FKM GUIDELINE "FRACTURE MECHANICS PROOF OF STRENGTH FOR ENGINEERING COMPONENTS" – OVERVIEW AND EXTENSION TOPICS

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Abstract

The German guideline "Fracture Mechanics Proof of Strength for Engineering Components" [1] has been released 2001 as a result of activities sponsored by the Research Committee on Mechanical Engineering (FKM), task group "Component Strength". The guideline describes basics for the integrity assessment of cracked components subjected to static or cyclic loading and provides a step-by-step computational procedure for the use in engineering practice. The guideline was formulated based on a number of national and international reference documents, in particular SINTAP [2], R6 [3], BS 7910 [4] and DVS-2401 [5], recent research results and some own key aspects. Since 2004 it is also available in English. The procedures and solutions of the guideline are implemented in the computer program FracSafe [6]. The latest 3rd edition of the guideline (2005) includes several new topics. These allow for the consideration of

- special effects at cyclic loading,
- mixed mode loading,
- dynamic (impact) loading,
- stress corrosion cracking,
- probabilistic aspects in fracture mechanics calculations.

In addition, the compendium of the stress intensity factor and limit load solutions is extended and adjusted according to the state-of-the-art. Some new examples and case studies are included to demonstrate the application of the procedure to engineering problems. This paper gives an overview of the guideline [1] and describes new features available since its 1st edition.

Overview

The FKM guidelines

- Analytical Strength Assessment [7] and
- Fracture Mechanics Proof of Strength for Engineering Components [1]

were developed in the working group "Component Strength" of the Research Committee on Mechanical Engineering (FKM, Germany) supported and sponsored by the German Federation of Industrial Research Associations "Otto von Guericke" (AiF).

Both documents describe the assessment of components subjected to static and cyclic loading, the first one without considering defects using the conventional methods of strength of materials, and the second one with considering defects using fracture mechanics methods. So they complement one another. Software for each guideline exists. For the here presented guideline it is FracSafe [6], which can be used in German and English. The guidelines are applicable for components made of steel, cast iron and light metal alloys at temperatures below creep temperature and for welded structures.

The 1st and 2nd edition of the FKM guideline "Fracture Mechanics Proof of Strength for Engineering Components" included the assessment of components

- at static loading with respect to crack initiation, stable crack growth, crack instability or plastic collapse using the failure assessment diagram (FAD) and
- at cyclic loading with respect to fatigue limit and fatigue crack growth using linear elastic fracture mechanics (LEFM).

The 3rd edition contains several essential extensions and supplements aiming at considering special effects at cyclic loading, mixed mode loading, dynamic loading, stress corrosion cracking and probabilistic aspects in fracture mechanics calculations. Note that the most of the included new topics are hardly considered in national or international standards and that they are often still under research. The user has to be given assistance with the guideline for solving his problems, but he has to be aware that in most cases finding a solution takes time and money. The results from the new included topics have to be analysed more critically than the results based on failure assessment procedures and practical applications of many years, which are the basis of the 1st and 2nd edition.

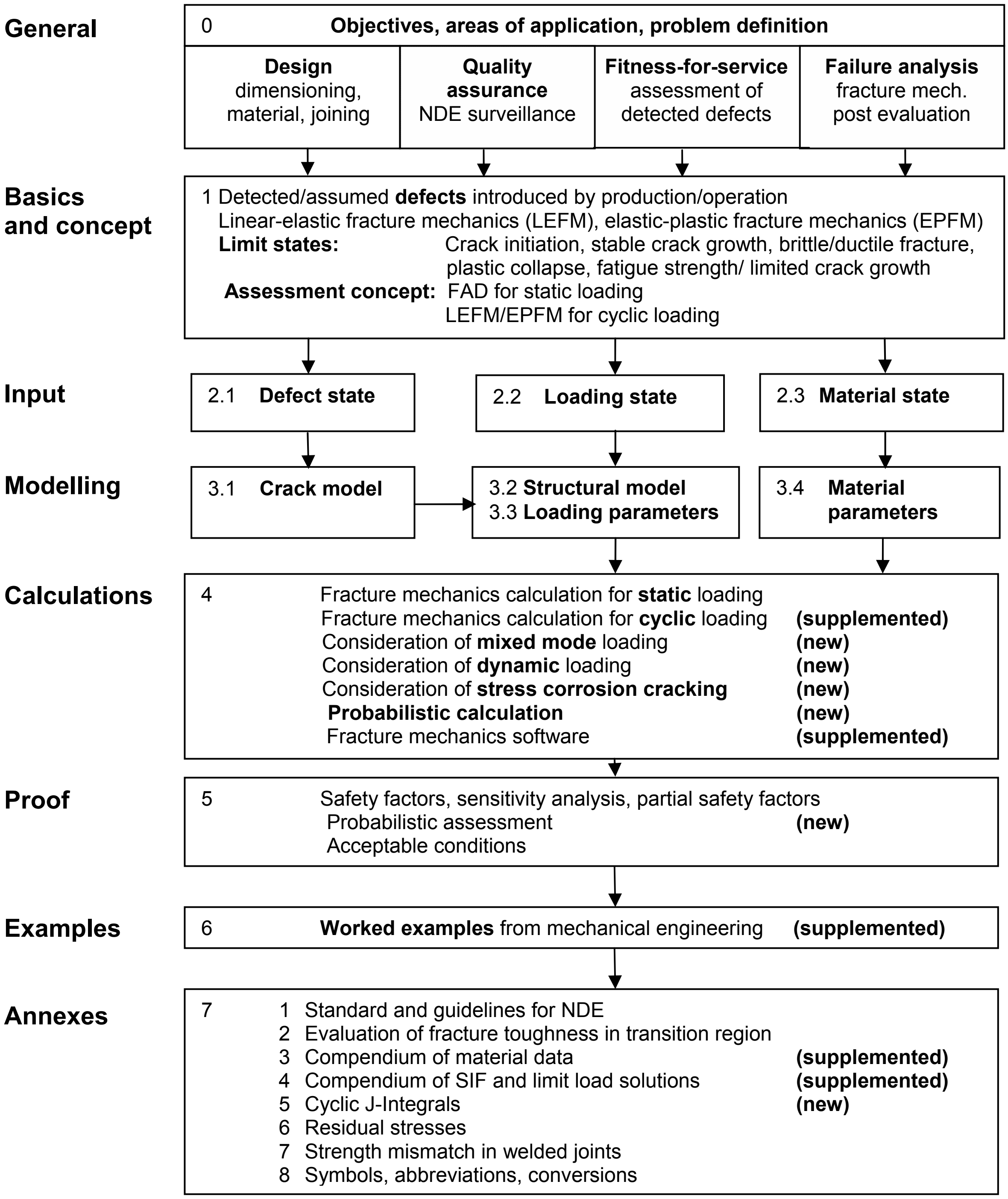

Figure 1. Structure of the FKM guideline “Fracture Mechanics Proof of Strength for Engineering Components”

The structure of the guideline is shown in Figure 1. In Chapter 1 the basics of fracture mechanics and relevant assessment concepts are introduced. Then the input parameters for the procedure, such as defect state, loading and material state, are described in Chapter 2. In Chapter 3 the quantitative implementation of the input leads to a structural model with a crack, for which fracture mechanics loading parameters can be calculated. Relevant material parameters have to be chosen to describe the failure mode. Calculations performed according to Chapter 4 yield safety factors or a failure probability, respectively, and conclude on the safety of the cracked component, Chapter 5.

Calculation at Cyclic Loading

In the previous editions, calculations at cyclic loading are based on LEFM using the stress intensity factor range ΔK. Crack propagation above threshold value ΔK_{th} can be described using an appropriate fatigue crack growth relationship, e.g. after Paris-Erdogan [8] or NASGROW [9]. The new edition includes a qualitative comparison of several load interaction models at variable amplitude loading.

The calculation of crack propagation is now also possible on the basis of elastic-plastic fracture mechanics (EPFM) using the cyclic J-Integral ΔJ and the effective cyclic J-Integral ΔJ_{eff} , respectively. The procedure follows the work of Vormwald [10,11] and Dankert [12,13]. The cyclic J-Integral is calculated from local, elastic-plastic stress-strain parameters, as shown in Figure 2. In this approach load interaction effects are described automatically using load history dependent crack closure stresses σ_{cl} and strains ε_{cl}.

The concept can also be used for short cracks and components without defects. For the latter, a fictitious initial crack has to be defined. Crack growth propagation is then calculated using a cyclic J-Integral ΔJ, e.g. after

$$\frac{da}{dN} = C_J \cdot (\Delta J)^{m_J} \tag{1}$$

with constants C_J and m_J . However, in most practical applications the stress intensitiy factor range ΔK is used. Separation of LEFM and EPFM regions can be done with the help of a modified Kitagawa diagram, Figure 3. The use of ΔJ is therefore limited to components under high local stresses as they occure at notches or at small cracks.

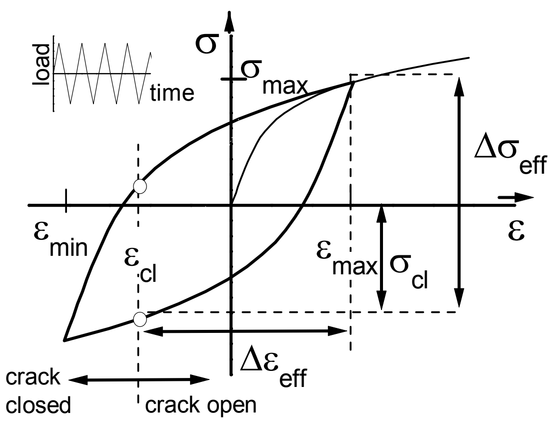

Figure 2. Definition of local stress-strain parameters

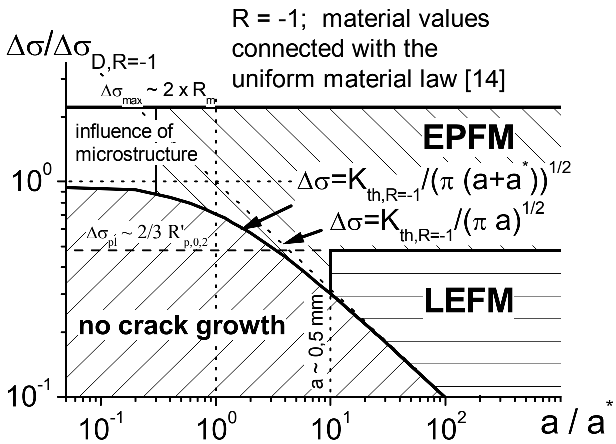

Figure 3. Modified Kitagawa’s diagram for stress ratio *R*=-1

Consideration of Mixed Mode Loading

According to the mode of loading and the resulted displacement components at the crack tip the following modes, Figure 4, are distinguished:

- Mode I – opening
- Mode II – in-plane shear
- Mode III – out-of-plane shear.

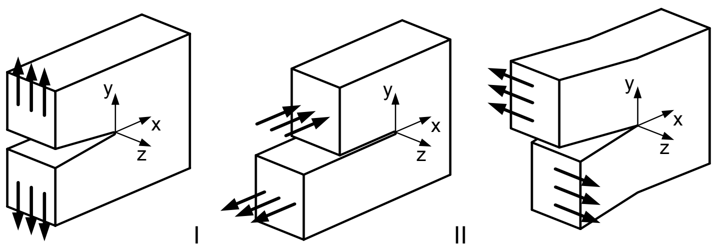

Figure 4. Crack displacement modes I, II, III

Mixed-mode loading results when due to component geometry, loading and the local crack tip orientation the crack displacement modes I, II and/or III occur simultaneously. The assessment procedure is based on LEFM and only proportional loading is considered. The singular parts of the stress-strain fields at the crack tip are described by the stress intensity factors K_I, K_{II} and K_{III}. Selected solutions for stress intensity factors are available in the annex part of the guideline. The development of a simple calculable crack model from the defect state and the structural model from the loading state has to account for all stress components in the crack plane. Rotating or projecting the defect in a reference plane, as it is done in the previous editions where only mode I problems are considered, is not allowed.

The assessment is then performed using an equivalent stress intensity factor K_V, see e.g. [15]. A summary of the procedure is shown in Table 1.

Table. 1: Procedure for assessment of mode II, III and mixed-mode loading based on [15,16,17]

	Static loading	**Cyclic loading**
Loading parameter	$K_V = \frac{K_I}{2} + \frac{1}{2}\sqrt{K_I^2 + 5{,}34{K_{II}}^2 + 4{K_{III}}^2}$	Analogue $\Delta K_V = f(\Delta K_I, \Delta K_{II}, \Delta K_{III})$
Material parameter	K_{Ic} Special cases $K_{IIc} = 0.87\ K_{Ic}$ $K_{IIIc} = K_{Ic}$	ΔK_{Ith}
Assessment	Brittle fracture $K_V = K_{Ic}$	Fatigue endurance $\Delta K_V < \Delta K_{Ith}$

An application of the procedure in the EPFM region is not validated. The use of the FAD approach at static loading, originally developed for mode I conditions, is possible for mixed-mode problems, but is also not validated.

Crack propagation at proportional cyclic loading can be calculated based on the criteria of local symmetry ($K_{II} = 0$, $K_{III} = 0$) for instance using Paris-Erdogan equation [8]

$$\frac{da}{dN} = C \cdot (\Delta K_I)^m \, . \tag{2}$$

This can produce curved crack paths. The analysis of such problems requires a numerical simulation of a mode I crack geometry, which fits the loading and geometry of the component. For plane problems suitable software has been developed and is available, for instance [18]. For three dimensional crack growth simulation application-oriented results exist, for instance [19].

Consideration of Dynamic Loading

During the operation of machines and equipment high impact type loading can occur, for instance, through collisions with moving or rotating parts as well as overloads caused by transport accidents or simply by components falling down and hitting the ground. The loading rates are typically within the range of 1 m/s to 100 m/s and the related times to failure are milliseconds or even microseconds. The safety assessment of dynamically loaded components can be performed based on the procedures for static loading. However, it requires taking into account time-dependent and local loading and material parameters.

Cracked components can be described by geometrically simple structural models as in the static case. The stress intensity factor K is used as loading parameter. However, elastic wave propagation through the component due to impact loading has to be considered leading to time-dependent stress-strain fields at the crack tip characterized by the parameter $K_I^{dyn}(t)$. This is generally evaluated by numeric methods. Depending on the component geometry and the crack location with respect to the applied force, especially at the beginning of the loading process, higher stresses and strains than those calculated at quasi-static loading $K_I^{qs}(t)$ can temporarily occur. This is due to focussing effects and the onset and development of oscillations of the activated elastic waves and can be taken into account by a geometry-dependent dynamic correction function $k^{dyn}(t)$

$$K_I^{dyn}(t) = k^{dyn}(t) K_I^{qs}(t) \, . \tag{3}$$

Figure 5 shows an example of $k^{dyn}(t)$ for a three-point bending specimen under impact loading [20].

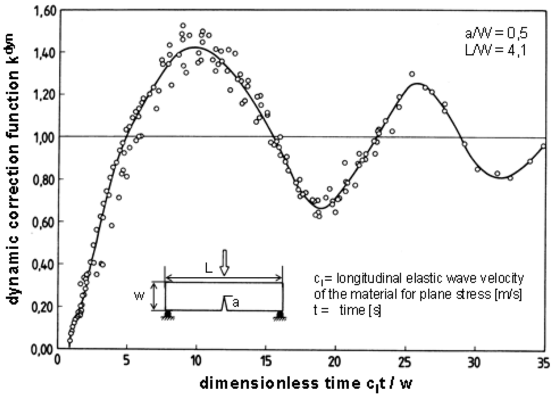

Figure 5. Dynamic correction function k^{dyn} for impact-loaded three-point bending specimens [20]

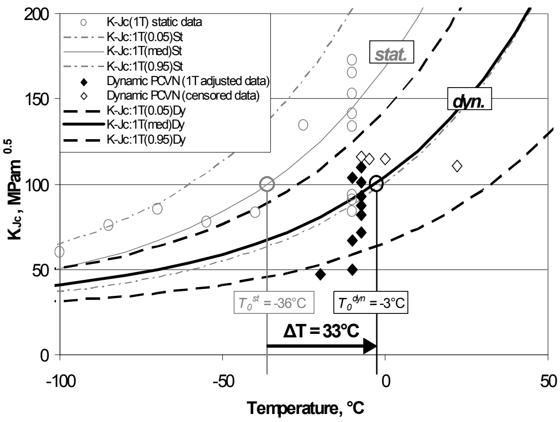

Figure 6. Static and dynamic master curve for the material 6JRQ43; crack tip loading rate 2×10^4 MPa$\sqrt{m}$s^{-1} [22]

Material fracture resistance is characterised by the dynamic fracture toughness K_{Id} which is a function of the temperature T and loading rate. Two typical ranges can be distinguished on the $K_{Id}(T)$ curve:

- in the brittle (lower shelf) and ductile-brittle (transition part) regimes, the increasing loading rate results in a considerable decrease of the fracture toughness;
- in the ductile (upper shelf) regime, the fracture toughness generally increases with the loading rate, so that a conservative failure assessment can be based on the use of the quasi-static fracture resistance curve.

The dynamic fracture toughness should be determined under temperature and loading rate corresponding to the component service conditions. The use of a dynamic master curve according to [21] is possible. Figure 6 compares the static and dynamic master curves for a pressure vessel steel [22]. A considerable embrittlement effect can be noticed due to increasing loading rate. Alternatively the crack arrest curve K_{Ia} (ASTM E 1221) can be employed as a lower bound for K_{Id}.

Fracture assessment in the upper shelf regime can follow the procedure for the static loading. In the lower shelf and brittle-to-ductile transition regimes, the condition

$$\max \left\{ K_I^{dyn}(t) \right\} < K_{Id}(T, \dot{K}) \tag{4}$$

must be satisfied for a safe exclusion of crack initiation. Depending on the failure consequences, the accuracy in determining the load parameters and facture toughness, appropriate safety factors can be additionally applied.

Consideration of Stress Corrosion Cracking

Stress corrosion cracking is crack initiation and propagation in materials under static tensile loading in a corrosive active medium. It is not possible to describe crack initiation with fracture mechanics methods. In many cases crack propagation can be described with linear elastic fracture mechanics methods, that means using the stress intensitiy factor K. Crack propagation occurs, when stress intensity is high, the corrosive medium is active and the material susceptible to stress corrosion. Susceptible to stress corrosion are many material/medium combinations, some important are:

- Austenitic and austenitic-ferritic CrNi-steels in chloride containing atmospheres,
- High strength steels and high strength titanium alloys in atmospheres, which can emit hydrogen as for instance H_2O, H_2S, NH_3 and other acids,
- Mild steels and low alloyed steels in hot nitrate, carbonate and sulfide solutions and bases,
- Aluminium alloys in chloride containing atmospheres (for instance water, seawater),
- Magnesium alloys in seawater,
- Copper alloys in ammonium, amin and nitride containing atmospheres and
- Nickel alloys in nuclear reactors coolant (boiling water).

Susceptibility increases with increasing temperature. Fracture often occurs macroscopic brittle, which means without large visible plastic deformation. Dependent on material and heat treatment stress corrosion cracks can grow transcrystalline or intercrystalline. Crack tips are often, but not always branched. In many cases multiple cracks, parallel cracks or crack fields can occur. Crack velocity *da/dt* depends on many factors. The dependency on stress intensity factor in principle is shown in Figure 7. It can be divided in three regions.

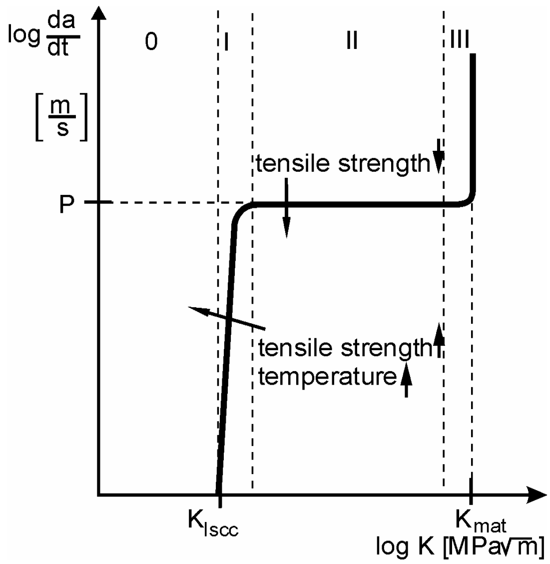

Figure 7. Stress corrosion crack velocity *da/dt* versus stress intensity factor in a corrosive medium

No crack growth occurs theoretically for

$$K < K_{Iscc} \,. \tag{5}$$

Lifetime is infinitely. But it should be stated that the relevant value of K_{Iscc} can change by and by, for instance because of changed atmosphere, temperature, electrode potential, irradiation etc..

For the most practical applications region II is essential and can be used as conservative assumption. For values K in this plateau region the crack velocitiy

$$\frac{da}{dt} = konst. = P \,. \tag{6}$$

Lifetime can be calculated from

$$t = \frac{a_{final} - a_{initial}}{P} \,. \tag{7}$$

Probabilistic Assessment

As input data is often subject to a scatter or uncertainties, a deterministic analysis has usually to be complemented by a sensitivity study with varying respective parameters. Instead, statistical methods can be applied to describe uncertainties in the flaw size and shape measurements, a scatter in the fracture toughness and material strength data, as well as uncertainties in the definition of both primary loads and secondary stresses. Then a direct probabilistic assessment can be performed to calculate the failure probability of a cracked component P_f or to quantify the influence of the scatter in the input data on results of a crack growth prediction. On this note, the probabilistic analysis can be considered as an extension or an alternative to the sensitivity study or to the use of partial safety factors [2, 23]. In contrast to the latter approach, no failure probability has to be assumed but this is to be calculated on the basis of the experimentally determined or postulated statistical distributions for the input parameters. Methods and examples of the probabilistic assessment of cracked components can be found in numerous publications, e.g. [24-27]. Recommendations for a probabilistic failure assessment given in the guideline apply mainly to components under static loading.

<u>Scatter and uncertainties of input data</u>

Variations in the input data as a result of inaccuracies of measurements, natural scatter of material data, as well as uncertainties in defining respective parameters can be described by statistical distributions. Given the probability density function $f(x)$ of a variate x, the distribution function $F(x)$ is determined by

$$F(x) = \int_{-\infty}^{x} f(u)du \tag{8}$$

The distribution function is characterised by its mean, standard deviation, coefficient of variation, shape and scale parameters, etc. Among functions frequently used in engineering calculations are the normal, lognormal, Weibull and exponential distributions.

Input: flaw, loading und material state

The flaw state is characterised by the probability of detection (POD), on one hand, and the flaw size distribution, on the other hand. In the most cases, the corresponding distribution functions are established and calibrated in comprehensive experimental investigations, e.g. on the basis of long-term inspection activities or non-destructive tests performed by different laboratories. Data available in the literature, e.g. POD functions [23-26], reflect particular component geometry, NDE technique, material state and, therefore, are rarely transferable to the specific case to be investigated.

The loading is preferably treated as a deterministic parameter. However, uncertainties in the definition of residual stresses as well as random amplitude fatigue loading can be rationally resolved by using statistical methods.

Material strength properties and especially the fracture toughness are subject to considerable scatter which has to be accounted for in a probabilistic analysis. The use of the master curve [21] is an example of a probabilistic treatment of the fracture toughness in failure analyses.

Computation of the failure probability

A Monte Carlo simulation (MCS) is recommended to compute high failure probabilities, e.g. above $10^{-3}...10^{-5}$. Given statistical distributions for the input parameters (vector $\boldsymbol{X}$) and the limit state function $g(\boldsymbol{X})$ separating the safe and unsafe regimes, certain number N of deterministic calculations are performed for randomly selected input data. The number N_f of failure cases in relation to the total number of simulations gives an approximate value of the failure probability

$$P_f = \frac{N_f}{N} \tag{9}$$

which converges to the “exact” value with increasing number of simulations.

Figure 8 shows an example of the probabilistic failure assessment for a pipeline with a spiral weld using the FAD approach and MCS. A long surface crack was postulated on the outer surface, in the weld. Different statistical distributions were assumed for the crack depth, the primary and secondary stresses, the yield and the tensile strength, and the fracture toughness. The limit state function follows in this example the SINTAP recommendations for the material with discontinuous yielding. Using MCS with 10^3 to 10^6 simulations, failure probabilities of $P_f = 4\times10^{-3}$ and $P_f = 3\times10^{-2}$ were calculated for the mean crack depth μ_a = 2 mm and μ_a = 3 mm, respectively.

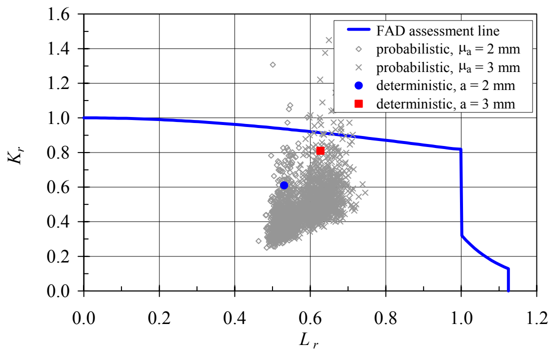

Figure 8. Probabilistic failure assessment in FAD

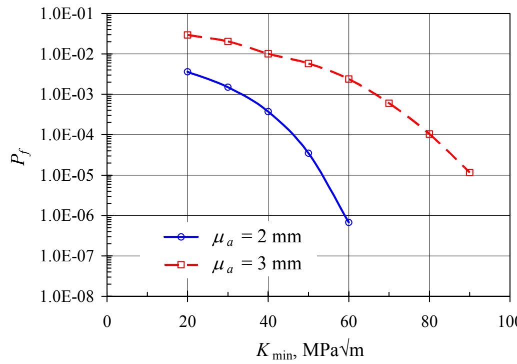

Figure 9. Failure probability vs. lower bound of the fracture toughness

At low failure probabilities usually requested for safety relevant components, the use of MCS becomes rather inefficient due to extremely high computational time. In these cases the failure probability can be computed directly by applying the first- or second-order reliability methods (FORM or SORM, respectively), or a modified MCS version, the Monte Carlo simulation with importance sampling (MCS-IS). All these methods require the computation of the so called design point which makes the principal contribution to the analysis effort.

Interpretation of Results, Assessment

The calculated value of the failure probability essentially depends on the quality of input data. Both assumptions on the type of distribution functions with the related parameter fit and the selected method for computing the failure probability may considerably affect the analysis result. Therefore, the absolute value of the failure probability should be handled with particular care. Generally, a probabilistic assessment should be considered as a reasonable supplement to the deterministic analysis, for instance, to study the impact of different input parameters and their variations on the component integrity. Accordingly, in the example considered above, the failure probability was shown to considerably depend on the crack size and the fracture toughness. Further assuming the Weibull distribution for the fracture toughness [21]

$$P_{Kmat} = 1 - \exp\left[-\left(\frac{K_{mat} - K_{\min}}{K_0 - K_{\min}} \right)^{\beta} \right] \tag{10}$$

with K_0 = 169 MPa√m und β = 4, the requested level of failure probability can be defined as a function of the lower bound fracture toughness K_{min} , Figure 9.

Examples and Annexes

For better illustration and understanding of the extended topics, 9 additional examples were included. Altogether there are now 20 worked examples in the guideline. They cover typical engineering components as shafts, plates, pipelines, casings and tracks and demonstrate the use of the guideline in design, qualitiy assurance, fitness for service and failure analysis.

The document contains following annexes:

- standards and guidelines for non-destructive test methods,
- determination of fracture toughness in the transition region,
- materials data (standard mechanical and fracture mechanical),
- stress intensity factor and limit load solutions,
- cyclic J-Integrals,
- residual stresses,
- mismatch in welded components (special option for FAD) and
- symbols, abbreviations, conversions.

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