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EUROPEAN FITNESS FOR SERVICE NETWORK



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1. Executive publishable summary

Engineering structures may contain imperfections (pores, flaws, defects, local thin area or cracks) during the fabrication stage or during the service life. The structural significance of such imperfections, particularly crack-like flaws needs to be assessed to prevent failure of the component during service. If a flaw is found in a structural component during in-service inspection, an assessment is needed in accordance with a respective code whether the flaw should be removed (repaired) or component replaced or flaw is being left in the component to continue to use the component. Therefore, engineering assessment procedures containing analytical expressions need to be **further developed** and **unified - particularly in Europe-** to assess (primarily to provide conservative estimation of the critical condition) the structural significance of the flaws or damages. For this very purpose, FITNET Thematic Network has started to work from February 2002 to May 2006.

FITNET was a thematic networking project designed to develop a **European Fitness-for-Service Procedure** (FFS) for assessing the structural integrity of metallic welded or non-welded structures transmitting loads. In particular it embodies techniques for dealing with defects known or postulated to be present in a structure together with the possible growth of such defects by a range of mechanisms and the assessment techniques required to evaluate failure risk. It is intended to provide an umbrella scheme into which results from EC-funded projects, national programmes and in-kind contributions are harnessed to the common goal of a fitness-for-service procedure based on European advanced technology.

FITNET Thematic Network (TN) has worked together with 62 experts from 16 European countries and 41 organisations. Additionally, experts from Japan, USA, Korea and Norway have provided in-kind contributions to the development of FITNET FFS Procedure. This network has smoothly operated for 4,5 years under the guidance of project coordinator (GKSS, M. Kocak) and FITNET Management Committee (represented by project contractor partners (GKSS-Germany, JRC-Belgium, VTT-Finland, TWI-UK, University Cantabria-Spain, CESI-Italy, CORUS-UK, CAT-France, BE-UK, SHELL-The Netherlands).

Acronyms and countries of the FITNET members are:

IWT-Germany, BZF-Hungary, CSM-Italy, HSE-UK, ALSTOM-UK, FhG/IWM-Germany, UMFS-, SCK/CEN-Belgium, ADVANTICA-UK, CRF-Italy, CEIT-Spain, FORCE-Denmark, RUG-Belgium, INNOSPEXION, KUT-Poland, ROLLS-ROYCE-UK, DNV-Sweden, TUD-Germany, IIS-Italy, MPA-Germany, University



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of Aveiro-Portugal, University of Maribor, Slovenia, SKODA-Czech Republic, BUREAU VERITAS-France, CETIM-France, DLR-Germany, NPL-UK, IdS-France, EMPA-Switzerland, EPFL-Switzerland, HITACHI-Japan, Osaka University-Japan, Korea University-Korea, BATELLE-USA, Norwegian University of Sci.-Norway.

The FITNET FFS Procedure covers four major failure modes, namely fracture, fatigue, creep and corrosion and their all aspects essential for advanced design and safety in all industrial sectors. The FITNET FFS Procedure aims to include most recent advances in structural integrity assessment while providing fully validated methodologies, assessment routes including well selected case studies or worked examples for determining the FFS of various structures and welded components manufactured from metallic materials.

To support this initiative, **FITNET TN** embraces the results obtained in EC-funded projects such as SINTAP, ASPOW; HIDA, DISMEW, INTEGRITY, PLAN, VOCALIST, JOTSUP, WAFS, IDA, WEL-AIR as well as IST Project from Japan. It also includes the recent advances in international, national standards as well as industrial codes such as API 579, BS 7910, R5/R6.

FITNET TN aimed also to provide the technical and industrial focal point for the definition of any future R&D projects which may be required to address specific structural integrity & damage tolerance analysis aspects of the power generation and petro-chemical plants, offshore, pipelines, aerospace, transport/railway and civil engineering structures etc. as well as for demonstration projects to realise and distribute a prototype software products.

In order to updating the level of knowledge of the FITNET consortium with respect to application and needs of the future end-users of the FITNET FFS procedure, a survey was conducted by JRC-Petten in various European languages. The questionnaire entitled; "Current Application and Future Requirements for European Fitness-for Service (FFS) Technology" finalised during the first months of the project duration. The results of the survey have confirmed the overall objectives of the FITNET TN and provided recommendations for the working units where procedure development works were based on.

During the FITNET FFS Procedure development work numbers of working documents have been prepared and discussed by the members. Sections of the FFS Procedure were first drafted by an expert(s) on the field and circulated to the group of experts for comments and modifications. Final drafts of the sections were edited by the coordinator and provided to all members and to the FITNET web site (www.eurofitnet.org). The 7th version (MK7) of the FITNET FFS

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Procedure was available in the web site for comments and revisions of the FITNET and CEN Workshop Agreement (CEN W22) registered members. The FITNET FFS Procedure is written in 3 volumes, and 4 modules within these address fracture, fatigue, creep and corrosion. The contents of the FITNET FFS Procedure in three volumes are as follows:

- Vol. I: FITNET FFS Procedure**
- Vol. II: Case Studies and Tutorials**
- Vol. III: Annex**

The FFS Procedure volume which contains prescriptive sections (12 of them): provides engineering methodologies for assessing flaws to reach a decision about the component. Four major analysis modules (Fracture, Fatigue, Creep and Corrosion) are described in Vol. I. The volume II contains informative sections (Sections 13 and 14) and Vol. III presents numbers of needed information (K-solutions, limit loads etc.) to carry out the analysis. The overall flowchart of the FITNET FFS procedure is given in Figure 1.

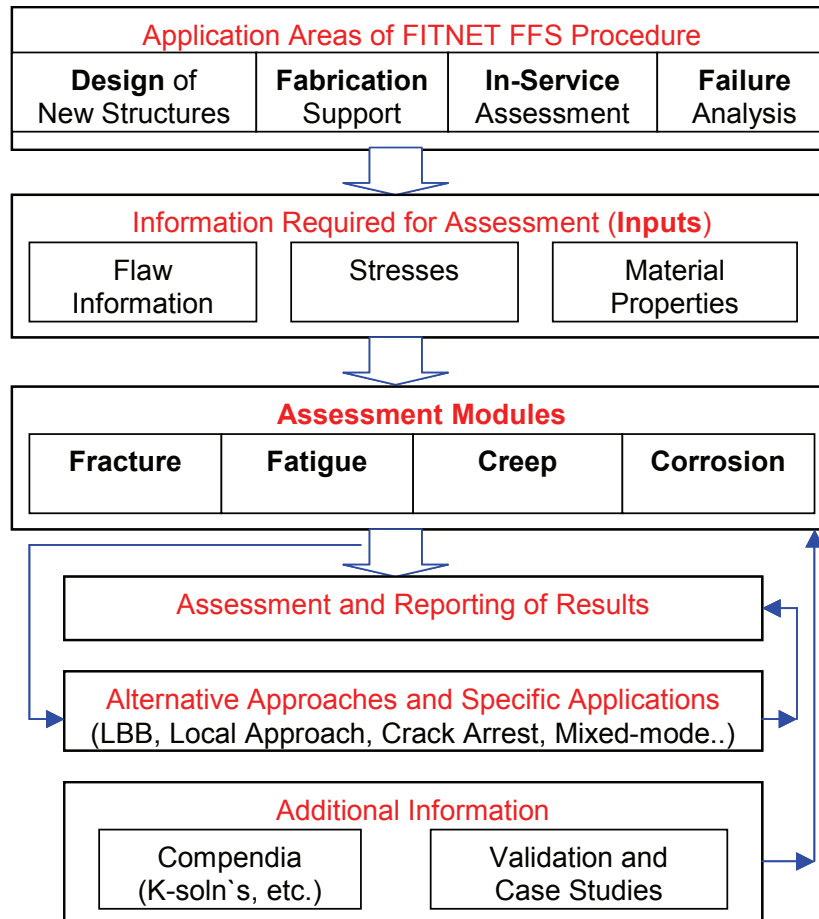


Fig. 1. Overall flowchart of the FITNET FFS Procedure

2. Objectives and strategic aspects

A number of industrial sectors, such as nuclear power, petrochemical, offshore, **aerospace** or pipeline weld applications have established Fitness-for-Service (FFS) standards in place for the assessment of flaws found in-service. Some methods for design and remaining life assessments of fatigue-loaded structures are still unduly conservative in different loading regimes. Hence, there was a need to generate a general purpose, unified, comprehensive and updated FFS methodology in Europe by covering four major failure modes (fracture, fatigue, creep and corrosion) in metallic load bearing components with or without welds.

As a result, the European Community funded the project FITNET has started in February 2002 in the form of a Thematic Network (TN) to review the existing FFS procedures and develop an updated, unified and verified European FITNET FFS Procedure to cover structural integrity analysis to avoid failures due to fracture, fatigue, creep and corrosion.

FITNET is an umbrella Thematic Network providing a scheme into which both funded and un-funded contributions were harnessed to the common goal of substantially extending the fitness-for-service procedures used within Europe. These developments were based on European advanced technology and have embraced results obtained in successfully completed projects such as SINTAP. The completed projects have been widely recognised as providing the framework for European wide standards for fracture related aspects of fitness for service. SINTAP is already included in a CEN European technical report, which also incorporates BS 7910, R6 and German FKM-Richtlinie "Bruchmechanischer Festigkeitsnachweis", 2001.

FITNET Fitness-for-Service analysis of engineering structures aimed to provide better design principles, support for fabrication of new components, prevention of service failures due to fracture, fatigue, creep and corrosion damages (**no coverage of structural instability due to buckling**).

FITNET FFS Procedure can be used to establish the size limits for defects in various engineering structures and can provide substantial cost savings in operating such structures. The use of the FITNET FFS Procedure involves making an assessment of a component containing a defect to ensure its structural integrity for its intended design life or until its next inspection period. The outcome of the assessment of a component in service is a decision to operate as is, repair, monitor (including re-setting of inspection intervals), or replace.

In the absence of a widely available and applicable European code, many turns to the recently released and currently revised procedure from the American Petroleum Institute (API 579) or the forthcoming ASME-approved version, which provide guidance on the approaches to be used. Such documents will then become *de facto* world standards and Europe will lose control and hence the influence that accompanies such influential design procedures.

FITNET FFS aims to fill this gap by providing an appropriate framework for collating on-going R&D, providing a well-validated document to the CEN under the CEN Workshop Agreement 22 as well as fostering training and disseminating activities in new European Community member states. Furthermore, in-kind contributions from international experts from USA, Japan and Korea have contributed to the development of the procedure and international acceptance of the FITNET FFS Procedure.

The provision of the unified and well-validated FITNET FFS Procedure (in Final Draft MK7 version) and an effective dissemination of gained knowledge within the network and training of young engineers in Europe will enable a more consistent level of structural safety to be achieved throughout the EU. This will lead to an advanced design of plant and structures to be undertaken in order to increase the competitiveness of European industry as well as ensuring their structural safety and durability to minimising the risk of failures and accidents.

This unified flaw assessment procedure is the main output of the FITNET project. It provides a unique and comprehensive fitness-for-service document with numbers of novel features. All major parts and approaches have already been validated and hence it provides technically sound “ready-to-use” procedure for the European manufacturing and plant operating industries.

The standardisation methodology of the FITNET FFS Procedure has been established in the form of **CEN Workshop Agreement 22 (CWA 22)**. CEN Workshop Agreement provides a type of CEN document below a standard. After publishing of the FITNET FFS Procedure with CWA 22 code, CEN promotes the CWA document towards CEN Standard via its respective technical Committee(s) dealing with the fitness-for-service area.

Working under the CEN Workshop Agreement requires transparency in development of the CWA document. It is, therefore, a rule of the CEN WA that activities should be accompanied by one of the European standardisation body and requires registration of interested experts world wide. Italian Standardisation Body (UNI) has therefore accompanied the CWA 22 work of the FITNET Consortium. UNI has provided the FITNET FFS documents for

public comments and these are being accepted or commented by the respective experts of the FITNET.

The FITNET FFS Procedure (version MK7) is the final document for public comments and new revised version (MK8) will be submitted to the CEN in two volumes (Vol. I Procedure and Vol. II Annex). The tutorials and case studies volume will not be a part of the CEN WA22 and it will remain as a property of FITNET Network.

Comparison between planned overall objectives and achievements:

1) FITNET TN has primarily planned to develop a unified European procedure for Fitness-for-Service assessment of engineering metallic structures containing postulated or real flaw with respect to Fracture, Fatigue, Creep and Corrosion. It has aimed to enhance existing FFS procedures and conduct validations of the procedures.

This objective has been reached with great success.

2) FITNET TN has planned to contribute standardisation of FFS procedure.
This objective has been achieved with the establishment of CEN Workshop Agreement W22 and provision of the FITNET document to the CEN.

3) FITNET TN has aimed to provide a technological platform between experts to identify future needs and challenges.

For this target, FITNET TN has contributed to the development of Structural Safety concept of the European Technology platform ETPIS.

Future planning:

1) Implementation of FITNET FFS Procedure within the activities of each contractor and member.

2) Development of European Structural Safety Network to contribute to the development of overall industrial safety concept.

3) Conducting FITNET FFS Training Seminars in Europe and new member states.

4) Development of 7th FP projects dealing with structural safety. To this end Structural Safety issues of the next generation oil and gas pipelines in Europe has already been identified (together with Technology Platform ESTEP) as a strategic challenge. The FITNET members will be partners of this collaborative action.

3. Scientific and Technical Performance

3. 1 Introduction

Engineering structures may contain imperfections (pores, flaws, defects, local thin area or cracks) during the fabrication stage or during the service life. The structural significance of such imperfections, particularly crack-like flaws needs to be assessed to prevent failure of the component during service. If a flaw is found in a structural component during in-service inspection, an assessment is needed in accordance with a respective code whether the flaw should be removed (repaired) or component replaced or flaw is being left in the component to continue to use the component.

Therefore, various engineering assessment procedures [1-17] containing analytical expressions have been developed to assess (primarily to provide conservative estimation of the critical condition) the structural significance of the flaws or damage. Conventional design approaches and operation principles implicitly assume that the component (load-carrying) is defect-free. However, even components fabricated by “good workmanship” principles may contain or develop cracks and hence need to be assessed using modern FFS methodologies for provision of structural safety, improvement of in-service inspection intervals and/or for establishment of life extension measures.

The presence or occurrence of damage in engineering components may have different origins and growth mechanisms depending on the application area, the type of the component and loading conditions etc. Four major failure modes; *fracture*, *fatigue*, *creep* and *corrosion* have generally been identified as the most frequent failure modes of engineering structures and hence different FFS methodologies have been developed to cover these failure mechanisms. Certainly, failure of a component may include numbers of these four basic mechanisms and their interactions at different stages of the damage process in service. For example, fabrication flaws or cracks occurred during the service may subsequently propagate during the high temperature exposure as a consequence of the combined effects of creep and cyclic loading. In such circumstances, the assessment of high temperature structural integrity should also be covered by the use of more than one approach or procedure.

Additionally, welded structures require special procedure for structural integrity assessment of the weld flaws or cracks at the vicinity of the weld joints. First of all, most of the structural welds exhibit microstructural, geometrical and mechanical heterogeneity (strength mis-match, residual stresses etc.) which should be taken into account during the fitness-for-service analysis. Advanced

welding technologies are emerging (e.g laser beam and friction stir welding) and hence increasingly used in new designs and structures as an effective method to reduce the fabrication cost, distortion and residual stresses etc. Newly developed FFS procedures should cover such structures by taking into account of the special features of these welds.

3. 2 Features of the FITNET FFS Procedure

FITNET is a European Thematic Network (TN) project designed to promote the development of an engineering FFS procedure for assessing the structural integrity of metallic welded or non-welded structures transmitting loads. In particular it embodies techniques for dealing with crack like defects, flaws known or postulated to be present in a component together with the possible growth of such defects by a range of mechanisms and the assessment techniques required to evaluate failure risk.

The Procedure currently covers four major failure modes, namely;

Fracture, Fatigue, Creep and Corrosion in metallic components.

It is obvious that if the damage mechanism of a component in-service cannot be identified, flaw assessment using FITNET FFS should not be performed. This implies that an identification of “cause of cracking” or firm understanding of the damage mechanism is essential decision step in the FITNET FFS Procedure. It aims to provide a multi-disciplinary engineering assessment of metallic components to demonstrate whether they are fit for design, fabrication and operation considerations with postulated or real flaw using analytical methods. It is highly structured procedure according to the “cause of cracking” or “damage mechanism” of the flaw or damage and set in modular organisation to provide user and update-friendly forms.

FITNET TN has provided an umbrella scheme into which results from EC-funded projects, national programmes and in-kind international contributions (e.g., from USA, Japan, Korea) are harnessed to the common goal of a unified FFS procedure based on well established existing procedures and recent developments in the field of FFS technology. The pre-requisites for such an expert FFS methodology are:

- i) Be advanced, fully validated methods for determining the fitness-for-service of various metallic structures or components with and without welds.*
- ii) To cover fracture, fatigue, creep and corrosion (including metal loss) governed postulated or real structural damage and all aspects essential for advanced design, fabrication in all industrial sectors*

iii) To be readily usable by general industry and make a major contribution to cost and weight saving, particularly for small and less technically advanced companies, whilst still improving structural safety

To satisfy these requirements, FITNET TN embraces results obtained in a number of completed European Community funded projects such as SINTAP, ASPOW, HIDA, DISMEW, INTEGRITY, PLAN, WAFS, JOTSUP and VOCALIST. It has also embraced advances in flaw assessment procedures such as SINTAP, industrial codes such as R5, R6, API 579, as well as national and international standards such as BS 7910, ASME Sec. XI, A16, WES 2805.

During the development of the FITNET FFS Procedures, close contact and collaborations with experts from Japan, USA and Korea have been established. Some of the experts from these countries have worked with the FITNET working groups and provided technical contributions for the development of various sections. Recent developments in the field of FFS in these countries were presented at the international FITNET 2006 Conference [18] with the papers prepared by D A Osage and M Prager which has reported “*Recent Developments and Improvements in API 579*”, paper no. FITNET 06-01 and K Hasegawa and H Kobayashi have presented “*Current Status of Fitness-for-Service Rules in Japan*”, paper no. FITNET 06-02. Additionally, Y-J Kim et al have provided a paper on the “*Recent Works on Developing Structural Acceptance Criteria for Local Wall Thinning of Nuclear Pipings within Korea and Japan*”, paper no. FITNET 06-03.

The FITNET FFS flaw assessment methodologies are in the form of a **step-by-step procedure** set out for assessing a welded or non-welded metallic component containing a known or postulated flaw under static, dynamic, creep loading conditions or a component subject to a corrosion damage (e.g. metal loss). Figure 1 is showing the overall structure of the FITNET FFS procedure which is implemented in three volumes:

- Vol. I FITNET FFS Procedure
- Vol. II: Case Studies and Tutorials
- Vol. III: Annex

The FFS Procedure volume which contains prescriptive sections (12 of them): provides engineering methodologies for assessing flaws to reach a decision about the component. The volume II contains informative sections (Sections 13 and 14) and Vol. II presents numbers of needed information (K-solutions, limit loads etc.) to carry out the analysis.

FITNET FFS assessment results can provide information on material selection and hence the most suitable component fabrication route for safe and economical performance. Analysis results can yield, for example, the required minimum fracture toughness for a given loading conditions and postulated defect

size or can provide minimum tolerable defect size (e.g., weld imperfection) for a given material, loading conditions and fabrication route. Again applicability of the FFS analysis in an efficient manner to support the fabrication route and quality assurance in addition to the conventional *good workmanship* principles will depend on the capability of the applied NDE technique and its probability of detection of a flaw. According to practical workmanship criteria, no crack or defect that occurs during the fabrication of a component is acceptable if the size

of the defect exceeds the detection limit of the NDE method used (i.e., some small flaws smaller than this limit may exist in the component). At this stage, FITNET FFS methodology can provide an engineering analysis to predict the critical condition of a new component using either a postulated larger defect or a defect size defined by the NDE detection limit and hence can give an opportunity to the designer for possible reselection of failure criteria (i.e., against crack initiation or allowance for crack growth with respective inspection intervals), design load, material type or fabrication route.

When a defect has been detected in a component that has been in service, the conservative assumption for the analysis of continuum damage is that the crack initiated early in life. This approach should be adopted unless there is evidence to the contrary. However, the FITNET FFS procedure is not being developed only for the assessment of damage of structures in-service, but also aims to be applied to a component that has not yet seen operation as well as to a failed component to clarify the cause of the failure. Therefore, the FITNET FFS Procedure is applicable to four major stages of a typical component life:

- 1) Design of New Structures
- 2) Fabrication Support and Quality Assurance
- 3) Assessment of In-Service Damage
- 4) Failure Analysis

For the application of a FFS procedure to optimise the *design of a new component*, usually a *postulated defect* is used to assess the critical condition of a component for a given material, load/stress conditions and geometry of the component. In this context, a postulated initial defect size may be based on the non-destructive evaluation (NDE) detection limit. Depending on the design philosophy (safe-life or damage tolerant (fail-safe) design etc.) in combination with the NDE technique as well as a good description of the loading conditions of a new component, FITNET FFS can provide information for re-selection of material, design and fabrication route and NDE technique.

The FITNET FFS assessment requires, in general, for *the components in-service* the following interdisciplinary inputs:

- Description/knowledge (mechanism) of damage
- Determination of operating conditions, load/stress analysis
- Flaw characterisation (location, sizing via NDE)
- Material properties (incl. environmental effects)

The quality of the major input data (flaw size, stresses and material properties) has a significant effect on the FFS analysis results, and hence efforts should be

made to generate or use a good data bank. After conducting an assessment for a given component with an in-service flaw, a sensitivity analysis with modified or a new set of input data can provide accurate description of the limiting conditions of the component.

If flaw indications are detected during in-service inspections of a component, the indications are carefully examined to determine the dimensions of these flaws. If multiple discrete flaws are in the same cross-section, the flaws interact and hence may need to be treated as a single flaw, using the distance between adjacent flaws as the combination criteria.

Before performing a FFS analysis for flaws detected in in-service components, an investigation should be carried out to determine the most likely cause of cracking. At least, this should involve a combination of non destructive testing, visual examination and metallurgical examination (e.g., **fatigue crack growth tends to be transgranular whereas creep crack growth is generally intergranular**). If it is possible to identify the mode and mechanism of cracking, this should provide qualitative information on the relative contributions of the different mechanisms and phases to the overall damage process. Based on the results, a selection of the analysis Module should be made. Short descriptions of the modules are given in the following sections.

Furthermore, **special assessment routes** of the damage in structural welds need be addressed. An assessment of a flaw or damage in welds should in the extent of microstructural and microchemical aspects which may play a role in development of the corrosion damage. For example, residual stresses, hardness, and joint geometry are factors to be considered. Additionally, too high heat input, inadequate filler wire may lead to sensitisation at grain boundaries or at precipitate particles, elongated and clustered inclusions, local hard zones etc. These and especially weld strength mis-match aspect in the fracture analysis of the weld flaws make weld joints a special topic to be covered.

3.3 FITNET Fracture Module

Coordinated by: S. Webster, CORUS, UK

3.3.1 Introduction

The FITNET fracture module is one of the corner stones of the new European fitness-for-service procedure for welded and non-welded metallic structures. The FITNET fracture module (**Section 6**) has built upon the previous SINTAP [6, 7] European project as well as recent developments in R6 and BS 7910. It has also benefited from developments carried out by members of FITNET and also those in other European projects as well as international standards. There have also been contributions from non- European partners in Japan, USA and Korea.

Section 6 of the FITNET FFS procedure specifies methods for analytical assessment of the structural significance of flaws or cracks in metallic structures with or without welds. The analysis provides predictions with respect to residual strength of the component or welded structure containing postulated flaw or real crack.

Major elements of the Section 6 have been based on the concepts developed in the SINTAP project but these have been substantially improved as a result of technical developments that have taken place since the SINTAP procedure was written in 1999. In addition the project is indebted to the help given it by the R6 procedure [1] for the provision of several aspects of recent improvements to this procedure.

3.3.2 The SINTAP Project

SINTAP (**S**tructural **I**NTegrity **A**ssessment **P**rocedure) was a multidisciplinary collaborative project, part-funded by the European Union, involving 17 organisations from 9 EU countries. The culmination of the work was a procedure that is applicable to a wide cross-section of users because of its ability to offer routes of varying complexity, reflecting data quality and the scope for a final interpretation reflecting the preference of the user.

A review of the project and the main technical developments is contained in a special issue of the Journal Engineering Fracture Mechanics [7]. One of the main achievements of the SINTAP Project was to establish the compatibility of the Failure Assessment Diagram (FAD) and Crack Driving Force (CDF) analysis approaches. These two approaches are illustrated in Fig 2. The former method is used in approaches such as R6, BS 7910, API 579, SAQ, EXXON, INSTA and MPC whilst the CDF approach is favoured in ETM and GE-EPRI procedures.

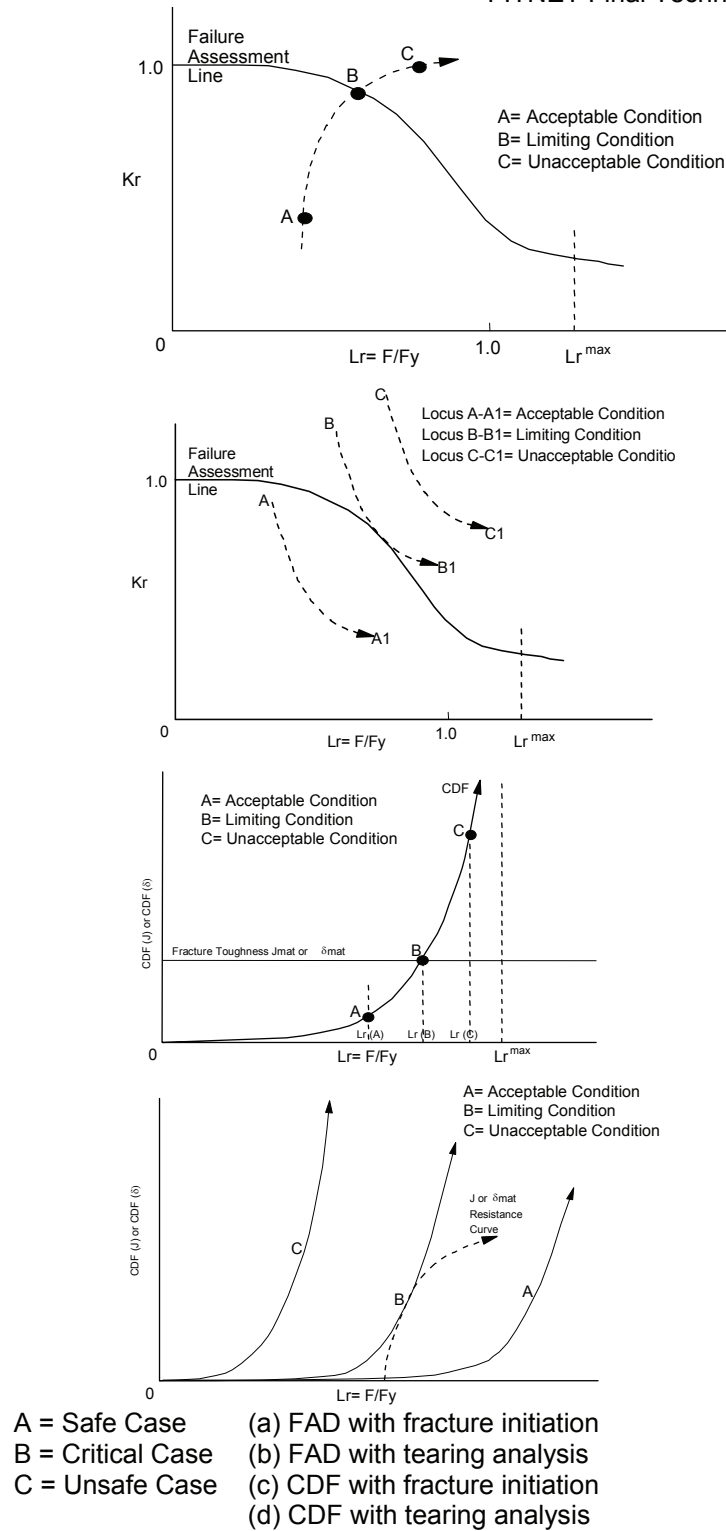


Fig. 2: Failure Assessment Diagram (FAD) and Crack Driving Force (CDF) Approaches for Fracture Initiation and Ductile Tearing Analyses

◀ The basis of both approaches is that failure is avoided so long as the structure is not loaded beyond its maximum load bearing capacity, defined using fracture mechanics criteria and plastic limit load analysis. The CDF approach involves comparison of the loading on the crack tip (often called the crack tip driving force) with the ability of the material to resist fracture (defined by the material's fracture toughness or fracture resistance). Crack tip loading must, in most cases, be evaluated using elastic-plastic concepts and is dependent on the structure, the crack size and shape, the material's tensile properties and the loading. In the FAD approach both the comparison of the crack tip driving force with the material's fracture toughness and the plastic load limit analysis is performed at the same time. Whilst both approaches are based on elastic-plastic concepts, their application is simplified by the use of only elastic parameters. ▶

It was found that the major discrepancies arose primarily because of the limit load or stress intensity factor solutions rather than any fundamental difference in concept. Furthermore, although FAD and CDF routes represented two different calculation methodologies, the underlying principles were the same, comparison between the applied stress and the material's resistance. It was only a result of their development, through different simplifications, that they diverged and hence analysis routes were formulated that enabled both approaches to be utilised from the same input data.

◀ **A key aspect of the SINTAP and now the FITNET procedure is that a range of assessment routes can be followed which reflect the quality of the input data.** The most sophisticated and accurate levels require high quality input data, whilst assessments can still be carried out with knowledge of only basic parameters but this is penalised by a higher degree of conservatism. The underlying principles of the FITNET FFS fracture analysis method are:

- ◀
- A hierarchical structure based on the quality of available data inputs;
 - Decreasing conservatism with increasing data quality;
 - Detailed guidance on determination of characteristic input values such as fracture toughness;
 - Analysis in terms of a Failure Assessment Diagram (FAD) or Crack Driving Force (CDF);
 - Method of incorporating the effect of weld strength mismatch;
 - Guidance on the treatment of constraint in fracture assessment
 - Compendia of stress intensity factors, limit load solutions and weld residual stress profiles. ▶

3.3.3 Features of the Fracture Module and Assessment Routes

The FITNET Fracture Module is based on fracture mechanics principles and the purpose of the analysis is to determine the significance, in terms of fracture and plastic collapse, of flaws postulated or present in structures and components.

◀ The procedure is based on the principle that failure is deemed to occur when the applied driving force acting to extend a crack exceeds the material's ability to resist the extension of that crack. This material 'property' is called the material's fracture toughness or fracture resistance. ▶

The procedure can be applied during the design stage, during fabrication as a quality control tool or throughout the lifetime of a structure to evaluate residual life or life extension and, finally, for the forensic failure analysis of components.

The fracture analysis of the component containing a crack or crack-like flaw is controlled by the following three parameters:

1. Component and crack geometry.
2. Fracture resistance of the material or weld metal or heat affected zone.
3. Applied load including secondary loads such as residual stress.

The procedure aims to provide an analytical procedure to facilitate these calculations for the following practical applications:

- (a) **Design of a new component**, the structural significance of a **postulated crack** can be analysed. The dimensions of this postulated crack should be chosen such that it will be detected in quality control or in-service inspections. If a crack of this size is demonstrated not to achieve a critical size over the projected lifetime of the component then no critical situation should be expected for smaller undetected cracks. Alternatively, a critical crack size can be determined in order to specify NDI requirements for quality control and in-service inspections. Alternatively, for a given postulated flaw size and stress level, optimum material (in terms of toughness) can be selected. Furthermore, for a given postulated flaw size and selected material, a critical load level can be described at the design or fabrication stages of the component.
- (b) **Crack detected in-service**, a decision can be made as to whether or not it is critical for the applied loading case. If necessary, the applied load can be reduced in order to avoid the critical state. If the analysis is combined with a fatigue crack extension analysis the residual lifetime of the component can be

predicted and based on this non-destructive inspection (NDI) intervals can be specified which ensure a safe further service for a limited time.

Sometimes it is necessary to assess the structural integrity of a component containing multiple flaws. The fracture module and the associated Annexe F provide an assessment methodology that includes spacing criteria and interaction rules for such situations.

Where non-coplanar flaws exist, each is first re-characterized in order to obtain parallel cracks. A summary of the flaw alignment rules is given in Fig. 3. As can be seen, the problem is reduced to two cracks that will be either coplanar or in parallel planes (non-coplanar). Following alignment the flaws can be evaluated for possible interaction according to the combination rules given in Fig. 3.

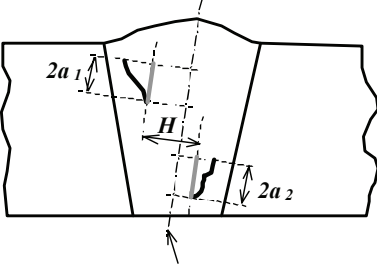
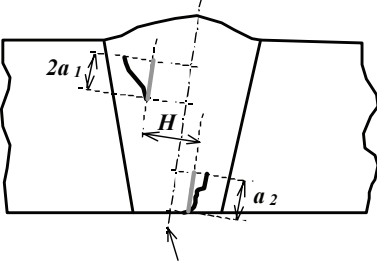
	ALIGNMENT CRITERION
<i>Adjacent non-coplanar embedded flaws</i>  <i>Plane normal to the maximum principal stress</i>	$H \leq \min(2a_1, 2a_2)$
<i>Adjacent non-coplanar surface and embedded flaws</i>  <i>Plane normal to the maximum principal stress</i>	$H \leq \min(2a_1, a_2)$

Fig. 3: Flaw alignment criterion

The flaw combination rules shown in Fig. 4 should be followed when failure by brittle fracture cannot be excluded. However, the **FITNET FFS provides alternative flaw combination rules that can be applied when plastic collapse of a structural component is the only failure mode expected.** The

flaw combination rule for ductile material behaviour is based on the flaw length limit $2c_{GSY}$ which is calculated as:

$$2c_{GSY} = \frac{1-R}{1+R} \frac{Wt}{a_{\max}}$$

Where R is the yield-to-tensile ratio of the base material, W is the plate width, t is the plate thickness and $a_{\max}$ is the depth of the deepest flaw. Having determined the value of $2c_{GSY}$, the flaw interaction rules become:

$$s \leq \frac{1+R}{2R} \left(\sum 2c_i - 2c_{GSY} \right)$$

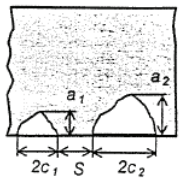
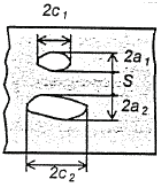
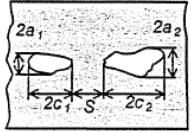
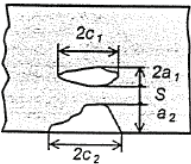
CASE	COMBINATION CRITERIA	EFFECTIVE DEFECT DIMENSIONS
A 	For a_1/c_1 or $a_2/c_2 > 1$: $S \leq \min(2c_1, 2c_2)$ OR $S \leq \max(0.5a_1, 0.5a_2)$ else: $S \leq \max(0.5a_1, 0.5a_2)$	$a = \max(a_1, a_2)$ $2c = 2c_1 + s + 2c_2$
B 	$S \leq a_1 + a_2$	$2c = \max(2c_1, 2c_2)$ $2a = 2a_1 + s + 2a_2$
C 	For a_1/c_1 or $a_2/c_2 > 1$: $S \leq \min(2c_1, 2c_2)$ OR $S \leq \max(a_1, a_2)$ else: $S \leq \max(a_1, a_2)$	$2a = \max(2a_1, 2a_2)$ $2c = 2c_1 + s + 2c_2$
D 	$S \leq \frac{2a_1 + a_2}{2}$	$2c = \max(2c_1, 2c_2)$ $a = 2a_1 + s + a_2$

Fig. 4: Default planar flaw interaction rules

3. 3. 4. Analysis Options

The overall FITNET fracture assessment scheme with its decision making steps is shown in Figure 5 which illustrates the determination of critical crack size, critical load and required minimum fracture resistance of the material.

There are a number of different analysis options available to the user, each being dependent on the quality and detail of the material's property data available. As for the choice of route, the user may choose this at the outset or it may be self selected. Self-selection occurs when an unsatisfactory result at one level is re-analysed at a higher level. Simple rules determine when this can be achieved and the optimum route minimises unnecessary work and complexity. The higher the level of analysis undertaken, the higher is the quality required of the input data and the more complex are the analysis routines. Conversely, the lower the level of analysis the more conservative the result, but the lowest level which gives an acceptable result implies satisfactory results at higher levels.

◀ The analysis options are characterised mainly by the detail of the material's tensile and fracture data used. There are three **"Standard"** Options, two **'Advanced'** Options and a **'Basic'** Option. ▶ These options are listed in Table 1 together with the types of input of data required to fulfil the needs of the various analysis routines.

The different options produce different expressions for $f(L_r)$, which defines the FAD or CDF to be used in the analysis.

A subdivision of the option arises from the details of the fracture toughness data used. There are two possibilities for this, one characterising the initiation of fracture (whether by ductile or brittle mechanisms), the other characterising crack growth by ductile tearing. The value of fracture toughness to be used in the FITNET procedure is termed the characteristic value.

The 'Standard' **Option 1** level of analysis is the minimum recommended level. This requires knowledge of the materials yield or proof strength and tensile strength plus a value of fracture toughness, K_{mat} , obtained from at least three test results that characterise the initiation of brittle fracture or the initiation of ductile tearing. For situations where data of this quality cannot be obtained, there is a 'Basic' level of analysis, Option 0, which requires only the material's yield or proof strength and Charpy data.

The 'Basic' Option uses correlations and, as such, is very conservative. However the correlations to be used in FITNET have been developed based on recent work and these developments are discussed in the paper [19] presented at the FITNET 2006 Conference.

In weldments where the difference (strength mis-match) in yield or proof strength between weld and parent material is **smaller than 10%, the homogeneous procedure can be used** for both under-matching and overmatching and in these cases the lower of the base or weld metal tensile properties is used. For higher levels of mismatch and for $L_r > 0.75$, the Option 2 analysis, Mismatch, can reduce conservatism. This method requires knowledge of the yield or proof strengths and tensile strengths of both the base and weld metals and also an estimate of the mismatch yield limit load. Numbers of mismatch yield load solutions are given in Annex B.

The equations used to generate $f(L_r)$ for Options 1 and 2 are based upon conservative estimates of the effects of the materials tensile properties for situations when complete stress strain curves are not known. More accurate and less conservative results can be obtained by using the complete stress strain curve and this option is given by the Stress-Strain Option 3 alternative. In this case every detail of the stress strain curve can be properly represented and where weld strength mismatch effects are important these can also be allowed for.

One of the two 'Advanced' options is designed to be used when numerically determined values of elastic and elastic-plastic J-integral are available and the other allows for constraint conditions that are different from those that exist in common fracture toughness test specimens.

It is also advisable, in order to prevent unnecessary effort, to consider when refinement of the analysis carried out could potentially provide an improved accuracy and when a significant improvement is unlikely. Figure 6 presents a graphical interpretation of when accuracy improvements are likely based on the area of the FAD diagram in which the assessment point falls.

It should also be remembered that there are several options should the initial analysis fail to provide assurance that the situation analysed will not lead to failure. Another analysis option can be used, provided the data are available, however, if this is not the case, then the user can choose to refine their knowledge of the applied stresses, defect size / location and / or the material properties. In other words moving to another analysis option is not necessarily the preferred or most cost effective route.

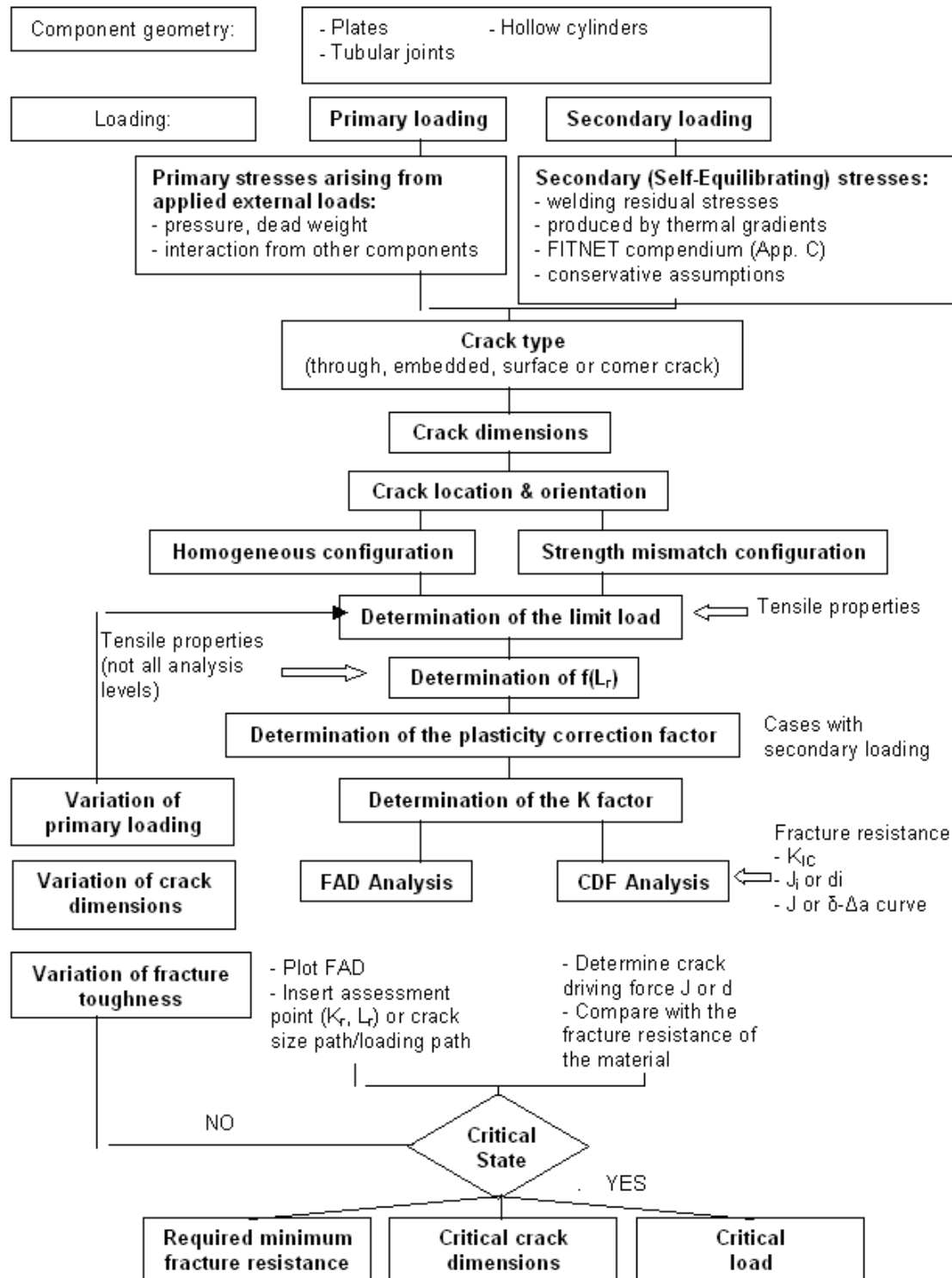


Fig. 5: Overall flow chart of the FITNET FFS Fracture Module

Table 1. Analysis Options of the FITNET FFS Fracture Module.

ANALYSIS OPTIONS	DATA NEEDED	WHEN TO USE
BASIC OPTION		
OPTION 0 Basic	YS or PS	When no other tensile data available
STANDARD OPTIONS		
OPTION 1 Standard	YS or PF; UTS	- For quick result - For $M < 10\%$
OPTION 2 Mismatch	YS or PS, UTS, M, Limit loads	- Allows for mismatch in YSs of weld and base metals
OPTION 3 Stress-strain	Full σ - ϵ curves	- More accurate and less conservative than Options 1 and 2. - Weld mismatch option included.
ADVANCED OPTIONS		
OPTION 4 J-Integral Analysis	Needs numerical analysis of cracked body	
OPTION 5 Constraint Analysis	Estimates of fracture toughness for crack tip constraint conditions relevant to those of cracked structure. Needs numerical cracked body analysis.	Allows for loss of constraint in thin sections or predominantly tensile loadings

YS: Yield Strength,
PS: Proof Strength,
UTS: Ultimate Tensile strength
M: Weld Strength Mis-match Factor
($M = \text{YS of weld} / \text{YS of base metal}$)

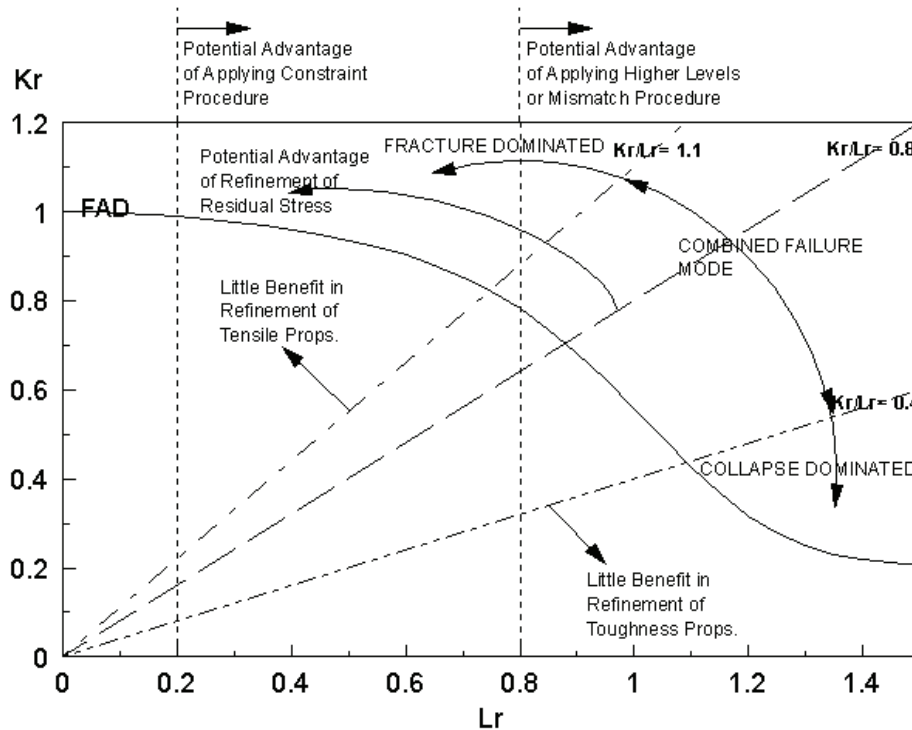


Fig. 6: Summary of FAD regions for consideration of potential refinement of data or analysis level

3. 3. 5 Weld Strength Mis-match

A normal assessment requires use of the tensile properties of the weakest constituent in the vicinity of the crack. The homogeneous material procedures can still be used when mismatch is greater than 10% and conservative results will be obtained if the tensile properties of the lower strength constituent are used.

A procedure for estimating any change in reserve factors arising from the presence of stronger or weaker materials, weld **strength overmatch** and **under-match** respectively, is presented in the procedure.

The homogeneous or base metal procedure should be used for the weld metal strength mis-match level smaller than 10% for both overmatching and under-matching. For higher level of under-matching case, the predictions may be unsafe if base metal properties are used. This situation has often been observed

in higher strength aerospace Al-alloy laser beam or friction stir welds where usually strong loss of weld metal strength occurs. Furthermore, higher strength steel welds for navy applications may exhibit also significant level of undermatching due to the selection of wire with respect to good weldability.

For higher (>10%) degree of overmatching cases, the use of base metal tensile properties will yield over-conservative predictions, but the analysis will be safe. In order to assess whether there is likely to be value in invoking the mismatch levels, the following should be noted:

- The maximum benefit arises in collapse dominated cases and is at most equal to the ratio of the flow strength of the highest strength material in the vicinity of the crack to that of the weakest constituent;
- There is little benefit for $L_r < 0.8$, where L_r is based on the tensile properties of the weakest constituent;
- There is little benefit for cracks in under-matched welds under plane stress conditions;
- For deep circumferential cracks in circumferential welds in pipes under pressure, there is benefit in taking account of overmatching. There is, however, little benefit for shallow cracks.

The most important input to the defect assessment method for strength mismatch is the **mismatch limit load solution**. Annex B of the FITNET FFS document contains a compendium of the limit load solutions including those accounting for material mismatch. An overview of the Annex B is given in a paper presented at the FITNET 2006 conference [20].

3. 3. 6 Constraint Effects

The ability to utilise the effective loss of constraint relevant to shallow surface cracks is potentially of great practical significance. In order to claim benefit from reduced constraint, it is necessary to perform additional calculations and to have more information on fracture toughness properties and the areas where this additional effort is likely to be justified, are:

- Benefit is greatest in components subjected to predominantly tensile loading rather than bending;
- Tension loading in the plane of the crack increases constraint and therefore will reduce any beneficial effects; conversely compressive loads in the plane of the crack increase benefits;
- Benefits are greater for shallow cracks than for deeper cracks;

- There is little benefit for an assessment for ductile materials based on initiation toughness as the fracture toughness at initiation tends to be insensitive to constraint;
- There is more benefit for cleavage fracture or for an Option 2 ductile case where fracture toughness increases with reducing constraint;
- There is little benefit at low values of L_r (< 0.2) for cases dominated by primary loads;
- There is little benefit for collapse-dominated cases.

The FITNET procedures are considered to be the most comprehensive guidance on the treatment of constraint currently available. The recent developments produced within the VOCALIST and the NESC-IV projects [21] have been incorporated into the Fracture Module and the Annex K which gives the provisions for determination of the input parameters for the constraint analysis. An overview of the FITNET guidance for quantifying the effects of constraint on the behaviour of a defective structure is fully covered in a paper also presented at the FITNET 2006 Conference [22].

3. 3. 7 Other Provisions for Fracture Assessment

The FITNET FFS Procedure provides series of alternative and specific assessment routes to cover the special features of the case under consideration. There are numbers of special areas of the structural integrity assessment that need to be considered separately to provide a detailed description of the case parameters to be used in the assessment. Special methodologies are given to cover such cases as;

- leak before break,
- crack arrest,
- load history effects,
- mixed-mode fracture and
- statistical treatment of fracture toughness data in ductile-to-brittle transition region.

The alternative and specific assessment routes provided in the document aim at the reduction of possible conservatism if the assessment did not take into account the special features of the cases considered.

The FITNET FFS Procedure also provides information on the emerging fracture assessment methodologies such as local approach to fracture, structural integrity

assessment of thin walled structures as well as structural components containing non-sharp defects. In addition advice is given on loading rate effects on the material's resistance to fracture and on the statistical treatment of fracture toughness data when two fracture toughness distributions are present.

One of the novel assessment methodologies incorporated in to the FITNET FFS procedure is the assessment of **thin wall structures** with and without welds. The thin wall assessment method is based on the assessment procedure given in the main body of the Fracture Module but also adds a number of specific items:

- The general equations are used in combination with the new crack tip driving force parameter $CTOD-\delta_5$ proposed specifically for thin wall structures [23]
- Use of lowest tensile properties (due to anisotropy of rolled thin plates) of base plates is recommended to avoid non-conservatism in the assessment. Furthermore, intrinsic (all-weld metal) weld metal tensile properties need to be determined for the analysis of welded thin-wall structures. This can be done using micro-flat tensile (MFT) specimens of 0.5 mm thickness. This recommended technique and its use is reported in [24-26]. For the assessment of weld or heat affected zone flaws, intrinsic tensile properties of the weld joint should be used.
- The $CTOD-\delta_5$ R-curve (see Fig. 7) has to be obtained on specimens (C(T) or M(T) type) with a thickness, B, identical to the component to be assessed. The crack length, a, and initial uncracked ligament, W-a, should be equal or greater than four times the thickness, B. The fulfilment of these requirements should provide geometry independent R-curves. (**Note:** this statement cannot be generalised and therefore, geometry independence of the R curve has to be checked when the method is applied to new materials or welds. In cases where no geometry independency is stated, the lowest R-curve has to be used which is usually obtained using C(T) specimens).
- In order to avoid extrapolation of the $CTOD-\delta_5-\Delta a$ curve beyond its validity limits the stable crack extension, Δa , at the maximum load in the component should not exceed the Δa range that is covered by the experimental R-curve. As a rule, the width W of C (T) type test specimens should not be smaller than about 150 mm.
- During the testing of thin walled C(T) specimens, distortion of the specimen may occur and hence Mode-II type crack tip loading may develop. In order to avoid this, it is recommended to use rigid anti-buckling guides to maintain Mode-I type of crack tip loading during the $CTOD-\delta_5-\Delta a$ R-curve determination.

An application of FITNET Fracture Module thin-wall option to the laser beam and friction stir welded thin aerospace Al-alloys was conducted [24-26] to validate proposed procedure. The Figures 8 and 9 [26] are showing the tested panel configurations and comparison between experiments and FITNET FFS predictions using Option 1 and Option 3. It should be noted that in this case, C(T) type of specimens of T-joint welds were tested to generate the R-curve of weld joint as shown in Figure 8.

An extensive validation of the proposed assessments methods has been carried out and this is described in the paper [27] presented at the FITNET 2006 Conference.

Hence, the assessment methods given in the Fracture Module, together with the alternative and specific assessment routes, therefore provide flaw assessment methodologies which will meet the needs of a wide range of practical applications.

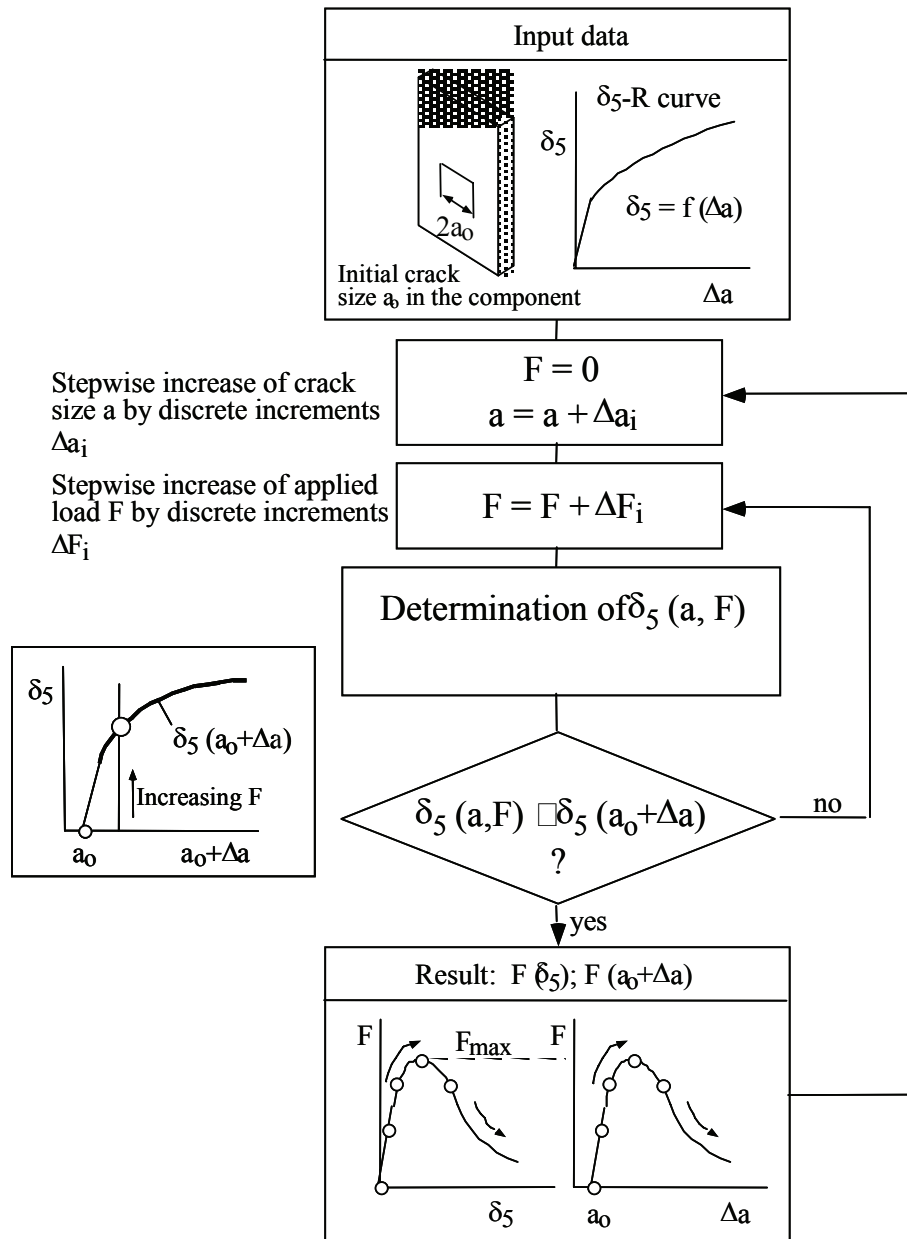


Fig. 7: Flaw-chart for the determination of the applied load- δ_5 and the applied load – stable crack extension. The determination follows the Crack Driving Force (CDF) philosophy.

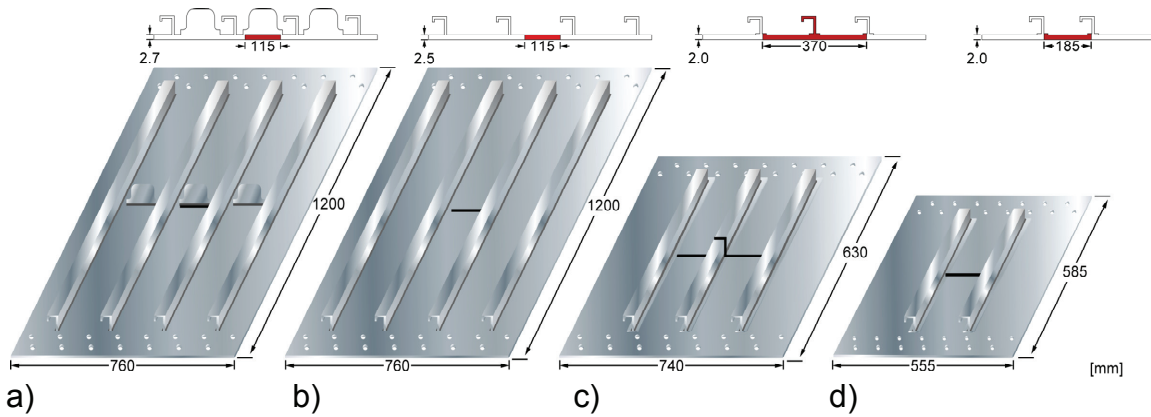


Fig. 8: Schematic representations of the laser beam welded thin wall Al-alloy M(T) panels with T-joints of longitudinal stringers and transverse clips;
a) Four stringer panel with three transverse clips with the notch at the weld toe of the central clip
b) Four stringer panel with skin crack, c) Three stringer panel with broken central stiffener (two bay crack), d) Two stringer panel with one-bay crack. [26]

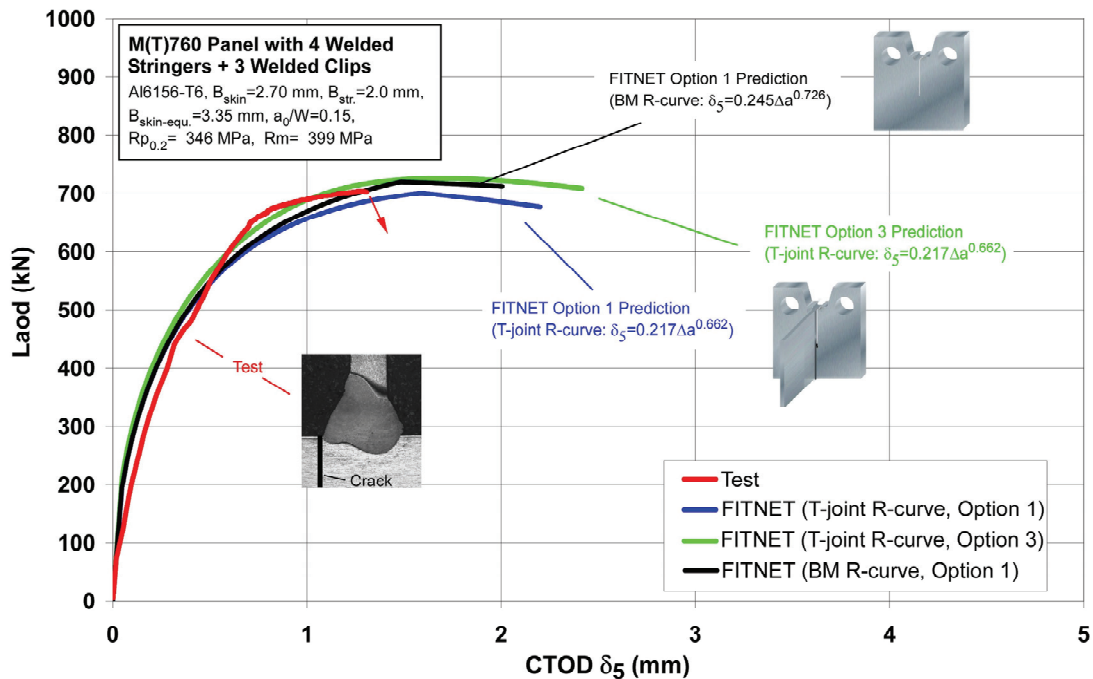


Fig. 9 Comparison between experimental results obtained from 760 mm wide Al-alloy M(T) panels (base meta-BM- and laser beam welded panels shown in Fig. 8a) and FITNET FFS predictions of the Load vs. CTOD δ_5 curves of the four stringer panel with three welded clips [26].

3. 3. 8 References

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3.4 FITNET Fatigue Module

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3.4.1 Introduction

Section 7 of the FITNET FFS procedure specifies methods for assessing defects in structures operating fatigue loading conditions. The FITNET fatigue module provides a series of assessment routes, as shown in Figure 10 for evaluating the fatigue damage due to cyclic or fluctuating loads.

By providing a range of assessment routes, the module aims to cover the needs of analysts which can vary according to the basic fatigue resistance data available (S-N curves or fatigue crack growth laws) and the level of knowledge of local stress distributions (nominal, structural or notch stresses). Further, it exploits the global framework of the FITNET FFS Procedure to provide access to K solutions, basic materials properties, residual stress distributions, guidance on NDE, etc

Two basic scenarios are foreseen:

a) ***There is no pre-existing flaw***, and the goal of the analysis is to determine the accumulation of fatigue damage at a critical location. In this case the basic approach is to determine the fluctuating stress range at the location in question and to relate this to appropriate fatigue life curves.

Three different routes are considered (Routes 1, 2 and 3), depending on the choice of stress or strain to be used in the assessment. Any of the routes can be used to determine the accumulation of fatigue damage during the specified operational life (referred to later as 'cumulative fatigue assessment') or to ensure that no significant fatigue damage will be introduced, so that the life can be regarded as being infinite (a 'fatigue limit assessment'). The second approach may be required if there is a risk of unstable fracture from a small fatigue crack or the number of fluctuating stress cycles to be endured in service is very large, typically greater than 10^9 .

b) ***A real or postulated flaw is present***, and the goal of the analysis is to determine its fatigue life.

Two different routes are considered, fatigue crack growth analysis in Route 4 and *the use of S-N curves* in Route 5. The **Route 4** is required if the flaw is planar or if it is necessary to quantify the progress of the crack propagating from a planar or non-planar flaw (e.g. to establish inspection intervals or to allow for

possible fracture at a particular critical crack size). The **Route 5** is used only to assess non-planar flaws.

3. 4. 2 Features of the Fatigue Module and Assessment Routes

FITNET FFS Fatigue Damage Assessment Routes are organized as following;

Route 1: Nominal Stress Analysis

Route 2: Structural Stress or Notch Stress

Route 3: Non-linear Local Stress-Strain Analysis

Route 4: Fatigue Crack Growth Analysis

Route 5: Assessment of Non-Planar Flaws

The overall assessment scheme is shown in Figure 10 and basic steps of the analysis are presented in Figure 11.

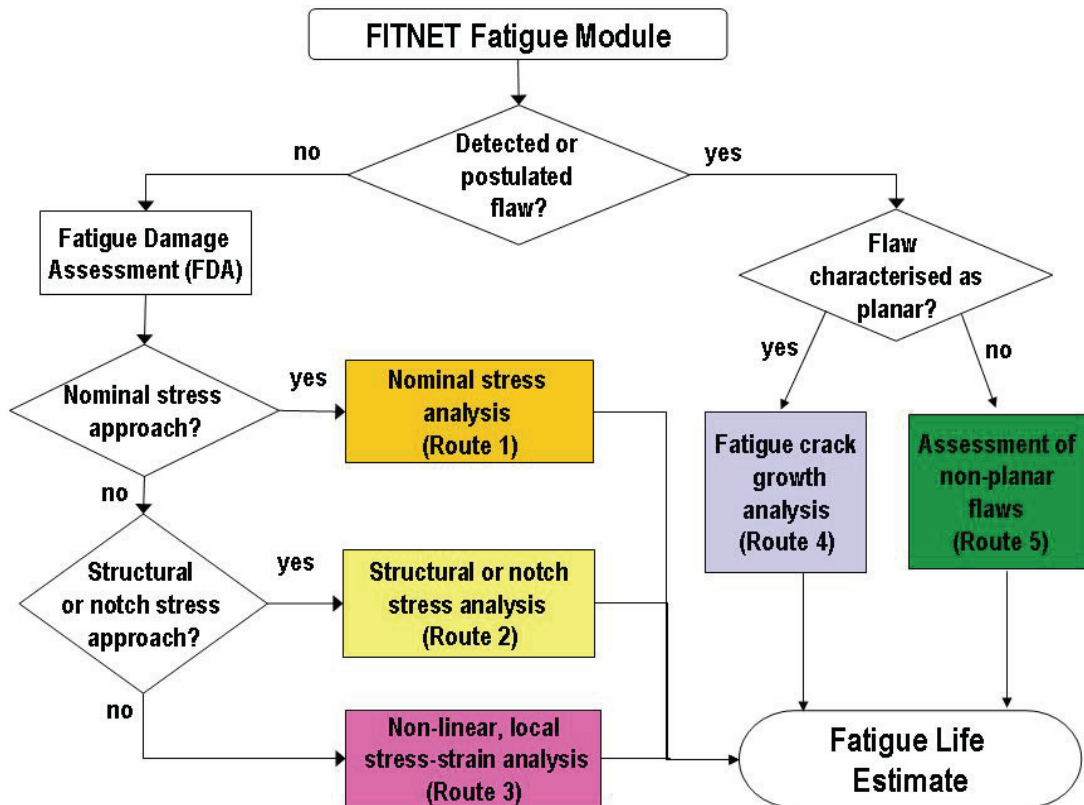


Fig. 10. Selection of the assessment routes of the Fatigue Module (Section 7) of the FITNET FFS Procedure.

Within these five assessment routes, above mentioned two basic application scenarios are foreseen in Fatigue Module. Both approaches; a) and b) can be applied to either welded or non-welded structures. It is noted that for a given component, both aspects may need to be considered in cases for which the location of a reported defect does not coincide with that of highest loading

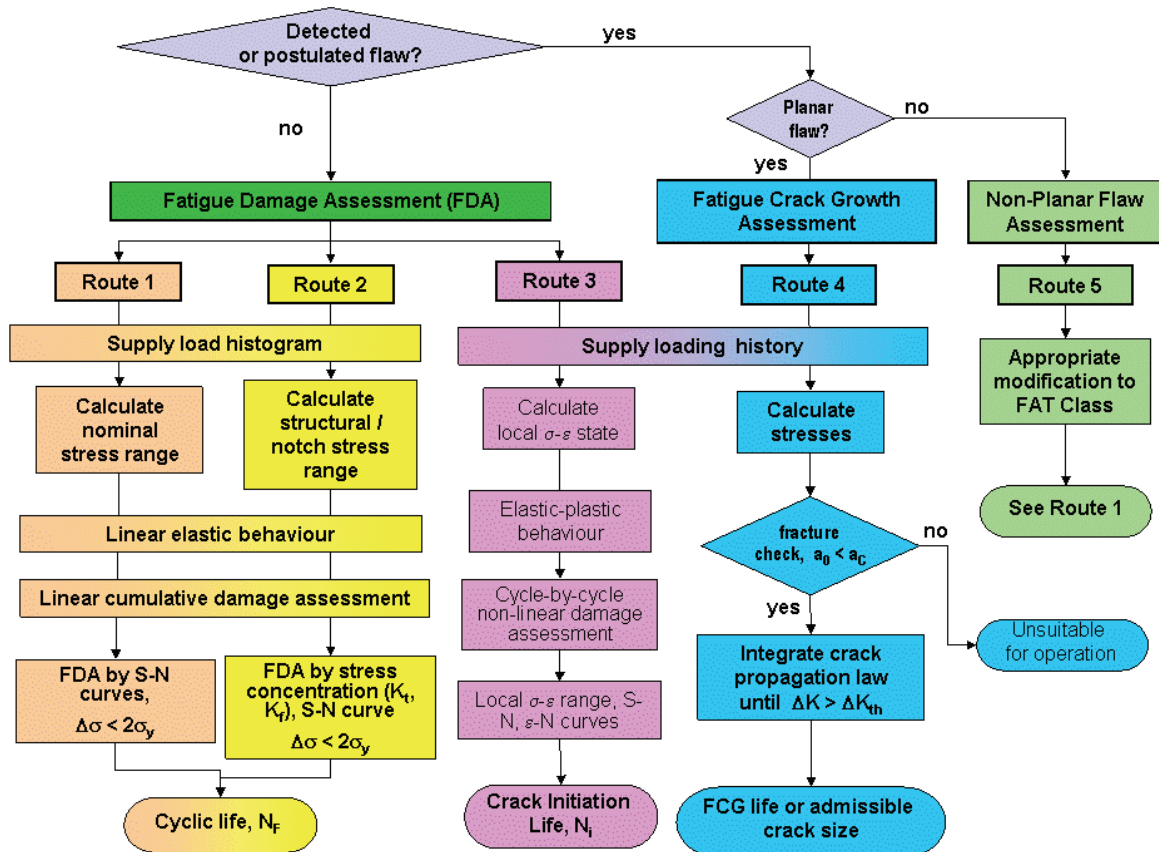


Fig. 11. Details of the flow chart of the fatigue damage assessment routes

Route 1 – Fatigue damage assessment using nominal stresses

This route considers nominal elastic stress values for the location of interest and the fatigue life N_f is determined from a set of S-N curves classified according to different classes or levels of fatigue resistance i.e. the effects of local geometric, weld or microstructural details and, if relevant, residual stresses are accounted for in the S-N curve itself. It is based on currently used procedures (e.g. IIW [28]) for welded joints. The linear cumulative damage law is used to deal with variable load spectra:

$$\frac{N_1}{N_{f1}} + \frac{N_2}{N_{f2}} + \frac{N_3}{N_{f3}} + \dots \leq 1$$

where D is a scalar measure of the allowable damage at the end of the required life (commonly $D=1$ but it can also be set to a value less than one).

Route 2 – Fatigue damage assessment using either structural stress or notch stress, coupled with appropriate S-N curves

Route 2 considers that the appropriate structural stress in a critical area of a component could be calculated by FEA or by formula. In some case it could also be measured by following specific methods. Two approaches are possible:

- a) calculate the structural stress and apply with appropriate class S-N curves;
- b) calculate a notch stress via stress concentration factors such as K_t or K_f and apply with appropriate S-N curves [29, 30].

Route 3 - Fatigue damage assessment considering elastic-plastic material behavior at critical features and strain-range based fatigue life curves

Route 3 is mainly directed at non-welded applications and foresees direct calculation of strains at a critical location using an appropriate elastic or elasto-plastic description of the material behaviour. The fatigue life is then determined from a strain range vs. cycles relation such as the Manson-Coffin law, for which the implicit failure criterion is related to crack initiation. It is also noted that the analysis can be taken further by considering subsequent crack growth using fracture mechanics (Route 4). These analyses can be performed cycle-by-cycle, allowing for non-linear damage accumulation effects if necessary.

Route 4 – Fatigue crack propagation

Route 4 addresses the assessment of detected or postulated planar flaws that can be considered as macro-cracks (i.e. with dimensions typically greater than millimetres). The initial flaw position, size and orientation can be determined in two ways:

- a) Based on the reported or detected size from non-destructive inspection results;
- b) Postulated defect, based on consideration of service experience, the manufacturing process, resolution limits of a NDE technique, from the threshold stress intensity factor etc.

Recommendations are given for assessing flaws in plain, unwelded material and for those associated with welds.

a) Flaws in unwelded material

The selected baseline fatigue crack growth equation is that originally proposed by Forman and Mettu and subsequently used in the NASGRO software for non-welded application. It accounts for the stress intensity factor range, the mean stress level and other important parameters and is considered a suitable universal formula for fatigue crack growth (FCG) analysis. It has the form:

$$\frac{da}{dN} = C \left[\left(\frac{1-f}{1-R} \right) \Delta K \right]^n \frac{\left(1 - \frac{\Delta K_{th}}{\Delta K} \right)^p}{\left(1 - \frac{K_{max}}{K_c} \right)^q}$$

where C , n , p , and q are material constants, f is the ratio of opening and maximum, K_{max} , stress intensity factors, R is stress ratio, K_c is the critical stress intensity factor, and ΔK_{th} is the threshold stress intensity factor range.

b. Flaws in either welded or unwelded material

For the assessment of flaws associated with welds or for assessing flaws in unwelded material for cases where the Forman and Mettu parameters are not available, use is made of the Forman and Mettu expression reduced to the standard Paris Law form:

$$\frac{da}{dN} = C.\Delta K^m$$

where C and m are constants that depend on the material, environment and the applied conditions, including any that are specifically relevant to flaws in welds, notably the presence of residual stress.

If it can be shown that ΔK is below an appropriately determined threshold value, the crack growth rate may be deemed negligible. These expressions can be integrated to provide estimates of crack growth over a fixed number of cycles or for the number of cycles required to reach a critical crack size, determined using the FITNET fracture assessment module. The acceptability of the real or postulated flaw can then be determined in relation to the required cyclic life.

K solutions for various crack and loading conditions are provided in Annex A.

Route 5 – Non-planar flaw assessment

Non-planar flaws can be assessed in the same way as planar flaws using route 4. Since they are not crack-like, this will be conservative. However, it may be the only option if it is necessary to quantify the growth of the flaw under fatigue loading and to ensure the margin against unstable fracture at a specific crack size. Otherwise, Route 1 using S-N curves for welded joints can be applied directly, in cases for which the equivalent fatigue strength are established for the non-planar flaw under consideration.. At present, this approach is only available for assessing slag inclusions or porosity in steel or aluminium alloy butt welds

Alternative approaches and specific assessments in fatigue are also included in the FITNET procedure. The objective is to identify limits between the modules in the overall FITNET FFS procedure for complex service conditions and also to consider "emergent" industrial approaches to assess fatigue life under specific conditions. The areas covered by this part are focused on:

- Equivalent constant amplitude stress
- Multi-axial fatigue assessment
- Contact and fretting fatigue
- Fatigue - creep interactions
- Fatigue - corrosion interactions

3. 4. 3 Application of the FITNET FFS Fatigue Assessment Routes

The FITNET FFS Fatigue Module routes were applied to the numbers of cases by Huther and Vormwald [31] and the work was reported at the FITNET 2006 Conference. As an example, an application of the FITNET fatigue crack propagation analysis route (**Route 4**) to the offshore tubular joint case is presented here.

Route 4: Fatigue crack propagation

In welded tubular joints of offshore structures made of a fine grained structural steel (S355) cracks can be initiated under sea wave loading. It has to be assessed, how these cracks behave and how inspection intervals have to be fixed or whether the structure with cracks achieves the required life time.

Component tests have been carried out under operation loading and environments in the laboratory to fix the method to be used by comparison of calculation and experiment. An extensive presentation of the investigations done can be found in [32].

Under conservative assumptions the crack progress is estimated with two different models and the suitability of the method is evaluated in comparison with experiments. The welded tubular joint with the critical regions in which cracks arise is depicted in Fig. 12, tubular joint.

Fig. 13 shows the location of the crack origin and the crack path. The crack occurs in the weld seam transition notch; it grows, however, into the base material.

Following gives the step-by-step procedure of the analysis of this case.

Step 1: Postulated flaws

An initial crack depth: $a = 1.0$ mm is assumed, since this crack depth is reliably detectable with NDE methods in the case considered. The crack spreads through the wall thickness.

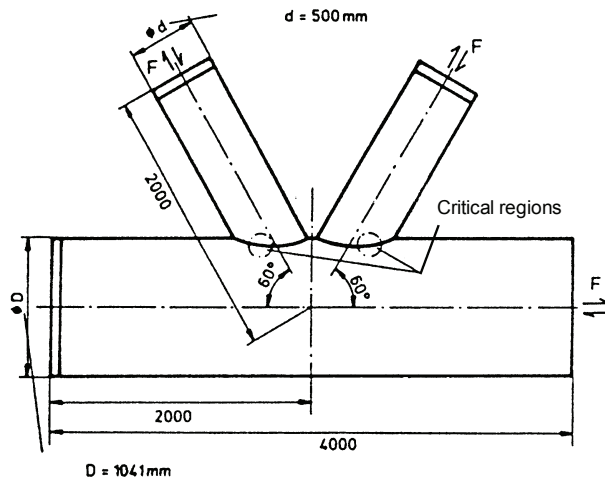


Fig. 12 Tubular joint

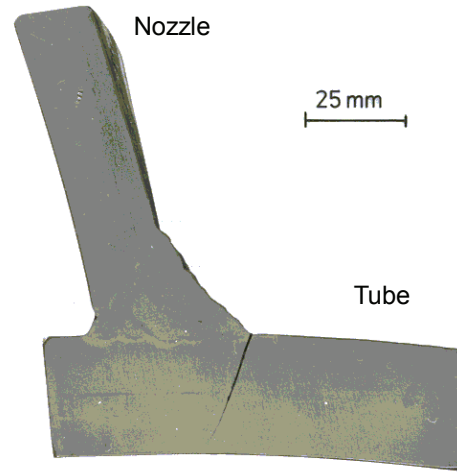


Fig. 11 Crack path

Step 2: Establish service conditions

The tubular joint is subjected to a cyclic loading ($R_F = -1$) with variable amplitudes the spectrum of which is distributed linearly. The common load sequence used in experiments has a sequence length of $N = 4.49 \cdot 10^5$ corresponding to one year service life, Fig. 14 and Table 2.

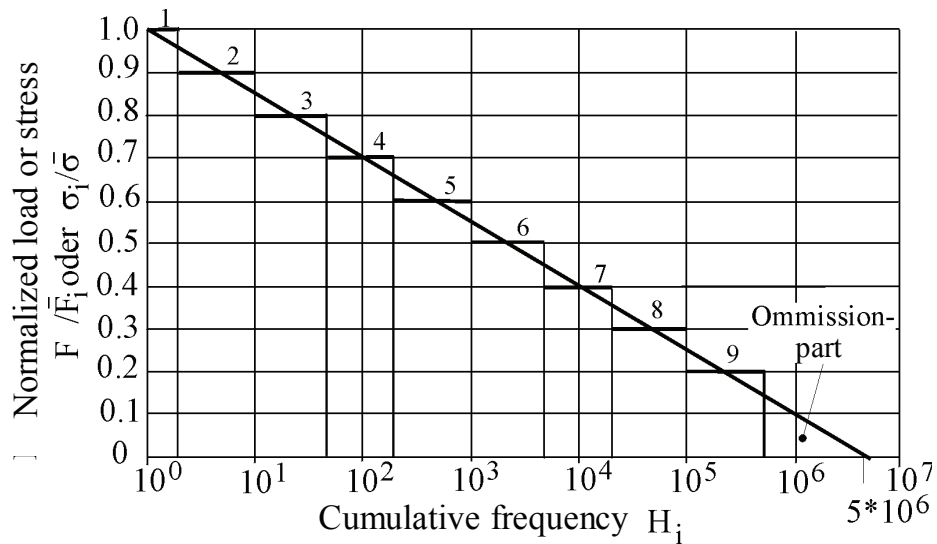


Fig. 12 Common load sequence used in experiments and discrete load steps (see Table 2) used for the calculation of the crack growth

Table 2 Load steps used for the calculation of the crack growth

i	F_i/F	N_i
1	1.0	2
2	0.9	8
3	0.8	40
4	0.7	150
5	0.6	800
6	0.5	4000
7	0.4	15000
8	0.3	80000
9	0.2	394000
Σ		494000

Step 3: Environmental effects

The investigations were carried out under artificial sea water environment according to ASTM D 1141-52 at room temperature.

Step 4: Collect materials data and perform stress analysis

The component consists of the fine-grained structural steel StE 355 with the component strength values determined on the semi-finished product before production of the tubes:

$$R_{p0.2} = 362 \text{ MPa and}$$

$$\sigma_{UTS} = 515 \text{ MPa}$$

For weld metal, heat affected zone, and base material identical material property values were assumed. The values of the base material were therefore used for the calculation.

For the tube material the crack growth rate in air and artificial sea water are available, Fig. 15. The constants of the Paris-Erdogan Equation for $R_K = 0.1$ are

$$C = 1.03 \cdot 10^{-8} \text{ and } m = 2.86 \text{ in air and}$$

$$C = 6.24 \cdot 10^{-9} \text{ and } m = 3.28 \text{ in artificial sea water (} da/dN \text{ in mm/cycle, } \Delta K \text{ in MPa}\sqrt{m} \text{, note the different units in Fig. 15)}$$

Residual stresses in tension are assumed, which cause locally a shift of the load ratio $R_F = -1$ to a stress ratio and stress intensity ratio $R_\sigma = R_K > 0$, so the value given for $R_K = 0.1$ can be used in the calculation. With increasing crack growth residual stresses are usually reduced. In the calculation with $R_K = 0.1$ this is not taken into account, but this leads to a conservative estimate.

Step 5: Prechecks

For the given task only the crack growth has to be considered. An assessment of the fatigue threshold value is not necessary.

As a component failure (limit state) fatigue crack extension up to break through the wall is fixed here. Thus, the fracture mechanics strength proof for static loading is omitted.

Step 6: Calculate crack growth

Two different crack models are considered,

- a) a semi-elliptical surface crack in a plate under tension and bending with a ratio $a/c = 1/15$ determined experimentally at a stress concentration area, Fig. 16 and
- b) a through-width surface crack in a plate, Fig. 17.

In the first phase of crack extension the crack model a) is closer to the reality. The crack shape changes, however, into model b) after reaching a certain crack size. The crack extends perpendicularly to the first principal stress direction.

The following solutions for the stress intensity factor K exist for the models a) and b):

- a) Semi-elliptical surface crack at a stress concentration under tension and bending stress according to **Error! Reference source not found.**

$$\Delta K = (M_{km} \cdot M_m \cdot \Delta \sigma_m + M_{kb} \cdot M_b \cdot \Delta \sigma_b) \cdot \sqrt{\pi a}$$

with

$\Delta \sigma_m$ – range of the tension stress,
 $\Delta \sigma_b$ – range of the bending stress,

where both come from a FE calculation of the structural stresses in the chord of the joint.

M_m, M_b – geometry factors for tension and bending and
 M_{km}, M_{kb} – geometry factors taking into account stress concentration for tension
and bending.

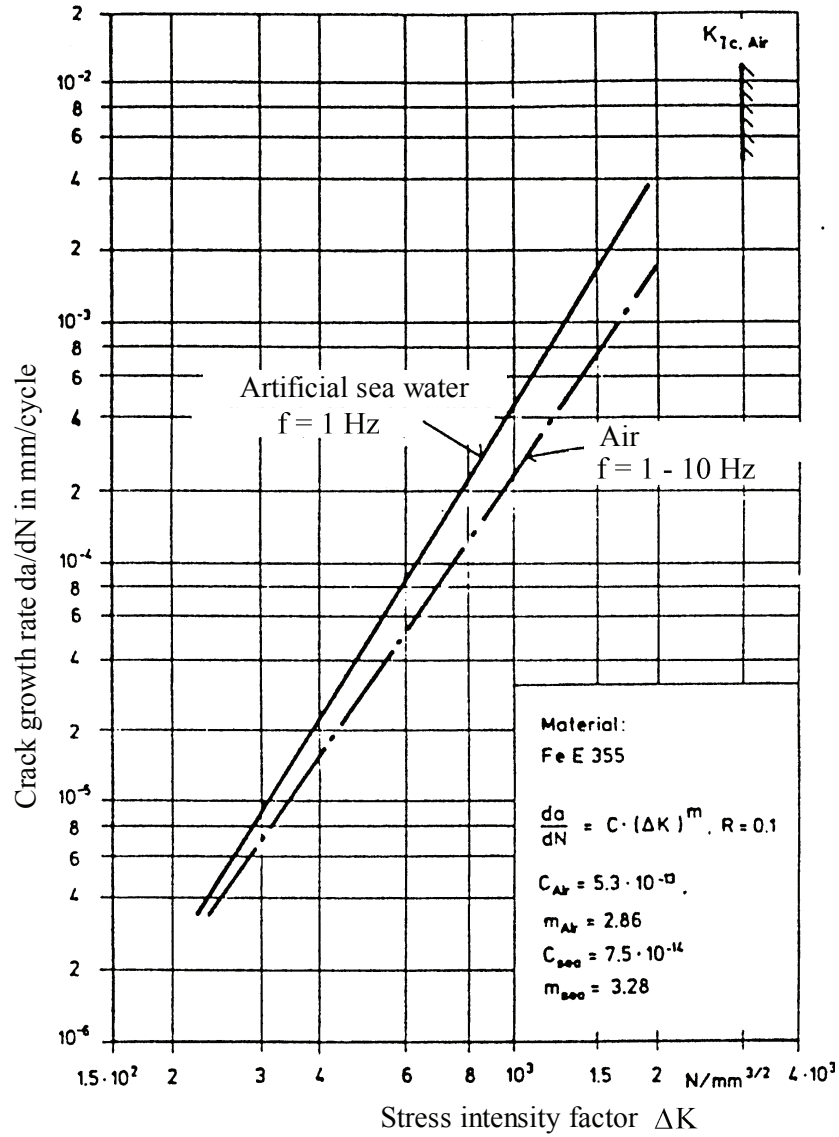


Fig. 13 Crack growth behaviour for S355 [31]

The values of M_m and M_b are given in the FITNET FFS procedure. Furthermore according to [34] it is

$$M_K = 1 + \left\{ (K_t - 1)^{-2.5} + \left[\sqrt{(\alpha^2 / \lambda + 1)} - 1 \right]^{-2.5} \right\}^{-0.4}$$

with

$$\alpha = C_4 + \sqrt{C_4^2 + (K_t - 1) / C_2}$$

and

$$C_4 = (C_3 \cdot K_t - C_1) / (2C_2) \text{ with}$$

$$C_3 = 0.517, C_2 = 1.16 \text{ and } C_1 = 2.48$$

as well as

$$\lambda = a / r$$

The shape factor K_t results from the notch radius r of the notch without crack and the tube wall thickness t according to 0 for bending as

$$K_t = 1.12(t / r)^{1/3.1}$$

Cracks with lengths $a > 1$ mm do not influence the values of M_K as long as it is $r < 5$ mm. For the tubular joint a notch radius of $r = 1$ mm is assumed.

b) Surface crack in a plate under tension and bending according to 0.

$$\Delta K = (\Delta \sigma_z \cdot F_0 + \Delta \sigma_b \cdot F_1) \cdot \sqrt{\pi a}$$

with the geometry functions

$$F_1 = Y \cdot \left[0.923 + 0.199(1 - \sin \beta)^4 \right]$$

$$F_1 = Y \cdot \left[0.923 + 0.199(1 - \sin \beta)^4 \right]$$

and

$$Y = \sec \beta \sqrt{(\tan \beta) / \beta},$$

$$\beta = \pi \cdot w / 2 \text{ and } w = a / t$$

The determination of the number of cycles N until failure is performed by integration of the crack growth relation of the initial crack depth $a_0 = 1$ mm up to reaching a critical crack depth at break-through $a_{crit} = t$ (t – wall thickness of the tube). With the use of the Paris-Erdogan equation it follows

$$N = \int_{a_0}^{a_{crit}} \frac{da}{6.24 \cdot 10^{-9} (\Delta K)^{3.28}}.$$

For the calculation the load sequence, Fig. 14 was subdivided into steps (Table 2) and applied block by block with constant $\Delta\sigma$.

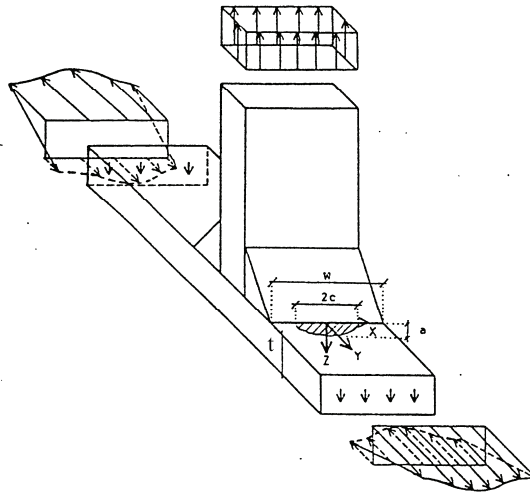


Fig. 16 Semi-elliptical surface crack in a plate under tension and bending [31]

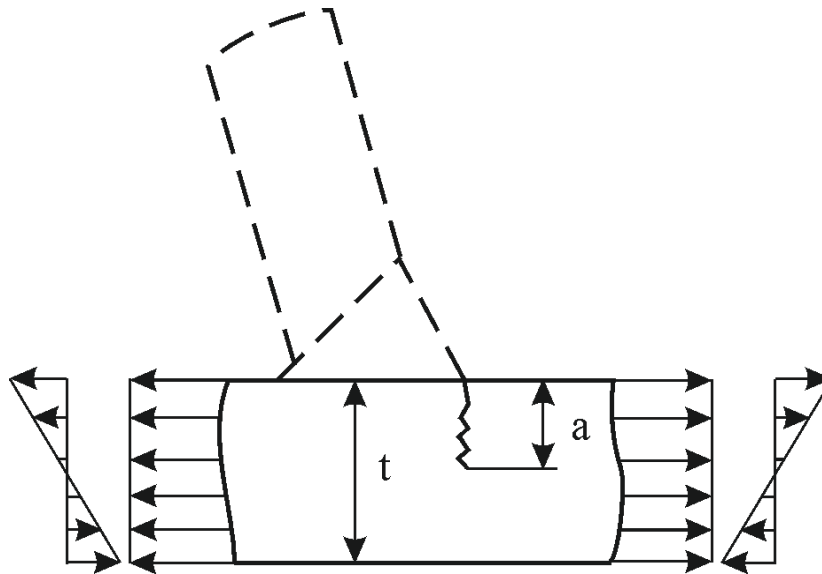


Fig. 17 Through-thickness surface crack in a plate under tension and bending [31].

The results are displayed in Fig. 18 starting from a crack depth of 1 mm, the results of the used models are not fundamentally different from each other.

In this figure, the calculated number of cycles ($N_{\text{calculation}} = 1.1 \cdot 10^6$ or $1.8 \cdot 10^6$) is smaller than that determined experimentally ($N_{\text{experiment}} = 2 \cdot 10^6$).

This difference is mainly based on the conservative assumptions. In reality, the residual tension stresses of the weld joint, taken into account in calculation by the stress intensity ratio $R_K = 0.1$, however, are not acting from beginning to the end of the crack growth. Model b) loses some of its conservatism due to neglecting the notch effect at the weld toe.

The estimation of the crack growth verified by component tests shows that both models, a) and b), are suitable to specify inspection intervals and estimate the component life time for the case under consideration. Due to the calculation carried out, one-year inspection intervals are to be recommended under the assumption

1 year = $5 \cdot 10^5$ load cycles.

An additional safety assessment or sensitivity analysis has not been applied.

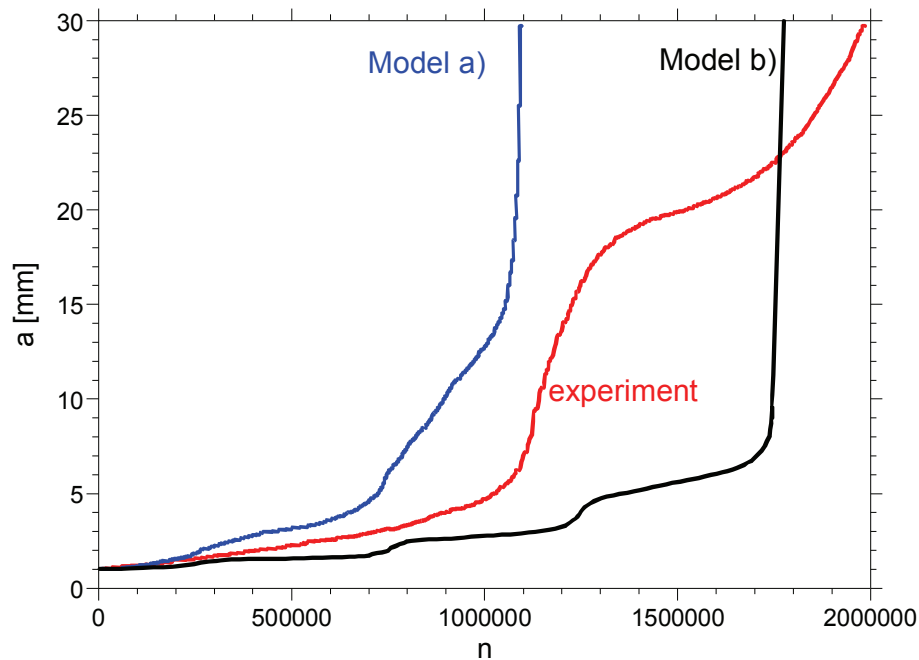


Fig. 18 Comparison of crack progress in experiment and calculation [31]

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3. 5 FITNET Creep Module

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3. 5. 1 Introduction

Methods for assessing defects in components operating at temperatures high enough for creep to be important were first introduced in the late 1980s [37]. The methods initially only applied to assessment of creep crack growth under steady loading but were later extended to creep-fatigue loading conditions. The R5 high temperature assessment procedure [38, 39], produced in the UK, formalized these methods. Subsequently, procedures for assessing defects at high temperature, similar to those in R5, have been included in British Standards [40], the French A16 procedure [41] and in API 579 [42].

Within the FITNET project, these existing procedures were reviewed and used as a basis for producing the creep module of the FITNET FFS procedure. This section first provides an overview of the basic methodology of the creep module. In developing the FITNET creep module, ongoing work by the FITNET partners was used to extend the module beyond existing procedures. This report highlights these extensions in three areas: treatment of secondary loading, failure assessment diagram methods, and probabilistic approaches.

Nomenclature

a	crack size
a_0	initial crack size
a_g	crack size after growth
a_{min}	crack size below which the crack growth rate is assumed to be constant
$\dot{a}$	crack growth rate
A	material constant (creep crack growth)
B'	material constant (cyclic crack growth)
C	material constant (cyclic crack growth)
$C(t)$	transient crack tip parameter
C^*	steady state crack tip parameter
$\overline{C^*}$	mean estimate of C^* during early cycles
da / dN	crack growth per cycle
$(da / dN)_c$	creep crack growth per cycle
$(da / dN)_f$	fatigue crack growth per cycle
d_c^{surf}	surface creep damage accumulated in a cycle
D_c^{surf}	total surface creep damage
E	elastic modulus

K_{Iid}	stress intensity factor (TDFAD)
K_{Ii}	crack initiation toughness (2CD)
K_{mat}^c	creep crack initiation toughness (TDFAD)
K_{max}	maximum stress intensity factor in cycle
K_{min}	minimum stress intensity factor in cycle
K^P	stress intensity factor due to primary load
K^S	stress intensity factor due to secondary loading
K_r	stress intensity factor ratio (TDFAD)
ℓ	material constant (cyclic crack growth)
L_r	load ratio P / P_L
L_r^{max}	cut-off on TDFAD
n	creep stress exponent
$P()$	probability
P	load
P_L	limit load
q	material constant (creep crack growth)
q_o	fraction of total load range for which crack is judged to be open
Q	material constant (cyclic crack growth)
r_p	size of the cyclic plastic zone
R	stress intensity factor ratio $(= K_{min} / K_{max})$
R'	length in estimate of C^*
R_K	stress intensity factor ratio (2CD)
R_σ	stress ratio (2CD)
t	time
t_i	initiation time
t_{cyc}	time to reach steady cyclic state
t_o	service life to date
t_g	time required for the crack to propagate by an amount Δa_g
t_h	hold time at high temperature
t_r	rupture time
t_{red}	redistribution time
t_s	desired future service life
t_{CD}	time for continuum damage failure
w	section width
Z	elastic follow-up factor
β, γ	material constants (creep crack initiation)
δ_i	critical crack tip opening displacement (creep crack initiation)
Δa_i	crack growth corresponding to initiation
Δa_g	crack growth
$\Delta \bar{\epsilon}_t$	total surface strain range (cyclic crack growth)
ΔK	stress intensity factor range

ΔK_{eff}	stress intensity factor range for which crack is open
$\dot{\bar{\epsilon}}_c$	equivalent creep strain rate
ϵ_c	creep strain
ϵ_e	elastic strain
$\dot{\epsilon}_c$	creep strain rate
$\bar{\epsilon}_f$	creep ductility
μ_c, δ_c	mean and standard deviation
$\bar{\sigma}$	short-term flow stress
$\sigma_{0.2}$	0.2% strength
$\sigma_{0.2}^c$	0.2% creep strength
$\sigma_{1.0}^c$	1.0% creep strength
σ_{npl}	nominal stress (2CD)
σ_{ref}	reference stress
$\dot{\sigma}_{\text{ref}}$	reference stress rate
$\sigma_{\text{ref}}^{\text{cyc}=1}$	reference stress for first cycle
σ_{ref}^p	reference stress for primary loading
σ_R	creep rupture strength
σ_y	yield stress
σ_u	ultimate tensile stress
Ω	normalized Gaussian distribution

3. 5. 2 Features of the Creep Module and Assessment Steps

The **FITNET FFS Creep Module** specifies methods for assessing defects in structures operating at high temperatures and under creep-fatigue loading conditions. The information required to perform an assessment is: the operating conditions; the nature of the defects; materials data; and structural calculations to correlate materials data with the behaviour of complex structures. Basic advice on the first three aspects is given in Section 5 of the FITNET FFS procedure. Section 8 concentrates on the structural calculations required to assess whether a given defect will grow to an unacceptable size in a given service life under a given loading history. A step-by-step procedure is provided to perform these assessments and methods for following each step are specified. The steps in the procedure are summarized in this section.

Overall FITNET FFS Creep Procedure

There are **13 steps** in the creep module of the FITNET FFS Procedure, as follows.

- STEP 1 Establish Cause of Cracking and Characterise Initial Defect
- STEP 2. Define Service Conditions
- STEP 3. Collect Materials Data
- STEP 4. Perform Basic Stress Analysis
- STEP 5. Check Stability under Time-Independent Loads
- STEP 6. Check Significance of Creep and Fatigue
- STEP 7. Calculate Rupture Life based on the Initial Defect Size
- STEP 8. Calculate Initiation Time
- STEP 9. Calculate Crack Size after Growth
- STEP 10. Re-Calculate Rupture Life after Crack Growth
- STEP 11. Check Stability under Time-Independent Loads after Crack Growth
- STEP 12. Assess Significance of Results
- STEP 13. Report Results

Some information for steps 1-4 is provided elsewhere in the FITNET document. Steps 5 and 11 use the fracture calculations in Section 6 of the FITNET FFS procedure. Therefore, attention is focused here on the specific materials data and calculations required to follow the creep module through steps 6-10.

3. 5. 3 Materials Data

For some situations, it is possible to take account of an incubation period, t_i , prior to crack extension. Creep crack incubation data may be expressed in terms of a critical crack tip opening displacement, δ_i , or, for widespread creep conditions, by the relationship:

$$t_i (C^*)^\beta = \gamma \quad (1)$$

where β and γ are material constants.

Creep crack growth data are generally presented as

$$\dot{a} = A(C^*)^q \quad (2)$$

where A and q are material constants.

Two different methods of calculating creep-fatigue crack growth are given. The method to be applied depends on the defect size and the severity of the applied loading. When the defect is sufficiently small to be embedded in a cyclic plastic zone the crack growth law is a high strain fatigue crack growth law (termed Method II) from the fatigue module of Section 7 of the FITNET FFS procedure, modified by a creep damage term. For larger defects, fatigue crack growth is calculated by a Paris law from Section 7, modified to allow for crack closure and simply added to a separate calculation of creep crack growth rates to give the total crack extension. This is termed Method I and is described by

$$\left(\frac{da}{dN} \right)_f = C \Delta K_{\text{eff}}^\ell \quad (3)$$

where C and ℓ are material constants and ΔK_{eff} is the stress intensity factor range for which the crack is judged to be open. The Method II crack growth rate law is

$$\left(\frac{da}{dN} \right)_f = B' a^Q \quad a_{\min} \leq a \leq r_p \quad (4)$$

where $a_{\min} = 0.2$ mm is the crack depth below which the crack growth rate is assumed to be constant. B' and Q depend on material, strain range and environment, and can be determined experimentally. This law applies for a total surface strain range $\Delta \bar{\epsilon}_t$. Further information on fatigue crack growth data is contained in Section 7 of the FITNET FFS procedure.

3. 5. 4 Basic Creep-Fatigue Calculations

In the absence of cyclic plasticity in the uncracked body, the effective stress intensity factor range ΔK_{eff} is

$$\Delta K_{\text{eff}} = q_o \Delta K \quad (5)$$

where $\Delta K = K_{\max} - K_{\min}$ and q_o is the fraction of the total load range for which a crack is judged to be open. This may be estimated conservatively from:

$$\begin{aligned} q_o &= 1 & R &\geq 0 \\ q_o &= (1 - 0.5R) / (1 - R) & R &< 0 \end{aligned} \quad (6)$$

where $R = K_{\min} / K_{\max}$.

For creep rupture and crack growth evaluation, it is necessary to evaluate a reference stress. The reference stress for simple primary loading is determined by the methods of limit analysis and is defined by:

$$\sigma_{\text{ref}}^p = P \sigma_y / P_L(\sigma_y, a) \quad (7)$$

In cases of cyclic loading the load P is evaluated from the stress, produced by the shakedown analysis, at the time in the cycle corresponding to the creep dwell. P_L is the value of P corresponding to plastic collapse assuming a yield stress σ_y .

For steady state creep, the crack tip stress and strain rate fields (and hence creep crack growth rates) are characterised by the C^* parameter. A reference stress estimate of C^* is

$$C^* = \sigma_{ref}^p \dot{\epsilon}_c [\sigma_{ref}^p(a), \epsilon_c] R' \quad (8)$$

Here, $\dot{\epsilon}_c$ is the creep strain rate at the current reference stress and creep strain, ϵ_c , accumulated under the reference stress history up to time t . The characteristic length, R' is defined by

$$R' = (K^p / \sigma_{ref}^p)^2 \quad (9)$$

where K^p is the stress intensity factor due to primary load only.

As both K^p and σ_{ref}^p are directly proportional to the loading P , the value of R' is independent of the magnitude of P . However, R' does vary with crack size and, when creep crack growth is being considered, both K and σ_{ref}^p should be calculated for the defect size equal to the size of the original crack plus the amount of creep crack growth. The value of R' is also different at the surface and deepest points of a semi-elliptical surface defect due to differences in the values of K^p .

For other than simple primary loadings, estimates of C^* are given below in the section describing **novel features of the FITNET FFS creep module**.

Time is required for stress redistribution due to creep from the initial elastic state at the start of a creep dwell. The requirement for the stress redistribution to be complete and widespread creep conditions to be established is expressed in terms of a redistribution time, t_{red} . This is defined conveniently in terms of the reference stress for cases of primary load only as

$$\epsilon_c [\sigma_{ref}^p(a), t_{red}] = \sigma_{ref}^p(a) / E \quad (10)$$

where $\epsilon_c [\sigma_{ref}^p(a), t]$ is the accumulated creep strain at the reference stress for time, t , and crack length, a , from uniaxial creep data.

Equation (10) applies for steady creep loading under primary stresses. When calculating crack growth under significant cyclic loading, it may be necessary to consider the early cycles before the steady cyclic state is reached. Time is required for the material response to the cyclic loading to reach a steady cyclic state or shakedown. This time, t_{cyc} , can be estimated in terms of the reference

stress for the first cycle, $\sigma_{ref}^{cyc=1}$, and the reference stress under steady cyclic conditions for combined primary and secondary loading, σ_{ref} , as:

$$\varepsilon_c \left[\frac{(\sigma_{ref}^{cyc=1} + \sigma_{ref})}{2}, t_{cyc} \right] = Z \frac{(\sigma_{ref}^{cyc=1} - \sigma_{ref})}{E} \quad (11)$$

where Z is an elastic follow-up factor, which controls the rate of stress relaxation to steady state creep.

For times less than the redistribution time, it may be necessary to calculate the transient crack tip parameter $C(t)$. An interpolation formula for $C(t)$ during the transition between initial elastic loading and steady state secondary creep is

$$\frac{C(t)}{C^*} = \frac{(1 + \varepsilon_c / \varepsilon_e)^{1/(1-q)}}{(1 + \varepsilon_c / \varepsilon_e)^{1/(1-q)} - 1} \quad (12)$$

where ε_c is the accumulated creep strain at time t , ε_e is the elastic strain and q is the exponent in the creep crack growth law of equation (2) with $q \approx n/(n+1)$ where n is the creep stress exponent. For times in excess of the redistribution time, $C(t)$ approaches C^*

3. 5. 5 Assessment Calculations

3.5.5.1 Calculate rupture life, t_{CD}

Both stress-based and strain-based approaches may be used for assessing creep damage. For loadings which are predominantly constant and primary, the stress is well known and stress/time-to-rupture relationships are used. For predominately primary loading, the time, t_{CD} , for creep damage to propagate through a structure and lead to failure is

$$t_{CD} = t_r[\sigma_{ref}^p(a)] \quad (13)$$

where $t_r(\sigma)$ is the rupture time at stress, σ , from conventional stress/time-to-rupture data.

If t_{CD} is less than the remaining assessment time then remedial action must be taken. For damage due to cyclic relaxation, the strain accumulated is limited in each cycle and ductility methods replace equation (13).

3.5.5.2 Calculate crack incubation time, t_i

The incubation time, t_i , is defined for engineering purposes as corresponding to 0.2 mm crack extension. The method for representing incubation data then depends on observed specimen response. For steady state creep conditions with an essentially constant displacement rate, the incubation time in test specimens is correlated with experimental estimates of C^* by equation (1). Use of the estimate of C^* from equation (8) for the initial crack size a_0 , then provides an estimate of t_i . More generally, incubation times can be related to measurements of a critical crack opening displacement, δ_i , which can then be used to calculate a critical reference strain as

$$\varepsilon_c[\sigma_{ref}^p(a_0), t_i] = [\delta_i / R'(a_0)]^{n/(n+1)} - \sigma_{ref}^p(a_0) / E \quad (14)$$

For elliptical or semi-elliptical defects, the incubation time should be taken as the lower of the values obtained at points corresponding to the major and minor axes of the ellipse or semi-ellipse.

3. 5. 5. 3 Calculate crack size after growth, a_g

The extent to which crack growth calculations are required depends on the relative magnitudes of the service life to date, t_o , the desired future service life, t_s , and the incubation time, t_i .

This may be summarised as follows.

- If $t_o + t_s < t_i$, the crack will not incubate and $a_g = a_0$.
- If the crack incubates during the assessment time, then it is necessary to calculate the crack size, a_g , after growth in time $t_o + t_s - t_i$.
- If the crack has incubated prior to the assessment, then it is necessary to calculate the crack size, a_g , after growth in time t_s .

The time required for the crack to propagate by an amount Δa_g is denoted t_g .

There are a number of different regimes for calculations of crack growth and these are set out below.

(A) Cracks growing inside the cyclic plastic zone, r_p , at the surface of the component.

In this regime the Method II high strain creep-fatigue crack growth law should be used. This is equation (4) for insignificant creep. When creep is significant, the creep-fatigue crack growth per cycle is given by:

$$\frac{da}{dN} = \left(\frac{da}{dN} \right)_f (1 - D_c^{\text{surf}})^{-2} \quad (15)$$

where $(da/dN)_f$ is the fatigue crack growth per cycle from equation (4) and D_c^{surf} is the total surface creep damage (taking account of stress state, if necessary) accumulated up to the current time from every cycle

$$D_c^{\text{surf}} = \sum_{j=1}^N (d_c^{\text{surf}})_j \quad (16)$$

where $(d_c^{\text{surf}})_j$ is the creep damage accumulated in the j 'th cycle and the summation is carried out up to the current time. The term $(d_c^{\text{surf}})_j$ is evaluated at the surface of the uncracked component and is given by the ductility exhaustion method as

$$(d_c^{\text{surf}})_j = \int_0^{t_{h,j}} \frac{\dot{\bar{\epsilon}}_c}{\bar{\epsilon}_f(\dot{\bar{\epsilon}}_c)} dt \quad (17)$$

where $0 \leq t \leq t_{h,j}$ is the j 'th creep dwell period, $\dot{\bar{\epsilon}}_c$ is the instantaneous equivalent creep strain rate during the dwell and $\bar{\epsilon}_f(\dot{\bar{\epsilon}}_c)$ is the creep ductility at that strain rate, accounting for stress state. The strain rate is evaluated at the instantaneous stress during the dwell obtained from stress relaxation data.

When $D_c^{\text{surf}} \rightarrow 1$, equation (15) predicts an infinite crack growth rate. However, this should not be interpreted as predicting the failure of the component. This corresponds to the exhaustion of creep ductility at the surface and the instantaneous crack depth, a , should be set to the depth of the cyclic plastic zone, r_p .

If r_p is greater than the crack depth that the structure can safely tolerate then remedial action should be taken. Cracks deeper than r_p are subjected to

nominally cyclic elastic deformation and the Method I growth law should be used as set out below.

(B) Crack length, a , greater than the cyclic plastic zone size, r_p , at the surface of the component.

In this regime, the Method I crack growth rate law of equation (3) is used and the total crack growth per cycle, da/dN , is obtained as the simple sum of the contributions due to cyclic and creep crack growth rates:

$$da/dN = (da/dN)_f + (da/dN)_c \quad (18)$$

The fatigue crack growth per cycle $(da/dN)_f$ is given by equation (3) with the constants modified for hold-time effects only if creep-fatigue interactions are shown to be significant. If fatigue crack growth is insignificant, this term is omitted. The creep crack growth per cycle in equation (18) also depends on loading regime as set out in (i) - (iv), below.

(i) Steady state creep crack growth for times $t > t_{red}$, with insignificant cyclic loading

For the load controlled case and the attainment of steady state creep conditions the creep crack growth is obtained from creep crack growth data in the form of equation (2).

Equation (8) is used to estimate C^* for crack sizes between a_0 and a_g for use with equation (2).

The creep crack extension per cycle, $(da/dN)_c$, is evaluated as the integral of equation (2) over the dwell period, t_h :

$$\left(\frac{da}{dN} \right)_c = \int_0^{t_h} A(C^*)^q dt \quad (19)$$

(ii) Non-steady state creep crack growth, $t < t_{red}$, when cyclic loading is insignificant.

For times less than the redistribution time ($t < t_{red}$), equation (2) is generalised to

$$\dot{a} = A[C(t)]^q \quad (20)$$

For situations where $t_i + t_g > t_{red}$, the effects of the redistribution period can be allowed for by using the crack growth rates of equation (2) multiplied by a factor of 2 for $t < t_{red}$, i.e.

$$\begin{aligned} \dot{a} &= 2A(C^*)^q & \text{for } t_i \leq t < t_{red} \\ \dot{a} &= A(C^*)^q & \text{for } t \geq t_{red} \end{aligned} \quad (21)$$

If the total time for the assessment does not exceed t_{red} , then this simplified treatment of transient creep is not adequate and it is necessary to use the parameter $C(t)$ explicitly, from equation (12), to estimate creep crack growth. The creep crack extension per cycle, $(da/dN)_c$, including transient effects is then evaluated over the dwell period, t_h , as in equation (19).

(iii) Early cycle creep crack growth, $t < t_{cyc}$, when cyclic loading is significant.

For a component outside strict shakedown a mean estimate of C^* during the transient period, $\bar{C}^*$, may be used up to t_{cyc} of equation (11). Where only elastic analysis is available, $\bar{C}^*$ is defined as:

$$\bar{C}^* = (\sigma_{ref}^{cyc=1} + \sigma_{ref}) \dot{\epsilon} R' / 2 \quad (22)$$

where $\dot{\epsilon}$ is evaluated as $\dot{\epsilon}[(\sigma_{ref}^{cyc=1} + \sigma_{ref})/2]$.

As crack growth is approximately linearly dependent on C^* , the crack growth during the time t_{cyc} is not particularly sensitive to the value of t_{cyc} but depends primarily on the accumulated creep strain, $Z(\sigma_{ref}^{cyc=1} - \sigma_{ref})/E$. For the early cycles, prior to structural shakedown, the creep crack extension per cycle, $(da/dN)_c$, is evaluated over the dwell period, t_h , as in equation (19).

(iv) Steady cycle creep crack growth, $t > t_{cyc}$, when cyclic loading is significant.

At $t \geq t_{cyc}$, $\bar{C}^*$ is replaced by C^* calculated from the loads in the steady cycle obtained from a shakedown analysis.

3. 5. 6 Novel Features of the Creep Module

The approach described above, which estimates creep crack growth through reference stress techniques, is common to a number of procedures. However, the FITNET FFS creep module also contains some novel features, **three of which are described in this section.**

3. 5. 6. 1 Treatment of Secondary Loading

One recent development [43] incorporated in the FITNET FFS creep module is the treatment of combined primary and secondary stresses. Under combined loading, it is necessary to modify the reference stress of equation (7) to allow for the increased stress levels due to secondary thermal or residual stresses. The stress intensity factor for the secondary loads, K^s is calculated and the total reference stress for the combined loading becomes

$$\sigma_{ref} = \sigma_{ref}^p \left(1 + K^s / K^p \right) \quad (23)$$

Conservatively, this reference stress simply replaces σ_{ref}^p in the C^* calculation of equation (8) and in the calculations of incubation and crack growth. However, this is overly conservative for components subjected to low primary stresses and high secondary stresses. Therefore, a method is given that allows for relaxation of this total reference stress due to creep, and reduction of secondary stress effects if the crack grows away from regions of high secondary stress. The result is

$$\frac{\dot{\sigma}_{ref}}{\sigma_{ref}} + \left[\frac{K^s}{(K^p + K^s)} \left\{ \frac{\partial K^p}{K^p \partial (a/w)} - \frac{\partial K^s}{K^s \partial (a/w)} \right\} - \frac{\partial \sigma_{ref}^p}{\sigma_{ref}^p \partial (a/w)} \right] \frac{\dot{a}}{w} + \frac{E \dot{\epsilon}_c}{Z \sigma_{ref}} = 0 \quad (24)$$

Where

$\dot{\sigma}_{ref}$ is the rate of change of the total reference stress from the starting value of equation (23), w is the section width and Z is the elastic follow-up factor.

The term involving the derivative of σ_{ref}^p expresses the increase in reference stress arising from the reduction in limit load with increasing crack size. The term involving $\dot{\epsilon}_c$ quantifies relaxation due to creep strain. The terms involving derivatives of the stress intensity factors allow for the relaxation of secondary

stresses when a crack grows away from a region of high stress. In some cases, particularly those involving high local secondary stresses such as those due to

repair welding, this relaxation due to crack growth is dominant. The relaxed value of reference stress is used to calculate C^* from equation (8). The creep module also gives expressions for calculating the transient parameter $C(t)$ for combined loading.

3. 5. 6. 2 Failure Assessment Diagram Methods

The methods set out above evaluate parameters such as C^* and $C(t)$ and combine these with experimental data describing creep crack incubation or growth. However, in Section 6, the fracture module uses the concept of a Failure Assessment Diagram (FAD). Recently, FAD approaches have been extended to the creep regime: in the UK using a Time Dependent Failure Assessment Diagram (TDFAD) and in Germany using a similar Two Criteria Diagram (2CD). The TDFAD and 2CD methods are described and contrasted in the creep module and are briefly summarized here. More detailed information is contained in [44-48].

The TDFAD is based on the FAD specified in Section 6 and involves a failure assessment curve relating the two parameters K_r and L_r , which are defined in equations (25) and (26) below, and a cut-off $L_r^{\max}$.

For the simplest case of a single primary load acting alone

$$K_r = K_{I \text{ id}} / K_{\text{mat}}^c \quad (25)$$

where $K_{I \text{ id}}$ is the stress intensity factor and K_{mat}^c is the appropriate creep crack initiation toughness value, and

$$L_r = \sigma_{\text{ref}} / \sigma_{0.2}^c \quad (26)$$

where σ_{ref} is the reference stress of equation (7) and $\sigma_{0.2}^c$ is the stress corresponding to 0.2% inelastic (plastic plus creep) strain from the average isochronous stress-strain curve for the temperature and assessment time of interest.

The determination of $\sigma_{0.2}^c$ from a proper isochronous curve is discussed in [49] and is particularly important for assessment of ferritic steels and weldments. The failure assessment diagram is then defined by the equations

$$K_r = \left[\frac{E \cdot \varepsilon_{\text{ref}}}{L_r \cdot \sigma_{0.2}^c} + \frac{L_r^3 \cdot \sigma_{0.2}^c}{2 \cdot E \cdot \varepsilon_{\text{ref}}} \right]^{-1/2} \quad L_r \leq L_r^{\text{max}} \quad (27)$$

$$K_r = 0 \quad L_r > L_r^{\text{max}}$$

In equation (27), E is Young's modulus and ε_{ref} is the total strain from the average isochronous stress-strain curve at the reference stress $\sigma_{\text{ref}} = L_r \cdot \sigma_{0.2}^c$, for the appropriate time and temperature. Equation (27) enables the TDFAD to be plotted with K_r as a function of L_r , as shown schematically in Figure 19. The cut-off, L_r^{max} , is defined as

$$L_r^{\text{max}} = \sigma_R / \sigma_{0.2}^c \quad (28)$$

where σ_R is the rupture stress for the time and temperature of interest. However, for consistency with the methods in Section 6, the value of L_r^{max} should not exceed $\bar{\sigma} / \sigma_{0.2}$ where $\bar{\sigma}$ is the short-term flow stress and $\sigma_{0.2}$ is the conventional 0.2% proof stress. As in Section 6, $\bar{\sigma}$ may be taken as $(\sigma_{0.2} + \sigma_u) / 2$ where σ_u is the ultimate tensile strength.

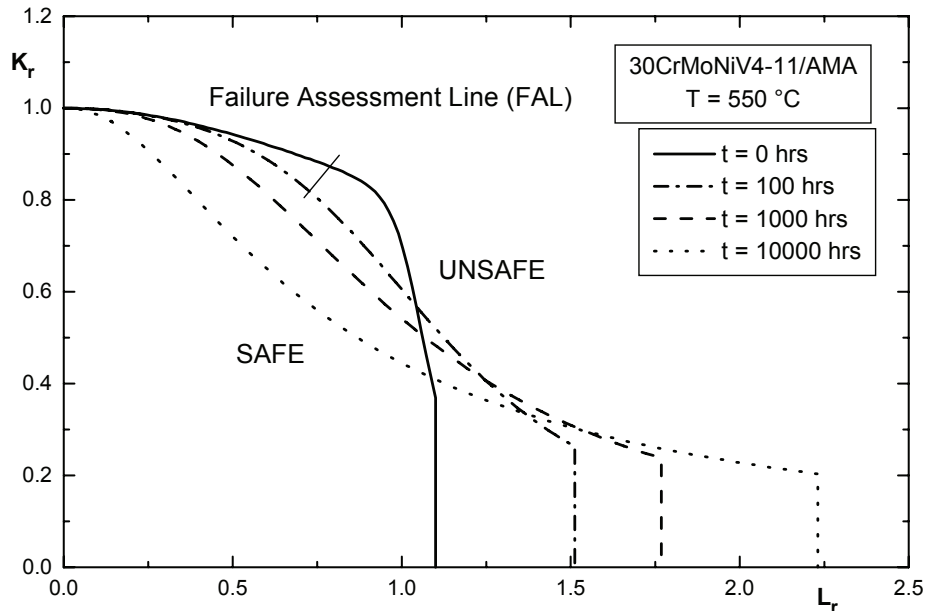


Fig. 19. Schematic FAD based on data from a 1CrMoV steel at 550°C.

A central feature of the TDFAD approach is the definition of an appropriate creep toughness which, when used in conjunction with the failure assessment diagram, ensures that crack growth in the assessment period is less than a value Δa . Creep toughness values may be estimated indirectly from conventional creep crack incubation and growth data or evaluated directly from experimental load versus displacement information. Information is provided in the creep module. Application of the TDFAD to weldments is reported in [50].

In the **Two Criteria Diagram** (2CD) for creep crack initiation the nominal stress $\sigma_{n pl}$ describes the stress situation in the ligament, i.e. in the far-field of the creep crack and the elastic parameter $K_{l id}$ at time zero characterizes the crack tip situation. These loading parameters are normalised in a 2CD (Figure 20) by the respective time and temperature dependent values, which indicate the material resistance against crack initiation. The normalised parameters are the stress ratio

$$R_{\sigma} = \sigma_{n pl} / \sigma_R \quad (29)$$

for the far-field and the stress intensity factor ratio

$$R_K = K_{l id} / K_{li} \quad (30)$$

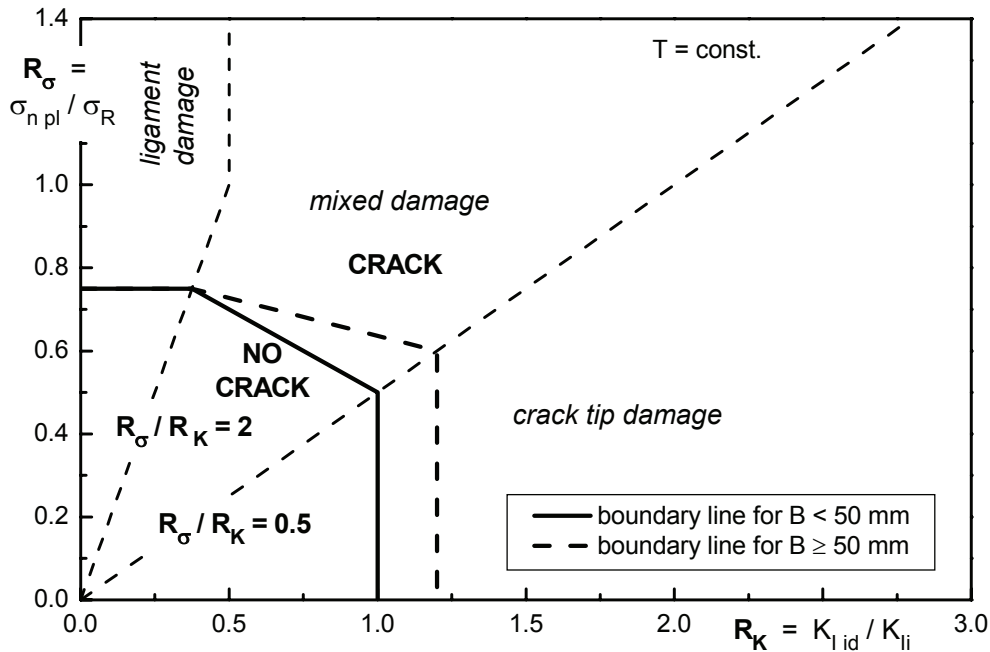


Fig. 20. 2CD for creep crack initiation in creep ductile steels.

for the crack tip. The value σ_R is the creep rupture strength of the material and the parameter K_{II} characterizes the creep crack initiation of the material. This parameter has to be determined from specimens with a high ratio K_{Iid}/σ_{npl} , preferably using C(T)25-specimens.

The 2CD distinguishes three fields of damage mode separated by lines of constant ratio R_σ/R_K . Above $R_\sigma/R_K = 2$ ligament damage is expected, below $R_\sigma/R_K = 0.5$ crack tip damage is expected and between these lines a mixed damage mode is observed. Crack initiation is only expected above a boundary line. The boundary line in Fig. 20 moves to lower values of R_K for creep brittle materials leading to a smaller 'no crack' zone.

The FITNET FFS Creep Module compares the parameters in the TDFAD and 2CD approaches. For a 1CrMoV-steel at 550 C, both approaches are shown to give conservative predictions of creep crack initiation. Also, the creep crack initiation toughness in the TDFAD tends to become equal to the critical stress intensity factor in the 2CD for long times. Further work is required to analyse the results of the different approaches in detail and then apply both approaches to assessment of incubation in structural geometries.

3. 5. 6. 3 Probabilistic Approaches

The main input data required for assessing structures prone to creep damage are the rupture time, defined as a function of the temperature T and stress σ . A lognormal distribution can be selected to describe the randomness of the rupture time as follows:

$$\ln \tau = \mu_c + \delta_c \Omega \quad (31)$$

where τ is the random variable - rupture time, Ω is the normalized Gaussian distribution function $N(0;1)$ and μ_c and δ_c are the mean value and standard deviation of the rupture time, expressed in the logarithmic base, respectively.

The total accumulated creep damage D_c can be obtained using the life fraction rule. Assuming that the operation of the investigated structure is broken into a series of blocks $[\sigma_i; T_i]$ during which the load/stress σ_i and the temperature T_i are sensibly constant, the total accumulated damage is then given by the following equation:

$$D_c = \sum_{i=1}^n \frac{\Delta t_i}{\tau_i(\sigma_i; T_i)} \quad (32)$$

where Δt_i is the time during which the structure is subjected to the stress σ_i and temperature T_i . Values τ_i are given by equation (31).

Substituting equation (31) into equation (32) and introducing the relation $t_{ri} = \exp[\mu_c(\sigma_i; T_i)]$ lead to:

$$D_c = \exp(-\delta_c \Omega) \sum_{i=1}^n \frac{\Delta t_i}{t_{ri}}. \quad (33)$$

The total creep damage accumulation D_c must be less than unity ($D_c < 1$) for rupture not to occur within the investigated structure. The probability that D_c is less than 1 can be expressed as follows:

$$\begin{aligned} P(D_c < 1) &= P(\ln D_c < 0) = P\left(-\delta_c \Omega + \ln \sum_{i=1}^n \frac{\Delta t_i}{t_{ri}} < 0\right) \\ &= P\left(\Omega > \frac{1}{\delta_c} \ln \sum_{i=1}^n \frac{\Delta t_i}{t_{ri}}\right) = 1 - N(Z) \end{aligned} \quad (34)$$

where N is a normalized Gaussian distribution function and Z is defined by the following equation:

$$Z = \frac{1}{\delta_c} \ln \sum_{i=1}^n \frac{\Delta t_i}{t_{ri}}. \quad (35)$$

As the creep damage cannot exceed a value of 1, the probability $P(D_c \geq 1)$ reduces to the probability $P(D_c = 1)$ and hence using equation (34), the probability of rupture is given by:

$$P(D_c = 1) = N(Z). \quad (36)$$

In the case of a cracked structure operating in the creep regime, the creep crack growth rate can be correlated satisfactorily in terms of the creep fracture parameter C^* using equation (2). The material constants A and q can both be considered as random variables. However, experimental results show that the

parameter q does not exhibit significant scatter and hence it is generally considered as a constant. The scatter in the random variable A is usually described by a lognormal distribution as follows:

$$\ln A = \mu_A + \delta_A \Omega, \quad (37)$$

where Ω is the normalized Gaussian distribution function $N(0;1)$ and μ_A and δ_A are the mean value and standard deviation of the logarithm value of A , respectively.

When several of the inputs to the creep crack growth assessment are considered as random variables (e.g. initial crack size, creep rupture time, creep crack growth constant A), the determination of the distribution function of the crack size becomes a complex mathematical expression that is hard to evaluate using numerical integration. In this case, the use of suitable numerical methods, such as Monte Carlo techniques, is required. However, if a sensitivity analysis of the key inputs to the creep crack growth assessment shows that the scatter in the creep crack growth constant A has a dominant effect, then the other input data can be assumed constant and a simplified procedure can be employed. In this case, equation (2) can be integrated numerically and the crack size $a(t_1)$ at time t_1 can be derived as follows:

$$\begin{aligned} a(t_1) &= \int_0^{t_1} A(C^*)^q dt = \exp(\delta_A \Omega) \int_0^{t_1} A^{av} (C^*)^q dt \\ &= \exp(\delta_A \Omega) \cdot a^{av}(t_1) \end{aligned}, \quad (38)$$

where

$$A^{av} = \exp(\mu_A), \quad a^{av}(t_1) = \int_0^{t_1} A^{av} (C^*)^q dt. \quad (39)$$

The probability of the crack size $a(t_1)$ being less than a given crack size a_f is given by:

$$\begin{aligned} P(a \leq a_f) &= P(\ln a \leq \ln a_f) \\ &= P\left(\Omega \leq \frac{\ln a_f - \ln[a(t_1)]}{\delta_A}\right) = N(Z_A), \end{aligned} \quad (40)$$

where the random variable Z_A has the normalized Gaussian distribution function $N(0;1)$ and is defined by the following relation:

$$Z_A = \frac{\ln a_f - \ln[a(t_1)]}{\delta_A} . \quad (41)$$

Equation (40) defines the distribution function of the crack size at time t_1 . If the calculation is performed for different values of time t_1 then the distribution function of crack size becomes a function of time. Furthermore, the probability of exceeding the crack size a_f is $P(a > a_f) = 1 - N(Z_A)$. If a_f is selected as the critical crack size, the probability of fracture is given by the value $1 - N(Z_A)$.

This part of the technical report has given an overview of the creep module of the FITNET FFS procedure. The basic approach is well established but has been set out in a new and compact way in the creep module. The creep module also contains some novel features, which enable advanced assessments to be made. Some of these novel features have been described in this section.

3. 5. 7 Application of FITNET FFS Procedure Creep Module for the Assessment of a Pressure Vessel

3. 5. 7. 1 Introduction

In power generation and petrochemical plants the re-assessment of components operated in the creep regime which have completed their design life has become a routine procedure. The estimation of residual life (based on material creep strength and service data) is generally accompanied by the execution of metallographic replicas and non destructive tests: these in-field activities often highlight the presence of flaws which exceed the acceptability criteria indicated by fabrication codes, but can rarely be related to the last stage of a bulk creep damage. Sometimes, on the contrary, such defects have been clearly originated during fabrication (e.g. lacks of fusion/penetration in nozzle to shell welded joints).

Even when repair operations do not look critical from a technical point of view, they may be not easily feasible in many circumstances, for example in cases where a local post weld heat treatment is not advisable and a wide zone of a large equipment (reactors or towers) must be treated. Moreover, maintenance times tend to be stretched beyond scheduled deadlines, and, consequently, a significant increase of costs is often registered.

In Italy the recommendations introduced in 1992 for the residual life assessment of pressure equipments operated in the creep regime have been recently renewed with the publication of ISPESL Technical Procedure N° 48/2003 [2]. The assessment of flaws with fitness for service procedures, however, is not dealt with in detail, and no reference is made to existing standard or recommendations whose use could be considered reliable and safe. As a consequence, detected flaws are often immediately repaired without exploring the advantages of a possible assessment; moreover, when the presence of the flaw is tolerated, this decision is always taken on the basis of operating experience and a quantitative assessment is never attempted.

Therefore, G. Canale and G. L. Cosso, Istituto Italiano della Saldatura (IIS), Italy have applied FITNET FFS Procedure Creep Module for the residual life assessment of a pressure vessel operated in a petrochemical plant. Their work, presented at the FITNET 2006 Conference (Paper No. 06-26) aimed to demonstrate that, in most cases, the FITNET assessment procedure is relatively easy to use and can rapidly and reliably demonstrate the acceptability of flaws in components operated in the creep regime. The technical case has been selected among the equipments actually examined by the Italian Institute of Welding (IIS). Each step of the procedure is considered in detail, in order to offer an accurate

description of the procedure itself; some considerations are also proposed about the possible use, in this context, of finite element techniques.

3. 5. 7. 2 Description of the Technical Case

The component under examination is a nozzle to shell welded joint in a refinery pressure vessel. The material adopted for fabrication is a low alloyed Cr-Mo steel (nominal chemical composition 1Cr-0.5Mo, ASTM A387 Gr. 12 for shell plates, ASTM A182 Gr. F12 for nozzle and flange). The equipment is operated at 500°C and 9.8 bar; the internal pressure is approximately constant, as generally occurs in petrochemical plants, and therefore no interaction between creep and fatigue has to be taken into account.

The component is subjected to its first re-assessment, as the design life (100000 h) has been completed. According to ISPESL Technical Procedure mentioned above, a maximum further service period, without any inspection, can be conceded, whose duration will be the minimum between 50000 h and 60% of residual life. In order to obtain the maximum allowable service period, therefore, it must be demonstrated a residual life of at least 84000 hrs.

Non destructive tests have revealed the presence of a surface breaking flaw (5 mm in height and 40 mm in length) located within the heat affected zone of the joint (Fig. 21), on equipment outer surface. The execution of replicas in the flaw zone has highlighted a minor metallographic damage and the absence of microvoids or other indicators of bulk creep damage; stress corrosion or other environmentally assisted mechanisms are also to be excluded. Taking into account position and dimensions, the origin of the flaw might be an hydrogen induced welding crack not detected during fabrication. The FITNET procedure is then adopted, in order to quantify the influence of the flaw on component residual life.

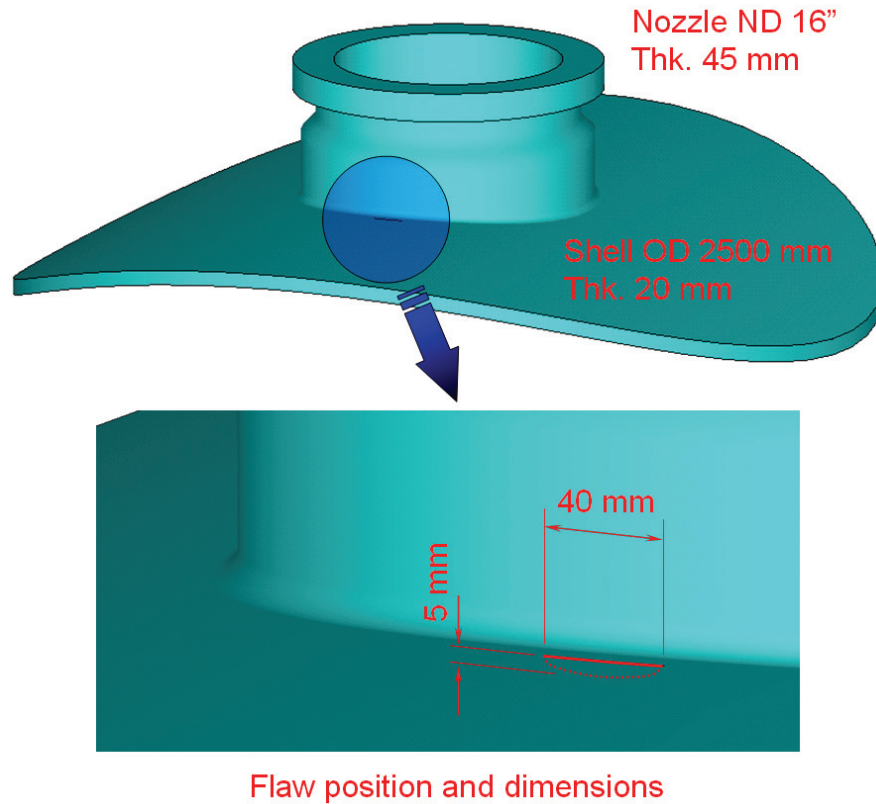


Fig. 21: Description of the technical case with flaw position and dimensions

3. 5. 7. 3 Application of the Procedure

Here, the application of the procedure is described in detail, following the assessment steps defined by the flowcharts Figures 8.1÷8.2 (Section 8) in FITNET FFS Procedure creep module and also given in Section 3.5.2 of this report.

Step 1: Establish cause of cracking and characterize initial defect

Some considerations about flaw origin have already been pointed out in the previous paragraph: as there is no evidence of bulk creep damage or environmentally assisted phenomena, the need of special considerations can be excluded. As far as flaw characterization is concerned, an uncertainty margin has to be accepted in determining flaw height through ultrasonic technique, as discussed below (see Step 12); as this parameter plays a fundamental role in the assessment, a proper sensitivity analysis shall be carried out in order to demonstrate assessment reliability.

Step 2: Define service conditions

The equipment has been operated at constant pressure and temperature (9.8 barg and 500°C). The same values shall be considered for future service; no significant fatigue loadings have to be taken into account.

Step 3: Collect material data

The assessment according to creep module prescriptions requires a detailed characterization of material properties. In the following lines the data needed are briefly summarized, together with the reference standards adopted in the case under examination.

Young modulus, yield strength and tensile strength are given, over the whole temperature range of common application, in ASME Boiler & Pressure Vessel Code, Section II “Materials”, Part D “Properties”. Creep strength data can be deduced from the same code on the basis of allowable stress values given in the creep range, even if other technical references are available, where material creep strength is often defined through parametric representations (e.g. ECCC Recommendations [51]). It must be underlined, in this context, that experimental data on welds are relatively poor, especially for long durations (>10000 h), and generally show creep strength values significantly lower than those characterizing the corresponding base materials. ISPESL Technical Procedure suggests, for welded components, the adoption of a reduced strength which is commonly set, when specific data are not available, at 90% of base material creep strength.

As shown in detail in the following lines, the FITNET creep module foresees the assessment of the component for possible time-independent fracture. In fault or test loading conditions, the presence of a crack might induce a brittle failure: an evaluation of material toughness is therefore needed. To this aim, the FITNET FFS Procedure provides methods based on Charpy V-notch impact tests; in the case under consideration, they have been adopted taking into account the limits for Charpy test results stated by the Italian fabrication code (Raccolta S [52]) both for base material and welded joints. Further procedures, in this context, are given in BS 7910 [53] and API RP 579 [54].

Finally, material behavior in terms of creep strain and creep crack growth is probably the most difficult to be determined. Data on creep strain during the primary stage are seldom available; for the second stage, however, some references exist which allow an indicative estimation of the relationship between strain rate, stress and temperature for a wide range of materials. In the case under examination the data proposed by EN 10028 [55] have been adopted: European standards, in fact, often indicate the average stress values needed to

obtain a given creep strain (1%) after 10000 h and 100000 h over a wide range of temperatures. By approximating the strain curve with a secondary stage only, the data can be easily fitted with the Norton model:

$$\dot{\varepsilon} = A\sigma^n e^{-\frac{C}{T}} \quad (1)$$

This hypothesis can be considered satisfactory after the redistribution time, when the stress-strain field at crack tip has reached the steady state conditions.

As far as creep crack growth data are concerned, the average values proposed in FITNET Creep Module have been assumed (Annex L, Table L.3, taken from Table. T1 in BS 7910); further hypotheses have also been adopted in the sensitivity analysis, in order to take into account the possibility of a faster crack propagation rate. As the component has already spent a significant service period, data about crack incubation have been considered unnecessary.

Step 4: Perform basic stress analysis

The stress analysis performed for the application of the procedure should follow the evolution of the stress-strain state due to the development of creep strains. For complex geometries, this can be easily done with the adoption of numerical structural analyses. FE codes currently available generally provide several options to model creep behavior. As anticipated above, a Norton creep constitutive law has been considered appropriate for the case under consideration. The solution has been determined at different times, until steady state conditions have been reached (Figure 22).

Step 5: Check stability under time-independent loads

The stability of the flawed component against fast fracture has been checked taking into account the loading condition represented by hydrostatic test, when the risk of brittle failure is most significant. For this assessment (which has been performed according to FITNET FFS Procedure fracture module prescriptions) a simple linear elastic stress analysis is needed, in order to determine the stress distribution acting on the flawed cross section. It is then possible to determine reference stress and stress intensity factor through the analytical solutions proposed by the FITNET FFS Procedure.

This step also may need a FE structural analysis. When the flaw is close to gross structural discontinuities (nozzles, stiffeners, shape transitions), in fact, the definition of the actual stress distribution on the flawed cross section cannot be easily determined through analytical techniques.

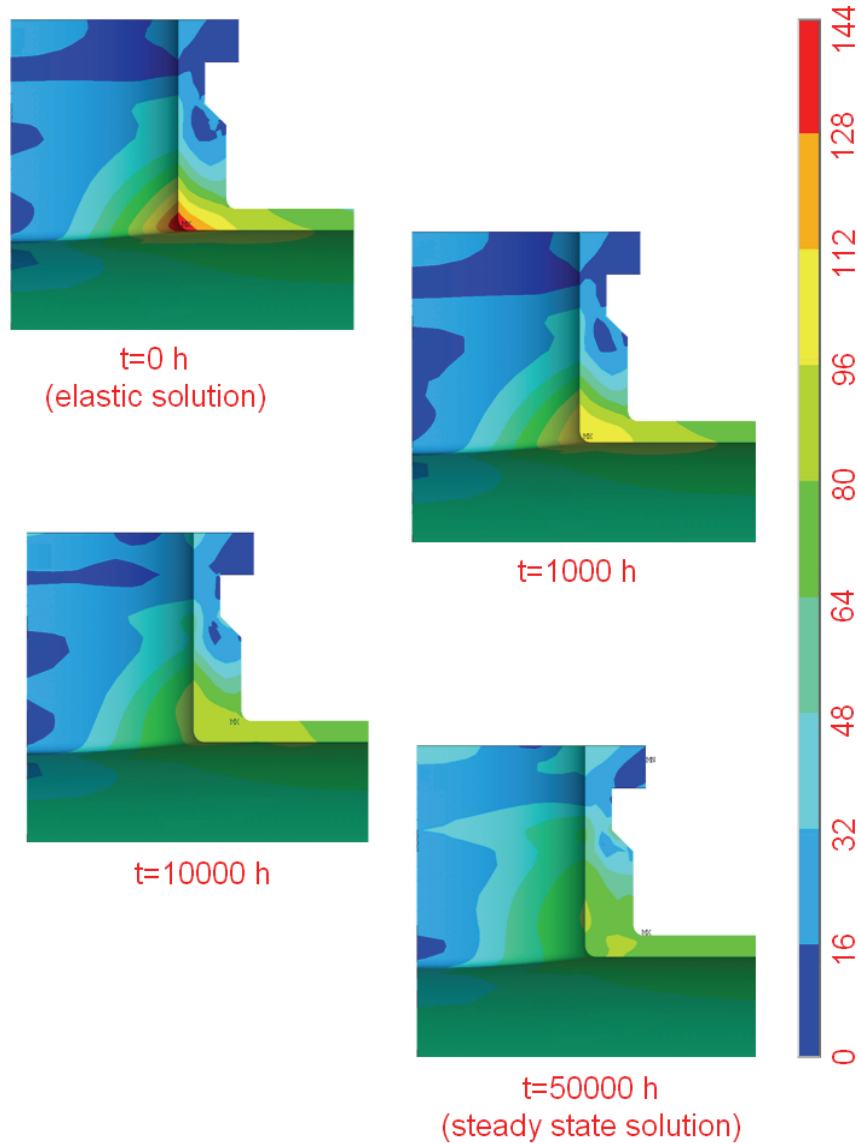


Fig. 22: Stress intensity distribution determined at different times by the structural analysis (MPa)

For the evaluation of reference stress and stress intensity factor, on the contrary, FE methods are not strictly necessary, as the analytical solutions defined for simple geometries give accurate results also at gross discontinuities (provided the stress distribution on the flawed section is accurately described). In the examined case, the flat plate geometry with a surface-breaking flaw has been chosen. Even if the actual geometry looks quite different, the numerically calculated stress intensity factor (determined at the deepest point of the flaw with

the Virtual Crack Extension technique) is very close to the analytical value (a difference of less than 5% has been recorded). As it could be reasonably expected, moreover, the solution is substantially independent on plate width.

The assessment is performed through the definition of a FAD diagram, as described in FITNET FFS Fracture Module, where component strength against both plastic collapse and brittle fracture is checked. A quantitative estimation of welding residual stresses is needed for the assessment, even when a post weld heat treatment has been adopted during fabrication. To this aim, simplified methods are proposed by the FITNET FFS procedure; further suggestions and indications are given in the documents mentioned above (API RP 579, BS 7910 etc.).

Step 6: Check significance of creep and fatigue

In its required future service, the examined component will be operated under constant pressure and temperature: therefore, no significant fatigue loadings have to be considered. Taking into account operating temperature and stress levels, on the contrary, creep damage has reasonably to be taken into account, even if the check for insignificant creep (FITNET FFS procedure, Section. 8, Cl. 8.7.1) has not been performed.

Step 7: Calculate rupture life based on the initial defect size

The consumed life fraction and the residual life have been calculated on the basis of stress analysis results (see step 4) and material creep strength (see Step 3). For the latter a Larson Miller polynomial representation has been adopted.

The assessment has been performed considering both the maximum stress intensity value and the reference stress on the flawed section (which is always lower, because of the position of the crack). A contribution to consumed life fraction has been calculated for each time interval between one solution and the next. All contributions have been simply added to give the total value. In Figure 3 the evolution of maximum stress intensity and consumed life fraction is indicated. The assessment evidences that, on the basis of initial flaw dimensions, the component can be safely operated for the required service life.

Step 8: Calculate initiation time

As the component has already been operated for 100000 h, the definition of the initiation time has been considered insignificant; at any rate, this choice results in a conservative assessment.

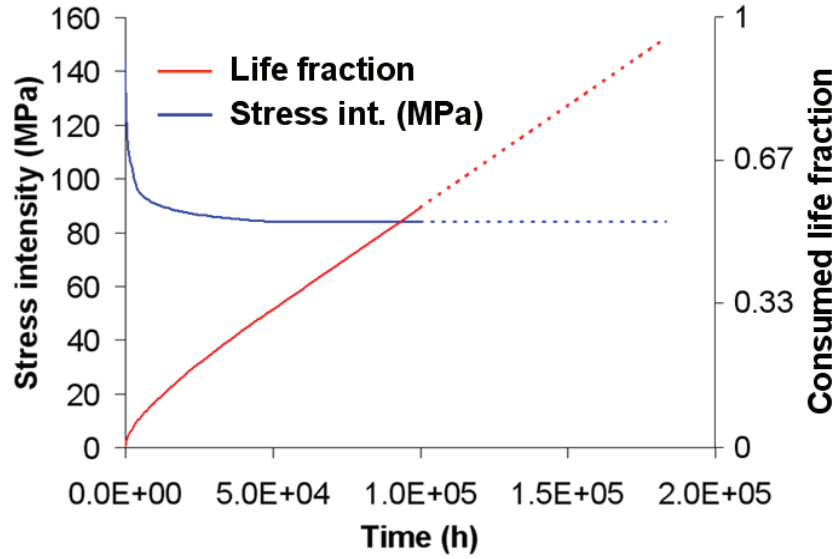


Fig. 23: Time history of stress intensity factor and consumed life fraction. The dashed lines indicate the expected values over the required future service period

Step 9: Calculate crack size after growth

The assessment is performed when the redistribution stage has already been completed; thus Eq. 2 can be adopted to evaluate creep crack growth:

$$\dot{a} = A(C^*)^q \quad (2)$$

As anticipated in step 3, the values of A and q proposed in FITNET Creep Module (Table L.3) have been adopted. C^* is related to the stress-strain rate field at crack tip in creep steady state conditions, and is given by the known definition:

$$C^* = \int_{\Gamma} W_s^* dy - T_i (\partial \dot{u}_i / \partial x) ds \quad (3)$$

where:

- Γ represents an anticlockwise path surrounding the crack tip;
- W_s^* is given in Eq. 4 below;
- T is the traction vector;
- u is the displacement vector.

$$W_s^* = \int_0^{\dot{\varepsilon}_{ij}^C} \sigma_{ij} d\varepsilon_{ij} \quad (4)$$

As some finite element codes provide post-processing routines for the evaluation of J integral with a non-linear elastic constitutive law, the known correspondence between J and C* (when a Norton power law is used for creep strain rate) can be used for the numerical calculation of C*.

Another possible option is the numerical integration of Eq. 3 on a proper path (Fig. 24). With the adoption of the sub-modeling technique, this last method has been used for a numerical evaluation of C* for initial flaw dimensions. The result obtained is really close (with a difference of less than 10%) to the approximate value given by Eq. 5:

$$C^* = \sigma_{ref} \dot{\varepsilon}_{ref} \left(\frac{K_I}{\sigma_{ref}} \right)^2 \quad (5)$$

Step 10-11: Re-calculate rupture life after crack growth and check stability under time-independent loads after crack growth

These steps are conceptually analogous to Steps 5 and 7 described above; of course the assessments have to be performed taking into account flaw final dimensions.

Step 12: Perform sensitivity studies

The significance of the results obtained by the assessment should always be checked, trying to quantify the influence of the different variables involved. At least those entities characterized by a larger uncertainty margin should be examined. In this case, it is reasonable a deeper investigation on the following aspects:

- are chosen material parameters appropriate to model creep crack growth?
- what is the possible inaccuracy in flaw characterization?

In order to quantify the influence of the chosen creep crack growth parameter, further assessments have been performed:

- considering the upper bound value of A (instead of the average one) indicated in Table L.3;
- considering the approximate value of A given in BS 7910 (Cl. T.1.6) and based on creep ductility (for which a conservative value of 5% has been assumed).

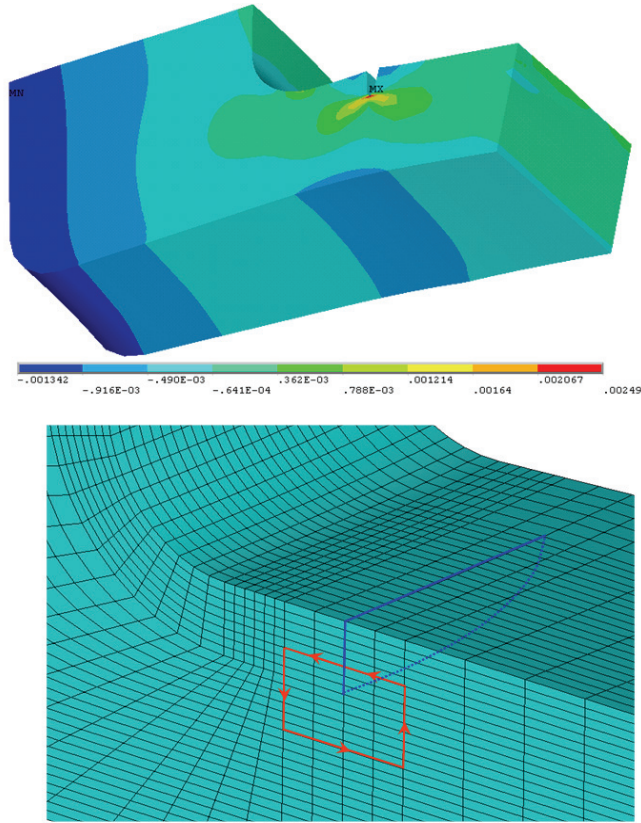


Fig. 24: Creep strains along the direction perpendicular to flaw plane and path used for C^* estimation

The accuracy in flaw characterization is a point of significant importance, so that the advice of a technician or engineer experienced in non-destructive testing may be opportune. When, as it is usually the case, the traditional ultrasonic technique is used to determine flaw depth, an uncertainty lower than ± 1 mm already looks very difficult to be obtained. In the examined problem, therefore, an initial flaw depth of 7 mm has been considered in sensitivity studies. A total of six assessments have been performed, combining two different values of initial flaw depth and three different values of A in creep crack growth law. The increase in flaw depth over the required future service period is represented in Figure 5.

As it can be noticed, in most cases crack growth is limited and has been demonstrated to be acceptable (taking into account steps 10 and 11); only when a relatively large underestimation of flaw depth is assumed in conjunction with a pessimistic evaluation of creep crack growth parameters, final dimensions are unacceptable. If compatible with plant operation, a

monitoring strategy can be proposed (with inspection intervals not longer than two years, i.e. about 18000 h).

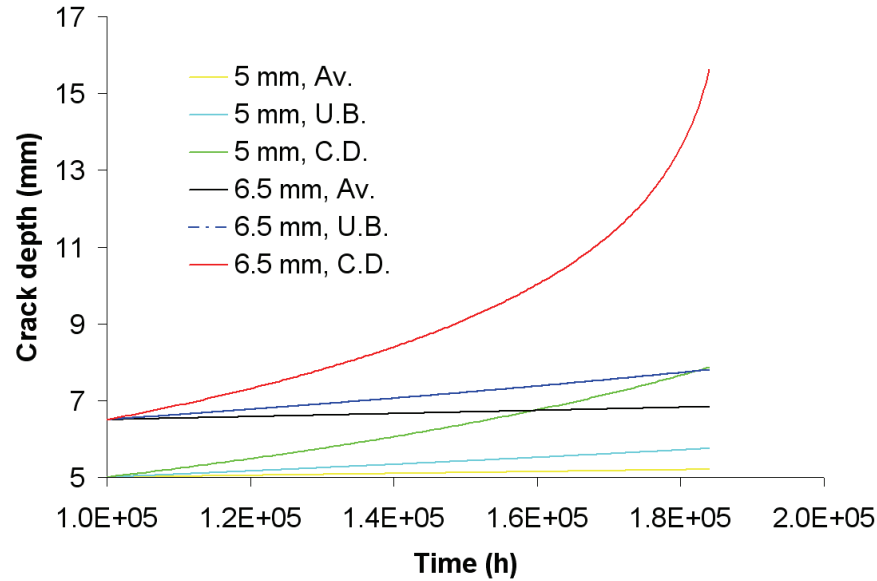


Fig. 25: crack growth at the deepest point over the required service period (“Av.” indicates average values of creep crack growth law parameters; “U.B.” upper bound values; “C.D.” values based on creep ductility according to BS 7910)

Step 13: Report results

This final step must not be neglected, as a detailed report always guarantees an easier check and, when needed, a quicker re-assessment. A detailed list of the adopted references and a complete description of hypotheses and assumptions is always opportune.

Conclusions

The creep module of the FITNET FFS Procedure has been adopted for the assessment of a real component, where a flaw, not related to the last stage of creep damage, has been detected at a nozzle to shell junction. The practical application of creep module prescriptions evidences how, in most cases, a relatively simple assessment can be helpful to decide if repair operations are really needed or the component can still be safely operated. A deeper investigation through the use of FE models has confirmed the reliability of the analytical procedure.

3. 5. 8 References

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3.6 FITNET Corrosion Damage Module

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3.6.1 Introduction

The corrosion damage module of the FITNET FFS Procedure is given in Section 9 and provides guidelines on the appropriate steps to take when an environmental assisted, either by stress corrosion or corrosion fatigue, crack as well as local thin area (LTA) has been detected in service and an assessment of the implications for structural integrity has to be done.

Such an evaluation should be made in the context of the perceived consequences of failure using appropriate risk-based management methodologies. Since this is plant/component specific it is beyond the scope of this module. Hence, this module deals primarily with the Fitness-for-Service assessments of damage types due to ;

A) Environmental assisted cracking (EAC)

- A1) Stress corrosion cracking,
- A2) Corrosion fatigue and

B) Local Thinned Area (LTA).

3 6. 2 Enviornmental Assissted Cracking (EAC)

When assessing the integrity of structures with cracks or crack-like defects, it is necessary to consider whether sub-critical crack growth is a potential factor. If so, an estimate of the amount of tolerable growth during the design lifetime or between in-service inspections is required. In that context, structural integrity assessment has to take into account the distinct characteristics of the damage processes associated with environmental assisted cracking (EAC). The conditions in which EAC occurs is often represented by Figure 26 and involves a combination of stress, environment and microstructural susceptibility, although it should be emphasized that this interaction occurs at a highly localized level and it is the *local* characteristics of these variables rather than the nominal bulk values that are critical.

In this section, subcritical crack growth due to stress corrosion cracking (predominantly static load or slow rising load) and corrosion fatigue (predominantly cyclic load) is considered, with crack growth rate prediction in

service based principally on the application of fracture mechanics in terms of either stress intensity factor (K) in the case of stress corrosion cracking, or the range of stress intensity factor (ΔK), in corrosion fatigue.

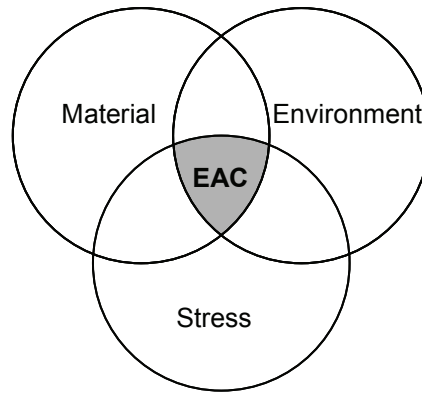


Fig. 26. Schematic diagram showing the inputs that lead to the formation of EAC (Stress Corrosion Cracking and Corrosion Fatigue).

Underlying that assumption is the presumption that the flaws or cracks are of a dimension that allows a description of the mechanical driving force by linear elastic fracture mechanics (LEFM). In practice, for some systems, a significant amount of life may occur in the short crack regime that, if known, should be taken into account in the assessment. Figure 27 illustrates the transition in mechanical driving force with flaw size for a stress corrosion crack; similar behaviour is observed for corrosion fatigue cracks.

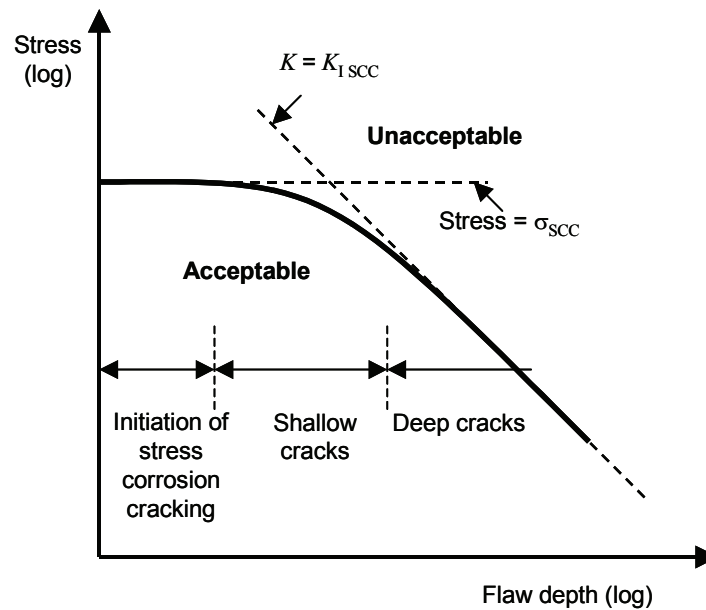


Figure 27. Schematic diagram of the two-parameter approach to stress corrosion cracking

Here, cracks may have initiated from the surface at irregularities created by surface roughness or at locations of stress concentration, from pits or other localised corrosion sites, or from shallow defects (e.g. at the toe of a weld). The threshold stress, σ_{SCC} , applied to nominally plain surfaces is the stress above which any initiated crack will continue to propagate. It is not simply a threshold for initiation as cracks may initiate but then stop growing. K_{ISCC} is the threshold stress intensity factor for sustained crack growth (above this value any initiated crack will continue to grow and below, growing cracks will arrest). The full line in Figure 27 delineates the conditions for sustained crack growth. Below this line, any crack developed will become non-propagating.

In many practical applications cracks are often not detected until the depth is of a size commensurate with the application of linear elastic fracture mechanics but there are exceptions where relatively long but shallow cracks may be detected. In that case, an approach to crack growth and life prediction must account for the extent of growth in the shallow crack regime, as this may be a significant fraction of the life.

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

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

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

Only brief descriptions of the some assessment steps are given in section below to provide basic features of the Module. Readers and users should refer to FITNET FFS Procedure Section 9, Corrosion Damage Module.

STEP 1 Characterise the nature of the crack

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

STEP 2 Establish cause of cracking

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

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

Define service conditions

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

Stress:

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

Service environment (local environment: crevicing, hideout/evaporation, deposits), excursions etc.:

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

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

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

STEP 3 Define material characteristics

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

Surface finish and cold work:

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

Welding:

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

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

Thermal aging:

Materials operated at high temperature for extended periods can undergo thermal aging induced microstructural and microchemical changes that often increase stress corrosion susceptibility. Common examples include cast stainless steels undergoing spinoidal decomposition of the ferrite with very significant hardening and aging of precipitation-hardened stainless steels such as 17-4PH. Once hardness values exceed 350HV experience shows that the risk of environmentally induced cracking in aqueous environments increases and above 400HV cracking failures are practically guaranteed. Another problem is thermally

induced sensitisation of austenitic stainless steels (particularly if the C-content exceeds 0.03% and they are not stabilised by Nb or Ti) due to the precipitation of chromium carbides at the grain boundaries on prolonged service at (or slow cooling through) temperatures in the range 425°C (or less for low temperature sensitisation) to 875°C.

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

Irradiation damage:

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

Material processing and microstructural and microchemical orientation

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

STEP 4 Establish data for stress corrosion cracking assessment

K_{ISCC} determination

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

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

Should it be decided that K_{ISCC} values obtained under static loading are appropriate, these can be determined using the procedures described in ISO 7539 Part 6 [56]. This document describes both crack initiation and

crack arrest methods using fatigue pre-cracked, fracture mechanics type specimens tested under constant load or constant displacement. For some systems, the value may vary depending on the method of measurement, e.g. increasing K or decreasing K experiments. As a fatigue precrack is somewhat artificial and may affect the transition to a stress corrosion crack, a decreasing K , crack arrest, type of experiment may be more pertinent.

The procedure for testing under rising load or rising displacement conditions is described in ISO 7539 Part 9 [57]. The loading or crack mouth opening displacement rate is the critical parameter and it is best to test over a range to obtain conservatively the minimum, lower shelf, value of K_{ISCC} . This may be lower than that obtained by conventional static loading or fixed displacement test under otherwise identical test conditions.

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

Stress corrosion crack growth determination

The crack velocity during stress corrosion testing of pre-cracked fracture mechanics specimens can be measured using the procedures given in ISO 7539-6 [56] and the crack monitoring methods given in ISO 7359-9 Annex C [57]. These techniques enable the stress corrosion crack velocity, da/dt , to be determined as a function of the stress intensity factor, K .

Establish data for corrosion fatigue assessment

ΔK_{th} determination

The threshold value of the stress intensity factor range (ΔK_{th}) in corrosion fatigue is influenced by crack size and by the stress ratio. In the short crack regime, cracks can grow at ΔK values seemingly below ΔK_{th} , because the latter is commonly determined from long crack measurement and because LEFM becomes invalid (Fig. 27). Also, in the long crack regime, increasing the stress ratio, $R = \sigma_{min}/\sigma_{max}$, will usually reduce the threshold value because of diminished impact of crack closure. For that reason a high R value for the threshold is a sensible conservative assumption. In the same context as stress corrosion cracking, it is important to simulate sensibly the service conditions in terms of the environment and loading conditions, particularly frequency and

waveform. Consequently data from literature should be used with care. The ISO 11782-2 standard on corrosion fatigue crack propagation [58] provides guidance on determination of ΔK_{th} .

Crack growth determination

Crack growth rates can be determined based on the ISO standard. The form of the crack growth rate curves cannot be generalised as they are system specific. Some schematic examples for constant amplitude loading are shown in Fig. 28. Here, a 'cyclic stress corrosion cracking' threshold, K_{FSCC} , as proposed by Komai [60] is a better concept to have in mind in relation to **Error! Reference source not found.** 28, rather than K_{ISCC} , as it will prevent the simple transfer of data from static load testing.

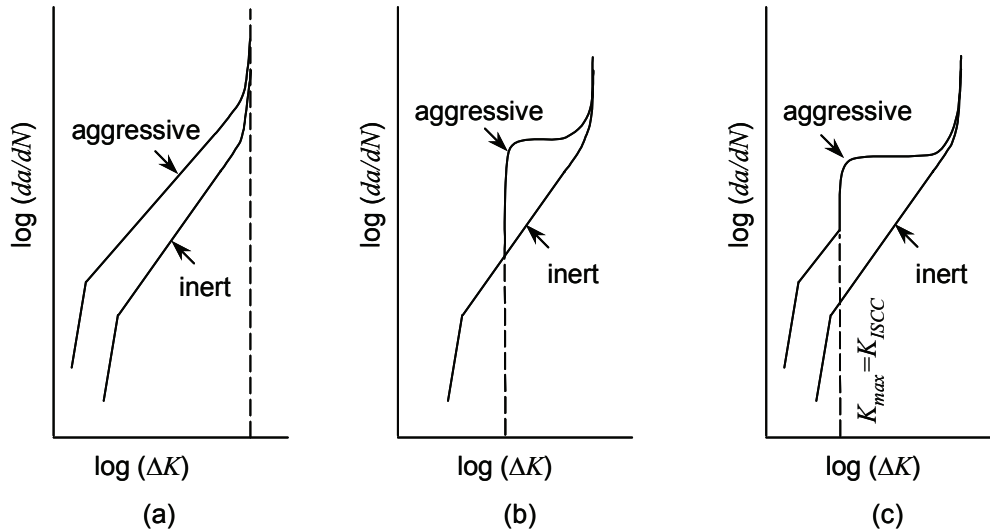


Figure 28. Basic types of corrosion fatigue crack growth behaviour [59].

see procedure for further details

Corrosion fatigue crack growth data

see procedure for details

STEP 5 Undertake structural integrity assessment

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

Step 5a – Perform a fracture assessment for the initial crack size, based on the measured detected value or upon a maximum value reflecting the uncertainty in detection. If the component is demonstrated to be acceptable, i.e. well within the Fracture Assessment Diagram (FAD) boundary of Figure 29 and, where applicable, the crack depth is small compared with through-wall thickness, then remedial measures to prevent further crack growth should be considered. Remedial measures may include reducing the stress so that $K < K_{ISCC}$ (or $\sigma < \sigma_{SCC}$ if the crack is not of a size compatible with LEFM) and crack arrest ensues, modifying the environment or the temperature.

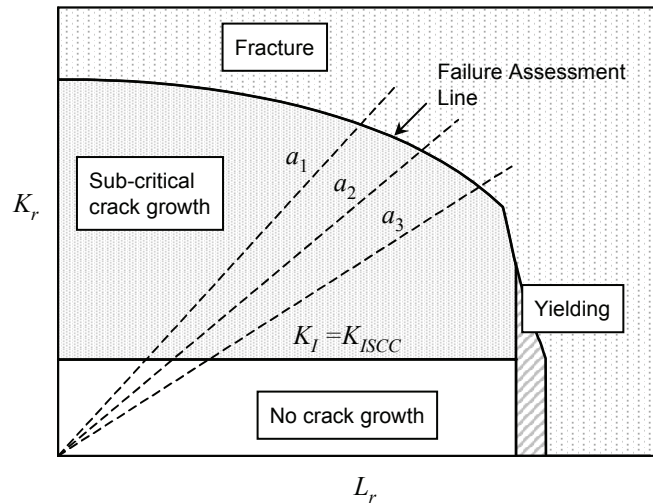


Figure 29. Fracture assessment diagram

Step 5b – If effective remedial measures are not possible and/or slow subcritical crack growth can be tolerated, then apply Corrosion Module Steps 1 to 3 to fully characterise the nature of the crack and the service conditions driving it. Establish whether a crack growth law exists for the material and service environment. If a crack growth law exists, then a crack growth analysis can be performed. Otherwise, where applicable, a leak before break (LBB) analysis

should be performed to determine if an acceptable upper bound crack size can be established.

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

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

Step 5e – Determine the time or number of stress cycles for the current crack size (a_0, c_0) to reach the limiting flaw size in relation to the FAD or LBB criteria. The component is acceptable for continued operation provided: the time or number of cycles to reach the limiting flaw size, including an appropriate in-service margin, is more than the required operating period; the crack growth is monitored on-stream or during shut-downs, as applicable, by a validated technique; the observed crack growth rate is below that used in the remaining life prediction as determined by an on-stream monitoring or inspections during shutdowns; upset conditions in loading or environmental severity are avoidable or are accounted for in the analysis. If the depth of the limiting flaw size is re-categorised as a through-wall thickness crack, the conditions for acceptable LBB criteria should be satisfied. At the next inspection, establish the actual crack growth rate and re-evaluate the new flaw conditions per procedures of this section. Alternatively, repair or replace the component or apply effective mitigation measures. An outline of the process is highlighted by the flowchart of Figure 30.

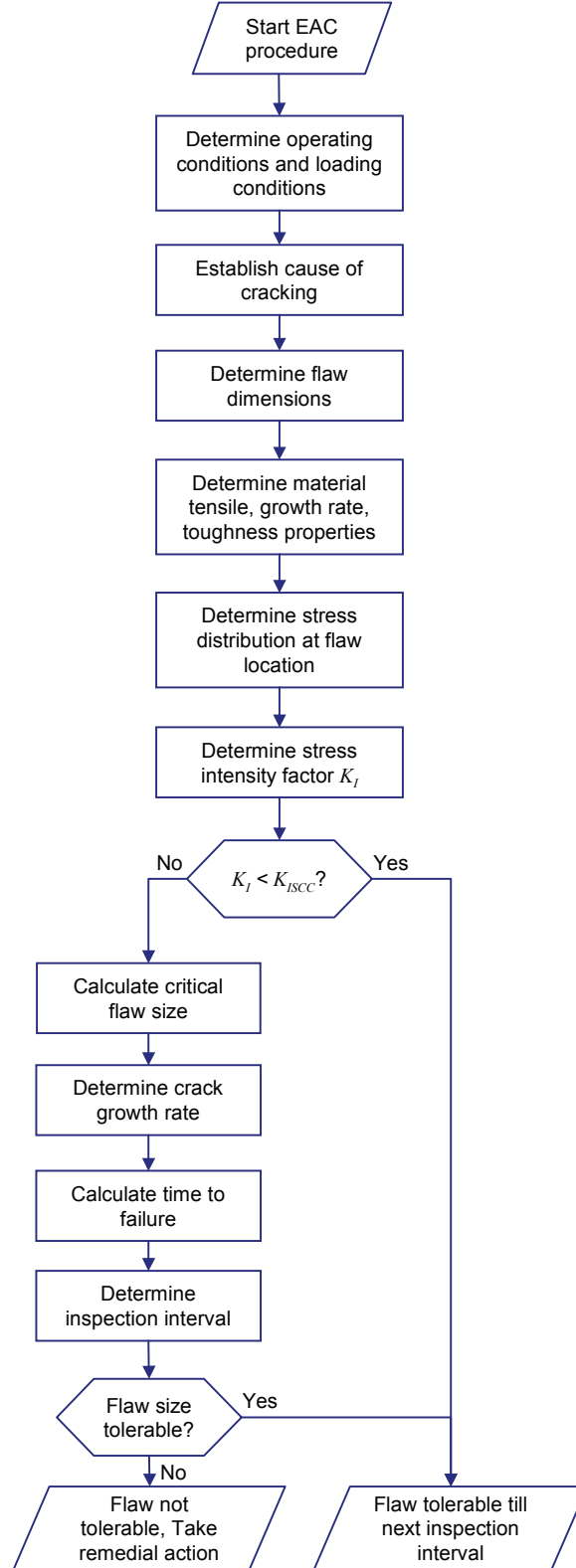


Figure 30. Flowchart for EAC Procedure

3. 6. 3 Assessment of Local Thin Area (LTA)

The methods specified in this section may be used to assess Local Thin Area (LTA) flaws in pipes and pressure vessels that have been designed to a recognized design code. The section deals with LTA flaws in pipes and cylindrical vessels in **Error! Reference source not found.** whereas spherical vessels and vessel ends are treated in section **Error! Reference source not found.** of the Corrosion Module of the FITNET FFS.

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

Here, brief outlines of the step-by-step procedure will be given.

Step 1: Establish cause of wall thinning

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

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

Step 2: Define service condition

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

Step 3: Collect material properties

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

Step 4: Analysis

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

Applicable flaws

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

- a) at the inner surface (e.g. internal corrosion);
- b) at the outer surface (e.g. external corrosion);
- c) in the parent material;
- d) in or adjacent to longitudinal and circumferential welds, with the following provisos.
 - There should be no significant weld flaw present that may interact with the corrosion flaw.
 - The weld should not undermatch the parent steel in strength.
 - Brittle fracture should be unlikely to occur.

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

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

Exclusions

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

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

- b) cyclic loading;
- c) sharp flaws (i.e. cracks) (see Section 6 on Fracture);
- d) combined LTA flaws and cracks;
- e) corrosion in association with mechanical damage;
- f) metal loss flaws attributable to mechanical damage (i.e. gouges);
- g) fabrication flaws in welds;
- h) environmentally induced cracking (see section **Error! Reference source not found.**);
- i) flaw depths greater than 80% of the original (i.e. not corroded) wall thickness (i.e. remaining ligament less than 20% of the original wall thickness);

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

- 1) any material that has been shown to have a full-scale fracture initiation transition temperature above the operating temperature;
- 2) material of thickness 13 mm and greater, unless the full scale initiation transition temperature is below the operating temperature;
- 3) flaws in mechanical joints, fabricated, forged, formed or cast fittings and attached appurtenances;
- 4) flaws in bond lines of flash welded (FW) or low frequency electric resistance welded (ERW) butt-welded pipe;
- 5) lap welded or furnace butt-welded pipe.

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

*NOTE: Detailed LTA assessment procedures including considerations of flaw interactions for the **cylindrical body, nozzles, and elbows** are given in Corrosion Module and is not included into this report. Figure 31 is giving the flow chart of the LTA assessment procedure.*

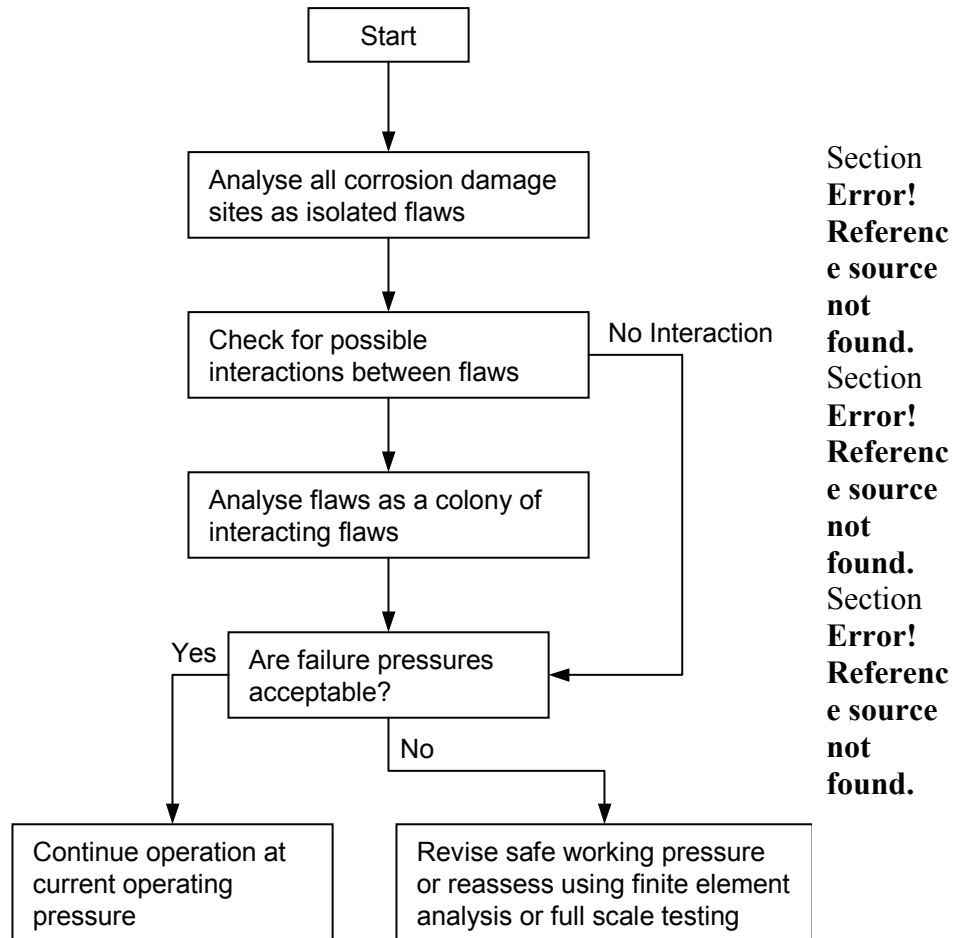


Figure 31. Flow chart LTA assessment procedure as given in BS 7910: 2005 (Flow chart is also giving the respective sections of the FITNET Corrosion Module).

Assessment of LTA at Elbows

To validate the failure pressure prediction for an elbow a series (Fig. 32) of finite element analyses (large deformation and finite strain) has been performed by D Ritchie and R Koers, SHELL as reported at the FITNET 2006 Conference (paper no. 28-06). The dimensions of the elbow are: elbow radius to pipe radius ratio $R_b/R = 3$, pipe radius $R=250$ mm and the wall thickness $t=20$ mm. The size of the local thin area is shown in Fig. 32. The depth of the local thin area is 25%, 50% and 75% of the wall thickness. The width of the local thin area is $\pi/2$ of the pipe in circumferential direction. Analysis has been performed for an elbow with an local thin area at the extrados, an local thin area at the intrados and for an elbow without an local thin area. The von Mises yield criterion has been used in the finite element analysis. The failure pressure of a pipe using a Tresca yield criterion is $\sqrt{3}/2$ times that using a von Mises yield criterion. The failure pressure based on the von Mises yield criterion gives an upperbound, and the Tresca yield criterion a lower bound of the failure pressure. Therefore the calculated failure pressure have been multiplied by a factor $\sqrt{3}/2$ to estimate the failure pressure of the elbow.

The approach followed in this validation case is to determine the failure pressure, (i) without a moment; and (ii) with a moment. The moment applied is the maximum moment allowed by code. The applied boundary conditions are such that at one end of the finite element model only radial displacements are allowed, and at the other end free movement is allowed. Free movement at one side gives a lower failure pressure than allowing only radial displacements at both sides.

The FE failure pressures without a moment are given in Fig. 33 together with the failure pressure predictions. It can be concluded that the FITNET predictions are conservative compared to the FEA results. The FE failure pressure of the elbow loaded by the limit moment are given in Figure 34. It can be concluded that the FITNET predictions are also conservative compared to the FEA results and that the failure pressure is not reduced for a moment equal to the limit moment.

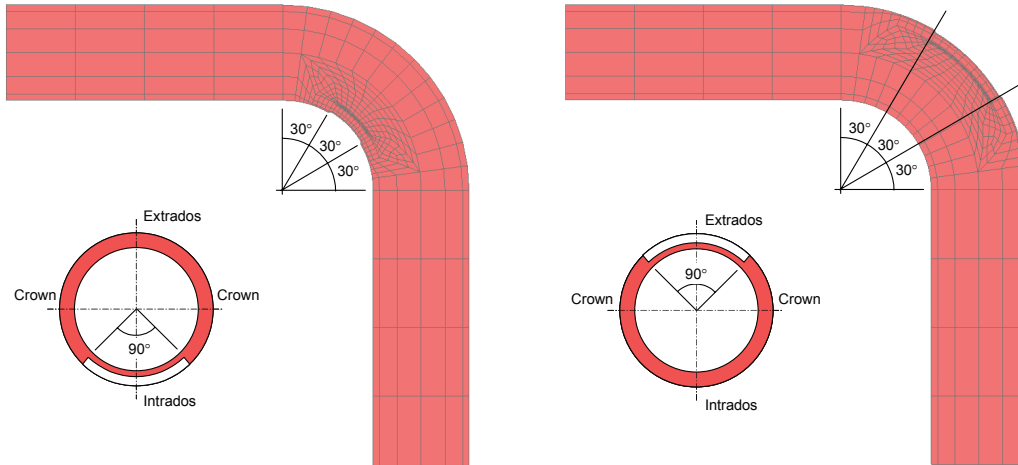


Fig. 32 – Finite element mesh with local thin area at the intrados (left) and at the extrados (right).

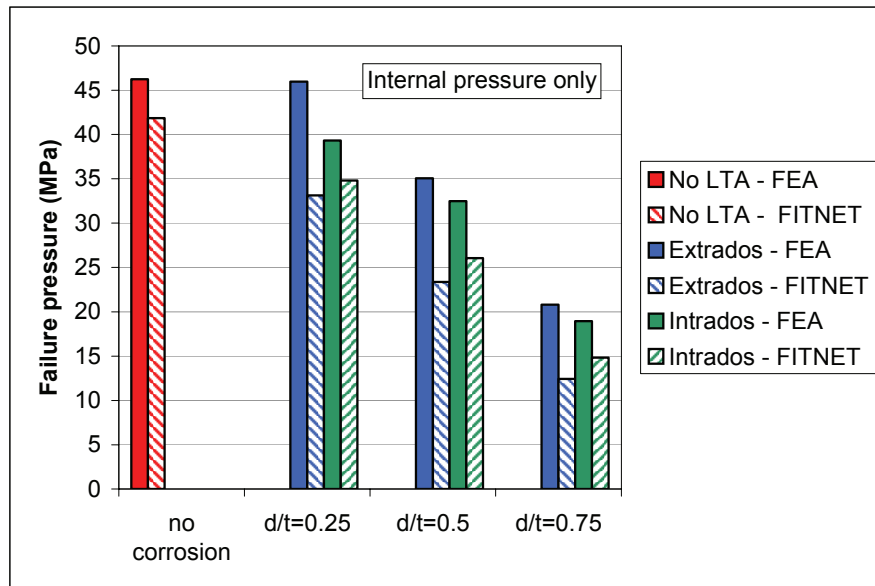


Fig. 33 – Comparison of the failure pressures determined using the FITNET failure pressure prediction and those obtained from finite element analysis.

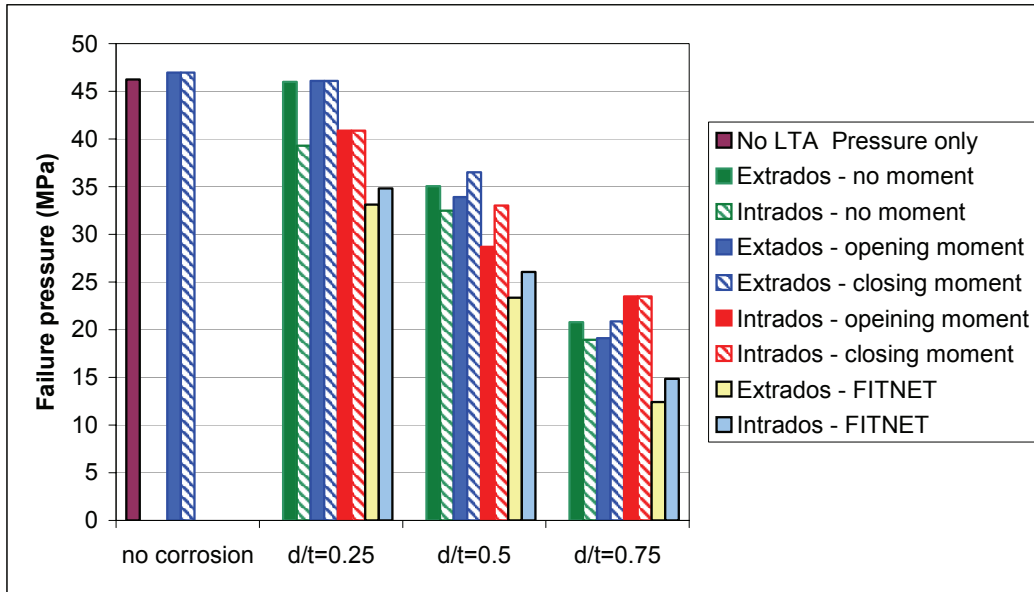


Fig. 34 – Comparison of the failure pressures determined using the failure pressure prediction and those obtained from finite element analysis for pressure and moment loading.

To conclude, in this Module, a procedural approach to evaluating the evolution of damage due to environmentally assisted cracking and treatment of LTA is now covered which includes: establishing the origin and nature of the crack; defining the service operational conditions and component history; applying crack growth calculations. An assessment of LTA topic has been specially addressed by D Ritchie and R Koers in a comprehensive paper (*Assessment of local thinned areas, FITNET 06-028*) and is presented at the FITNET 2006 conference. It describes the development of FFS assessment solutions for local wall loss for a range of geometries and structures of process pipework and pressure vessels. Simple equations are developed and presented for these structures including nozzles and bends as two examples are given above.

Furthermore, Y-J Kim and K Hasegawa et al [28] have reported the status of the recent studies on developing structural acceptance criteria for LTA of nuclear

pipings within Korea and Japan. This paper has included the results of the full-scale pipe tests with simulated wall thinning under monotonic and cyclic loading as well as results of the numerical work to determine net-section limit loads.

3. 6. 4 References

- [56] ISO 7539-6: 2003, Corrosion of metals and alloys – Stress corrosion testing – Part 6: Preparation of pre-cracked specimens for tests under constant load or constant displacement, International Standards Organisation.
- [57] ISO 7539-9: 2003, Corrosion of metals and alloys – Stress corrosion testing – Part 9: Preparation of pre-cracked specimens for tests under rising load or rising displacement, International Standards Organisation.
- [58] ISO 11782-2: 1998, Corrosion of Metal and Alloys – Corrosion Fatigue Testing – Part 2: Crack Propagation Testing using Pre-cracked Specimens, International Standards Organisation.
- [59] Austen, I.M., and Walker, E.F., “Proceedings of The Influence of the Environment on Fatigue”, London, 1977, Institute of Mechanical Engineers, London, 1997, pp 1-10.
- [60] Komai, K., “Proceedings of EVALMAT ‘89, Kobe, 1989”, Iron and Steel Institute of Japan, Tokyo 1989, pp 121-134.

3. 7 Validation of FITNET FFS Procedure

A through validation and verification process of a document (such as FITNET FFS) which deals with the structural safety is of an immense importance. It is a continuous process and with a wide range of coverage of numerous cases makes the respective document credible and technically sound. Having this in mind, a special effort has been made to use the fully validated existing sources and propose assessment routes and procedures with newly conducted validations.

Validation of the FITNET FFS predictions has been carried out using both small and large scale laboratory specimens and real structural cases covering various structural materials and welds. Aim the validations to obtain a prediction of a critical situation with reasonable conservatism. An example is given in Figure 35 to demonstrate the conservative estimation (*predicted $\sigma_{max} = 690$ MPa compared to the 850 MPa obtained in experiments*) of the maximum stress of a small scale M(T) specimen of a 13%Cr steel using CDF approach in Option 3 of the Fracture Module. In such conservative estimations, exercise has been refined to find the reason of over conservatism and find the means to reduce the conservatism in estimation by checking the reliability of the input parameters etc.

New validation studies have used existing well-documented cases as well as various partners are utilised the new experiments and numerical studies to cover new technological developments in structural safety related industrial cases. For example, cases of highly strength undermatching laser beam and friction stir welds in thin Al-alloy aerospace structures were studied and various Options of FITNET FFS Fracture Module were applied. Case studies Section and a separate paper (*Fracture analysis of thin-walled laser beam welded stiffened panels of Al-alloys using FITNET FFS Procedure, FITNET 06-19*) on the butt-joints and stiffened panels provide the details of this topic.

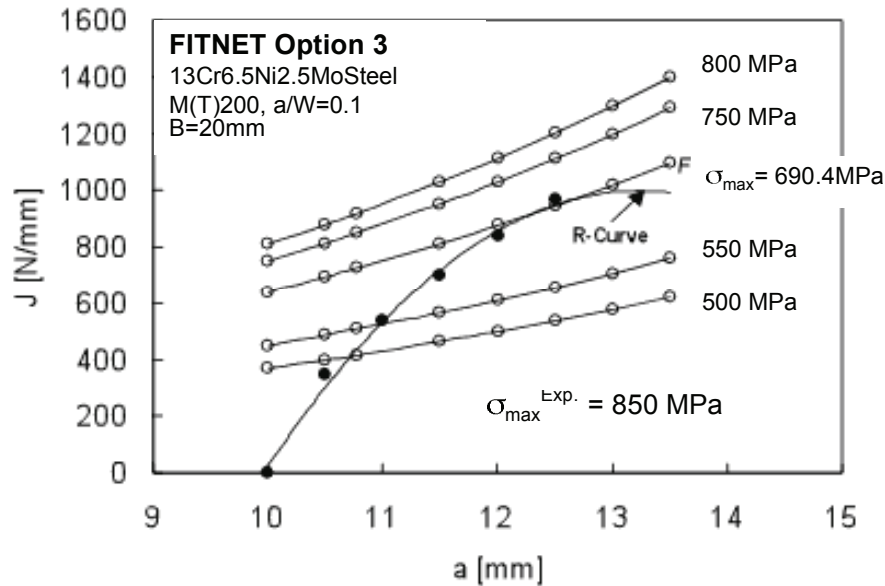


Figure 35. Crack driving force (CDF) route for prediction of maximum stress for 12 mm thick centre cracked high strength 13%Cr (supermartensitic) steel plate using FITNET Fracture Module **Option 3**. The J R-curve is determined using shallow cracked ($a/W=0.15$) SENB specimens.

Furthermore, fracture module of the FITNET FFS Procedure was applied to evaluate allowable crack sizes for the ARIANE 5 main stage tank bulkheads. A separate paper (*Validation of the FITNET analysis procedures for the assessment of ARIANE 5 thin-walled components, FITNET-06-032*) presents the comparison of various limit load solutions (e.g. surface cracks in plates and cylinders) and analytically obtained crack driving force results of the **Option 3** analysis is verified with the FE results with some conservatism.

Around 300 full-scale and large-scale fracture test results have been examined and interpreted in terms of FITNET FFS Procedure and/or the BS7910 Procedure by TWI. From this large programme, selected cases are provided to the case studies section (Section 13, Vol. II) and some are also reported in a separate paper (*Validation of fracture assessment procedures through full-scale testing, FITNET 06-018*) in this conference.

In another application of the FITNET FFS Procedure on the failure analysis of medical components was carried out at the University of Cantabria. The Basic

(Option 0) and Standard (Option 1) analysis routes were used to investigate the failure case of a Ti-alloy hip joint and results were used to explain the stages and development of the damage and of failure. The paper (*Application of FITNET Procedure for analysis of medical components, FITNET 06-016*) provides further details of this application.

FITNET FFS Fatigue Module has adopted the master S-N curve approach, as one of the fatigue assessment routes to conduct FFS analysis for complex weld joint geometries by taking advantage of the structural stress based K solutions. A series of examples are provided to demonstrate the use of this approach for design and FFS applications. The paper prepared by P Dong (*A FITNET Procedure for FFS-based fatigue evaluation using the master S-N curve approach, FITNET 06-034*) presents the principles of the structural stress method and validation cases in detail.

The FITNET FFS fatigue and fracture procedures were applied for the engineering critical assessment (ECA) of hydraulic cylinders (Figure 36) which operates under high cycle fatigue conditions. However, their design requires assurance against fatigue and static (safety against overloads) failures. The case was validated in this study was internally pressurized cylinders with surface crack and analysis has shown good agreement with the results of burst test and fracture mechanics analysis, see Figure 37. The work has demonstrated the usefulness of the FITNET FFS Procedure to evaluate the influence of defects on the in-service structural reliability of such components. The paper (*Assessment of tubes for manufacturing of hydraulic cylinders using FITNET FFS Procedure, FITNET 06-038*) reports on this validation case in detail.



Fig. 36. Specimen after burst test

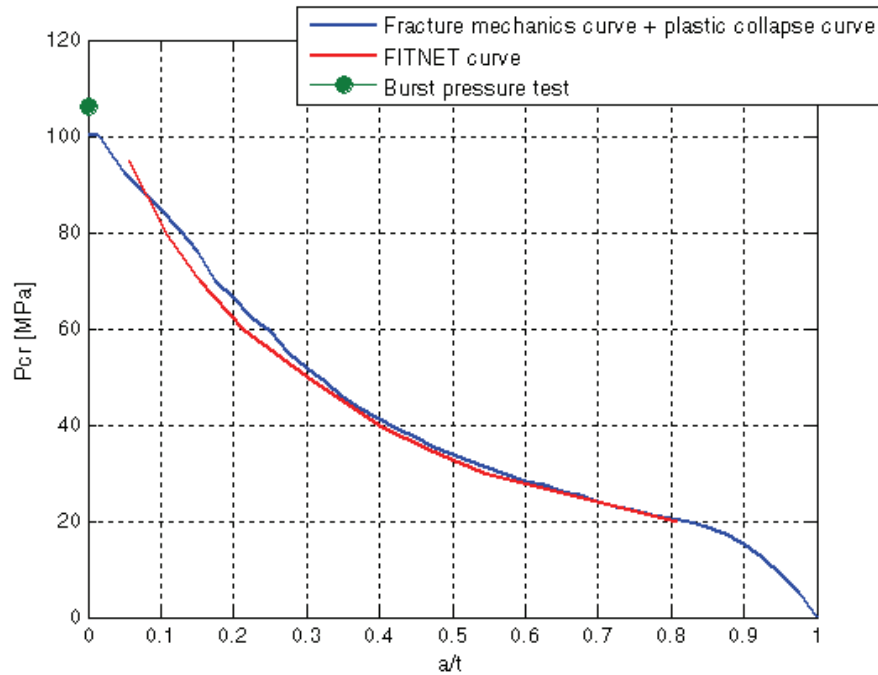


Fig. 37. Comparison of plastic collapse and fracture mechanics curves including FITNET FFS and burst pressure test results shown in Figure 36..

Italian Institute of Welding (IIS) has conducted a validation study of the Creep Module of the FITNET FFS Procedure for the residual life assessment of a pressure vessel operated in a petrochemical plant. The procedure has been adopted for the assessment of a real component, where a flaw, not related to the last stage of creep damage, has been detected at a nozzle to shell junction. The practical application of Creep Module prescriptions evidences how, in most cases, a relatively simple assessment can be helpful to decide if repair operations are really needed or the component can still be safely operated. Numerical analysis results have confirmed the reliability of the FITNET FFS Creep Module findings. The details of this work are presented in (*Application of FITNET FFS Procedure creep module for the assessment of a pressure vessel, FITNET 06-026*).

3. 8 Compilation of Case Studies

During the development of the FITNET FFS Procedure, number existing case studies have been reviewed and categorized according to their quality and coverage. Numbers of new case studies have been developed to validate the major routes and methodologies of the FITNET FFS Procedure. These activities are coordinated by the VTT Finland and reported at the FITNET 2006 Conference "*Compilation of Case Studies in FITNET FFS Procedure – FITNET 06-031*". The Section 13 in Volume II presents the compiled case studies.

3. 9 FITNET Training and Education

3. 9. 1 Introduction

During the development of the existing procedure, the FITNET members and experts (under the guidance of University of Cantabria, Spain) has been engaged to disseminate the FFS philosophy and generated knowledge. A set of special **Training and Education (T&E) Documents** has been prepared and provided during the Seminars to young engineers and students in various locations of Europe (so far in Spain, Slovenia and Hungary). The part of the developed documents during the training and education seminars is included into the FITNET FFS documentation under Section 14 Tutorials, Vol. II. This output is of a significant added value for higher education institutions and industrial trainings since it can readily be used in their curriculum and training activities respectively. The details and perspectives of this topic was reported in the FITNET 2006 Conference paper (*The education and training content of FITNET, FITNET-06-024*).

3. 9. 2 FITNET Seminars

Following the conclusions of the FITNET survey about training needs, the FITNET TN decided to provide training to engineers and university students by "Local Seminars" which were hosted and organised by the FITNET members in different countries. The following training seminars were organised:

-1st FITNET Training Seminar, organised by the University of Cantabria and hosted in Santander (Spain) from 16th to 18th of March, 2004. There were more than 60 attendants from Spain and Portugal.

-2nd FITNET Training Seminar, organised by the University of Maribor and hosted in Maribor (Slovenia) from 26th to 28th of October, 2004. There were over 30 attendants from Slovenia, Italy, Croatia and Serbia.

-3rd FITNET Training Seminar, organised by the Bay Zoltan Foundation and hosted in Miskolc (Hungary) from 19th to 21th of October, 2005. There were more than 30 attendants from Hungary, Ukraine, Slovakia, Serbia, Croatia, Sweden, Germany, UK, Italy and Czech Republic.

There was a homogeneous structure in all these seminars that followed the one proposed in the FITNET Training Package. Experts from industry and academia developed practical specific lessons covering fracture, fatigue, creep and corrosion-environmental assisted cracking in three different aspects: basic concepts, assessment procedures and case studies. Specific lessons on other areas such as residual stresses or software tools were also given. The last day of the seminars was dedicated to laboratory lessons, where attendants could acquire practical experiences.

As a summary, more than 150 attendants from 14 countries have participated on FITNET seminars. Also, they came from a wide range of organisations, such as nuclear, engineering and manufacturing companies, universities and research centres.

After completion of the FITNET project, it is planned to conduct series of seminars and workshops at various countries and industries. In year 2006, November, Japan and Australia is planned. FITNET coordinator will be holding these half day seminars to disseminate the FITNET procedure and results.

3.9.3 FITNET Training Package

The University of Cantabria, as WP6 leader, has developed a comprehensive and useful Training Package, which consists in a pdf document with around 500 pages in the form of power point slides. The idea is to provide easy-to-read pages in order to obtain a dynamic document with no major difficulties, complementing the well established FFS bibliography which is available nowadays.

The structure is divided in four main chapters corresponding to the four main failure mechanisms: fracture, fatigue, creep and corrosion-environmental assisted cracking. In all these chapters there are four different sections corresponding to basic concepts, assessment procedures concepts, FITNET procedure and case studies. With this format, the user acquires knowledge from the basic theory to its application to real cases through the use of industrial procedures or standards, emphasising the FITNET FFS procedure. Transversal links help the user with his/her training work.

The distribution of the upgraded versions of the training package has been performed in different ways:

- CDs to seminar attendants and FITNET members
- Fitnet website
- The final version of the FITNET is a cd offered as a complement of the final FITNET procedure document.

3. 9. 4. FITNET Tutorials

The consortium has prepared (lead by VTT, Finland) a Case Studies document, whose main objective is to validate the proposed FITNET FFS procedure and to provide training material.

As a complement of this activity, University of Cantabria, Spain has also prepared a document with different tutorials covering the four main failure modes and their interactions. These tutorials are examples that reproduce the process of assessing components following FITNET FFS procedure, not forgetting the theoretical fundamentals, in order to familiarize the user with the procedure. According with the structure of the procedure, nine tutorials are presented covering fracture/plastic collapse, fatigue, creep, corrosion or EAC assessments. Another two tutorials are transversal and cover a combination of failure mechanisms and the last tutorial represents the application of FITNET philosophy to a specific industrial sector (aeronautics).

Finally, Training and Education (T&E) programmes and activities are a decisive factor on research, knowledge transfer and competitive and sustainable economic growth. This obliges European authorities to make big efforts to promote T&E, from basic educational levels to research, university and industry environments. The main objective of the FITNET project has been the development of a FFS European procedure covering the four main failure modes but, being consistent with the previous paragraph, there has been an important effort in providing T&E tools and activities with the intention of transferring the results of the research to the industry operations. T&E appears as a key factor for the correct exploitation of research efforts.

FITNET T&E activities have been articulated through three international training seminars, a comprehensive training package and a tutorials document. It has been complemented with the offering of on-line and mixed education training subjects and programmes at different levels, the development of FFS software and the collaboration with other European training courses. The experience has been highly satisfactory and can be taken into account for future T&E programmes.

4.0 FITNET Procedure and European Standardisation

Standardisation at the European level for industrial structures and products is covered by CEN. The existing European fabrication and quality control codes do not provide methods to assess a metallic component containing a flaw or damage that result from operation after being in service. The FFS evaluations are quantitative engineering assessments that can be conducted to demonstrate the “structural fitness for service” of a metallic component (with or without weld) containing a real or postulated flaw or damage.

The current ***Final Draft of the FITNET FFS Procedure (dated 1st May 2006, version MK7)*** is a comprehensive FFS Procedure (prepared using the ISO templates) and submitted to CEN under the *CEN Workshop Agreement* (CEN WA22) via Italian standardization body UNI. The CEN Workshop Agreement works an international level with membership basis and makes the documents public at early stage of its development for comments. The received comments have been considered by the FITNET experts during the development of the final draft. The current document is called as Final Draft since it will be subject to further revisions after the second general assembly of the CEN WA22 meeting and FITNET 2006 Conference.

The FITNET FFS procedure, as mentioned, evaluates real and postulated flaws and damage associated with design, fabrication and in-service flaws of various primary structural components in different industrial sectors. FFS assessments have already been used to some extent by the CEN code committees for formulation of fracture toughness requirements and formulation of fatigue design curves. Having reached to a final draft stage, the FITNET FFS procedure with the process of circulation for public comments and revisions, the FITNET steering and experts groups will work with the respective CEN and ISO Code Committees (such as CEN TC 121 and ISO TC 44) to finalize the standardization of the document.

To Conclude;

FITNET FFS Procedure will follow the CEN CWA22 route for its standardization, as planned. This process will reach a milestone at the end of October 2006 by transferring of the **MK8 version** (revised MK7 version) of the document. Furthermore, developed FITNET FFS Procedure will be used for revision of existing codes, BS7910 and R6. BSI has officially requested to receive master copy of the FITNET FFS to use in next revision of the BS7910 standard.

5.0 Deliverables and Dissemination & implementation

A separate report on the Final Plan for using and disseminating the knowledge has been prepared for the European Commission. However, dissemination and implementation issues are briefly covered in this section.

The major deliverable of the project is the FITNET FFS Procedure in three volumes:

- Vol. I: FITNET FFS Procedure
- Vol. II: Case Studies and Tutorials
- Vol. III: Annex

The volumes I and III will be used as official documents for standardization within the framework of CEN Workshop Agreement (CWA 22). After completion of the period “open for public comments”, the FITNET FFS document will be submitted to CEN for distribution. This will be the major dissemination and exploitation of the project result.

However, national codes and standards or best practice documents of many industrial companies will have an opportunity to revise existing documents using FITNET results. For example, well-known BS 7910 standard plans to adopt various aspects of the FITNET FFS Procedure into a future revision of BS7910. Similarly, it is expected that other national codes will significantly benefit from the FITNET FFS document and improve their current versions during 2007 and 2008.

FITNET TN has provided **three training and education seminars** (each 3 full days) to young engineers and students in three European countries. Training materials have been collected/developed by the FITNET TN partners and used during these seminars and distributed as CD to all participants.

Furthermore, the University of Cantabria has begun to give an on-line subject on FFS on 2006 (*“Introduction to Structural Integrity Assessment Techniques”*), based on the FITNET Training Package. Next year, it will be offered to other Spanish universities and it will be also possible to offer it in an open way to any interested student of professional. The results are being very interesting, with considerable demand from civil and mechanical engineering undergraduate students and from PhD students.

Dissemination of the FITNET FFS Procedure has made a major step by organisation of a special FITNET session during the 24th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Halkidiki, Greece, 12-17 June 2005. Total seven technical papers were presented at

the conference. Furthermore, special Fitness-for-Service sessions were organized during the last two annual assemblies of the International Institute of Welding (IIW) 58th Annual Assembly, July 2005, Prague and 59th Annual Assembly, Sept. 2006, Quebec and FITNET FFS procedure and its applications on welds were demonstrated.

Finally, International Conference on Fitness-for-service FITNET 2006 was organized during 17-19 May 2006 at the SHELL Headquarters, Amsterdam. This conference has served a major public event for distribution of FITNET FFS Procedure (version MK7) in three volumes. Additionally, FITNET TN consortium members have made about 30 technical presentations to demonstrate the details of the procedure and its applications as well as validations.

Training & education and validations & case studies volume (Volume II) of the FITNET will not be part of the CEN Workshop Agreement 22 due to the nature of this volume. This document does not provide prescriptive procedure, but rather provides selected case studies and tutorials for education purpose. This volume will be separately be printed and used for further educative and training activities of the FITNET FFS Procedure. In this context, University Cantabria, Spain together with GKSS is planning to introduce a **European Master Course on the Fitness-for-Service Assessment** using FITNET concept and documentations. The preparation for this is currently on-going and it is planned to introduce in year 2007.

Future Fitness-for Service assessment activities within the International Institute of Welding (IIW) are planned to be coupled with the FITNET FFS Procedure and its use. Fracture assessment of welds part of the procedure will be submitted to the Commissions X and XI for adoption as an IIW best practice document.

The FITNET web site (www.eurofitnet.org) was established in 2002 and coordinated by TWI, will further be available for the FITNET TN members and external users to disseminate the knowledge and documents.

A summary of the major dissemination activities of the FITNET TN is given in Table 1.

Table 1. Overview table gives the summary of dissemination activities

Planned/actual Dates	Type	Type of Audience	Countries addressed	Size of audience	Partner responsible
March 2002	Project web-site	General Public	World-wide		TWI
May 2002	Project Flyer	General Public	World-wide		GKSS TWI
16-18 March 2004, Santander, Spain	1 st FITNET Training Seminar	Young Engineers, Students	Spain, Italy, Portugal, France	62	University Of Cantabria
27-29 Oct. 2004, Maribor, Slovenia	2 nd Training Seminar	Young Engineers, Students	Slovenia, Croatia, Yugoslavia, Italy, Austria	50	University of Maribor
July 2005	1 st version FITNET Demo Software				University of Maribor GKSS
19-21 Oct. 2005, Hungary	3 rd FITNET Training Seminar	Young Engineers, Students	Hungary, Ukrania, Sweden, Czech Rep., Poland	30	Bay Zoltan Foundation
12-17 June 2005, Greece	OMAE Int. Conf	Industry, Higher edu. and R&D	World-wide	40	CORUS, GKSS, Uni. Cantabria, TWI, SCK'CEN
July 2005, Prague.	IIW Annual Assembly	Industry, Higher edu. and R&D	World-wide	60	GKSS
11/12 2005	Publication Int. Journ. Welding in the World	Industry, Higher edu. and R&D	World-wide		GKSS
13 Feb. 2006 Aachen	DVM Training Seminar	Industry, Higher edu. and R&D	Germany	35	GKSS
17-19 May 2006 Amsterdam	Int. Conf FITNET	Industry, Higher edu. and R&D	World-wide	100	SHELL, GKSS, All members
17-19 May 2006 Amsterdam	30 Publications	Industry, Higher edu. and R&D	World-wide		All members
15 th June 2006 CEN, Brussels	Lecture	EPERC TG5 Members	France, UK, Belgium, Germany, Italy,	8	GKSS
01 Sept. 2006 Quebec	IIW Annual Assembly	Industry, Higher edu. and R&D	World-wide	60	GKSS
Sept. 4-7 2006, Poster	Int.Conf. Euromat, Lausanne	Industry, Higher edu. and R&D			GKSS
8-13 Nov. 2006 Tokyo, Osaka	Lectures	Industry, Higher edu. and R&D	Japan		GKSS, Osaka Uni.
15-23 Nov. 2006 Sydney	Lectures	Industry, Higher edu.	Australia		GKSS

FITNET Final Technical Report

		and R&D			
2007-2009 Proposal INNOCENT	EU MarieCurie Proposal	Young Engineers, Students	EC		Bay Zoltan Foundation,GKS S
2007-2008	Standardisation CWA 22 In CEN		EC		GKSS, CESI
2007-2008	Standardisation Adoption to BS7910		UK, EC, World wide		TWI
2007-2008	Standardisation Adoption to R5 and R6 codes		UK, EC, World wide		BE
2007-2010	Lectures, Publications on validations and applications		World wide		GKSS, All Members
2008 - 2011	SAFEPIPE Project for 7 th FP (Joint proposal of ETPIS and ESTEP)		Steel, oil and Gas and Pipeline industries EC		GKSS, CORUS, TWI, UNICAN, ADVANTICA, BE, UniGENT, DNV, SHELL, VTT, and other members

As mentioned above and separate report on the implementation of results, some of the contractors will continue to enhance the technical approaches used in the FITNET Procedure. For example VTT will continue to their work on the development of methodology for statistical treatment of incomplete Charpy toughness (CVN) datasets and incomplete CVN transition curves, aiming at a procedure for extrapolating Charpy transition temperature from the data at other temperatures based on a generic description of the CVN curves. In addition to parent steel, also weldments will be included to evaluate the applicability of the Charpy – fracture toughness correlation for inhomogeneous material. This development will utilise the new solutions and updated advice for the upcoming revisions of the FITNET Fracture Module.

Furthermore, VTT will continue to their work on the development of the bi-modal Master Curve (MC) analysis method, with the aim at extending the scope of standard MC analysis by describing the fracture toughness distribution of inhomogeneous material as the combination of two separate MC distributions. Feasibility of the bi-modal MC analysis in describing weld metal and HAZ fracture toughness of different steel types will be investigated.

GKSS will continue for validation of the procedure, particularly for welded structures in the field of energy (such as pipelines) and laser welded thin-walled structures of aerospace applications. It is planned to develop a **FITNET Industrial Module on Pipeline Engineering** together with European Technology Platform Steel (ESTEP) and European Pipeline Research Group (EPRG). This module will particularly be tailored to develop crack arrest and

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flaw assessment methodologies for welded high strength (X100 and X120
grade) steel pipelines. Here numbers of FITNET members will contribute.

Together with University of Maribor, FITNET software development will
continue to provide an engineering tool for assessment of commonly used
structural configurations.



The three volumes of the FITNET FFS Procedure and FITNET 2006
Proceedings

6.0 Network Management

The contractors of the network have formed a project steering committee and this has made regular meetings during the whole life-time of the project. Additionally, steering committee has made special (intermediate) meetings on the procedure development and CEN Workshop.

The coordination of the network has been full of smooth and enjoyable events during whole life-time of the project. No major difficulty has been experienced. The steering committee together with coordinator has handled all scientific and administrative issues with high efficiency.

6.1 Tasks of Contractors

The contractors have taken responsibilities of all Work Packages (horizontal tasks) and Working Groups (vertical tasks) where both have formed a matrix-type of organisation.

GKSS

GKSS was responsible for the coordination of the network and FITNET FFS procedure development. Has conducted monitoring and administration works of all versions of the FITNET procedure. Has conducted validations for weldment cases of fracture module. GKSS has also contributed to the development of Creep Module. Has given lectures in training seminars and conducting dissemination activities and representation of FITNET network. Has prepared all meetings and progress reports for the commission.

GKSS has completed all assigned tasks with great success.

JRC

JRC was one of the major developers of the Fatigue Module with Caterpillar. JRC has prepared and conducted extensive survey to determine the need and challenges of the FFS technology. The results of this survey have provided a road-map for the development of the activities and procedures. JRC has conducted proof readings of the various sections of the FFS procedure.

JRC has completed all assigned tasks with great success.

VTT

VTT was responsible for the development of the Case Studies section and was lead drafter of the master curve (fracture toughness) section of the fracture module. This section provides new solutions developed at the VTT.

VTT has completed all assigned tasks with great success.

TWI

TWI has developed one of the major Annexes (Annex A) and was major developer/drafter for sections in Fracture, Fatigue, Corrosion and lecturer in training seminars. TWI has provided cases for the case studies section and validation of the fracture procedure using in-house developed data. TWI has taken the responsibility of the FITNET Web-site and conducted with great success. TWI has conducted proof readings of the whole procedure and key partner for the implementation of the FITNET FFS results into the widely used BS 7910 national standard in UK.

TWI has completed all assigned tasks with great success.

UNICAN

University of Cantabria was responsible for the training and education activities. UNICAN was also contributing partner for development of fracture and corrosion modules of the FITNET FFS. Preparation of the training seminars and lectures were successfully made by UNICAN.

UNICAN has completed all assigned tasks with great success.

CESI

CESI has taken the responsibility to develop roadmap for the standardisation of the FITNET FFS Procedure. CESI has developed a business plan for the CEN Workshop Agreement work (CEN W22 docs.) and has contributed to the fatigue module development.

CORUS

CORUS has taken the responsibility of the Fracture Group and development of the Fracture Module of the FFS Procedure and was lead drafter of various sections of the fracture module and validations as well as lecturer in training seminars. CORUS was also provider of cases for the Annex on the case studies.

CORUS has completed all assigned tasks with great success.

CATER

Caterpillar was responsible for Fatigue Working Group and development of Fatigue Module and lead drafter of various sections of this Module and validations.

CATERPILLAR has completed all assigned tasks with great success.

BE

British Energy was responsible for the Working Group Creep and significantly contributed to the development of Creep Module. BE was also lead drafter of various sections of Fracture Module (e.g stress and constraint) and training seminars. BE has provided numbers of case studies covering fracture and high temperature issues.

British Energy has completed all assigned tasks with great success.

SHELL

SHELL was responsible for the fourth Working Group Corrosion and has developed Corrosion Module its validation. SHELL has demonstrated, in particularly, local thin area (LTA) assessment part of the module providing in-house FE-data. SHELL was also contributor for various fracture sections as well as host organisation of the FITNET 2006 Symposium in Amsterdam.

SHELL has completed all assigned tasks with great success.

Comparison between planned overall objectives and achievements of the project in terms of per workpackage is shown in following Table.

Overall Objectives of the Thematic Network as announced at the kick-off meeting, 25-26 February 2002

- 1) *To develop a unified, comprehensive FFS procedure covering Fracture, Fatigue, Creep and Corrosion modes of failures and submit to CEN for adoption*
- 2) *To validate the procedure using existing and new data and define areas need to be verified*
- 3) *To form a Pan-European Group of Experts from industry and academia*

These objectives have been fully accomplished.

Breakdown of the planned objectives and achievements are listed below per WP.

Workpackages & Objectives and Achievements		
Work Packages	Objectives	Achievements
WP1: Network Management GKSS	- To administer FITNET TN - To establish efficient communication and publicising the results - To submit FFS Procedure to CEN	Smooth management and communication of TN were experienced. FITNET has been represented efficiently CEN will receive in early 2007
WP2: State of the art JRC	- To map current R&D work - To establish need in FFS procedure - To determine priority areas	Extensive survey was carried out and priorities for the FFS procedure and training were established
WP3: Procedure Developm. GKSS	- To develop FITNET FFS Procedure - To coordinate the activities in 4 WGs - To provide FFS Procedure for validation studies	FITNET FFS Procedure is completed with its annexes, training packages and validation was conducted and presented at the FITNET 2006 Conference.
WP4: Case Studies VTT	To collect benchmark examples and case studies for validation and training and education	FITNET FFS Procedure Vol. II is prepared as separate volume for this purpose
WP5: Dissemination TWI	- To disseminate the results - To publicise the FITNET activities - To establish and run FITNET web-site	FITNET flyer was prepared and disseminated. The results were published in various conferences. FITNET web-site has been established and used.
WP6: Training and Education Uni. Cantabria	- To establish needs and methods for training on FFS - To collate and create data base of training material - To organise documents and lecturers for seminars	FITNET TN has organised 3 training seminars (Spain, Slovenia, Hungary) with training
WP7: Standardisation V. Bicego / CESI	- To promote CEN Standard on FFS - To monitor international developments on FFS - To assess needs for implementation of CEN standard	FITNET FFS Procedure has been developed under the CEN Workshop Agreement (CWA22) working with UNI-Italy and will be submitted to the CEN

6.2 Network Budget

The FITNET Network has completed its work at 31 May 2006 with the overall budget and distributions of costs are shown in the following Tables.

Principal Contractor	Revised Budget (€)	Actual Total Cost (€)	Remaining Budget (€)
GKSS.IWF	393343.00	487800.00	-94457.78
COM.JRC.IE	93012.00	113683.69	-20671.69
VTT.MT	116840.00	116081.00	759.00
WELDING.SID	123950.00	108995.12	14954.88
UCANT.LCM	119040.00	162131.43	-43091.43
CESI.BUGP	90485.00	91914.66	-1429.66
CORUSUK.STC	114258.00	124085.84	-9827.84
CATFR.SOPD.SCTS	121786.00	121111.73	674.27
BREG.ENG	117540.00	122708.97	-5168.97
SGSI.SRTCA	111744.00	98210.72	13533.28
Grand Total Contractors	1401998.00	1546723.94	-144725.94
Grand Total Members	264150.00	163721.44	100428.56
Grand Total Network	1666148.00	1710445.38	-44297.38

TOTAL PAYMENTS RECEIVED							
Total EC Funding	Advance	Year 1	Year 2	Year 3	Year 4	TOTAL	Remaining
1.600.000.00	540.224.00	95.973.89	352.107.92	66.146.71		1.054.452.52	545.547.48

The actual \grand total spending of the whole network is 1.710.445.38 €. This means, the overall FITNET network has put more work than planned programme without asking additional budget from commission.

The details of the budget situations of the contractors and members are reported in the final cost statement to the commission. According to the contractual arrangement and organisation of the network, each contractor was linked with numbers of members and hence cost statement of each contractor contains travel costs of respective member organisations.

The analysis of all claimed expenses of the contractors are fully justified and in agreement with the work that they have conducted during the reported final period.

7.0 Conclusions and Further Research

7.1 Conclusions

FITNET was a thematic networking project designed to develop a **European Fitness-for-Service Procedure** (FFS) for assessing the structural integrity of metallic welded or non-welded structures transmitting loads. In Europe, there has been a need to **further develop** and **unify** existing engineering assessment procedures (containing analytical expressions) to assess the structural significance of the flaws or damages. For this very purpose, FITNET TN has started to work from February 2002 to May 2006.

The FITNET TN has worked together with 62 experts from 16 European countries and 41 organisations. Additionally, experts from Japan, USA, Korea and Norway have provided in-kind contributions to the development of FITNET FFS Procedure. This network has smoothly operated for 4,5 years under the guidance of project coordinator (GKSS, M. Kocak) and FITNET Steering Committee (represented by project contractors: GKSS-Germany, JRC-Belgium, VTT-Finland, TWI-UK, University Cantabria-Spain, CESI-Italy, CORUS-UK, CAT-France, BE-UK, SHELL-The Netherlands).

Acronyms and countries of the FITNET members are:

IWT-Germany, BZF-Hungary, CSM-Italy, HSE-UK, ALSTOM-UK, FhG/IWM-Germany, UMFS-, SCK/CEN-Belgium, ADVANTICA-UK, CRF-Italy, CEIT-Spain, FORCE-Denmark, RUG-Belgium, INNOSPEXION, KUT-Poland, ROLLS-ROYCE-UK, DNV-Sweden, TUD-Germany, IIS-Italy, MPA-Germany, University of Aveiro-Portugal, University of Maribor, Slovenia, SKODA-Czech Republic, BUREAU VERITAS-France, CETIM-France, DLR-Germany, NPL-UK, IdS-France, EMPA-Switzerland, EPFL-Switzerland, HITACHI-Japan, Osaka University-Japan, Korea University-Korea, BATELLE-USA, Norwegian University of Science and Technology.-Norway.

The FITNET FFS Procedure covers four major failure modes, namely **fracture, fatigue, creep and corrosion and their all aspects essential for advanced design and safety of metallic structures of wide range of industrial sectors**. The FITNET FFS Procedure aimed to include most recent advances in structural integrity assessment while providing fully validated methodologies, assessment routes including well selected case studies or worked examples for determining the FFS of various structures and welded components manufactured from metallic materials.

FITNET TN aimed also to provide the **technical and industrial focal point** for the definition of future R&D agenda and specific projects which may be required to address specific structural integrity & damage tolerance analysis

aspects of the power generation and petro-chemical plants, offshore, pipelines, aerospace, transport/railway and civil engineering structures.

These objectives are realized by the development of the strategic research agenda for the European Technology Platform Industrial Safety (ETPIS), Focus Group on Structural Safety. Furthermore, efforts to develop a specific project on the Pipeline Integrity (**SAFEPIPE – European Safety System for High Performance Pipelines for Oil and Gas**).

To conclude:

***The unified flaw assessment procedure, FITNET FFS is the main output of the FITNET project.** It provides a unique and comprehensive fitness-for-service document with numbers of novel features. All major parts and approaches have already been validated and hence it provides technically sound “ready-to-use” procedure for the European manufacturing and plant operating industries.*

The road map for the standardisation of the FITNET FFS Procedure has been completed in the form of CEN Workshop Agreement (CEN CWA 22). CEN Workshop Agreement provides a type of CEN document below a standard. Italian Standardisation Body (UNI) has accompanied CWA 22 work to finalise the FFS Procedure. This will be finalised in early 2007 by the transfer of the document to the CEN.

***The major exploitable result of the project is the FITNET FFS Procedure** in two volumes (Vol. Procedure and Vol. III. Annex) will be used as official documents for standardization within the framework of the CWA 22.*

*FITNET TN has developed an extensive course notes for **training and education seminars** for young engineers and students. Training materials have been developed and used during the seminars and distributed as CD to participants of the training seminars held during the project life-time. An industrial and academic use of the FITNET FFS training and education documents is planned to be used further (e.g. Spanish FITNET Seminar in March 2007).*

7.2 Further Research

Wide spread application of the FITNET FFS procedure to various industrial and academic cases and hence its validation is an essential part of this fitness-for-service technology. Needless to say that structural safety related procedures such as FITNET FFS will gain credibility and trust of the end-users with its wide spread use and timely & transparent revisions. It is, therefore, planned to include this procedure into various structural safety related projects of the 7th FP.

Structural safety of major engineering structures can be covered with special extensions or modules of the FITNET FFS Procedure. For example, **development of structural safety assessment procedures of oil and gas pipelines (SAFEPIPE)** based on existing FITNET FFS can be achieved with the experts of pipeline technical community and industries.

Further research is needed for the assessment of defects in thin-walled and welded aerospace structures. First trials on this area have produced promising results with respect to fracture analysis. However, a new tailored module for the structural safety assessment of such applications is needed.

These examples can be extended further. However, main idea is to conduct further research to develop industrial sector specific modules to cover new emerging challenges and technological aspects. Multi-material structures using material-mix components are increasingly used to increase structural performance in terms of weight and cost-efficiency. These novel components needs interface engineering, design and interfacial defect assessment procedures.

There is a need to extend this fitness-for-service document for assessing of critical situations in service by using input data of modern “Structural Health Monitoring” practise. On-line damage sizing and monitoring of critical locations may provide new advanced possibilities for structural integrity assessments of complex structures.

There is further need to extend the use of FITNET FFS procedure for non-metallic structures. Current procedure is only applicable for metallic structures with and without weld joints. Here, identification of damage mechanisms of non-metallic structural materials has significant implications on the use of the procedure and hence respective new sections need to be newly developed.

Recently, European Technology Platform on Industrial Safety (ETPIS) has been established (see for further details; www.industrialsafety-tp.org). One of the Focus Groups of this TP is called **Structural Safety** and topics of its

strategic research agenda (SRA) covers numbers of future oriented research areas where FITNET FFS procedure may find its further use. The strategic research priorities identified for the Structural Safety area are covering following topics;

- Structural reliability based design
- Structural health monitoring (SHM) and risk informed inspection
- Structural safety of aged and repaired structures and life extension
- Fitness-for-service (FFS) of structures
- Integrity of multi-material (hybrid) structures
- Structural safety against natural hazards and accidental loads

Efforts will be made to generate collaborative research projects within these priorities, however, technological and further innovative aspects of such research proposals will be needed to combine methodological and technological innovations to solve new emerging challenges of structural safety.

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