FITNET

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Technical Report

Final Report for Work Package 2 "State-of-the-Art and Strategy"

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Disclaimer

Contents

1 INTRODUCTION

This final report for Work Package 2 provides an assessment of the state-of-the-art for FSS (fitness-for-service[1]) technology and makes recommendations for developing the FITNET procedure. It draws from several sources:

a) the mapping of on-going R&D (deliverable D2.1 of this WP)
b) the survey on current practices for FFS (deliverable D2.2 of this WP)
c) reviews available in the literature
d) input from FITNET's main technical working groups (WG1 Fracture, WG2 Fatigue, WG3 Creep, WG4 corrosion) and the dedicated task groups on K solutions, residual stresses and materials properties.

The initial section of this report summarises the input available to the network members in the initial phase of the project.

The subsequent sections are intended to provide a condensed summary of the proposed content of the FITNET procedure. They also aim to identify technical areas a) for which the procedure would provide guidance material, or b) that could be enhanced with respect to existing procedures.

It is stressed that the report reflects the status of the project and of the discussions relating to the development of the FITNET procedure up to September 2003 only.

1.1 Proposed Scope of FITNET FFS

The aim is the development of a European Fitness-for-Purpose/Fitness for Service Procedure for assessing the structural integrity of metallic welded or non-welded structures transmitting loads [1]. In particular it will embody 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.

The FITNET-FFS procedure will have four major modules namely: fracture, fatigue, creep and corrosion. It is aimed to have similarly structured modules and to be coherent with currently used procedures. It should be user-friendly and accessible to engineers working in industrial environments. Special effort will be made to develop welding sections for each module (similar to the SINTAP procedure) to treat conventional and advanced (e.g laser beam, friction stir etc.) structural welds in all four major failure modes.

Fig. 1 shows the overall modular concept that will form the basis of the procedure.

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[1] In this document no distinction is made between the terms fitness-for-service and fitness-for-purpose, although FFS is preferred.

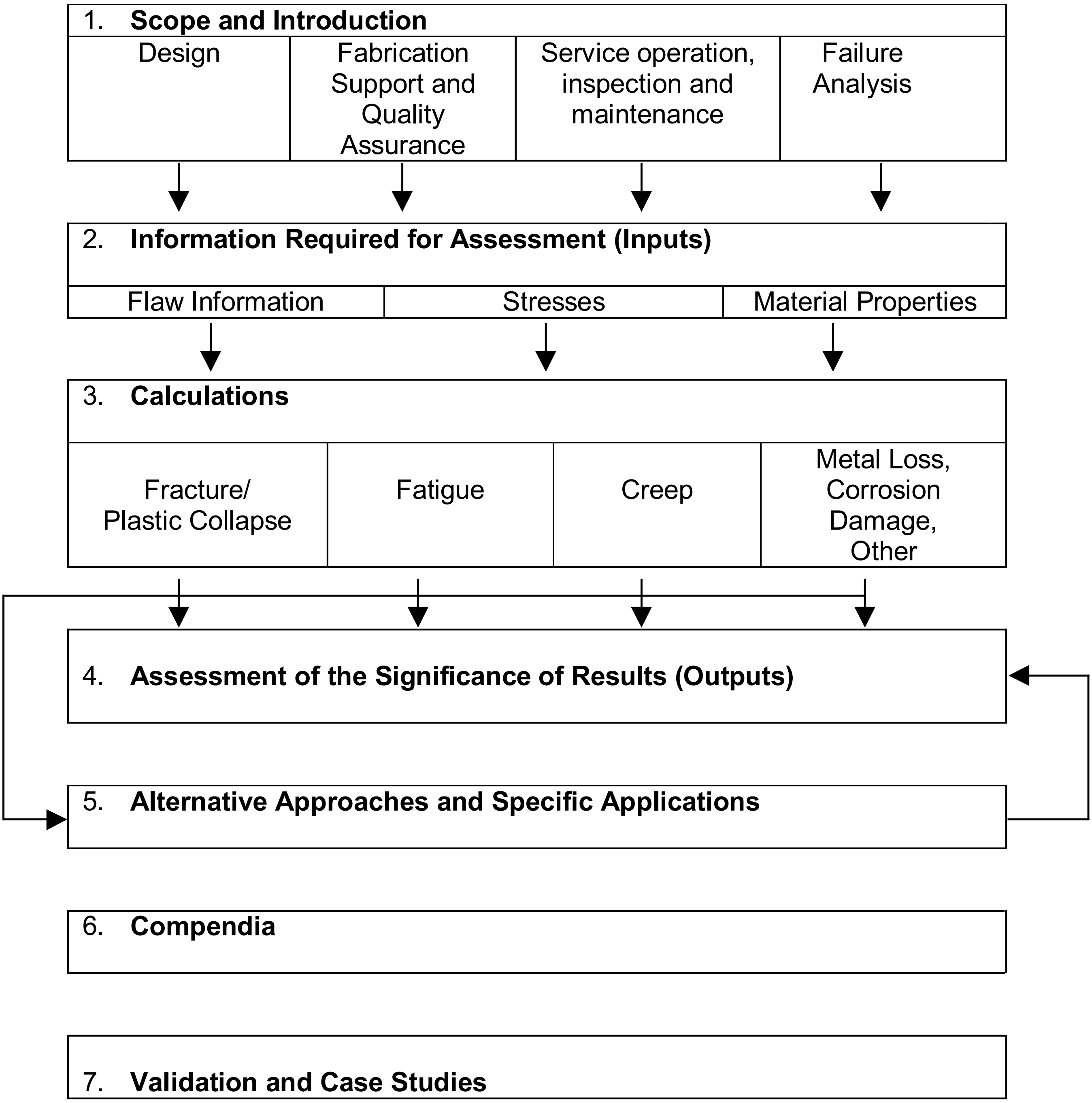

Fig. 1 The modular scheme proposed for the FITNET-FFS procedure.

1.2 Current R&D Mapping

A collation of on-going R&D projects relevant to the development of fitness-for-service procedures was made based on the input from the members of the FITNET Thematic Network [2]. The project titles are shown in Table 1 under 5 groupings. The number of responses received per area in Fig. 2. There is a reasonable spread across the working areas, although its noticeable that fracture is clearly the area of largest interest. The response for the corrosion area appears weak. The biggest response in terms of countries was from Germany and the UK. There was surprisingly little input from several industrialised countries with traditional interest in FFS, for instance France and Sweden.

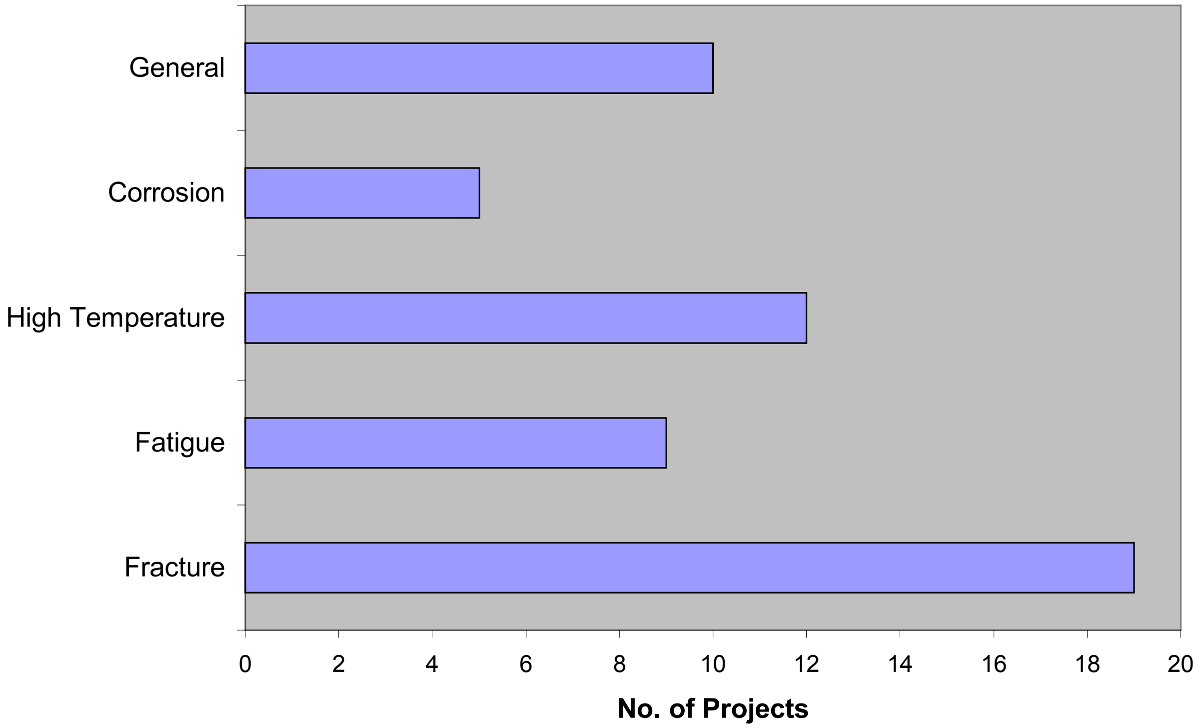

Fig. 2 Number of running R&D projects identified under 5 selected main themes.

Table 1: Summary of Running R&D Projects Relating to FFS Procedure Development

FRACTURE

- Structural integrity Assessment for Dynamic Loading and Crack Arrest
- Fracture avoidance in laser welded thick structural steel plates with a yield strength between 235 and 890 MPa
- Steel selection for fracture avoidance in steel ships
- Numerical investigation of the fracture behaviour of laser welded structural steels with strength between 355 and 890 MPa and development of fitness for service rules.
- Steel selection criteria for structural steels related to the fatigue strength catalogue of Eurocode
- An energy balance approach to crack arrest
- From processing to properties: Characterisation of toughness
- Prediction of structural behaviour on the basis of small scale specimen testing
- Role of Loading History in the Fracture Assessment of Structures
- Structural integrity Assessment for Dynamic Loading and Crack Arrest.
- Fracture resistance of the steels for containers of spent nuclear fuel
- Development of a Unified Procedure for Fracture Mechanics Tests
- Validation of Constraint Based Assessment Methodology in Structural Integrity
- NESC-IV: An Investigation Of The Transferability Of Master Curve Technology To Shallow Flaws In Reactor Pressure Vessel Applications
- Assessment of Aged Piping Dissimilar Metal Weld Integrity
- Structural Margin Improvements In Aged-Embrittled RPV With Load History Effects
- Examination of the fracturing process with magnetic and electro-emission measuring technique
- Development of toughness requirements for plastic design

FATIGUE

- Fatigue behaviour of welded high strength steel components under combined multiaxial variable amplitude loading.
- Fatigue design of stainless steel welds
- Enhanced Life Prediction for Three Dimensional Fatigue Cracks
- Enhanced fatigue performance of higher strength steel welded joints
- HISTESHIP: Application of high grade-steel plates for welded deck components for ships and bridges submitted to medium/high service loads
- Improved assessment of steel buildings performance during earthquakes
- Therfat: Thermal Fatigue Evaluation of Piping System "T" Connections
- Battelle support to ASME Div 2 Rewrite
- FEA Procedures for Fatigue Design and Evaluation of Welded Structures

Table 1 (cont.): Summary of Running R&D Projects Relating to FFS Procedure Development.

CREEP

- British Energy R5 Procedures
- Integrity Assessment During Operation: EPERC Technical Task Force 5: Small Punch project
- Integrity of repair welds in high temperature plant operating under steady and cyclic load conditions
- Small punch testing method.
- ESIS TC11 - Working Group: High Temperature Testing of Weldments
- IIW – International Institute of Welding: Commissions IX, X and XI
- VAMAS – TWA 25: Creep/ Fatigue Crack Growth in Components
- Development of a non-continuum model to predict reheat crack growth
- ECCC (European Creep Collaborative Committee) WG3 test data assessments, WG1.2 Creep Crack Initiation prediction methods
- CRETE (Creep Crack Growth test method development)
- Arbeitsgemeinschaft für warmfeste Stähle Working Group W14 “Kriechrisswachstum”
- Arbeitsgemeinschaft für warmfeste Stähle: Working Group W10 “Hochtemperaturverhalten unter veränderlicher Beanspruchung”
- Validation, expansion and standardisation of procedures for high temperature defect assessment
- Probabilistic and Sensitivity of Crack Assessment in High Temperature Plant and Applicability of HIDA Procedure

CORROSION

- The application of FAD in the assessment of environmental assisted cracking and fracture conditions
- Shell Handbooks for Corrode Pressure Equipment
- Assessment of metal loss defects in pipelines using finite element analyses
- Application of new fracture mechanics concept to hydrogen damage evaluation
- A Review Of Methods And Recommended Procedures To Evaluate The Static Strength Of Corroded Nozzles In Steel Pressure Vessels

GENERAL THEMES

- Performance criteria for cold formed structural steel
- Comparison of Model Tests and Full Scale Data with Theory
- British Energy R6 Procedures
- British Standards BS7910 Guide for assessing the significance of flaws in metallic structures
- Extending Plant Life Through Improved Fabrication and Advanced Repair Methodology
- PVRC JIP on Improved Weld Residual Stress Estimates and Local PWHT requirements
- Lifetime management of transit oil and gas pipelines in Central and Eastern European countries, development of a multimedia-based expert system - LIMATOG
- Optimisation of a welded spherical valve construction
- Databank of failure case studies
- Software for German FKM Guideline “Fracture Mechanics Proof of Strength for Engineering Components”
- German FKM Guideline “Fracture Mechanics Proof of Strength for Engineering Components II”
- Defect Assessment Software IWM VERB 7.0
- Mechanics and its application to Technology
- Activities of the European Pipeline Research Group (EPRG)

1.3 Survey Results

The original FITNET project proposal noted the results of surveys made at the end of the 1990's, IIW, CEN and the PLAN Network on use of Fitness-for-Service methods. The principal findings were:

- 50% of all Fitness-for-Service development activities are in the EU but with significantly lower emphasis in eastern member states.
- 92 organisations from 67 states worldwide would like to see Fitness-for-Service methods standardised.
- Out of 56 examples of uses of Fitness-for-Service procedures, the greatest is by research institutes and the power generation industries: The use of Fitness-for-Service by SMEs is still limited, despite the potential financial benefits.
- There is a large number of procedures in existence but many are 'in-house' and only have 1 or 2 users: Over 50% of respondents in one survey used mainly UK-derived methods.

J. Wintle [3] has reported on a more recent survey conducted by TWI in 2001 among its industrial members world wide. The main conclusions were:

- 53% use FFS assessment
- only 43% believe that the regulator/safety authorities accept FFS assessment
- 59% use published procedures (API 579 and BS7910 are those most frequently cited)
- Ranking of reasons for undertaking FFS was: determining residual life of damaged plant, ensuring safe operation beyond design life; down-rating damaged plant; demonstrating tolerance to defects within a safety case; extending inspection intervals and reducing duration of outage and shutdown

The ranking of frequency of type of equipment assessed was: general pressure vessels; process piping; shell and tube heat exchangers; transportation pipelines; storage tanks; fired heaters and boilers; active equipment (valves, pumps, compressors and turbines)

In October 2002 FITNET performed its own survey on "Current application and future requirements for European Fitness-for Service Technology" [4]. 68 replies were received, corresponding to an overall reply rate of 14%. The weight given to the results of the survey should bear in mind the restricted sample size. Concerning the profile of the respondents, engineering service organisations and research institutes constituted almost 48% of those replying, whereas the remaining 52% were split between industrial research, end-users and academic organisations. With respect to the size, most of the replies (61%) came from large organisations (more than 500 employees) whereas in terms of field of activity a good balance was obtained, with organisations covering the power generation, petrochemical, pipeline, offshore and process industries.

According to the replies received, the following conclusions can be drawn.

- Fitness-for-Service assessments are mainly conducted during service (re-rating, life assessment), by in-house engineers.
- Regarding the Fitness-for-Service procedures, the most popular are BS7910/PD6493, followed by R6, ASME and SINTAP, with a fairly large number of organisations relying on application-specific, in-house developed procedures. It also emerged that wide recognition and familiarity with a procedure are the most likely reasons for its choice, rather than technological considerations or acceptance by notified bodies. This underlines the task ahead

in establishing harmonised Fitness-for Service assessment procedures. Encouragingly, 90% of the respondents confirmed their strong interest in the development of a European Fitness-for-Service Code.

- The major difficulties encountered in applying Fitness-for-Service assessments were found to be the estimation of the residual stresses and of the applied loads/ loading history of the components. Material properties /thermal history i.e. ageing, were voted as almost equally challenging to these. The replies also confirmed that there is still need for improvement, probably not as urgent as the aforementioned issues, when it comes to NDE reliability and the presence of adequate rules for applying FFS procedures. However, even though that was the overall feeling, the level of difficulty identified in the survey for these different issues was found to depend somewhat on the size of the organisation replying. Large companies (> 500 staff) and medium-size organisations identified residual stresses as the most problematic area, whereas small sized firms were equally concerned about the material properties/thermal history and the availability of reliable and easy to apply NDE methods.
- As would be expected, almost two thirds of the respondents are using computerised systems to support FFS assessments, and mainly statistical fracture, plastic collapse and fatigue assessment. For finite element analysis software, some known commercial packages such as ANSYS predominate, whereas in the area of assessment/supporting software the 'CRACKWISE' program seems to be the most popular package. Nevertheless, there is a great range of products used and in many cases these are in-house developed modules.
- 81% of respondents agreed that there is a need for training on FFS procedures with the majority of the replies giving top priority to training for practical application of these procedures. Concerning technical content of training, the respondents seem to prefer general topics such as integrity and life assessment concepts or damage criteria, rather than more specific fields.. Online condition monitoring ranked lowest in the priority list for training items. A strong interest in prospective FITNET courses was registered. The most popular options were externally organised courses of several days duration but also training through software packages, taking advantage of new technologies and e-learning tools.
- Two thirds of the responses gave encouragement to the possible development of a professional qualification for competence in the application of FFS technology. For the other third against such an initiative, one factor may be the fear that it could become a legal requirement as opposed to simply an indication of professional quality.
- Most of the organisations indicated that their R&D activities related to FFS focus on issues such as fracture, fatigue and inspection techniques. Overall their future R&D priorities are to improve the materials data available (highest-ranking R&D priority theme for large companies, in particular) and then the assessment procedures. However, small and medium-sized firms feel that fracture assessment will also be in the near future the main challenging issue for their R&D departments. Large companies ranked as the lowest priority item the improvement of materials sampling whereas overall there was not such a strong interest in granting top priority to research for improving high temperature assessment procedures and probabilistic methods.
- Respondents identified verification cases, software tools and availability of general procedures as equally important tools for promoting FFS methods.

1.4 Recent Literature Reviews

With the increasing interest in FFS procedures, several major reviews have been undertaken over the last 3 years. The most notable of these is the nine-volume Comprehensive Structural Integrity [5] series, published by Elsevier in 2003. Several FITNET members were among the leading contributors to this publication. Its scope encompasses: fracture mechanics, fatigue, creep, materials, dynamics, environmental degradation, numerical methods, failure mechanisms and damage mechanics, interfacial fracture and nano-technology, structural analysis, surface behaviour and heart valves. Structures considered include: pressure vessels and piping, off-shore structures, gas installations and pipelines, chemical plants, aircraft, railways, bridges, plates and shells, electronic circuits, interfaces, nanotechnology, artificial organs, biomaterial prostheses, cast structures, mining etc. It does not, however, provide integrity assessment procedures as such. The following sections summarise the status of the different damage mechanism areas identified in the FITNET modular structure.

1.4.1 Fracture Mechanics Assessment Methods

a) Chapter 7.01 [6] of the above-mentioned Comprehensive Structural Integrity series provides an excellent overview of codes for failure assessment. It covers both the underlying philosophies as well as implementation in fitness-for-purpose standards such as R6, ETM, BS7910, API 579, RSE-M, etc. It also summarises the procedures applied in different industrial fields, including:

- Aeronautic and space industries
- Nuclear and fossil fuel power generation
- Chemical and petrochemical
- Pipelines
- Steel construction and offshore
- Others

b) Although now 3 years old, the Special Issue of the International Journal of Pressure Vessels and Piping on Flaw Assessment Methods, published in December 2000, still provides an excellent overview of the international state-of-the-art for procedures for general application. There were six papers concerning developments in Europe. The first of these covers the Structural Integrity Assessment Procedures for European Industry (SINTAP) procedure [7,8] produced by a European consortium involving nine countries. Since it effectively represents a synthesis of best practices, more details are given here. Its underlying principles 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;
- the choice of representation of results in terms of a failure assessment diagram (FAD) or crack driving force (CDF);
- specific methods incorporating the effect of weld strength mismatch;
- guidance on dealing with situations of low constraint and, for components containing fluids, leak before break analysis;
- compendia of solutions for SIFs, limit load solutions and weld residual stress profiles.

The procedure provides advice on the basis inputs and calculations needed. The aspects covered are tensile properties, fracture toughness data, flaw characterisation, and the treatment of primary and secondary stresses. While some of this information is standard, there are novel developments, which may be summarised as follows:

- Assessments have been made of tensile data so that, in the absence of detailed data, estimates of strain hardening properties, Lüders strain and yield to tensile strength ratios can be made from limited information.
- Statistical treatments of fracture toughness data have been developed that take account of the number of specimens regardless of failure mode. In the cleavage regime for ferritic steels, the so-called Master Curve approach has been further developed to provide improved estimates of lower bound fracture toughness. In the absence of toughness data, improved correlations are given to enable fracture toughness data to be estimated from Charpy impact energy.
- The flaw characterisation rules in the SINTAP procedure are essentially those in the British Standards document BS 7910 [9]. The SINTAP procedure, however, goes beyond this in providing guidance on the reliability of non-destructive examination techniques.
- The basic approach in the SINTAP procedure for treating primary and secondary stresses is that in R6 [10]. However, an alternative, new approach has been developed in which the effect of the secondary stresses is described by the factor V.
- New SIF factor solutions have been developed for defects in cylinders for complex primary or secondary stress fields.
- A large number of mismatch limit load solutions have been provided for plates and cylinders which leads to reduced conservatism compared to classical methods where mismatched welds are treated as being composed entirely of the lowest strength material.
- The compendium of weld residual stress profiles covers a range of geometries with surface and through-thickness residual stresses being given for longitudinal and transverse orientations. Residual stresses can be determined from knowledge of the material and weld heat input when these are known or more conservatively from bounding stress fields. Advice on the effects of post-weld heat treatment is also included.

Brickstad et al. [11] described procedures developed over a number of years for use in Sweden. Papers by Wiesner et al. [12] and Budden et al. [13] indicated the recent developments in the British Standards and R6 approaches[2]. Schwalbe and Zerbst [14] presented the Engineering Treatment Model which is a J- or COD-estimation scheme developed at GKSS. Faidy [15] presented the recently finalised RSE-M procedure developed specifically for nuclear power plant applications in France.

Developments in Japan[3] and China were covered in three papers. The first two of these, by Kobayashi et al. [16,17], addresses JSME developments. Li et al. [18] describe a Chinese procedure. These are new procedures that have both reviewed and made use of information in existing procedures and have also utilised results of new research to refine and extend existing advice.

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[2] BS 7910 and R6 have since been updated to include new developments such as those made for SINTAP.

[3] An update on some more recent developments in Japan is given by Japanese fitness-for-service code for nuclear power plants - summary of flaw evaluation procedures, Watanabe et al. [19], concerning a Japanese fitness-for-service code and handbook for nuclear power plant components.

The final paper from Anderson and Osage [20] describes the American Petroleum Institute fitness-for-service guide API 579. This comprehensive guide had just been released in 2000. It is particularly comprehensive, covering a wide range of flaws and damage mechanisms, including local metal loss, pitting corrosion, blisters, weld misalignment, and fire damage, the emphasis of [20] is on the assessment of crack-like flaws. The authors also stated their intention to convert API 579 into a joint API/ASME fitness-for-service guide. Osage provides an update on the development of API 579 in [21].

In his editorial R. Ainsworth noted that all of the procedures have common features. Many use failure assessment diagram (FAD) methods of the type introduced in R6. Others use the reference stress methods, which underpin modern FAD approaches, to develop estimates of crack driving forces. All the procedures require common inputs such as stress intensity factor and limit load (or reference stress) solutions. On the other hand there are also differences often driven by the need to develop rules for specific industrial applications.. Some of these are in basic inputs such as flaw characterisation rules and methods for treating secondary stresses. Others occur where some procedures have been extended to address issues such as weld strength mismatch or loss of crack tip constraint, for example.

c) B. Dogan made a survey of FFS procedures as part of the activities of the European PLAN network, and the results were published initially in 2001 [22] at the PLAN Conference. In all 28 different procedures were cited by the network members, although R6, R5, BS PD6493/6539 (now combined in BS7910) and ASME XI were the most widely used. His conclusions again drew attention to the many similarities between the fracture mechanics procedures, and recommended that emphasis be given simplifying the methodologies and to extending the applicability to a wider range of materials and geometries.

1.4.2 High Temperature Defect Assessment

The high temperature area (creep range) has been addressed by a number of European R&D initiatives over the last 20 years, with several major projects currently running, including HIDA [23], ECCC and Integrity (see R&D mapping). As noted in the recent review by Dogan [24], this has been mirrored by the development of mature assessment procedures for creep crack growth and creep-fatigue crack growth, in particular R5 and BS7910. The ASME code is predominant for life assessment in the absence of a detected or postulated defect. By far the main application area is the power generation industry, although the petrochemical sector also contributes. Dogan makes the following conclusions:

- There are many similarities between the codes/procedures since most have been developed as a result of experience gained from material specific programs. They have been further verified using the same material. Therefore, improvements to the codes can be made by simplification of the methodology so that it can be made more applicable to a wider range of materials and geometries.
- The use of fracture mechanics parameters should be considered further and the ranges of their applicability defined. However, the use of different techniques of evaluating and assessing a certain problem is also to be commented on, as it will act as sensitivity analysis producing lower and upper bounds of the predictions.
- When a defect is discovered or where a hypothetical defect is assumed the codes should be able to check the flaw sensitivity of a proposed design and it should be possible to benefit from the incubation period before the crack starts to grow. The consistent way of

critically comparing approaches is to apply the Codes to the same test cases. Future developments in defect assessment procedures will follow the route of simplified and unified procedures for components operating at low and high temperatures.

In terms of future developments for in-service applications of high temperature FFS, the Integrity/HIDA-III conference held in September 2002 drew attention to the following issues associated with repair welds:

- The deliverables of FITNET should not merely constitute an archive of current procedures, there must be an emphasis on whatever methods/varieties serve better the operating opportunities/challenges created through in vivo data collection.
- In the future FFS procedures will be needed for handling both existing and new weld materials and weld methodologies, i.e. plant "regimes" that today may not be well-defined.
- Fully re-furbished overlay welded components are prime candidates for FITNET case studies, given that relevant and sufficient data are available.
- Knowledge maintenance should be a theme for the "training" aspects of the FITNET programme.
- There is a need to address how advanced inspection (e.g. TOFD), replication and innovative techniques such as ultrasound laminography will be handled in FITNET.
- Surface flaws are sometimes not the prime issue for predicting the initiation phase of long-term creep cracking
- Emphasis needs to be put on high quality materials data

1.4.3 Metal loss, corrosion

For pipeline applications, the Pipeline Defect Assessment Manual (PDAM) provides guidance on the assessment of corrosion, gouges, plain dents, kinked dents, smooth dents on welds, smooth dents with gouges, manufacturing defects in the pipe body, girth weld defects, seam weld defects, cracking environmental cracking. PDAM is the result of a joint industry project sponsored by fifteen international oil and gas companies. The assessment of corrosion and of dents is described in two recent publications by the developers of PDAM [25,26].

2 INFO/GUIDANCE ON ASSESSMENT INPUT

2.1 Flaw and/or Inspection Information

The defect assessment procedure may be applied to components containing planar defects, including cracking or lack of fusion. It may be applied to defects that are discovered during pre-service or in-service inspections. The objective is to decide whether a defect is innocuous and will never affect the integrity of the structure, whether remedial action can be deferred until some time in the future or whether repairs are needed immediately. The procedure may also be applied at the design stage to hypothetical defects, in order to set inspection sensitivity or to check that a proposed component is tolerant to defects.

Defects are generally of irregular shape. The maximum depth and maximum length are generally used. Methods to determine the size and the circumscribing shape, such as a rectangle or ellipse, are available in BS 7910 and R6, for example, and could be implemented in the FITNET procedure. BS7910 and R6 also provide methods for characterising and assessing the interaction of multiple defects. In the event of ligament failure re-characterisation may be necessary.

An elliptical defect, inscribed within a rectangle, is often used. In BS7910, the length is defined as $2l$ and the depth as $2a$, but the depth of a semi-elliptical surface breaking defect is taken as a.

Where there is doubt about the accuracy of the size of defect established by the inspection procedure, it may be necessary to assume a larger defect to ensure a safe assessment. Upper bound sizes for defects should generally be used.

Where the plane of the defect is not aligned with a plane of principal stress further consideration is needed. Current codes place rigid restrictions in such cases and suggest that specialist advice should be sought.

FITNET has launched a dedicated task group on NDE performance. A document entitled “Guidelines to bridge ECA requirements and NDE possibilities” has been released for the 3rd FITNET progress meeting.

2.2 Stresses, Loads, Environment

The service loads, possible presence of residual stresses and service temperatures for the component should be established for each operating condition. The previous history of the plant can usually be obtained from operating records. At the design stage it should be stipulated that these records should be kept. Where service stresses and service temperatures depend on plant output, the previous history should be broken down into a series of blocks, during which the stress and temperature are sensibly constant.

In addition to establishing the total time at each of the steady operating conditions, any events likely to contribute to fatigue damage must also be taken into account. Where vibration or thermal fluctuations occur during periods of nominally constant load operation, an estimate of the frequency and magnitude of the fluctuations is required. Where transient thermal or mechanical loads occur at start up or shut down or with change in plant output, the number of load cycles and their magnitude must be estimated.

The relevant stresses to be used in the assessment should be those that would exist in the local region of the defect if the body were un-cracked. They should not include stress intensification effects due to the defect itself, as the Procedure naturally takes these into account.

It is sometimes necessary to separate the stresses into different categories. This can follow the principles of the ASME Boiler and Pressure Vessel Code, BS 5500, R6, A16 or BS7910. However care is needed in dealing with secondary and peak stresses. All stresses which are induced by internal pressure and external loads must be categorised as primary. For peak stresses, it is necessary to distinguish between those due to internal pressure and external load, and those brought about by secondary stresses resulting from thermal loading or residual stresses in welds.

In carrying out the stress categorisation, it is important to take into account any elastic follow up due to the spring action of adjacent parts of the structure. Unless it can be otherwise demonstrated, long range thermal and residual stresses must be categorised as primary.

Two values of stress intensity factor are needed for fracture and creep assessments. The stress intensity factor K_I^p is calculated using the primary stresses. The stress intensity factor $K_I^{(p+s)}$ is calculated using the sum of the primary and secondary stresses. Local stresses arising from all causes are added if the crack tip is situated in the peak stress region.

Stresses may be presented and categorised in a linearised format as in BS 7910. Many of the difficulties inherent in stress categorisation and in linearisation can be avoided for more complex structures if a detailed finite element analysis is performed to calculate the stresses in the vicinity of the defect. Stress intensity factors can then be evaluated using a weight function method.

FITNET has launched dedicated tasks to provide guidance on stress analysis and to update the existing compendia on K solutions and on weld residual stresses.

2.3 Materials Properties

The basic materials data required for an assessment comprise the following, which must be in the relevant range of stresses and temperatures taking into account the material condition (e.g. new or damaged due to service condition). Where creep, fatigue or corrosion can be excluded then the requirements may be reduced.

- Yield stress/0.2% proof stress
- Creep strain versus time curves
- Stress to rupture versus time to rupture curves
- Ultimate tensile stress
- Fatigue threshold
- Fatigue endurance data
- Fatigue crack propagation rates
- Stress corrosion cracking rates

- Fracture toughness properties

Allowance needs to be made for any deterioration (if any), which may occur during service, due to ageing and environmental effects. Allowance should also be made for any reduction in fracture toughness and any increase in creep, corrosion and fatigue crack propagation rates, which may occur in material, which has suffered significant bulk creep damage.

It is preferable to use data, which are derived from the material actually used in the component. Often these are not available. The procedure should provide the information on the more commonly used materials. It is important to undertake a sensitivity analysis, when using the data of the parent material, to allow for the possible presence of poorer material in the component. In making a preliminary assessment, "worst case" material data can be used in the analysis; for example, upper bound data for fatigue crack growth rate and lower bound data for fracture toughness and tensile properties. However, care needs to be taken to guard against excessive pessimism. When the "worst case" assumption does not provide satisfactory margins, a more thorough investigation may need to be carried out.

Of relevance to the determination of creep properties, it is worth noting that from 1997 to 2001 the ECCC was part supported by the EC's Thematic Network programme via the WELD-CREEP project. Recommendations were developed for the generation and assessment of creep test data for weldments, and working groups were established to collate and assess test data for ferritic and austenitic steel weldments, dissimilar metal joints, post exposed (ex-service) materials, high temperature bolting steels/alloys and nickel-base alloys for gas turbine applications. The current activity is EC-supported through the ADVANCED-CREEP Thematic Network project and is focussing on developing guidelines for the assessment of creep strain, creep ductility, stress relaxation and creep crack initiation test data determined from and for application to uniaxial and multiaxial geometries (including components). Technical groups are developing common methodologies relating to the properties listed above for new low and high alloy ferritic steels, austenitic steels and nickel base alloys in virgin, welded and service exposed conditions. Concerning FFS applications, inside WG1.2 a survey on miniature test methods has been conducted, suitable for materials sampled from components, and a comparison of creep crack initiation assessment methods (namely TDFAD in R5 and the German 2-Criterion Approach) is being performed with the results being reported to FITNET.

Also of relevance to creep properties is the output from the LICON project which developed an advanced damage enhancement methodology for predicting the long-term creep-rupture behaviour of new generation steels (such as P91, P92, E911), and their welded joints, from the results of relatively short duration multi-axial specimen tests. The methodology relies on the acceleration of creep damage development under multi-axial loading conditions to enable extended extrapolation of rupture strength into the long time creep rupture regime. The approach provides similarity with the loading conditions experienced in real components and enables a more accurate evaluation of the future in-service performance of welded components made of new generation steels for which no long-term service experience exists.

For the fatigue crack growth properties, the WG2 group has launched a task on assembly of a fatigue database.

3 ASSESSMENT PROCEDURES

3.1 Fracture

The fracture assessment procedure developed within FITNET will be based on that derived by the SINTAP project and recent amendments made to other procedures such as R6-Rev.4, BS 7910 and API 579. Those aspects of the SINTAP procedure to be improved are:

- Identified errors in the existing document and compendia are to be corrected and the procedure published in a journal so that it can be used and referenced openly. The aim of this is to increase the use of the procedure so that a wider range of suggestions for improvement is available to the FITNET TN community.

- Test standards are not incorporated for ‘standard’ tests, and will not be in FITNET. However where standards are not available yet, e.g. .for impact loading or mixed mode, this will be addressed by providing state-of-the-art documents / references for the informative guidance of the users.

- The statistical and probabilistic aspects incorporated in the SINTAP procedure need to be improved because of the growing awareness and acceptability of determining the fracture risk of a structure or component. In addition the limitations / accuracy of deriving toughness values from the Master Curve will be re-examined in view of this requirement.

- Additional guidance on individual limit load determination will be given and results from other projects, such as the recently completed EC funded LISA project, will be added to the existing compendium if they are relevant. Also both K and limit load solutions will be provided for a number of special geometries such as biaxially loaded plates, stiffened panels (e.g welded by laser beam) and clad materials,

- The residual stress profile compendium will be extended to cover modern welding methods including laser, friction stir and electron beam welding. The K solutions and residual stress profiles in the current SINTAP compendium are given as polynomial expressions, but of different orders. The possibility of re-formatting these to simplify their use will be examined.

- Analysis of the practically relevant situation of shallow surface cracks will be studied and this may be treated as a particular aspect of the variation in local constraint or may be treated as a special case in view of the practical importance of this situation.

- The defect interaction rules will be updated and their relevance for different fracture modes examined.

The following topics are subject areas, which were not covered by SINTAP:

- The particular requirements for analysis under high loading rate applications will be studied. BS 6729:1987 is one existing standard for testing and a new section is being developed within the general toughness testing standard BS 7448:1991. However the use of these data in analyses is not currently covered and there are several problem areas associated with transferring between loading rate, strain and stress intensity factor rate.

- Similarly with crack arrest, this is a wide subject area which covers aspects such as dynamic enhancement of crack tip loading, regions of varying fracture resistance, varying stress-strain field at crack stoppers, brittle zones etc. There are currently many approaches, some old, some new and different industries have their own favourites / approaches. The whole subject area will be assessed in order to determine what guidance can be given within FITNET FFS procedure.

- Mixed mode / biaxial loading is a practical situation and some guidance is given in some current standards but further discussion is needed to ensure that the guidance is both relevant and incorporates all current knowledge. Similarly thin walled structures, both steel and aluminium (particularly with strength undermatched laser and friction stir welded components), need to be considered and an analysis methodology determined.

To support the development of guidance material for these and other aspects, WG1 has formed sub-groups on:

- Crack arrest
- Mixed Mode
- Master Curve
- Limit Load
- Defect Interaction

3.2 Fatigue

In the proposed FITNET-Fatigue procedure the three major domains have been considered: crack initiation, short crack growth, and long crack growth. It will also address other industrial approaches in order to take into account the endurance S-N concept, the stress concentration concept (KT), and multi-axial loading modes.

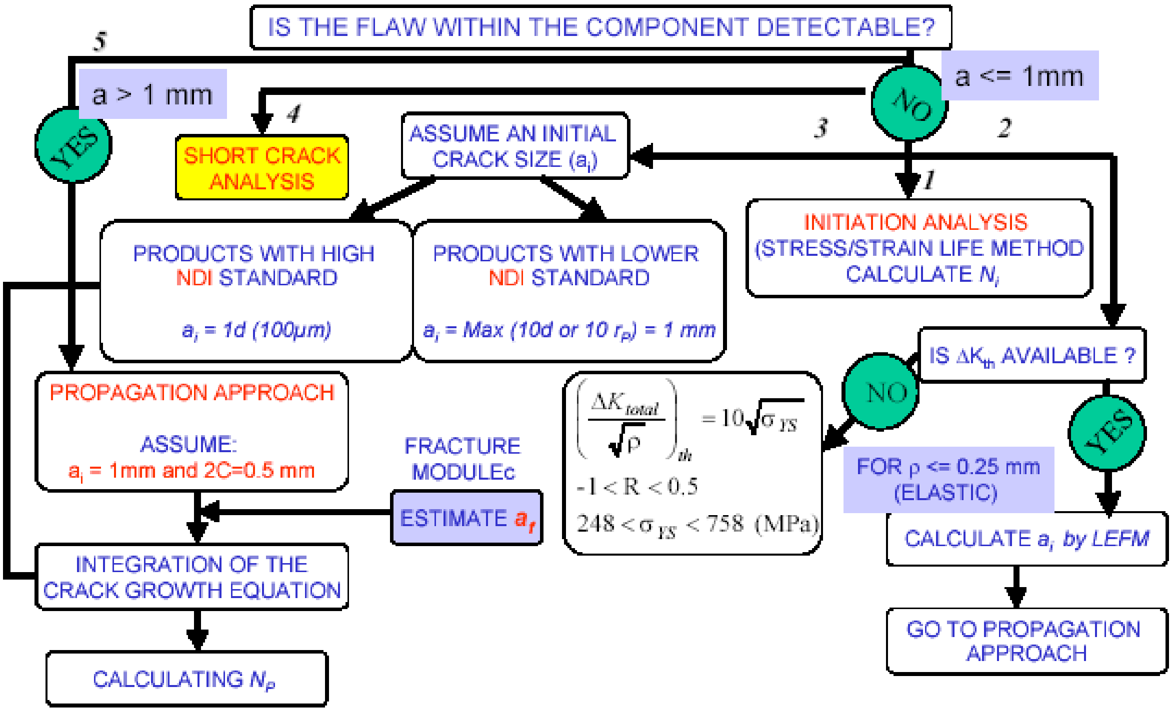

Fig. 3 Overall fatigue evaluation scheme proposed in February 2003.

The proposed procedure (Fig. 3) foresees 5 separate assessment routes. Routes 1 to 4 cover different approaches to the case that no flaw/defect is detected on the component. Route 5 deals with the propagation of a detected flaw.

No detectable flaw

If no flaw is detected, the procedure provides 4 different options for proceeding with the analysis.

Route 1) No detectable flaw – initiation analysis: An assessment is made of the crack initiation life, based on local stress or strain ranges in combination with fatigue data for uncracked specimens or components.

Route 2) No detectable flaw – postulated defect based on the threshold stress intensity factor: if the threshold stress intensity factor is known for the material or weld in question, a critical defect size can be calculated via LEFM. Based on this, the crack propagation analysis (Route 5) is used to determine the extent of growth or the component life.

Route 3) No detectable flaw – postulated defect based on statistics/experience with a component or weld type - see [27, 28] for examples.

Route 4) No detectable flaw – short crack growth analysis: procedure proposed by M. Vormwald

Detected Flaw/Defect

Route 5) – Detected Flaw: This route covers the assessment of a crack-like defect, either as detected by NDE or a postulated defect e.g. from consideration of the quality of the fabrication technique and quality control (see Route 3).

The selected baseline fatigue crack growth equation is that originally proposed by Forman & Mettu [29] and subsequently used in the NASGRO software [30]. 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. This equation is as follows:

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

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 of stress intensity factor range.

3.2.1 Fatigue Materials Database

The following shows the sources of fatigue data already identified. These will be supplemented by the collation of data being made as a distinct WG2 task. The representation of the data in a format compatible with the above NASGRO fatigue crack growth function needs also to be considered.

1) NASGRO Database
2) Available experimental data
3) D. Taylor, A Compendium Of Fatigue Thresholds And Growth Rates, EMAS Publication, 1985.
4) Data provided in BS 7910
5) Data provided in ASME Section XI
6) A. Hobbacher, Recommendations pour la conception en fatigue des assemblages et des composants soudés,, IIW Document- XIII-1539-96/XV-845-96
7) Determination Of The Threshold Value According To Barsom And Rolfe.
8) B. E., Boardman, "Crack Initiation Fatigue Data, Analysis, Trends And Estimation; Proceedings of the SAE Fatigue Conference, P-109, 1982, 59-73.
9) Lawrence, V. B. and Forman, R.G., Structures and Applications of NASA Fracture Mechanics database, Computerisation of Networking of Materials, 3rd volume, ASTM STP 1140, Philadelphia, 1992.
10) Hudson, M.C. and Seward, S.K., Compendium of Sources of Fracture Toughness and Fatigue crack growth data for metallic alloys, International J. of Fracture, Vol. 14, 1978, Pp. R151-R184 .
11) Hudson, M.C. and Seward, S.K., Compendium of Sources of Fracture Toughness and Fatigue crack growth data for metallic alloys, International J. of Fracture, Vol. 20, 1982, Pp. R59-R117.

3.3 Creep

This review outlines the requirements for a remaining life assessment of components containing cracks at elevated temperatures. It is also applicable to initial design for analysing the behaviour of postulated defects.

Information is needed in a high temperature procedure about loading conditions under normal and abnormal operating conditions and methods for characterising defects. These aspects have been covered in Sections 2.1 and 2.2 and are only briefly discussed. More detailed attention is given to the elevated temperature crack growth calculations which make use of limit analysis methods and fracture mechanics concepts. Several levels of complexity are discussed depending on the criticality of the problem and the materials properties data available. Approximations are presented when only some data are available. Various means of analysis and detailed advice are available so that procedures can be applied irrespective of the amount of data available. The required level of safety factors used will, however, need to be determined from available data and the extent of its scatter.

The following is based on information in a number of existing procedures (including R5 and BS7910, see [24]) and recent European projects (including HIDA [23]). The inclusion of probabilistic methods to indicate confidence limits in design and life assessment is also described. Where this is not possible sensitivity analyses should be performed.

3.3.1 General considerations in a procedure

A number of points need to be considered in order to assess the results of applying a high temperature assessment procedure or specifying factors of safety. These are

- the level of safety that is attributed to the structure
- the availability, the amount and the extent of scatter of relevant data
- the consideration of unexpected loads during operation
- residual stresses that may exist due to welding and loading processes.
- the ability or otherwise to perform NDT after fabrication and in-service inspection
- the degradation or otherwise of the material and the available properties for the degraded material
- advice and statistical data available on the expected failure rates of the component with respect to the suggested safety factors

The existing procedures do not suggest general factors of safety to be applied to life predictions due to crack initiation, growth and final failure. The decision about this is left to the assessor or deduced from advice in the documents. The value chosen will depend on the degree of pessimism introduced into the input data and on the results of sensitivity analyses. The introduction of sensitivity analysis and probabilistic methods in the assessment procedures assist the user in determining remaining lifetimes in the operating structures.

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3.3.2 Cracking behaviour at high temperatures

Under high temperature operating conditions creep or fatigue may be the primary mechanism in initiating and growing a crack. Crack propagation can continue until structural failure takes place. Local plastic damage or creep damage may build up ahead of a crack due to thermal or cyclic loading. Alternatively the net section may fail through a short-term phenomenon - plastic collapse if the material is ductile or fast fracture if the material is brittle. Various calculations such as the crack opening displacement at initiation and the collapse loads may be needed.

Following the initial loading of a component, a crack may blunt and, in these circumstances, there will be an incubation period before a further short crack forms and propagation starts. Where blunting does not occur, crack propagation may be assumed to start immediately on loading. The crack grows by a fracture mechanics controlled mechanism. Where new plant is under consideration, it may be possible to benefit from the incubation period, starting the crack growth calculations at the end of this period.

When a defect is discovered after a component has been in service, the conservative assumption should be made that the crack initiated earlier in life, unless there is strong evidence to the contrary. In this case it is also current practice to discount the time to crack initiation.

3.3.3 Application of the procedure

The available procedures are implemented in a series of well-defined steps, often shown as flow charts. The individual steps can refer to

- a component before it enters service, containing either a postulated defect or one discovered during inspection,
- a defect, which has been discovered after a component has been in service for a period of time.

The flow charts contain variations and choices available to the user in accordance with their level of expertise and the level of information available on the component under consideration. Furthermore the documents emphasise the importance of the need for sensitivity and/or probabilistic analyses in performing the assessment task.

Some typical steps in an assessment are listed here.

STEP 1: Establish cause of cracking

Prior to performing calculations, an initial investigation should be carried out to identify the most likely cause of cracking. For postulated defects the minimum crack size should be established taking into account the NDT capability. This may include a combination of non-destructive testing, visual examination and metallurgical examination. If possible, a dimensional check should be carried out on the component to establish if there has been any significant distortion during fabrication for remaining life assessment during its operational life.

Significant plasticity away from the crack tip, particularly if accompanied by distortion of the component, is often an indication that there has been local overloading due to primary or secondary stresses, or some form of over-stressing and that the material is nearing the end of its safe working life. Any crack propagation and failure calculations which are carried out must take into account the properties (both static and fatigue) of the material in its damaged state.

If it is assumed that overheating in the fabrication and operational stage, over-stressing and environmental effects are absent, crack growth in the structure is most likely to be associated with a pre-existing defect which has not been detected by pre-service inspection or with a crack which has been initiated by some form of fatigue loading. Pre-existing defects often occur in welds and certain precautions are described, particularly in R5, before applying the assessment procedure.

STEP 2: Define previous plant history, future operational requirements and relevant stresses

The loads, possible presence of residual stresses and service temperatures for the component should be established for each operating condition. This has been discussed in Section 2.2 and is not discussed further here.

STEP 3: Characterise defects

Defects are generally characterised as a rectangle or ellipse, as discussed in Section 2.1. For crack growth assessments, it is necessary to define not only the initial flaw but also the flaw including the crack growth. This may involve a change in aspect ratio.

STEP 4: Establish material properties

The basic materials data required for assessments are listed in Section 2.3. More information on the specific data used in the high temperature assessment methods is given in the appropriate calculation steps below.

STEP 5: Check the fatigue component

For assessments at high temperature, it is necessary to check whether fatigue loading can be neglected. The methods of BS 7910 could be used to evaluate fatigue crack propagation but detailed advice is being developed within FITNET as discussed in Section 3.2. The value of ΔK, the stress intensity factor range, is calculated for such purposes.

STEP 6: Perform defect assessment

The principal steps in a defect assessment could be as follows:

- determine margin against fast fracture, assuming an initial defect size or a measured defect dimension, using various levels of the Failure Assessment Diagram (FAD), by the elastic-plastic methods proposed in R6 or BS7910 (see Section 3.1).
- evaluate fatigue threshold and crack propagation rates and estimate the amount of fatigue crack growth at intervals during the future life of a component (see Section 3.2).

- determine the creep rupture life of the component, using initial defect dimensions.
- evaluate crack propagation rates and estimate the amount of creep crack growth at intervals during the future life of a component.
- check that steady creep conditions apply at the crack tip; if not, revise crack growth estimates.
- determine crack dimensions at the end of each interval.
- repeat calculation of margin against fast fracture, by the elastic-plastic methods using the new crack dimensions at the end of each interval.
- if the end-of-life margin against fast fracture is satisfactory, no remedial action is needed
- if the end-of-life margin against fast fracture is unsatisfactory, the intermediate calculations can be used to establish the time at which this margin ceases to be acceptable and to define when remedial action is necessary

Methods of performing the calculations are given in detail in the existing procedures and a summary is given here. Many of the procedures have been developed from the reference stress methods in R5 and, therefore, have strong similarities. It should be noted that it is often possible to demonstrate that the component has adequate future life by making conservative assumptions about stress level, temperatures and material properties. Where such calculations do not give satisfactory margins, a more thorough investigation should be performed.

STEP 7: Define Fatigue Crack Propagation Rates

The fatigue crack propagation rate is generally defined by the equation

$$(da/dN)_f = C(\Delta K)^m \tag{1}$$

where C and m are material constants, $(da/dN)_f$ is the crack extension per cycle due to fatigue and ΔK is the range of stress intensity factor arising from the cyclic loading. Mean, upper bound and lower bounds to crack propagation data for the relevant steels used in the component are available in various sources and could be collated in the FITNET procedure. Where information is not available in the literature for a specific temperature range and specific steel of interest, additional tests may be needed.

Equation (1) is written for the rate of growth in the depth a of the crack. This may differ from the rate of growth in the length ℓ of the crack, defined by a similar equation, because of differences in ΔK at the two positions. Therefore, the change in aspect ratio (a/ℓ) is also considered. Throughout this section, equations are written only for growth in the terms of a for brevity. Detailed discussion about fatigue is given in Section 3.2.

STEP 8: Creep Crack Propagation Rate

Creep crack propagation data are usually collected in terms of the parameter C* in the form

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

where A and q are constants. Both mean and upper bound values are presented in BS7910 for some materials. Use of upper bound data introduces conservatism into the estimates of remaining life.

For materials not covered by the procedure, two methods are available to estimate crack propagation rates, although the results may not be upper bound.

Where the creep rupture ductility of the material is known, a guide to crack propagation rates can be obtained by taking q as 0.85 and estimating A in equation (2) from

$$A = 0.003/\varepsilon_f \qquad (3)$$

for $\dot{a}_c$ in m/h, where ε_f is the creep rupture ductility of the material in a uniaxial test at a reference stress σ_{ref} defined in equation (7) below (note that the fractional strain is used, not the percentage strain). Sources of creep rupture ductilities for certain steels are given in the existing procedures. Where the creep rupture ductility is not known, a guide to propagation rates can be obtained from the equation

$$\dot{a}_c = 0.005\left[(K_a^p)^2/(\sigma_{ref}\, t_{R(ref)})\right]^{0.85} \qquad (4)$$

where K_a^p is the elastically calculated stress intensity factor at maximum depth for a crack characterised by the dimensions *a* and ℓ, σ_{ref} is the reference stress; and $t_{R(ref)}$ is the time to rupture at the reference stress. A similar calculation should be made for growth in the *l* direction using K_l^p.

The driving force C^* in eqn (2) is calculated from

$$C^* = \sigma_0 \dot{\varepsilon}_0 b h_1 (F/F_0)^{n+1} \qquad (5)$$

for a material with creep strain rate described by $\dot{\varepsilon}_c = \dot{\varepsilon}_0 (\sigma/\sigma_0)^n$ with F being load, F_0 being a normalising load proportional to σ_0 , b a characterisation dimension and h_1 a non-dimensional function of crack size determined from FE analysis. More simply and for more general creep strain laws, C^* may be estimated from

$$C^* = \sigma_{ref} \dot{\varepsilon}_{ref} (K^p/\sigma_{ref})^2 \qquad (6)$$

Here σ_{ref} is the reference stress

$$\sigma_{ref} = F\sigma_y / F_L(a, \ell; \sigma_y) \qquad (7)$$

and $\dot{\varepsilon}_{ref}$ is the corresponding creep strain rate from uniaxial deformation data. The formulation automatically covers primary creep. F_L is the limit load for a material with yield stress σ_y allowing for the presence of the crack.

STEP 9: Incubation period

Where incubation time data are available from test specimens, the incubation time for the component can be correlated with C* provided both specimen and component are in the secondary stage of creep. Then, the incubation time t_I can be deduced from

$$\frac{t_{Icomp}}{t_{Ispec}} = \left(\frac{C^*_{spec}}{C^*_{comp}}\right)^{n/(n+1)} \qquad (8)$$

where subscripts comp and spec refer to the component and the specimen respectively.

Where data are not available for the material used in the component, or secondary creep is not applicable, the incubation period can be estimated from the equations given below. First, if secondary creep holds but only rupture data are available, an estimate of incubation time is given in BS7910 as

$$t_I = 0.0025\left(\frac{\sigma_{ref}\, t_{R(ref)}}{(K_a^p)^2}\right)^{0.85} \qquad (9)$$

Where experimental data are available and the crack opening displacement at initiation of creep crack growth, δ_I is known, then provided that the creep strain versus time curve for the material, at the relevant stress and temperature, can be represented by an equation of the form

$$\varepsilon_c = D\sigma^n t^p \qquad (10)$$

then t_I can be obtained from the equation

$$t_I = \left[\frac{(\delta_I / R')^{n/(n+1)} - \sigma_{ref}/E}{D\sigma_{ref}^n}\right]^{1/p} \qquad (11)$$

where $R' = (K^p/\sigma_{ref})^2$. More general equations are given in R5 when creep strain data do not follow equation (10).

STEP 10: Assessment To Include Creep-Fatigue Loading

Extensive work suggests that linear summation of the time dependent creep and the time independent fatigue portions of crack growth adequately describes high temperature failure under cyclic loading, in most cases. Cases where the cyclic loading perturbs the stresses applicable during the creep part of a cycle or where there is a significant creep-fatigue interaction are discussed in a recent revision to R5 (Issue 3 of that document). These cases are being discussed within WG3 of the FITNET network in order to include up-to-date advice in the FITNET procedure.

Provided linear summation holds, the crack growth rate due to creep is calculated, as in equation (2), from constant load (or constant displacement) creep crack growth tests. The crack extension due to creep in a single fatigue cycle, $(da/dN)_c$, is thus

$$(da/dN)_c = \dot{a}_c/(3600f) \qquad (12)$$

where f is the frequency. The crack growth per cycle due to fatigue is calculated from equation (1). The predictions made using these equations may be over conservative where the stresses at one end of the cycle are compressive. If the margins against failure are insufficient, the fatigue crack growth calculations can be refined using the method given in R5 to allow for crack closure. The corrections for compressive stress given in the fatigue section of BS7910 should not be used, as these are inapplicable when creep occurs. Total crack growth per cycle, (da/dN), is given by

$$da/dN = (da/dN)_c + (da/dN)_f \qquad (13)$$

This linear summation combines creep and fatigue components.

Special considerations for welds

Cracks in welds are a complication in the analysis and need special treatment. In most cases the measurement of residual stresses is not a practical solution and estimates of stress level may need to be considered. In addition, properties of the heat affected zone and the weld metal usually differ from those of the parent material and local residual stress may need to be taken into account. However the interaction between these regions are not always clear or well documented. Therefore tests may be needed to deal with weld properties.

Many of the defects found in high temperature plant are associated with weldments. These defects may arise during fabrication, post-weld heat treatment or in service. Furthermore, since weldments contain wide metallurgical and mechanical property variations, the defects are often located in non-homogeneous material, which has a significant effect on crack growth.

It should be possible to assess defects in austenitic and ferritic weldments, including Type IV cracking using the methods described above with some modifications that are discussed in R5 and involve application of a factor on reference stress. This is similar to the treatment of mismatch in the SINTAP procedure where a modified limit load is used to define the load parameter L_r. However, dissimilar metal weldments, where cracking occurs at the interface between the austenitic weld metal and ferritic parent metal, need special consideration as also discussed in R5.

The properties of the weld metal and the heat affected zone are usually considerably different from those of the parent material, in terms of creep strength, crack propagation rate and fracture toughness. It is important to identify the part of the weld in which the crack is situated and then to use properties appropriate to that location.

Residual stresses in the vicinity of a weld can have a significant influence on crack propagation and failure and must be considered in the assessment. Typical residual stress distributions in some commonly used types of weld are provided in R6, BS7910 and the SINTAP procedure These residual stress compendia are for as-welded residual stresses but at high temperatures, or components subjected to a post-weld heat-treatment, these will often be over-conservative due to relaxation of the residual stress.

Where it can be confirmed that the component has been subjected to a post weld heat treatment, which reduces the residual stresses to a negligible level, they can be ignored in the assessment. It may also be possible to take credit for a reduction in residual stress when a component has been in service for a sufficiently long period at a sufficiently high temperature.

Remedial Action

If failure by excessive crack growth is indicated within the required service life, or if the sensitivity analysis gives unacceptable results, then remedial action is required, such as repair of the component or removal of the defect.

Alternatively, a change in service parameters (load, temperature, desired service life) may be made and the assessment procedure repeated either to demonstrate acceptance or to estimate at what time repair will be necessary. Finally, it may be possible to obtain data on the material actually used in the component to remove pessimism in the assessment resulting from the use of bounding data. The sensitivity analysis is particularly useful for indicating which material properties may significantly influence the assessment. For example, if remedial action is required because the desired service life exceeds the rupture life calculated, there is no point in generating creep crack growth in an attempt to improve the assessment.

3.3.4 Sensitivity Analysis and Life assessment using probabilistic methods

Assuming the final defect size gives an acceptable end-of-life safety margin, a sensitivity analysis should be recommended. BS7910, R6 and R5, describe the principles. The sensitivity analysis should consider the effects of different assumptions (e.g. stress levels, material properties and defect size). The UK codes stress the fact that a sensitivity analysis is an important factor in the life assessment procedure since only then should the user finds confidence in the calculations that have been performed.

Probabilistic aspects of defect assessment are relatively new and as yet are not fully adopted in defect assessment codes. The plans for guidance documents on this aspect are considered further in Section 4 below.

3.3.5 Other Considerations and Ongoing Activities

The French A16 procedure uses the RCC-MR concept of evaluating damage at a distance d from the crack tip. The procedure for the initiation and growth of short cracks considers the stress state at a distance d ahead of a notch-like defect. In its simplest form, this is given by $\Delta K/(2\pi d)^{1/2}$, where ΔK is the range of stress intensity factor. For Type 316 stainless steel d is taken as 50μm, so for ΔK equal to 5 MPam$^{1/2}$, for example, the stress range is about 280 MPa. The so-called σ_d approach has also now been included in R5 as an alternative method to the C* route described in Section 3.3.4 and may also be suitable for inclusion as an alternative approach in the FITNET procedure.

For the growth of short cracks, R5 includes a procedure for calculating creep-fatigue growth within the surface cyclic plastic zone. The fatigue growth is given by

$$\frac{da}{dN} = Ba^{Q} \qquad (14)$$

where Q is a constant and B is a function of total strain range. This short crack growth law has a degree of built-in pessimism by assuming surface (maximum) values of strain range whereas in practice the strain field may decay with distance into the structure, as with residual thermal fields. Creep-fatigue crack growth is obtained by increasing the rate given by equation (14) by a factor that depends on surface creep damage. The calculations are continued until the crack has extended to the extent of the cyclic plastic zone and then growth reverts to the fracture mechanics based approach of Section 3.3.4.

In Germany, a two-criteria diagram approach to creep crack incubation has been developed over a number of years with particular attention to ferritic steels at long times. In the U.K., a similar time-dependent failure assessment diagram approach has been developed and incorporated in R5 as an alternative approach to that in Section 3.3.4. These two approaches are being compared within the Advanced Creep Network and the developments are being monitored within FITNET. The methods are not only applicable to creep assessments but may also be useful for defining conditions for which the creep parts of the FITNET procedure need not be used (e.g. initiation of creep crack growth does not occur in the service life). It is also possible that the methods may provide a smooth transition in methodology with increasing temperature rather than a step change at the temperature for which creep needs to be considered.

3.4 Metal Loss and Environmentally Assisted Cracking

The objective of this module is to provide a structured approach to corrosion damage assessment for pressure containing equipment, including pressure vessels (incl. Nozzles), process pipework and pipelines. This will be primarily based on the Working handbooks used in the Shell Group (as described in the WG4 Presentation at the 2nd FITNET meeting in September 2002), together with relevant background documents and case studies. The background to these is summarised as follows:

- Handbook solutions are based on tested procedures which have been in use for many years.
- API 579 for failure of cylinders and end caps
- R6 and BS7910 for circumferential failures due to axial loads
- EPERC strain based design by analysis criteria were used to develop data for the nozzle models
- 4-point failure criteria used for the nozzles
    - Rupture of the vessel shell either longitudinal or circumferential
    - Shear of the nozzle from the vessel by external nozzle loads
    - Longitudinal failure of the nozzle due to internal pressure
    - Circumferential failure of the nozzle due to external nozzle loads

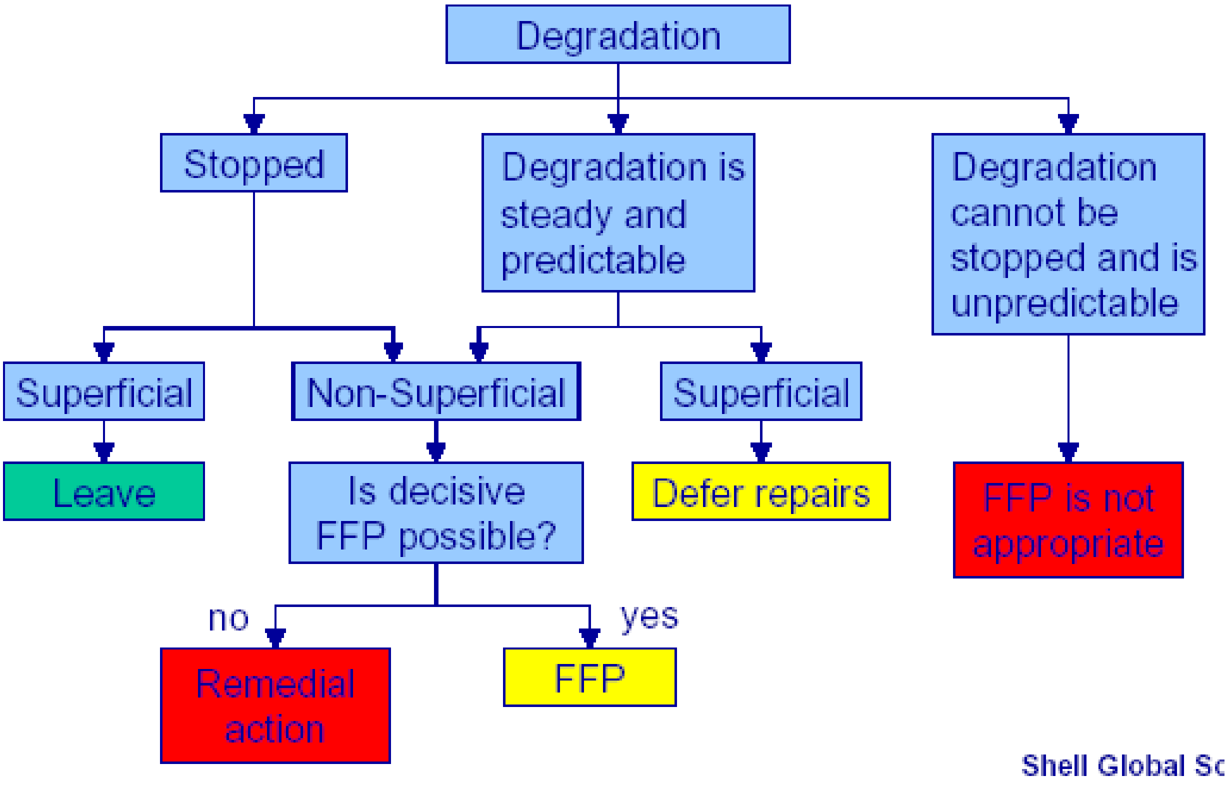
They can be used without restriction, based on the following criteria

- General principle is that all equipment should be able to survive a hydrotest similar to the shop test.
- Hydrotest pressure based on the allowable stress and the full wall thickness
- Maximum allowable stresses for design temperature
- General corrosion losses should not produce general yield of the vessel
- A minimum safety factor of 1.55 for a vessels regardless of design code

The following section outlines a proposed approach for addressing corrosion damage.

a) Pre-FFS Assessment

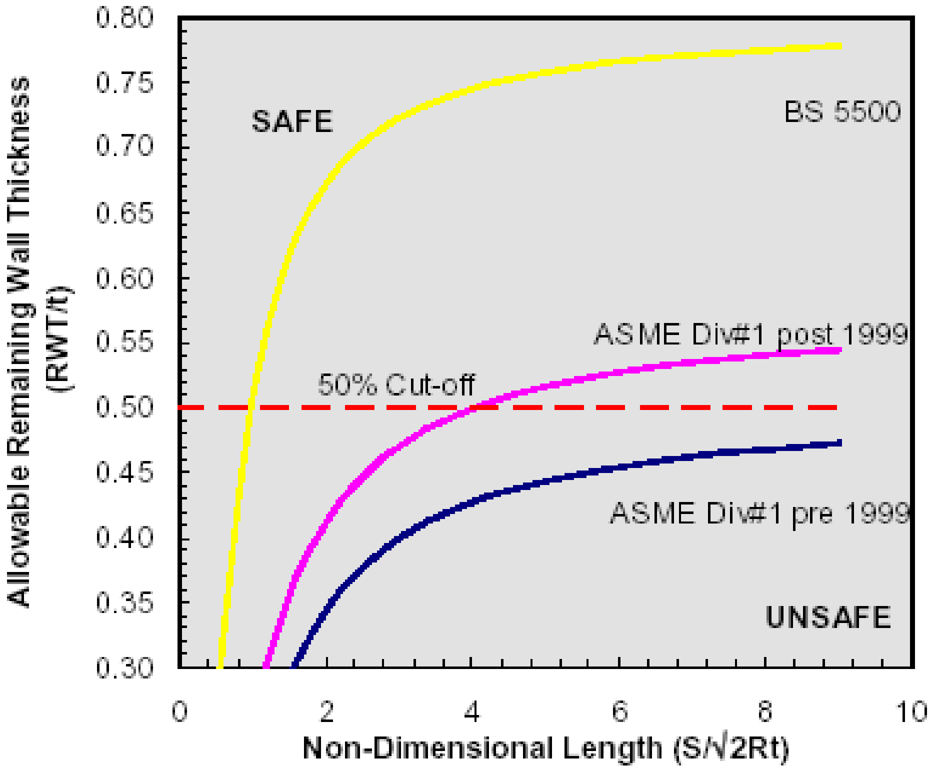
Before embarking on an FFS assessment, several factors need to be considered, as illustrated in the following flow chart (here the terms FFP and FFS are used interchangeably):



b) <u>Structure of guidance</u>

Criteria for structuring the procedure include:

- Simple
- Use minimum information
- Clear indication of where specialists could use more advanced techniques or information
- Coupled to design codes
- Results should be related to whether damaged equipment can still be used within the design envelope



Example of simple go-no go advice for pressure vessels with local corrosion

c) Post Fitness for Purpose Requirements

- Results to be recorded and registered in an asset database and introduced into operating procedures
- Restrictions on process control, e.g. reduced working
- pressure
- Reduced capacity, e.g. limit to safe working pressure
- Restrictions relevant to system upgrades
- Additional requirements for future inspection
- Additional maintenance requirements

4 ASSESSMENT CONCEPTS

4.1 Purpose of the FFS assessment

The FITNET FFS procedure is to be used for the assessment of a metallic structure containing a real or postulated defect. It provides information to support engineering decisions on:

a) allowable load(s) for a given defect size/location
b) critical defect size/location for given loads
c) leak-before-break analysis
d) required minimum material properties for given defect size and loading
e) calculated remaining life
f) determination of inspection intervals

4.2 Assessment Concept and Criteria

The FITNET FFS procedure will be based on the use of either Failure Assessment Diagrams (FAD) or Crack Driving Force Diagrams (CDF).

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 both fracture mechanics criteria and plastic-limit analysis. The fracture mechanics analysis involves comparison of the loading on the crack tip (often called the crack tip driving force) with ability of the material to resist fracture (defined by the material's fracture toughness or fracture resistance). The 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 with the plastic load limit analysis is performed at the same time.

The CDF philosophy differs in that the evaluation of fracture failure and plastic collapse are not simultaneously calculated. Therefore, two independent steps are needed: a direct comparison between applied stress or load and flow stress or limit load; and a diagram plotting the applied stress intensity factor, J-integral or CTOD, which is compared with the corresponding toughness values. Some analysts find the CDF method easier to interpret from a physical point of view; if the CDFD is used together with the J-R curve, the full crack propagation history is described and this also comes from a tearing analysis with the FAD method.

As part of SINTAP the advantages and disadvantages of each procedure were assessed and systematic analytical comparisons carried out. The inherent compatibility between the two approaches was demonstrated.

4.3 Level of the Assessment

Most existing procedures contain several levels of assessment, with increasing technical sophistication and accuracy. This aspect is most developed for the case of fracture assessment and for this aspect it is proposed to follow the SINTAP scheme:

Default Level

Standard Levels
1. Basic
2. Mismatch
3. Stress-strain

Advanced Levels
4. Constraint allowance
5. J-Integral analysis
6. Leak-before-break analysis

In the case of fatigue crack growth or environmentally assisted crack growth, the fracture assessment level used to determine the critical defect size needs to be defined.

For the high temperature regime a single assessment level is used but there is a range of levels for some of the calculation steps within the procedures.

5 PROBABILISTIC METHODS

5.1 Overview

Probabilistic aspects of defect assessment are relatively new and as yet are not fully adopted in defect assessment codes, although some guidance is contained in R6, R5 and BS7910, for example. However given the importance that the codes attach to sensitivity analyses the use of probabilistic methods is the natural next step in the development of the procedures. Moreover changes in legislation, the trend to life extension and increasing computing power have led to an increase in the use of reliability methods in many industrial sectors. The methods have already been applied in the nuclear, offshore, rail, shipping, aerospace, bridge, building, process plant and pipeline industries. Failure processes that can be addressed include fracture, collapse, fatigue, creep, corrosion, bursting, buckling, third party damage, stress corrosion and seismic damage. Essentially data are statistically fitted to find their relevant distribution. Invariably where there is insufficient set of data, a log-normal distribution is assumed. Then the calculations are performed many times with randomly generated material properties data (within the constraints set by the expert, the data distribution and the model). The output then needs to be analysed with different confidence levels according to the design levels set for the component.

The use of probabilistic methods is often part of so-called risk-based or risk-informed approaches to plant life management. The most direct application of these is for optimising maintenance activities, in particular non-destructive inspection. Recent reports from the UK Health and Safety Executive [31] and the European EURIS project [32] provide a useful overview of the application of such procedures. It is noted that in the nuclear field structural reliability models may also be linked to an overall probabilistic safety assessment (PSA) [33].

A focus of current European R&D in this area is the RIMAP project for risk based inspection and maintenance procedures for European industry. 17 European companies representing a broad industry base have joined forces to develop a European best practice and to verify its applicability in several case studies. The project addresses the petrochemical, chemical, pulp & paper, steel works, and the power industry specifically, although the techniques can easily be extended to other industry sectors.

5.2 Structural Reliability Models

The review of structural reliability models by Webster and Bannister [34] indicates some sources of suitable guidance material and relevant R&D projects. It covers methods, applications and software for structural reliability assessment as part of the PLAN network activities. Basic concepts of risk, reliability and consequences are introduced. The types of failure modes that can be addressed probabilistically are described with reference to global and local effects and time-dependency. Types of calculation methods are covered, with emphasis on Monte-Carlo Simulation and the First Order Reliability Method, and the sources and treatment of uncertainty described.

A review of codes providing guidance on target reliability levels related to consequence of failure, and industry practice in defining acceptable failure probability is presented. The levels generally depend on the reliability of the input data, the consequences of failure and the cost of reducing the risk. The capabilities of various commercial and development software are assessed; a range of reliability analysis software is available for general applications, covering any failure mode, and also for fracture specific applications.

Current trends include refinement of calculations of risk throughout a structure's lifetime: 'Reliability updating' coupled with structural health monitoring with sensors enables real-time reliability status to be defined. Risk consideration as a primary input in component/structure design is becoming more widespread and the use of the methods for optimisation of materials selection, design and cost is increasing.

In the field of nuclear plant, the on-going R&D project NURBIM [35] is benchmarking SRM’s relevant to assessment of passive components, with the aim of producing best-practice guidelines.

DNV (former SAQ) has developed a handbook and deterministic software called SACC for safety evaluation of cracked components based on the R6-method. DNV also developed simple probabilistic software within the SINTAP-project called ProSINTAP. The ProSACC project will update procedures and solutions (e. g. for K_I and limit loads) and produce software with which it is possible to perform both a deterministic and a probabilistic analysis.

6 VALIDATION & CASE STUDIES

A wide range of validation, verification and benchmark cases are available in the literature, in training material and as part of procedures themselves. The collation of such information is being addressed in FITNET Work Package 4.

7 ASSESSMENT SOFTWARE

Although software development is not part of FITNET, it is widely recognised that availability of commercial products which implement a procedure or which execute critical parts of the calculation can be a very significant factor in their uptake by industry. The following notes the products currently maintained by FITNET member organisations available.

1) R-Code (British Energy)
The R-Code software implements the defect assessment methodology in the British Energy creep (R5) and fracture (R6) procedures. Fatigue crack growth calculations can also be performed and the software contains compendia of K solutions, limit load solutions and residual stress distributions. The latest version (4.2) was released in 2003 incorporating changes made to R6 at Revision 4 subsequent to completion of the SINTAP project.

2) Crackwise3 (TWI)

- Automation of fracture and fatigue assessment procedures (BS 7910) for engineering criticality assessment and fitness-for-service evaluations.
- Decision-support software designed to assist engineers in evaluating the integrity of plant and structures containing defects
- Evaluates the effects of structural flaws over a broad range of materials and geometries
- A context-sensitive help system provides support for the novice and infrequent user

3) Defect Assessment Software IWM VERB
PC software for assessments of metallic components with defects, based on linear-elastic and elastic-plastic fracture mechanics (FAD and GE/EPRI method).

8 CONCLUSIONS & RECOMMENDATIONS

a) The FITNET survey on current use of FFS procedures and development needs has shown broad support for the development of a European FFS procedure and underlined the need to focus on application issues relevant to industrial users.

b) A modular concept for the FITNET FFS procedure has been developed. The four Working Groups have made an assessment of the state of the art and have formulated a strategy for development of assessment procedures. The situation is summarised as follows:

Module	**FITNET FFS**
1. Intro & Scope	To be defined (extend from SINTAP)
2.1 Flaw Information	Update SINTAP/BS 7910 as appropriate
2.2 Loads, Stresses	Update SINTAP/BS 7910 as appropriate, taking account of API579
2.3 Materials Properties	For fracture: Master Curve treatment as per SINTAP For fatigue, creep: database of references being collected
3.1 Fracture	Update SINTAP/BS 7910 as appropriate
3.2 Fatigue	Three levels: • crack initiation (as per IIW guidelines) • short crack growth (Vormwald procedure) • long crack growth (NASGRO function)
3.3 Creep	Procedure proposed (based on R5/BS7910) • 2-criteria methods to be added
3.4 Corrosion, metal loss, mechanical damage	Corrosion/metal loss: Shell Handbook approach
4 Assessment criteria	Criteria foreseen: a)allowable load(s) for a given defect; b) citical defect for given loads; c) leak-before-break ; d) minimum material properties for given defect and loads; e) remaining life; f) determination of inspection intervals
5 Special issues	To be defined
6 Compendia	Task groups formed for: • K solutions • NDE performance • Residual stresses • Stress analysis
7. Validation and case studies	WP4 Task

c) R&D should address as priorities the development of better materials data, improved assessment procedures and accurate residual stresses determination

d) Training should focus on the practical application of the FFS concepts and procedures.

e) Action is needed to promote the development of software products and verification cases to support analysts.

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