FKM - GUIDELINE FRACTURE MECHANICS PROOF OF STRENGTH FOR ENGINEERING COMPONENTS - PROCEDURES, COMPENDIUMS, EXAMPLES

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ABSTRACT

The German FKM-Guideline “Fracture Mechanics Proof of Strength for Engineering Components” has become an increasing interest for practical engineers in various industrial applications since its first release in 2001. In 2009 the 3rd revised edition in English and German was published. It describes basics for the integrity assessment of components with defects, such as cracks, subjected to static or cyclic loading and provides a step-by-step computational procedure. It allows the consideration of special effects at cyclic loading, mixed mode loading, dynamic (impact) loading, stress corrosion cracking and probabilistic aspects in fracture mechanics calculations. Twenty worked examples illustrate the application. The annexes contain for instance a compendium of material data and about 60 stress intensity factor and limit load solutions and some ΔJ-integrals. The procedures and solutions of the guideline are implemented in the computer program FracSafe, so they can be easily used. The paper gives an overview of the guideline.

KEYWORDS

Guideline, fracture mechanics proof of strength, failure assessment diagram, fatigue crack growth, integrity assessment

INTRODUCTION

The FKM guidelines

- Analytical Strength Assessment [1,2] and
- Fracture Mechanics Proof of Strength for Engineering Components [3, 4]

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 [5], 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 guideline was formulated based on a number of national and international reference documents, in particular SINTAP [6], FITNET [7], R6 [8], API-579 [9], BS 7910 [10] and DVS-2401 [11], recent research results and some own key aspects. It was discussed widely with experts from research and industry.

OVERVIEW

The structure of the guideline is shown in Fig. 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. Comprehensive worked examples and annexes complete the guideline.

INPUT AND MODELLING

Defects and crack model

For fracture mechanics proof of strength detected and assumed defects are considered. Every defect is treated as a crack. Different non-destructive test methods (NDT) for crack detection and sizing are explained and guidance is given for their crack detectability. For calculations conservative geometrically simple crack models are necessary, Fig. 2. Therefore NDE indications have to be transferred into crack dimensions. Defect orientation and shape and interaction of defects have to be considered. In most cases it is conservative to model defects as cracks normal to the maximum principal stress.

Loading and loading parameter

For assessment the local elastic stresses of the defect-free component acting within the region of the crack faces are relevant. A structural model with a crack has to be established using only geometry and stress data in the vicinity of the crack, Fig. 2. Simplifications are possible. Loading parameters are the stress intensity factor K, stress intensity factor range ΔK, FAD-parameter K_r and plasticity parameter L_r. For special cases the cyclic J-integral ΔJ can be used.

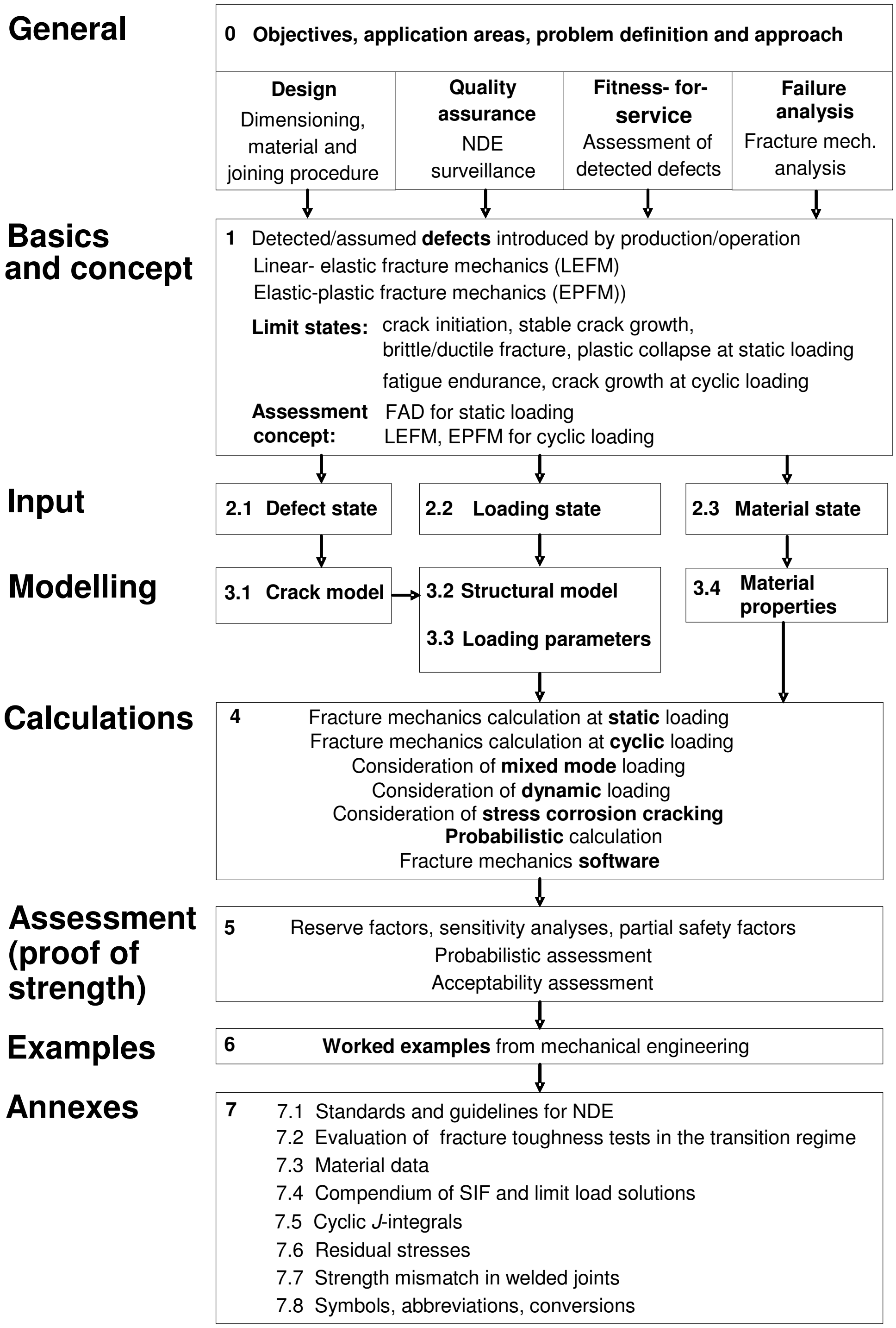

Fig. 1: Structure of the FKM Guideline “Fracture Mechanics Proof of Strength for Engineering Components”

Material and materials data

Necessary mechanical and fracture mechanical properties and influencing factors are explained. For the considered component and material state the following material values are required

- strength values R_e (R_{eL} or $R_{p0,2}$, discontinuous or continuous yield behaviour), R_m or true or engineering σ-ε-curve,
- fracture toughness K_{mat} at static loading and
- crack growth rate $da/dN=f(\Delta K)$ with fatigue crack threshold ΔK_{th} at cyclic loading.

Fracture toughness K_{mat} is different for brittle, ductile/brittle and ductile behaviour. It can be measured directly as e.g. K_{Ic}, J_i, $J_{0,2}$, $J_{0,2BL}$, $J(\Delta a)$ or determined indirectly from correlations with Charpy-energy *KV*. Fracture mechanics properties at dynamic loading and under stress corrosion cracking conditions are introduced.

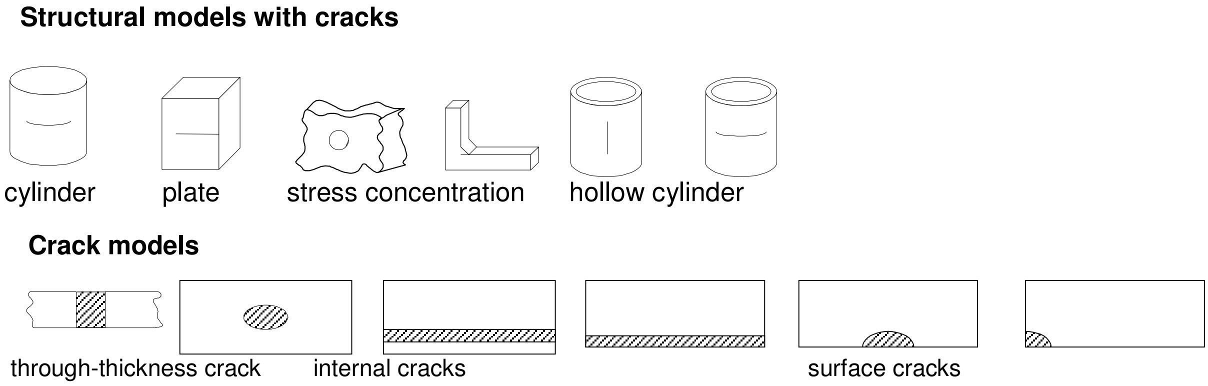

Fig. 2: Structural models with cracks and crack models of the guideline

CALCULATION PROCEDURE

Calculation at static loading

The analyses are based on the failure assessment diagram (FAD), Fig. 3., which applies to both brittle fracture (linear-elastic material behaviour) and ductile failure (elastic-plastic material behaviour) and takes into account possible plastic collapse. The critical states can be crack initiation or crack instability. The failure lines $K_r=f(L_r)$ employed in the FAD analysis of this guideline are according to [6, 7]. There is a basic level with different failure lines for continuous and discontinuous yielding behaviour and an advanced level, where σ-ε-curve is used. For the given geometry of the cracked component, loading conditions and relevant material property values, the coordinates (L_r, K_r) of an assessment point (if crack initiation is regarded as the limit state) or a locus of assessment points (if ductile stable crack extension is expected prior to failure) are calculated and compared with the failure line. The failure line envelopes the safe area, in which failure of the component with a defect is not achieved.

Calculation at cyclic loading

Calculations at cyclic loading usually employ the linear-elastic stress intensity factor range,

$\Delta K = f\ (\sigma_{max}-\sigma_{min},\ \textit{crack size, component geometry})$,

as a loading parameter and a material specific crack growth rate, $da/dN=f(\Delta K)$. Often used crack growth descriptions and different load interaction models for variable amplitude loading are explained. For the assessment of a cracked component first fracture mechanics fatigue endurance at $\Delta K < \Delta K_{th}$ has to be investigated. If this is not the case the calculation of crack propagation is performed by integrating an appropriate fatigue crack growth equation.

For small cracks and extensive plastic deformations at the crack tip, the cyclic J-integral ΔJ is used instead of ΔK as loading parameter. This parameter is formulated in a similar way as the J-integral with

$\Delta J = f$ ($\Delta\sigma$, $\Delta\varepsilon$, crack size, component geometry, cyclic σ-ε curve).

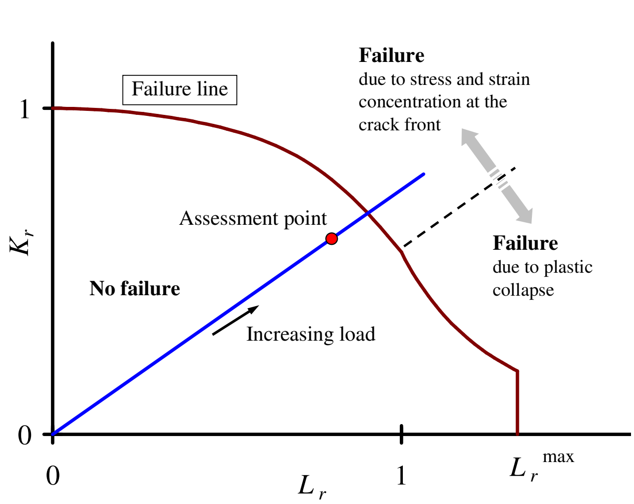

Fig. 3: Failure assessment diagram (FAD)

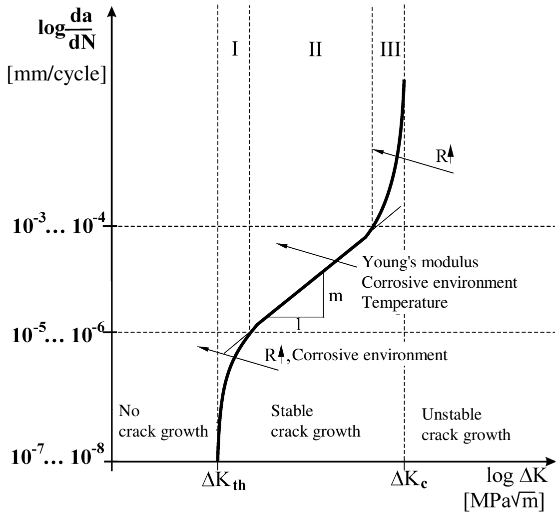

Fig. 4: Fatigue crack growth

Consideration of mixed mode loading

The assessment is performed using an equivalent stress intensity factor K_V. A summary of the procedure is shown in Table 1. The application of FAD assessment lines developed for mode I conditions is possible in principle. However no validation results are available so far for mixed mode loading.

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

Table 1: Assessment of mode II, III and mixed mode loading based on [12, 13]

Consideration of dynamic loading

The assessment of dynamically loaded components with typical loading rates of 1 m/s to 100 m/s can be performed based on the procedures for static loading. However, it requires taking into account time and position dependent stress state in the component and material properties at high loading rates.

The loading parameter used here is the dynamic stress intensity factor $K_I^{dyn}(t)$. It has to be compared with the dynamic fracture toughness K_{Id}, which is a function of temperature T and loading rate. Two typical ranges can be distinguished on the $K_{Id}(T)$ curve for ferritic steels:

- 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.

Furthermore the state of the art of determination of dynamic fracture toughness is explained.

Consideration of stress corrosion cracking

In many cases assessment can be done using stress intensity factor K. Crack propagation occurs, when stress intensity is high, the corrosive medium is active and the material susceptible to stress corrosion. Some important material/medium combinations are mentioned. 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. For $K<K_{ISCC}$ there is no crack growth. For the most practical applications a conservative assumption for crack velocity is $da/dt=constant=P$, so that lifetime can be calculated from $t=(a_{final}-a_{initial})/P$.

Probabilistic calculation

The probabilistic analysis can be considered as an extension or an alternative to the sensitivity study or to the use of partial safety factors. In contrary to the latter approach, no failure probability P_f has to be assumed but this is to be calculated on the basis of experimentally determined or postulated statistical distributions for the input parameters (defect, loading, material).

In the guideline general recommendations for data preparation and probabilistic failure assessment are given especially for components under static loading. Probabilistic calculations can only be performed using special software tools. Some computer programs available for probabilistic fracture mechanics analyses are mentioned.

ASSESSMENT (PROOF OF STRENGTH)

For the assessment of components with defects by FAD reserve factors for load, crack size and fracture toughness has to be calculated. Values >1 are requested to classify component conditions as acceptable. In sensitivity analyses the sensitivity of the reserve factors to the variation of individual input parameter has to be estimated. Alternatively the use of partial safety factors is possible or a probabilistic analysis can be done.

The last decision whether the component is safe or not depends on the user.

EXAMPLES

To facilitate a better understanding of the analysis methods and procedures, the application of the guideline is illustrated on several worked examples, Table 2. Depending on the particular case, the example either corresponds or is adapted to real service conditions.

Component	Problem definition	Notes
Shaft	Fitness-for-service	Example of modelling
Plate	Fitness-for-service	FAD/CDF, welded joint, residual stresses
Flywheel	Design	Dimensioning, defect assessment
Welded tubular joint	Quality management	Load spectrum, component tests
Box profile	Fitness-for-service	Manufacture defects
Welded structure	Quality management	NDE strategy
Pipe	Fitness-for-service	Spiral welded pipe
Generator shaft	Fitness-for-service	Change of design
Valve housing	Fitness-for-service	Steel casting
Pressure vessel	Fitness-for-service	Welded aluminium container, low temperature
Turbine shaft	Failure analysis	Manufacture defects, fatigue crack growth
Seal body	Failure analysis	Casting defects, conventional and fracture mechanics strength assessment
Railway rail	Quality management	Dynamic loading, probabilistic calculations
Drive shaft	Fitness-for-service	Fatigue endurance, mixed mode loading
Notched plate	Design	Application of ΔJ
Pipes	Fitness-for-service	Stress corrosion cracking
Pipe	Fitness-for-service	Probabilistic FAD assessment
Plate	Fitness-for-service	Statistical calculations of residual lifetime
Gear shaft	Failure analysis	Manufacture defects
Stiffened panel	Fitness-for-service	Numerical multiple crack growth simulation

Table 2: Worked examples

ANNEXES AND COMPENDIUMS

The guideline contains several annexes, which give additional information and provides support for solving problems arising in the fracture mechanics assessment. In particular the following issues are considered:

- standards and guidelines for non-destructive test methods (liquid penetrant, magnetic particle, eddy current, ultrasonic, radiographic, potential drop examination, visual inspection),
- determination of fracture toughness in the transition region,
- materials data for typical materials in mechanical engineering (standard strength values and Charpy energy, fracture mechanics materials data for static and cyclic loading from recommendations and literature, some material data for stress corrosion cracking),
- stress intensity factor and limit load solutions (basic solutions and approx. 60 solutions for different structural models with cracks, e.g. for plates and cylinders, and loading conditions, some for mixed mode loading),

- cyclic J-Integrals for plates with cracks at notches,
- residual stress profiles in welded components,
- special failure lines for FAD for mismatch in welded components and
- symbols, abbreviations and conversions.

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