceptable microstructure	655	19

*The grain size parameter is defined as the inverse diameter of the grain (mm^{-1})

conclusion

About 655 m tube length had to be replaced because of unacceptable grain size. None of the installed tubes were replaced. The refinements and remedial actions taken were as follows:

- refinement of the stress input
- grinding of the welds to reduce the stress concentrations and improve the inspectability and thereby decrease the chance of fatigue cracks initiating.
- to inspect this tubes more often for fatigue crack growth.

13.6 Pipeline corrosion

objective

Assessment of a pipeline containing a local thinned area due to corrosion

background

This example shows the assessment of a pipeline containing an isolated local thinned area (LTA) due to corrosion. The local thinned areas were found during an internal inspection of the pipeline using a magnetic flux intelligent pig. The largest reported LTA has a length equal to 220 mm and a depth equal to 30% of the wall thickness. The inspection accuracy quoted by the inspection tool provider is that the defect depth will be reported within a ±10% tolerance of the wall thickness a with confidence level equal to 80%. The standard deviation in the length measurement is less than 20 times the standard deviation in the depth measurement. The maximum allowable operating pressure of the line is 150 bar. The dimensions and the material properties are summarised as follows:

- outside diameter = 812.8 mm
- wall thickness = 19.1 mm
- specified minimum tensile strength = 530.9 MPa (API 5L grade X65)

FFP analysis

The local thinned areas have been assessed using the DNV recommended practice RP-F101 for corroded pipelines published in 1999. Within this recommended practice the accuracy of the inspection technique/tool used can be taken into account, see the DNV RP-F101 for details. The maximum allowable pressure of the pipeline containing the above corrosion defect is calculated using the following equation.

$$p_{corr} = \gamma_m \frac{2\,t\,SMTS}{(D-t)} \frac{\left(1-\gamma_d (d/t)^*\right)}{\left(1-\dfrac{\gamma_d (d/t)^*}{Q}\right)}$$

where

$$Q = \sqrt{1+0.31\left(\frac{l}{\sqrt{Dt}}\right)^2}$$

$$(d/t)^* = (d/t)_{measured} + \varepsilon_d \; StD[d/t]$$

with

d	= depth of corroded region
t	= nominal wall thickness
D	= nominal outside diameter
l	= longitudinal length corroded region

The other parameters are a function of the accuracy of inspection and are listed below (see the DNV RP-F101 for details):

γ_m	= 0.74
γ_d	= 1.28

ε_d = 1.00
$StD(d/t)$ = 0.08

The calculated maximum allowable pressure with the corrosion is 14.87 MPa (148.7 bar), which is lower than the required maximum allowable pressure of 150 bar.

refinement

Since the calculated safe allowable pressure of the pipeline with corrosion (148.7 bar) is only slightly lower than the required maximum allowable operating pressure (150 bar) it is decided to perform a more accurate inspection of the corroded area, using manual UT.

Using the accuracy sizing accuracy of UT ±0.2 mm, see the table on "performance of NDE methods used in accordance with existing codes and standards" in this guideline, the following parameters are obtained:

γ_m = 0.77
γ_d = 1.04
ε_d = 0.00
$StD(d/t)$ = 0.01

The calculated maximum allowable pressure with the corrosion is now 17.41 MPa (174.1 bar), which is higher than the current maximum allowable pressure of 150 bar.

mitigation

When a more accurate sizing is impossible, because of limited access, the line would be determined to be unsafe. In this case the maximum allowable operating pressure could be reduced to a value below the 14.87 MPa (148.7 bar).

conclusion

It was determined, on the basis of the intelligent pig results, that the pipeline is unsafe to operate at the required maximum operating pressure of 150 bar.

Based on a more accurate verification using manual UT, it was shown that it is safe to operate at 150 bar.

When a more accurate sizing is impossible, the line could be de-rated to a maximum allowable operating pressure below the calculated failure pressure of 14.87 MPa (148.7 bar) if this does not result in unacceptable financial losses.

It should be noted that separate action is required to either monitor future extension of the corrosion damage and/or measures should be taken to stop the corrosion.

reference

DNV Recommended Practice RP-F101, *Corroded Pipelines*, (1999).

Checklist for FFP assessments	
item	**input/results/comments**
1 General (also see Information Check List)	
1.1 Structure/equipment identification (detail)	Pipeline
1.2 Design code (pressure vessel, bridge, offshore etc.)	B31
1.3 Environment	Gas
1.4 Material	API 5L grade X65
1.5 Dimensions (width, thickness, etc)	outside diameter = 812.8 mm wall thickness = 19.1 mm
1.6 Post weld heat treatment	no
1.7 Consequences of failure:	
1.7.1 Brittle fracture (yes or no)	no
1.7.2 Potential risk to a person (yes or no)	no
1.7.3 Potential risk to personnel (yes or no)	no
1.7.4 Potential risk to the environment (Yes or no)	no
1.7.5 Potential financial consequences (Yes or no)	Yes, (unplanned) repair loss of production and costs (volume per day during shutdown plus any delivery penalties)
1.7.6 Target reserve factor or probability of failure	During design the pipeline was qualified as Safety Class "Normal" accordingly to DNV OS-F101, which corresponds with a annual failure probability equal to $<10^{-4}$
2 Loading conditions	
2.1 Design conditions e.g. temperature, pressure, static/dynamic loading, proof testing, design life, etc.	Maximum allowable operating pressure = 150 bar
2.2 Operating conditions e.g. temperature, environment, pressure, static/dynamic loading, re-hydrotesting, period to shutdown, etc.	Maximum allowable operating pressure = 150 bar
2.3 Design stress analysis available	yes
2.4 Define stresses	-
Primary stresses (tension, bending)	Internal pressure and no unsupported span to cause bending
Secondary thermal/residual stresses (post weld heat treatment)	Not applicable. No welds involved and plastic collapse is the failure mode
Proof testing (level of stress and temperature)	Yes, but not relevant for plastic collapse
2.5 Indication of over- or unconservatism in the loading conditions	Accurate. Due to pressure relief valves.
3 Material properties	
3.1 Material specification (base, weld) (Minimum requirements for tensile and impact properties)	API 5L grade X65 SMUTS = 530.9 MPa
3.2 Measured tensile and impact properties (base, weld)	Unavailable
Tensile Properties	-
Impact Properties	-
Full stress strain curve	-
Weld Configuration (max. weld bead heights, bevel angles, width of weld and HAZ, etc.)	Inapplicable. No welds involved.
3.3 Fracture toughness	Inapplicable. Plastic collapse is failure mode. No welds involved.
Estimated from Charpy V data	-
Estimated from a fracture toughness database	-
Material qualification data (CTOD, K, J, R-curve)	-
3.4 Transition temperature	Inapplicable. Plastic collapse is failure mode.
3.5 Crack growth law (e.g. fatigue), stress corrosion cracking, hydrogen embrittlement	Corrosion.

3.6 Embrittlement, ageing (temper embrittlement, irradiation embrittlement), hydrogen embrittlement.	Inapplicable.
3.7 Weld mismatch	Inapplicable. No welds involved.
3.8 Modulus of elasticity and Poisson's ratio	-
3.9 Indication of over- or unconservatism in materials properties	Minimum specified yield is used as input.
4 Flaw data and NDE aspects **Inspection history (frequency and extent of inspections)**	
4.1 Flaw type and cause (fatigue, lack of fusion, planar, volumetric, fabrication, in service etc.)	Corrosion damage
4.2 Flaw location (weld metal, fusion line etc.)	Base material
4.3 Flaw size and orientation	Largest 200 mm length and 30% of wall thickness
4.4 Basis for flaw data (NDE method) (NDE method(s) used and indicate procedure(s) used)	Inspection accuracy specified by provider of the magnetic flux inspection tool.
Probability of detection (influences-accessibility difficulties, less than 100% coverage)	
Defect accuracy (influences-accessibility difficulties, conditions)	Depth 10% of wall thickness
Extent of defects e.g. distribution of the defects, number of defects per metre, part(s) of the weld and part(s) of the equipment, etc.	Single corrosion patches
Defect growth rates (estimated defect growth rates (also corrosion rates) from periodic inspections)	Unknown. To be monitored.
4.5 Defect interaction (evaluation (including the recategorisation of subsurface to surface defects)	No interaction
4.6 Indication of over- or unconservatism in defect data	Inspection accuracy specified by tool provider and is based on tool qualification tests performed on a test loop with known defects.
5 Analysis option	
5.1 Decide if FFP is unnecessary e.g. a superficial repair is possible	FFP required. A repair is costly and would introduce unwanted high residual stresses.
5.2 Applied assessment procedure and level of analysis	DNV RP-F101, Corroded Pipelines
5.3 Fracture initiation (brittle fracture, ductile fracture initiation)	Plastic collapse is the failure mode of a critical corrosion defect in the base material, see 6.1.
5.4 Applied constraint factor (CTOD-K conversion)	Inapplicable, see 5.3 and 6.1.
5.5 Ductile tearing analysis (specify fracture resistance curve)	Inapplicable, see 5.3 and 6.1.
5.6 Crack growth (e.g. fatigue), (See Part I Figure 12)	Corrosion to be monitored
5.7 Leak before break or redundancy (See Part I Figure 13) or redundancy	The 220 mm long corrosion patch is not leak before break.
5.8 Probabilistic analysis (See Part I Figure 19)	
Applied method	DNV RP-F101, Corroded Pipelines
Applied distributions	
6 Limit load and stress intensity factor solution	
6.1 Applied limit load solution (plastic collapse)	DNV RP-F101, Corroded Pipelines
definition of flow stress	-
6.2 Applied stress intensity factor solution	Not applicable, see 5.3 and 6.1.
stress concentration factor	-
6.3 Indication of conservatism or unconservatism in solutions chosen	The applied solutions are conservative and by taking into account the inaccuracy of inspection the defect sizes, upperbound defect sizes were implicitly used in the analysis.
7 Significance of results	
7.1 Results sensitivity analysis	No sensitivity analysis was carried out. Inaccuracy taken into account using partial safety factors.
7.2 Reserve factor as a function of e.g. defect size, fracture toughness etc. versus consequences of failure (Check against item 1.7)	See item 6.3 and item 7.1.

7.3	Probability of result falling outside of FAD less than target probability values versus consequences of failure.	FAD not used. Probability of failure estimated to be $<10^{-4}$. See item 1.7.
8	**Conclusion**	
	If not fit for purpose then recommend which input parameters should be further refined, including monitoring with NDE and/or refer to mitigation check list.	-Safe after more accurate external UT inspection with an acceptable probability of failure in the light of the consequences. -Alternatively if more accurate inspection proves to be impractical the pipeline could be de-rated when the defect would be acceptable.

13.7 Heat Exchanger

objective

To demonstrate the influence of improved information on assessment results.

background

During the ultrasonic inspection of tube to tube-sheet welds of a heat exchanger, see Figure 41, defects were detected visually in the tube-sheet. These defects were located in the vicinity of the fillet between tube-sheet and gas outlet channel. Further inspection of this region with MPI revealed defects over the whole circumference of the tube sheet.

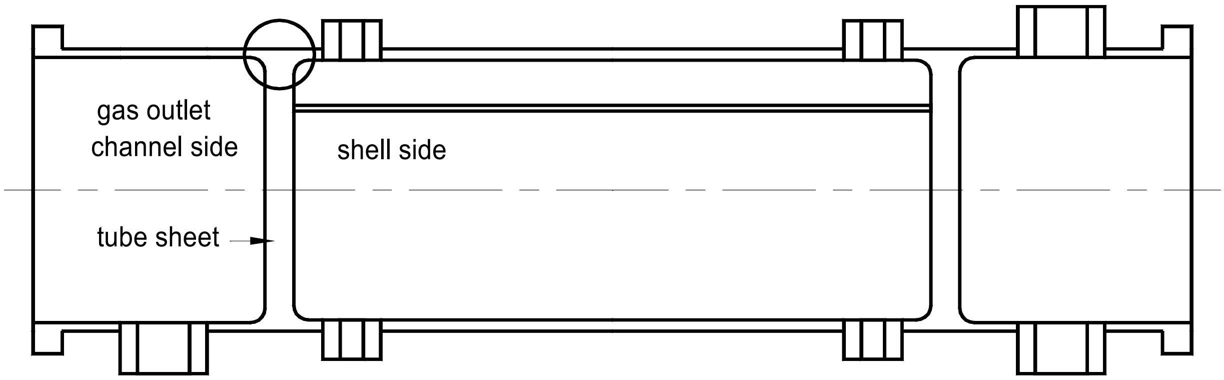


Figure 41 Heat exchanger with region of interest in circle

As a result it was decided to check for defects on the more critical and inaccessible high pressure shell side. Using manual ultrasonic inspection from the exterior surface, a region with defects was found as shown in Figure 42. There were serious doubts about the mechanical integrity of the heat exchanger so an assessment of the defects on shell side was carried out.

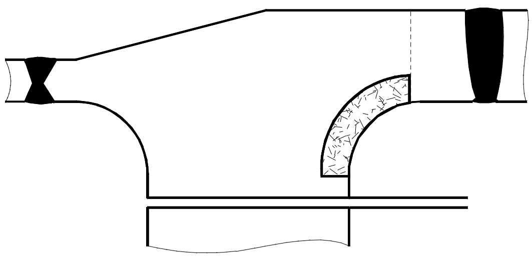


Figure 42 Region with defects and assumed fracture surface (dotted line)

approach

The heat exchanger is a pressure vessel designed according to a general code. A first assessment (I) was performed with the material properties from the design documents, the results from manual ultrasonic testing, and local stresses in the region of the defects, calculated with finite element analysis for the geometry without defects. This assessment resulted in the rejection of the heat exchanger. After an extended investigation of the defects using an advanced NDE method (TOFD) a refined analysis (II) was possible and FFP was demonstrated.

defect type, position and geometry

assessment I

With manual ultrasonic inspection a region with defects was found as shown in Figure 2. It was impossible to determine the nature and distribution of the defects. Therefore, a conservative circumferential surface flaw of constant depth was used. The depth (15 mm) was the maximum depth at which defects were found. The flaw was assumed to start at the fillet between shell and tube-sheet with its direction perpendicular to the shell.

assessment II

Extensive inspection with TOFD showed a large number of separate point reflectors. These were interpreted as defects with a diameter less than 2 mm. Defect categorisation resulted in penny-shaped flaws as shown in Figure 43.

A single upper bound surface flaw at the fillet between shell and tube-sheet, perpendicular to the shell, was used in the assessment. This flaw was conservatively assumed to have a depth of 6 mm.

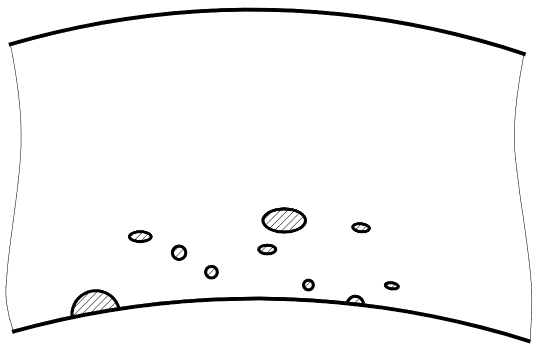


Figure 43 Defects in cross surface after categorisation

loading condition

The pressure within the shell and thermal expansion differences govern the design loads. Another load case existed because of the requirement that the heat exchanger be pressurised to proof test pressure at ambient temperature without damaging the equipment. Stresses were calculated for both load cases for the geometry without defects using an axi-symmetric finite element analysis. The maximum stresses in the region of interest, perpendicular to the flaw, occurred at the proof test pressure. The stresses in the cross section were linearised, resulting in a membrane and a bending stress. The internal pressure acting on the sides of the flaw tends to open the flaw. Therefore, this pressure has been taken into account in calculating the stress intensity factor.

material properties

Material properties from material certificates were used. Fracture toughness was derived from Charpy V impact test results at ambient temperature using BS 7910 lower bound relationship for the lower shelf and transition zone.

No loss of wall thickness was determined from the wall thickness measurements. Therefore it was concluded that there was no corrosion of the shell material.

FFP analysis

The number and magnitude of the stress variations were insufficient to cause defect extension during the service life. Hence, the defects were characterised as manufacturing defects introduced during the forging process of the tube-sheet.

An assessment according to BS 7910 level 2A has been performed. The results of this first assessment (I) showed that the defects were not tolerable because of brittle fracture. This was no surprise as very low fracture toughness together with conservative flaw dimensions and relatively high stresses at proof test pressure were used.

The analysis was then refined using the flaw size estimated using advanced NDE. The results of the refined assessment (II) showed that the vessel is fit for purpose. This assessment was conducted with the use of partial safety factors on stress and flaw size for a non-redundant component and a moderate failure consequence. The assessment point lies well within the FAD diagram.

conclusion

The use of inferior fracture toughness and defect size input data led to a rejection of the vessel, whereas the use of refined information on the defect size resulted in an acceptance of the vessel.

Check list for FFP assessments	
item	**input/results/comments**
1 General (also see Information Check List)	
1.1 Structure/equipment identification (detail)	heat exchanger
1.2 Design code (pressure vessel, bridge, offshore etc.)	pressure vessel
1.3 Environment	water
1.4 Material	ASTM A 182
1.5 Dimensions (width, thickness, etc)	external diameter=1422 mm wall thicknesst=76 mm
1.6 Post weld heat treatment	yes (defect not in weld region)
1.7 Consequences of failure:	
1.7.1 Brittle fracture (yes or no)	not at high operating temperature
1.7.2 Potential risk to a person (Yes or no)	no
1.7.3 Potential risk to personnel (Yes or no)	no
1.7.4 Potential risk to the environment (Yes or no)	no
1.7.5 Potential financial consequences (Yes or no)	yes
1.7.6 Target reserve factor or probability of failure	Determination of a target reserve factor is not feasible because of the choice of lower bound values for toughness. See also item 7.2
2 Loading conditions	
2.1 Design conditions e.g. temperature, pressure, static/dynamic loading, proof testing, design life, etc.	design pressure =116 bar temperature =330°C proof test pressure =174 bar
2.2 Operating conditions e.g. temperature, environment, pressure, static/dynamic loading, re-hydrotesting, period to shutdown, etc.	not used
2.3 Design stress analysis available	not used
2.4 Define stresses	
Primary stresses (tension, bending)	stresses at proof testing were used
Secondary thermal/residual stresses (post weld heat treatment)	no secondary stresses at proof test pressure
Proof testing (level of stress and temperature)	membrane stress =60 MPa, bending stress =162 MPa at ambient temperature maximum stresses in shell cross section perpendicular to assumed flaw results from FEM after linearisation
2.5 Indication of over- or unconservatism in the loading conditions	proof test pressure is conservative for normal operating condition
3 Material properties	
3.1 Material specification (base, weld) (Minimum requirements for tensile and impact properties)	ASTM A 182 measured properties used from material certificates
3.2 Measured tensile and impact properties (base, weld)	base material
Tensile properties	tensile strength =311 MPa, yield stress =479 MPa
Impact properties	Charpy V Cv=15 J at ambient temperature
Full stress strain curve	not available
Weld configuration (max. weld bead heights, bevel angles, width of weld and HAZ, etc.)	not applicable defects not in weld region
3.3 Fracture toughness	
Estimated from Charpy V data	K_{mat}=1225 N/mm$^{3/2}$ BS7910 lower shelf and transition behaviour
Estimated from a fracture toughness database	not applicable
Material qualification data (CTOD, K, J, R-curve)	not applicable
3.4 Transition temperature	ambient temperature is within transition region

3.5	Crack growth law (e.g. fatigue), stress corrosion cracking, hydrogen embrittlement	crack growth is not considered because there are very few load cycles in lifetime no environmental effects are present
3.6	Embrittlement, ageing (temper embrittlement, irradiation embrittlement), hydrogen embrittlement.	no environmental effects are present
3.7	Weld mismatch	not applicable (defects not in weld region)
3.8	Modulus of elasticity and Poisson's ratio	E=200 GPa; ν=0.3
3.9	Indication of over- or unconservatism in materials properties	tensile properties accurate fracture toughness conservative
4	**Flaw data and NDE aspects** **Inspection history (frequency and extent of inspections)**	
4.1	Flaw type and cause (fatigue, lack of fusion, planar, volumetric, fabrication, in service etc.)	No loss of wall thickness according to wall thickness measurements using 0° probes. Multiple defects. Fatigue not applicable, no environmental effects, therefore most likely fabrication defects.
4.2	Flaw location (weld metal, fusion line etc.)	in base material
4.3	Flaw size and orientation	Assessment I: Determination of orientation was impossible by manual ultrasonics. For the assessment, defects are conservatively assumed perpendicular to shell. Indications over the complete circumference and up to a depth of 13 mm from the inner fillet surface. Assume a circumferential surface flaw. Considering accuracy use depth a = 15 mm. Assessment II: After recategorisation one isolated surface breaking defect was found on the inside. Depth a = 4.9 mm and length 2c = 6 mm. Considering accuracy use a surface flaw depth a=6 mm and length c=a, perpendicular to shell.
4.4	Basis for flaw data (NDE method) (NDE method(s) used and indicate procedure(s) used)	Assessment I: Indications found by MPI at low pressure side. Inside of high pressure side is inaccessible, therefore manual ultrasonics performed from the outside. Indications not acceptable to GWMS code. Manual ultrasonics (PE) with 0° and angle probes is then used to determine the distance of indications to the surface and from this a conservative defect region. Assessment II: TOFD from the outside over whole circumference. Result: point reflectors defects with a diameter less than 2 mm.
	Probability of detection (influences-accessibility difficulties, less than 100% coverage)	Full circumferential coverage used. POD of NDE techniques used is Assessment I: 50 %; Assessment II: 65 - 85 % for the actual defect sizes. Since larger defects were assumed in the calculations the POD for such large defects will be of the order of 85%.
	Defect accuracy (influences-accessibility difficulties, conditions)	Assessment I: Accuracy on the distance of indications to the fillet surface is ± 2 mm. Assessment II: Accuracy on depth (a) is ± 1 mm and on length (2c) is ± 2 mm.
	Extent of defects	Assessment I: Indications over whole

	e.g. distribution of the defects, number of defects per metre, part(s) of the weld and part(s) of the equipment, etc.	circumference. Proper sizing impossible. Assessment II: Sizing and recategorisation possible.
	Defect growth rates (estimated defect growth rates (also corrosion rates) from periodic inspections)	No significant cycling to cause fatigue crack growth.
4.5	Defect interaction (evaluation (including the recategorisation of subsurface to surface defects)	Assessment I: Fully interacting multiple defects are assumed. Assessment II: Recategorisation according to BS7910 results in a representative single surface flaw.
4.6	Indication of over- or unconservatism in defect data	Assessment I: A conservative surface breaking circumferential flaw is used. Assessment II: Data is accurate. Length and depth errors are added to measured defect sizes.
5	**Analysis option**	
5.1	Decide if FFP is unnecessary e.g. a superficial repair is possible	Repair is complex because of subsurface defects and the thick wall of the vessel.
5.2	Applied assessment procedure and level of analysis	BS 7910 level 2A
5.3	Fracture initiation (brittle fracture, ductile fracture initiation)	Brittle fracture is assumed.
5.4	Applied constraint factor (CTOD-K conversion)	inapplicable
5.5	Ductile tearing analysis (specify fracture resistance curve)	not applicable
5.6	Crack growth (e.g. fatigue), (See Part I Figure 12)	inapplicable
5.7	Leak before break (See Part I Figure 13) or redundancy	inapplicable
5.8	Probabilistic analysis (See Part I Figure 19)	No probabilistic analysis carried out because of insufficient data.
	Applied method	inapplicable
	Applied distributions	inapplicable
6	**Limit load and stress intensity factor solution**	
6.1	Applied limit load solution (plastic collapse)	Internal surface flaws in cylinders oriented circumferentially (BS7910).
	definition of flow stress	Defined by FAD and tensile properties.
6.2	Applied stress intensity factor solution	Internal surface flaws in cylinders oriented circumferentially (BS7910).
	stress concentration factor	inapplicable
6.3	Indication of over- or unconservatism in solutions chosen	Solutions chosen are accurate.
7	**Significance of results**	
7.1	Results sensitivity analysis	For Assessment II the critical depth is 20 mm . (a/B=0.26 a/c=1)
7.2	Reserve factor as a function of e.g. defect size, fracture toughness etc. versus consequences of failure (Check against item 1.7)	Assessment I: reserve factor less then 1. Assessment II: the reserve factor on defect depth is 3.3 and on stresses and fracture toughness it is 1.8. These reserve factors are large and adequate for the moderate consequences mentioned in item 1.7
7.3	Probability of result falling outside of FAD less than target probability values versus consequences of failure.	See probabilistic analysis of the heat exchanger in the following example of a post mortem analysis.
8	**Conclusion**	
	If not fit for purpose then recommend which input parameters should be further refined, including monitoring with NDE and/or refer to mitigation check list.	Assessment I: Not fit for purpose, therefore refinement of defect size by NDE. Assessment II: FFP demonstrated.

13.8 Probabilistic analysis of a heat exchanger

objective

To demonstrate the use of a probabilistic analysis.

background

The same heat exchanger described in worked example is reconsidered using probabilistic methods. The heat exchanger was finally pressurised to determine the failure conditions. The material properties were measured on material removed from the vessel after failure. The probabilistic extension to the worked example on the heat exchanger is based on a report by B. A. van den Horn and M. G. van de Ruijtenbeek PMP report no. FF 96-39 February 1996.

FFP approach

The PD 6493:91 method (predecessor to BS 7910.) was used in the assessment. Three types of probabilistic analysis A, B and C were tried to obtain an idea of the effect of increasing quality of input data and to illustrate potential difficulties in performing probabilistic analysis. In order to keep the example simple, the analysis is limited to predicting the probability of brittle fracture where the loading is relatively low (e.g. no residual stresses). In addition only the variability of the defect size, fracture toughness, model uncertainty and loading are considered. See Table 1 for a summary of all the input data for the three different types of analysis.

analysis A using limited input data

defect distribution

An assumed defect distribution of surface breaking defects with depths varying between 10 and 15mm is chosen to represent the defects found. In order to obtain a fit the mean defect sized is fixed at 6.4 mm. The probability density function is given by:

$$F(a) = \lambda\, e^{-\lambda}\,(1-e^{-15\lambda})^{-1} \quad \text{for } f(a) = 0,\ a \geq 15 \text{ mm}$$

material properties

The elasticity modulus and Poisson's ratio are assumed to be deterministic (i.e. no scatter). Brittle fracture is assumed to be the fracture mode and plastic collapse is not considered. This means the scatter in tensile properties is not considered because the defects are not influenced by weld residual stresses and because of the assumption of brittle fracture rather than plastic collapse. The fracture toughness is assumed to have a Weibull distribution. The fracture toughness data (K_{Ic}) was derived from Charpy V data. A Weibull distribution was fitted to the K_{Ic} data. The mean value is 1290 N/mm$^{3/2}$ (sample mean) and the coefficient of variation (COV) is 0.28 (based on sample variance).

stresses

The linearised membrane stresses were determined using analytical formulae. The uncertainty in the model used to calculate stress (the model uncertainty) is defined conservatively with an assumed normal distribution.

analysis B with a refinement of only one input parameter

The stresses were more accurately calculated using a finite element analysis. The other variables remain the same as for the type A analysis.

analysis C with further refinement using input data from the scrapped pressure vessel defect size

The actual defects in the path of the fracture were sized and used to develop a distribution. Since an exponential distribution could not be fitted defects a histogram distribution was used.

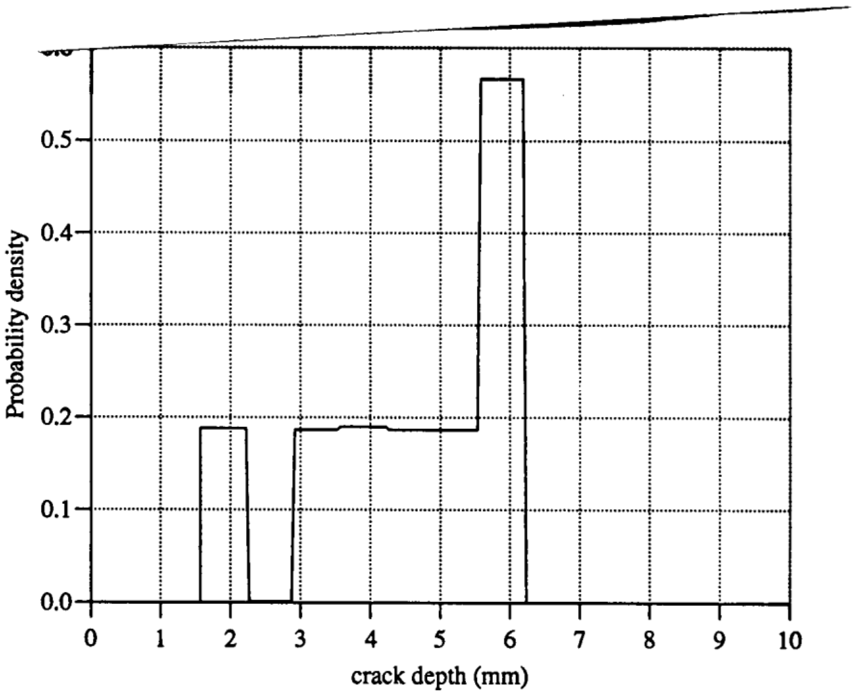


Figure 44 Probability density of embedded defects in the form of a histogram

fracture toughness

Five J_{Ic} measurements were made using material from the burst tested vessel. These values were converted to K_{Ic}. The individual values are 2680, 2680, 2070, 2190, 2220 N/mm3/2. (Note the total number of five results is less than the recommended minimum of 10 results in BS 7910 annex K5.) A Weibull distribution was fitted to the results by assuming the same mean and covariance as that of the sample.

loading and stresses

The same model uncertainty is assumed as for the type A and B analyses.

summary of inputs for the calculations

Table 10 Summary of inputs for the probabilistic calculations

Variable	Distribution	Mean, COV Analysis A	Mean, COV Analysis B	Mean, COV Analysis C
K_{Ic}	Weibull	1290 N/ mm$^{3/2}$, 0.28	1290 N/mm$^{3/2}$, 0.28	2638 N/mm $^{3/2}$, 0.12
pressure MPa	normal	10.34 MPa, 0.074	10.34 MPa,0.074	10.34 MPa, 0.074
model uncertainty	normal	1, 0.25	1, 0.15	1, 0.10
defect depth a	truncated exponential for A and B	λ= 0.056 for a defect between 0 & 15 mm	λ= 0.056 for a defect between 0 & 15 mm	
	histogram for analysis-C embedded defects			input for distributions are min. & max. values
	uniform for C surface defects			input for distributions are min. & max. values
defect aspect ratio a/c	histogram for C embedded defects			input for distributions are min. & max. values
	uniform for C surface defects			input for distributions are min. & max. values

results

The vessel burst at a pressure of 530 bar. The probabilities of failure are given in both tabular and graphical form. Four different analysis methods are used, namely numerical integration (the most accurate), Monte Carlo simulation (fairly simple to perform), FORM analysis (First Order Reliability Method), which is easy to perform and suitable for screening analyses) and a hybrid analysis combining numerical integration and a first order reliability method.

Table 11 Calculated failure probability at the mean working pressure

	analysis A	analysis B		analysis C	
			embedded defect	surface defect	all defects
Numerical integration (NI)	0.204	0.208	1.6 x 10^{-8}	3.6 x 10^{-8}	5.2 x 10^{-8}
Monte Carlo simulation	0.205	0.213	0	0	0
FORM analysis	0.220	0.223	not possible	not possible	not possible
Hybrid (NI/FORM)	0.206	0.208	1.7 x 10^{-8}	3.7 x 10^{-8}	5.4 x 10^{-8}

The numerical analysis avoids the need to fit the data to a known probability distribution. The FORM analysis cannot cope with the actual defect distributions, which cannot be fitted to a known probability distribution.

Table 12 Failure probabilities at different pressures

	probability failure pressure < design	probability failure pressure < proof test	probability failure pressure < burst test
analysis A	0.28	0.6	0.99
analysis B	0.28	0.64	0.99
analysis C	$<10^{-3}$	$<10^{-3}$	0.96

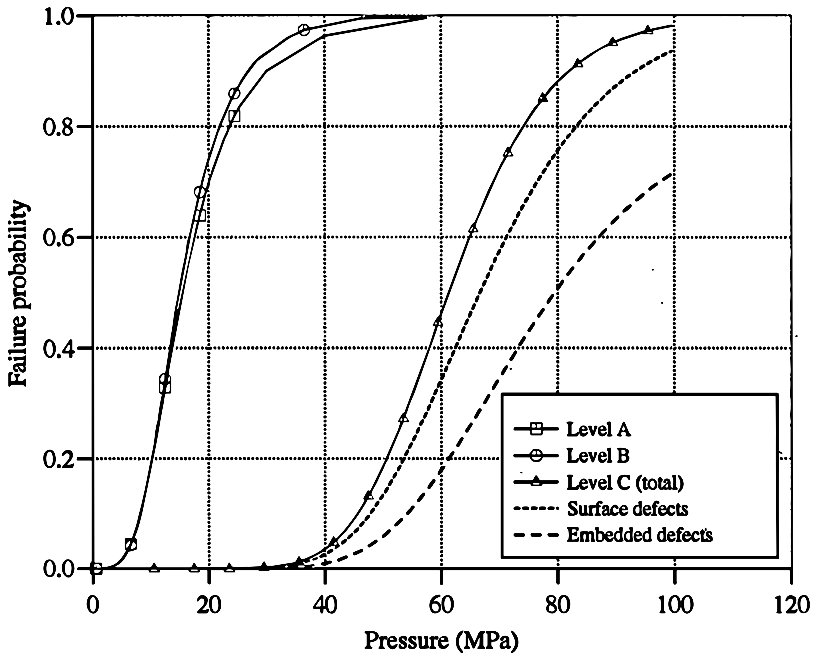


Figure 45 Failure probability versus pressure

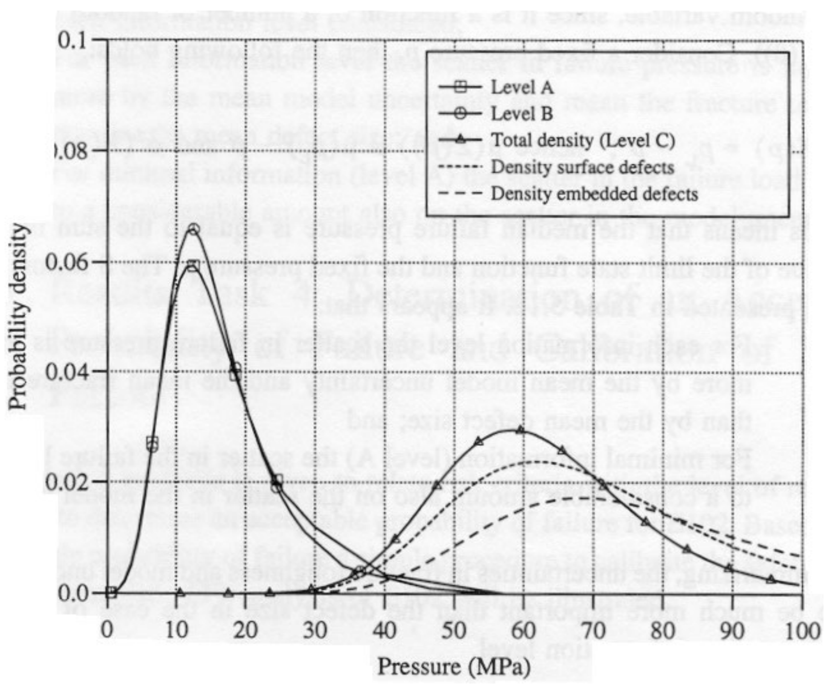


Figure 46 Failure probability density versus pressure

risk assessment

As mentioned previously in Section 4.7, this will depend on the particular situation. An idea of acceptable probabilities of failure that coincide with different consequence to give an acceptable risk is given in BS 7910, see Table 13. The BS table gives an allowance for redundancy (when there are alternative load paths allowing the re-distribution of stresses acting on a cracked member to other un-cracked members). For the case of a pressure vessel, there is no redundancy.

Table 13 An idea of acceptable probabilities of failure for different failure consequences (see BS7910)

failure consequences	redundant component	non-redundant component
moderate	2.3×10^{-1}	10^{-3}
severe	10^{-3}	7×10^{-5}
very severe	7×10^{-5}	10^{-5}

moderate consequences = plastic collapse and only potential financial consequences without threat to human life

severe consequences = brittle failure or potential threat to human life

very severe consequences = brittle failure and potential threat to multiple human lives

BS 7910 does not consider in its table the threats to the environment or financial consequences. Clearly there will be a need to consider all of the consequences and this could result in the need for lower probabilities of failure than those given in the table.

discussion

Convergence of probabilistic calculations needs to be checked. This can be done by varying the input for the calculations and in the case of Monte Carlo simulations by increasing the number of trials. A crosscheck between the results of different calculation methods including a check with a deterministic analysis is also recommended.

The acceptable probability depends on the severity of the consequences indicated above and the additional consequences of financial loss.

The failure of the heat exchanger would not result in personal injury or environmental damage. The consequences are rather high costs of replacement and loss of production with total costs significantly exceeding NLG 100k. In view of the previous comments and because the pressure vessel is a non-redundant structure, a requirement for a probability of failure of 10^{-3} is needed at the mean working pressure according to the table from BS 7910.

conclusions

The probability of failure decreases, in the example, as the quality of information increases. It is sensible to check a probability of failure result against the results obtained by other methods as a check. The FORM reliability method is a useful screening tool and can be used to perform efficient design calculations. It may become impractical to use when the input is actual, instead of idealised, assumed distributions of input data in the fabrication or service stages.

13.9 Separator

objective

To demonstrate how FFP can be used as an aid to determine inspection intervals.

background

Standard inspection intervals are normally determined by codes such as the Dutch "Rules for pressure vessels". This code also offers possibilities to extend the standard inspection intervals when certain conditions are fulfilled. The use of FFP can contribute to the classification of the “technical controllability” which is one of the conditions that determine the inspection regime.

The separator in this example, see Figure 47, is a high pressure vessel, operated more or less continuously. The outside of the vessel is inaccessible for NDE because of a heating jacket. After fabrication the vessel was inspected with standard NDE according to the code. No unacceptable indications were reported. After 5 and 11 years in service, part of the welds were inspected from the inside with Magnetic Particle Inspection (MPI) and no defects were found. After 16 years in service more comprehensive NDE was carried out from the inside using MPI and manual ultrasonics with a high sensitivity. Surface breaking defects at the inside as well as at the outside, and embedded defects were found at some circumferential welds.

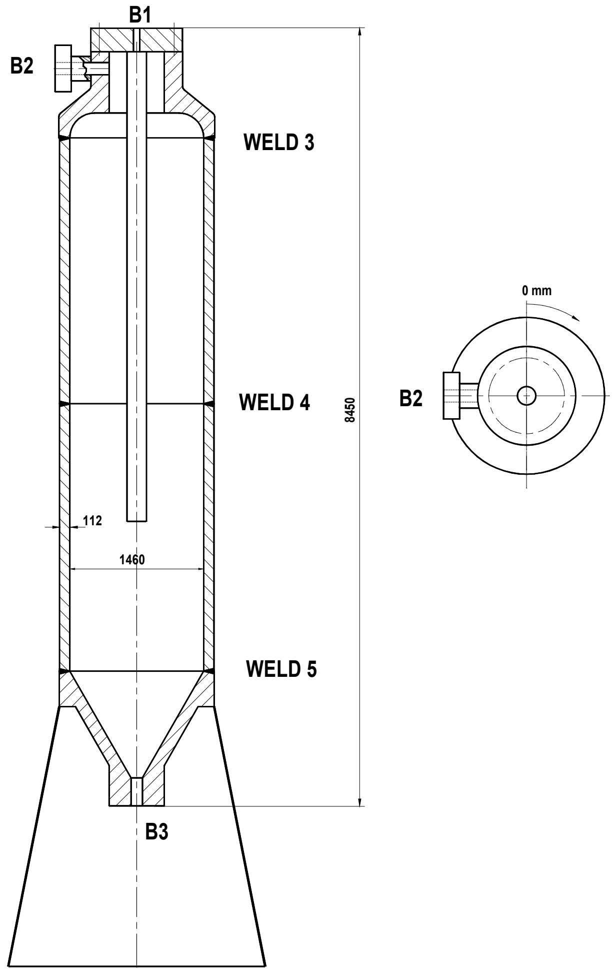


Figure 47 Illustration of the separator

approach

Accessible surface breaking defects at the inside were removed by smoothly grinding up to 6 mm deep. The resulting wall thickness was checked and proved to be satisfactory for the applied loads including a stress concentration factor. FFP assessments for the remaining defects (no grinding) were carried out. Critical defect depths and crack growth in the next 25 years were calculated. Crack growth has been back-calculated to the start of the service life using the size of the cracks that have been removed. These analyses gave insight in the severity of the cracks and could distinguish fabrication defects from defects that had arisen during service. This knowledge was used to classify the “technical controllability” and determine the inspection regime.

defect type, position and geometry

Three types of defects have been evaluated:

1 circumferential planar defect at the inside of weld 3, with dimensions based on the results of NDE and grinding (length 2c = 40 mm, depth a = 6mm)
2 embedded circumferential defects in welds 3 and 5, with the flaw length accurately measured using NDE and the flaw height assumed to equal the weld bead size (height 2a = 6 mm, length 2c = 15 mm and ligament height p = 40 mm respectively p = 50 mm)
3 circumferential planar defect at the outside of weld 3, with the length accurately measured using NDE and the depth based on weld bead size (length 2c = 120 mm, depth a = 6 mm).

loading condition

Loads have been derived from design data and historically measured internal pressures. Stresses were calculated with a simple axial-symmetric finite element model and linearised along the critical crack surfaces. Conservatively, secondary thermal bending stresses were treated as primary stress. The internal pressure acting on the sides of the flaw tends to open the flaw and therefore this pressure has been taken into account in calculating the stress intensity factor. For the fracture assessment, the relief pressure of the safety valve (31 MPa) was used.

The separator has been post weld heat treated. The residual weld stresses transverse to the weld are assumed to be 20% of the yield stress at design temperature.

For the crack growth calculations a dynamic load spectrum was determined by using the "rainflow" counting method. The historical internal pressure data within a representative period of three months was used.

material properties

From material certificates (heads and shell) and results of welding procedure qualification tests, conservative material properties were taken at the design temperature. Fracture toughness was derived from Charpy V values (lowest value of 6 experiments) at -10°C, while the operating temperature is 220°C. The upper shelf relationship from Barsom, Rolfe and Novak has been used and the results were conservatively rounded off.

FFP analysis

The FFP analysis was performed according to PD 6493:1991 level 2 (predecessor of BS 7910). Partial safety factors for moderate failure consequences were used because failure would not result in a severe hazard.

Crack growth was calculated cycle by cycle with "Paris law" ($da/dN=C(\Delta K)^m$) using parameters from PD6493:1991 ($C=3.10^{-13}$ and m=3; upper bound data for ferritic steels from literature for weld, heat affected zone and base materials). The fatigue data in PD 6493:1991 are applicable below 100 °C. Since the operating temperature is 220 °C, no valid data were available. Therefore the fatigue crack growth rates were increased by a factor of 10 to give conservative results according to judgement by an expert. This was done by increasing the parameter "C" by a factor of 10.

conclusion

The assessment shows that no significant risk of brittle fracture exists. Fatigue was not responsible for the defects because the mild loading spectrum resulted in insignificant calculated fatigue growth. Therefore it is concluded that all defects must have been there since fabrication and remained undetected during fabrication inspection and the first two in-service inspections.

The result of the FFP analysis and the absence of other failure modes means that the technical controllability of the separator is "high" whereas in an earlier stage this classification was "moderate". According to the Dutch code "Rules for pressure vessels (sheet T0102)" this change in classification offers the possibility to use an inspection regime with extended inspection intervals.

Checklist for FFP assessments	
item	**input/results/comments**
1 General (also see Information Check List)	
1.1 Structure/equipment identification (detail)	separator
1.2 Design code (pressure vessel, bridge, offshore etc.)	pressure vessel
1.3 Environment	non corrosive
1.4 Material	16MND6.05 steel
1.5 Dimensions (width, thickness, etc)	inside diameter 1460 mm wall thickness 112 mm length 8450 mm
1.6 Post weld heat treatment	full post weld heat treatment
1.7 Consequences of failure:	
1.7.1 Brittle fracture (yes or no)	no
1.7.2 Potential risk to a person (Yes or no)	no
1.7.3 Potential risk to personnel (Yes or no)	no
1.7.4 Potential risk to the environment (Yes or no)	yes
1.7.5 Potential financial consequences (Yes or no)	yes
1.7.6 Target reserve factor or probability of failure	see item 7
2 Loading conditions	
2.1 Design conditions e.g. temperature, pressure, static/dynamic loading, proof testing, design life, etc.	design pressure 324 bar, and temperature 300 °C in the fracture assessment the safety device relief pressure of 310 bar was used
2.2 Operating conditions e.g. temperature, environment, pressure, static/dynamic loading, re-hydrotesting, period to shutdown, etc.	operating pressure 272 bar, and temperature 240 °C cyclic data (3 months) pressure range/cycles pressure range/cycles < 10 bar 235 90-100 1 10-20 1 110-120 1 30-40 1 170-180 1 50-60 2 200-210 1 60-70 2 210-220 1 70-80 1 270-280 2 80-90 1
2.3 Design stress analysis available	not used
2.4 Define stresses	
Primary stresses (tension, bending)	membrane stress 0.3 MPa/bar (inside surface breaking flaws with pressure on flaw sides: membrane stress 0.4 MPa/bar) bending stress 0.174 MPa/bar for weld 3 bending stress 0.275 MPa/bar for weld 5
Secondary thermal/residual stresses (post weld heat treatment)	secondary bending stresses conservatively treated as primary stresses
Proof testing (level of stress and temperature)	not used
2.5 Indication of over- or unconservatism in the loading conditions	accurate, partial safety factor used was 1.1
3 Material properties	
3.1 Material specification (base, weld) (Minimum requirements for tensile and impact properties)	not used
3.2 Measured tensile and impact properties (base, weld)	lowest values from material certificates were used
Tensile properties	heads: tensile strength 590 MPa yield stress 439 MPa vessel wall: tensile strength 574 MPa yield stress 416 MPa The weld material tensile properties are higher than those from the base materials.
Impact properties	Lowest values of 6 experiments at -10 °C: vessel wall: Charpy V C_v=170 J heads: Charpy C_v=99 J
Full stress strain curve	unavailable

Weld configuration (max. weld bead heights, bevel angles, width of weld and HAZ, etc.)	Circumferential V-welds (no. 3 and 5 see Figure) with bead heights of 6 mm.
3.3 Fracture toughness	In the assessment a conservative fracture toughness of K_{Ic}=4000 MPa√mm was used. No partial safety factors are used.
Estimated from Charpy V data	vessel wall: K_{Ic}=6698 MPa√mm heads: K_{Ic}=5198 MPa√mm The upper shelf relationship from Barsom, Rolfe and Novak is used.
Estimated from a fracture toughness database	inapplicable
Material qualification data (CTOD, K, J, R-curve)	inapplicable
3.4 Transition temperature	The transition temperature is far below the operating temperature. Upper shelf fracture behaviour is assumed.
3.5 Crack growth law (e.g. fatigue), stress corrosion cracking, hydrogen embrittlement	$da/dN=C(\Delta K)^m$ fatigue crack growth is calculated with $C=3\cdot10^{-13}$ m=3, and $C=3\cdot10^{-12}$ m=3 no environmental effects
3.6 Embrittlement, ageing (temper embrittlement, irradiation embrittlement), hydrogen embrittlement.	no environmental effects
3.7 Weld mismatch	inapplicable
3.8 Modulus of elasticity and Poisson's ratio	$E=1.9\cdot10^5$ MPa $\nu=0.3$
3.9 Indication of over- or unconservatism in materials properties	conservative fracture toughness, no partial safety factor used
4 Flaw data and NDE aspects **Inspection history (frequency and extent of inspections)**	
4.1 Flaw type and cause (fatigue, lack of fusion, planar, volumetric, fabrication, in service etc.)	planar flaws after 17 year in service cause unknown, is object of analysis
4.2 Flaw location (weld metal, fusion line etc.)	in weld and HAZ inside vessel surface breaking at weld 3 HAZ, embedded at welds 3, 5 and outer surface at weld 3
4.3 Flaw size and orientation	All measured flaws are circumferential Inside surface flaw at weld 3: length 40 mm, depth 6 mm. Embedded flaw at weld 3: height 6 mm, length 15 mm, ligament 40 mm. Embedded flaw at weld 5: height 6 mm, length 15 mm, ligament 50 mm. Outer surface flaw at weld 3: depth 6 mm, length 120 mm.
4.4 Basis for flaw data (NDE method) (NDE method(s) used and indicate procedure(s) used)	Manual ultrasonics and MPI in combination with grinding was used from the inside. Flaw heights were estimated based on weld bead height.
Probability of detection (influences-accessibility difficulties, less than 100% coverage)	POD=50 % on average for all defects. For inside surface breaking defects POD=80%. Each weld that was inspected was fully covered. Some of the welds were not inspected
Defect accuracy (influences-accessibility difficulties, conditions)	Length of defects was accurate to +/- 2mm. Depth of defects, measured by grinding, was accurate to +/- 0.5 mm. Otherwise defect depths were estimated to be no deeper than a weld bead. Ligament height of embedded defects was accurate to +/- 4 mm.
Extent of defects e.g. distribution of the defects, number of defects per metre, part(s) of the weld and part(s) of the equipment, etc.	Defects are only found at welds. The number of defects per weld was 0-4. All defects were separated defects without interaction.
Defect growth rates	Historic inspection data are not accurate enough to

	(estimated defect growth rates (also corrosion rates) from periodic inspections)	determine crack growth rate. Calculated crack growth rate is <0.5 mm in 25 year.
4.5	Defect interaction (evaluation (including the recategorisation of subsurface to surface defects)	inapplicable
4.6	Indication of over- or unconservatism in defect data	accurate, partial safety factor used was 1.1
5	**Analysis option**	
5.1	Decide if FFP is unnecessary e.g. a superficial repair is possible	Grinding was carried out on inside surface breaking defects as a mitigation measure and to determine the defect depth. Because of the thick vessel wall, outer surface- and embedded defects repair is complex.
5.2	Applied assessment procedure and level of analysis	PD6493:1991 level 2
5.3	Fracture initiation (brittle fracture, ductile fracture initiation)	Both possibilities were taken into account.
5.4	Applied constraint factor (CTOD-K conversion)	inapplicable
5.5	Ductile tearing analysis (specify fracture resistance curve)	inapplicable
5.6	Crack growth (e.g. fatigue), (See Part I Figure 12)	Paris law was used, see above.
5.7	Leak before break (See Part I Figure 13) or redundancy	inapplicable
5.8	Probabilistic analysis (See Part I Figure 19)	No probabilistic analysis was carried out.
	Applied method	
	Applied distributions	
6	**Limit load and stress intensity factor solution**	
6.1	Applied limit load solution (plastic collapse)	inapplicable because the defects are too small.
	definition of flow stress	inapplicable
6.2	Applied stress intensity factor solution	For the circumferential external surface flaw and for the embedded flaws the flat plate solution was used.
	stress concentration factor	inapplicable
6.3	Indication of over- or unconservatism in solutions chosen	Accurate solutions were used
7	**Significance of results**	
7.1	Results sensitivity analysis	Critical defect sizes: Embedded defect at weld 3: height 63.4 mm, length 95.1 mm. Embedded defect at weld 5: height 62.4 mm, length 93.6 mm. Outer surface defect at weld 3: depth 63.2 mm, length 189 mm.
7.2	Reserve factor as a function of e.g. defect size, fracture toughness etc. versus consequences of failure (Check against 1.7)	The reserve factor on depth is about 10. This is sufficient for the consequences of failure.
7.3	Probability of result falling outside of FAD less than target probability values versus consequences of failure.	No probabilistic analysis was carried out.
8	**Conclusion**	
	If not fit for purpose then recommend which input parameters should be further refined, including monitoring with NDE and/or refer to mitigation check list.	-FFP is demonstrated because there is no risk of crack growth leading to brittle failure. -The defects are dormant fabrication defects.

13.10 Master Curve approach for determining a distribution of fracture toughness

The ‘Master Curve’ approach is based on a 28 Joule Charpy V transition temperature, T_{28J}, and a 100 MPa√m fracture toughness transition temperature, $T_{100\ Map}$. The fracture toughness at the fracture toughness transition temperature should be low enough to preclude ductile tearing and to eliminate and effects of extensive plasticity. A fracture toughness transition temperature corresponding to a fracture toughness equal to 100 MPa√m was therefore selected. The relationship is then modified to account for:

- thickness effect
- scatter
- shape of the brittle to ductile fracture transition curve
- required probability of failure.

The fracture toughness distribution in the brittle to ductile transition region can be represented by a three-parameter Weibull distribution with two of the three parameters specified [16],

$$P_f = 1 - \exp\left[-\left(\frac{K_{mat} - K_{\min}}{K_o - K_{\min}}\right)^4\right] \tag{1}$$

where P_f [-] is the cumulative failure probability at a fracture toughness K_{mat} [MPa√m], K_{min} [MPa√m] is the lower bound to the fracture toughness and K_o [MPa√m] is a temperature and specimen thickness dependent normalisation fracture toughness which corresponds to 63.2% cumulative failure probability (which is approximately 1.1 times the median fracture toughness). The exponent 4 is a measure of the scatter in fracture toughness. Although K_{min} itself can be regarded as “theoretical” in nature, but for structural steels, a fixed, experimental value of K_{min} equal to 20 MPa√m can be used.

The ‘Master Curve’ defines the shape of the shape of the brittle to ductile to fracture curve for the fracture toughness measured on 25.4 mm thick fracture mechanics specimens. The temperature dependence of K_o is described by,

$$K_o = 31 + 77\exp\left[0.019\left(T - T_o\right)\right] \tag{2}$$

where T [°C] is the temperature and T_o [°C] is the transition temperature where the mean fracture toughness, corresponding to a 25.4 mm thick specimen, is 100 MPa√m.
To take the effect of specimen thickness on brittle fracture toughness into account the measured fracture toughness need to be corrected using the following relation,

$$K_{mat} = \left(K_B - K_{\min}\right)\left(\frac{B}{25.4}\right)^{1/4} + K_{\min} \tag{3}$$

where K_{mat} [MPa√m] is the corrected fracture toughness corresponding to a specimen with a crack front length equal to 25.4 mm and K_B [MPa√m] the measured fracture toughness on a specimen with a crack front length equal to B [mm]. The value for K_{min} is again equal to 20 MPa√m.

The transition temperature T_o can be inferred from a series of fracture toughness tests. The ASTM standard outlines a test method for determining T_o. If it is not feasible to perform the necessary tests to measure T_o, it can be estimated from Charpy V data,

$$T_o = T_{28J} - 18\ ^\circ\mathrm{C} \tag{4}$$

and its standard deviation is 15 °C.

By combining Eq. 1 (= scatter effect), Eq. 2 (=shape transition curve), Eq. 3 (= thickness effect) and Eq. 4 (= relationship between Charpy V and fracture toughness reference temperatures), is the fracture toughness transition curve for brittle described by the following expression,

$$K_{mat} = 20 + \left\{11 + 77\exp\left[0.019\left(T - T_{28J} + 18\right)\right]\right\}\left(\frac{25.4}{B}\right)^{1/4}\left(\ln\frac{1}{1-P_f}\right)^{1/4} \tag{5}$$

where

K_{mat}	=	fracture toughness [MPa√m]
T	=	temperature [°C]
T_{28J}	=	28 Joule Charpy V transition temperature [°C]
B	=	specimen thickness [mm]
P_f	=	probability of failure [-]

A set of transition curves for a 25.4 mm specimen thickness and different failure probabilities is shown in Figure 48.

example determination of the “Master curve” parameters K_o and T_o

The determination of the “Master curve” parameters K_o and T_o has been standardised. An example has been given below.

fracture mechanics specimen	12.7 mm thick compact tension specimen
material:	A 533 grade B base metal
test temperature:	-75 °C
mumber of specimens	6

measured fracture toughness 12.7 mm thickness [MPa√m]	scaled fracture toughness to 25.4 mm thickness [MPa√m]
91.4	80.0
103.1	89.9
120.3	104.3
133.5	115.4
144.4	124.6
164.0	141.1

As a first step the measured fracture toughness data is converted to values for a 25.4 mm thickness. The next step is than to determine the scaling parameter K_o. This is calculated using the following relation

$$K_o = \left[\sum_{i=1}^{N} \left(K_{Ic(i)} - K_{\min} \right)^4 \Big/ (N - 0.3068) \right]^{1/4} + K_{\min} \tag{6}$$

The resulting value of K_o is than 117 MPa√m. The position of the “Master Curve” can now be determined using Eq. 2,

$$T_o = T - (0.019)^{-1} \ln\left\{ (K_o - 31) / 77 \right\}$$

$$T_o = -75 - (0.019)^{-1} \ln\left\{ (117 - 31) / 77 \right\} = -81^\circ C \tag{7}$$

The resulting “Master Curve” is plotted in Figure 49.

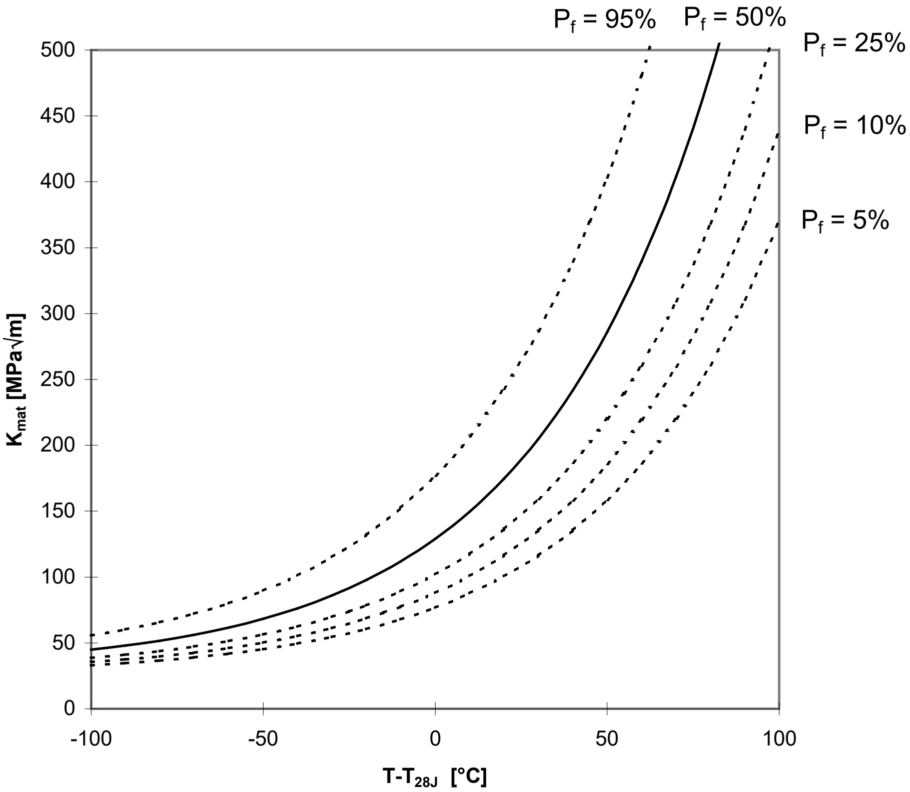


Figure 48 Master Curve with upper and lower 95 % tolerance bound

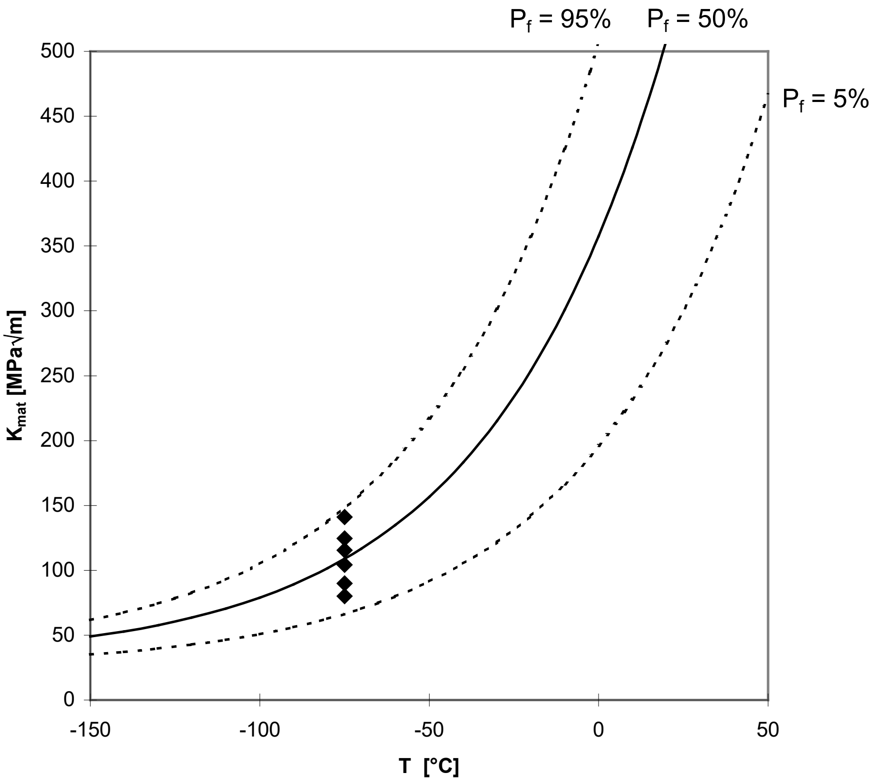


Figure 49 Example Master Curve, T_o = -81 °C and K_o = 117 MPa√m, for a A533 grade B material test at -75C using 12.7 mm thick fracture mechanics specimens

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