Guideline on Fracture Mechanics Proof of Strength for Engineering Components

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ABSTRACT*: The German guideline "Fracture Mechanics Proof of Strength for Engineering Components" was developed in a project of the Research Council of the German Mechanical Engineering Industry (FKM) to support designers and calculation engineers especially in small and medium-sized companies in solving fracture mechanics problems in their daily work. It covers the assessment of components under static loading with respect to crack initiation, stable crack growth, crack instability and plastic collapse and the assessment of components under cyclic loading with respect to fatigue strength and fatigue crack growth. The document is compatible to the European guideline SINTAP regarding the failure assessment procedures and to the British Standard 7910 regarding the fatigue crack growth calculations. It is an addition to a guideline on proof of static and fatigue strength with conventional methods developed in another project of FKM. The FKM Fracture Mechanics Guideline is applicable to components made of steel, cast iron and light metal alloys at temperatures below creep temperature and to welded structures. It can be applied during the design, fabrication or operational stages of the lifetime of a component. It can help in analysing component failures. The application of the FKM Fracture Mechanics Guideline is demonstrated on many detailed case studies. Annexes include compendia of materials data, stress intensity factor and limit load solutions, recommended residual stress profiles and a description of the account for material strength-mismatch.*

INTRODUCTION

Many industries are strongly dependent on the safe operation of plants and structures. In the case of damaged or defect containing components, the accurate determination of the significance of the damage or defect is required. Structural integrity procedures are used to demonstrate the fitness for service of engineering components.

The presented FKM Guideline "Fracture Mechanics Proof of Strength for Engineering Components" [1] was developed in a project by the Research Council of the German Mechanical Engineering Industry (FKM) in the working group “Strength of Components” to support designers and calculation engineers especially in small and medium-sized companies in solving fracture mechanics problems in their daily work. It is based on existing national and international documents and guidelines. It is a addition to the guideline „Proof of strength for engineering components“ [2], which was first developed in the same working group, where static and cyclic strength calculations for a wide range of components without flaws are described and which is widely used in industry.

To account for future developments towards an European standard for the assessment of components with defects, the presented guideline was developed to be compatible to SINTAP [3] regarding the failure assessment procedures and to BS 7910 [4] regarding the fatigue crack growth calculations.

CONTENT AND STRUCTURE

The FKM Guideline “Fracture Mechanics Proof of Strength for Engineering Components” describes

- the fracture mechanics proof of strength for components under static loading with respect to crack initiation, stable crack growth, crack instability, and plastic collapse
- the fracture mechanics proof of strength for components under cyclic loading with respect to fatigue strength and limited crack growth, and
- acceptance criteria for defect sizes, loading, and material properties.

The FKM Guideline can be used

- in the design stage to specify geometry, materials, and fabrication processes,
- in the fabrication and operation stage, to choose non-destructive test methods and to define inspection intervals,
- in the operation stage when defects have been detected, to prove fitness for service, and
- in cases of failure, to analyse the causes of failure.

The structure of the FKM Guideline follows the path from the problem statement to the assessment of results. It is shown as a flowchart (Figure 1) in the introduction of the guideline.

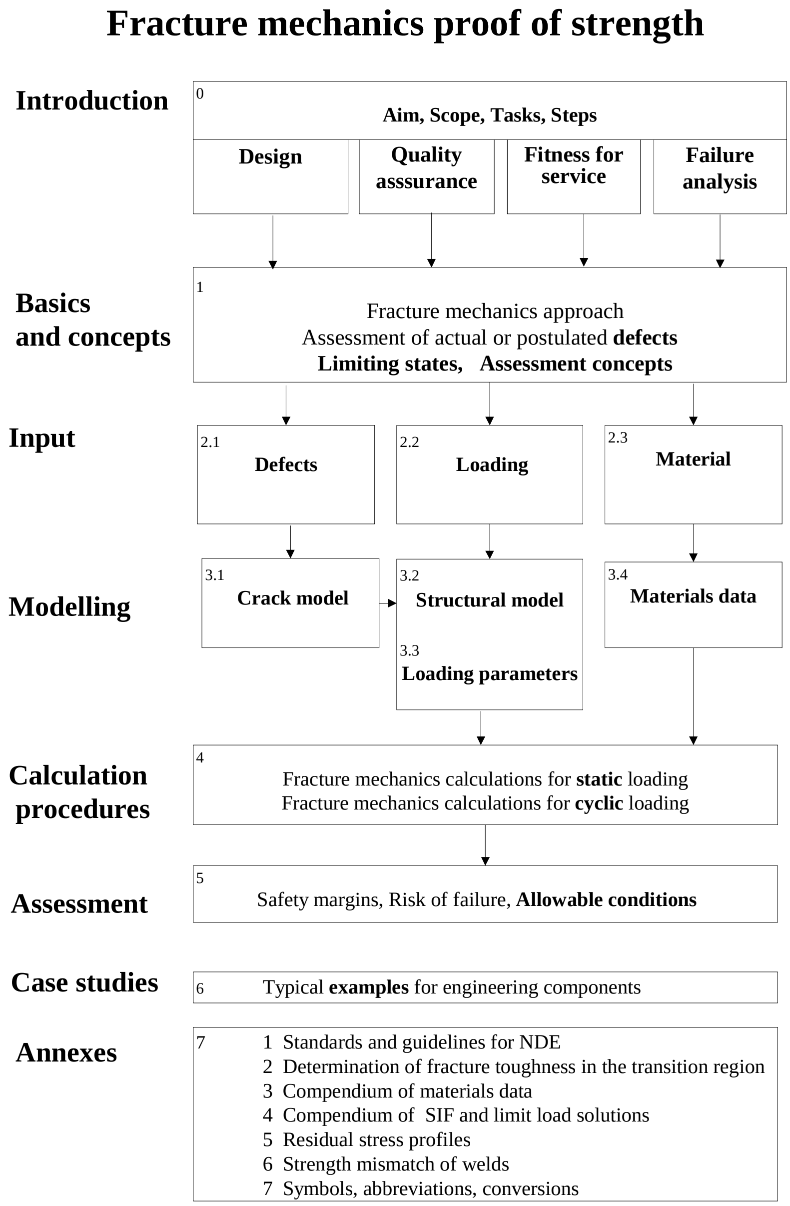

Figure 1: Structure of the FKM Guideline “Fracture Mechanics Proof of Strength for Engineering Components.”

The chapters of the document are introduced by survey-graphs describing the technical content and the location within the main flowchart (Figure 2). Additionally, a list of tasks to be done is included (see example in Figure 3).

1 Basics and concepts

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2 Input

2.1 Defect

- Defects ⟶ Cracks
- Defect description: Surface, embedded, through-wall cracks, cracks from notches
- Defect detection and sizing using non-destructive evaluation (NDE)
  - NDE for surface defects: dye penetrant, magnetic particle, ultrasonics, eddy current, potential drop
  - NDE for embedded defects: ultrasonics, radiography
- Fabrication quality

2.2 Loading

- Loading in the part of the component containing defect:
  - Elasticly calculated local stresses or stress ranges in the component without defect
  - Residual stresses

2.3 Material

- Properties: Testing, Scatter
- Tensile properties: R_e, $R_{p0,2}$, R_m, E, σ-ε-*Curve*
- Fracture mechnics properties
  - at static loading: brittle - K_{Ic}, ductile - δ_i, J_i, .., $\delta(\Delta a)$ or $J(\Delta a)$
  - at cyclic loading: ΔK_{th}, $da/dN=f(\Delta K)$

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3 Modelling

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Figure 2: Survey-graph of chapter Input: Technical content and context

Tasks	Sections Figures Tables
Characterisation of the defect	**2.1**
- Determine critical areas of component strength regarding material and/or loading	
- Select NDE method	T. 2.1-1
- Determine defects in critical areas	
- Determine defect dimensions	B. 2.1-3.. -6
- Take into account criteria for the quality of fabrication	2.1.4

Figure 3: List of tasks within the chapter INPUT (part of the table)

BASICS AND CONCEPTS

Cracks in components can reduce component strength; they can grow under service loads and induce brittle or ductile failure or plastic collapse. Sub-critical crack growth and fracture can be described by fracture mechanics concepts using the stress intensity factor (SIF), or more generally, in the framework of elastic-plastic fracture mechanics (EPFM), the J-Integral or the crack tip opening displacement (CTOD) as loading parameters.

To assess a component with a crack the magnitude of a loading parameter has to be compared with a corresponding material parameter. In case of static loading the result of the assessment based on EPFM can be shown in a Failure Assessment Diagram (Figure 4), where the location of an assessment point (for the limiting condition “crack initiation”) or of a locus of assessment points (for stable crack growth and instability) define safe or unsafe conditions. Here optionally “basic” or “stress-strain” assessment lines from [3] can be used. The advanced “stress-stain”-level is less conservative, but it requires more material input data.

For the assessment of cracked components under cyclic loading the material crack growth rate da/dN as a function of the SIF range ΔK (Figure 5) and the material fatigue threshold are used to prove the fatigue limit or to calculate fatigue crack growth.

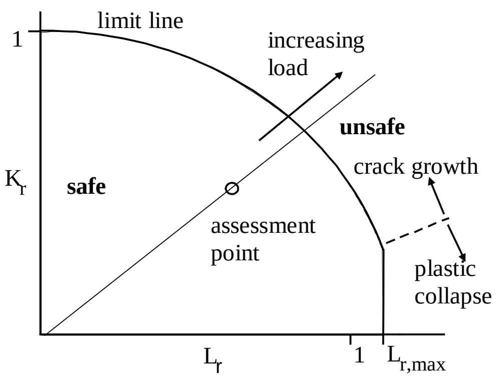

Figure 4: Failure Assessment Diagram (schematic)

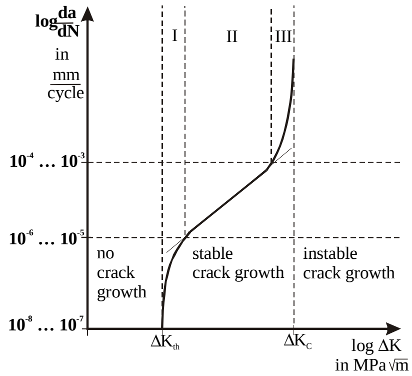

Figure 5: Crack growth rate (schematic)

INPUT AND MODELLING

The user is given advice on necessary data and their acquisition. The defect geometry, the loading, and the material data have to be modelled to obtain simplified and conservative cases as well as characteristic values of material data which enable the calculation of FAD loading parameters

K_r = SIF / (fracture toughness) and

L_r = (applied load) / (yield load of the cracked structure).

CALCULATION PROCEDURES

In calculation procedures for static loading the FAD assessment line and the respective assessment point(s) for the defected component are determined. On the “basic” level the assessment lines from SINTAP [3] are used, which are modified in comparison to BS 7910 [4] and to API 579 [5], and distinguish between materials with and without discontinuous yielding. Described are options “crack initiation” using the initiation fracture toughness K_{mat} and “crack instability” using the material resistance curve

$K_{mat}(\Delta a)$. Where residual stresses have to be considered, the plasticity interaction parameter ρ is calculated as in [3] , which corresponds to the advanced "detailed procedure" in [4].

The calculation procedure for cyclic loading can be used for constant or variable loading, but load interaction effects are not considered. A procedure for short crack behaviour is not included

ASSESSMENT OF RESULTS

Reserve factors *f* can be calculated for crack size, loading and crack toughness as

$$f_a = \frac{\text{limiting crack size}}{\text{crack size of interest}},$$

$$f_L = \frac{\text{load which would produce a limiting condition}}{\text{applied load}} \quad \text{, and}$$

$$f_{Kmat} = \frac{\text{crack toughness of material}}{\text{crack toughness which produces a limiting condition}}.$$

Sensitivity analyses are recommended to estimate the variation of the results as a function of inaccurate or scattered input parameters. Alternatively some advice on values of partial safety factors is given.

The allowable conditions have to be determined by the user of the FKM Guideline on the basis of

- reserve factors,
- the judgement of the consequences of failure and
- the costs related to different acceptability levels.

CASE STUDIES AND ANNEXES

A large part of the guideline contains case studies and annexes listed in Figure 1. There are 11 worked examples of the assessment of components from the area of mechanical engineering; voluminous compendia of SIF and limit load solutions and of materials data can be found in Annexes 3 an 4. As an example Figure 6 shows a compilation crack growth rates for steels to be used in fatigue crack growth analyses.

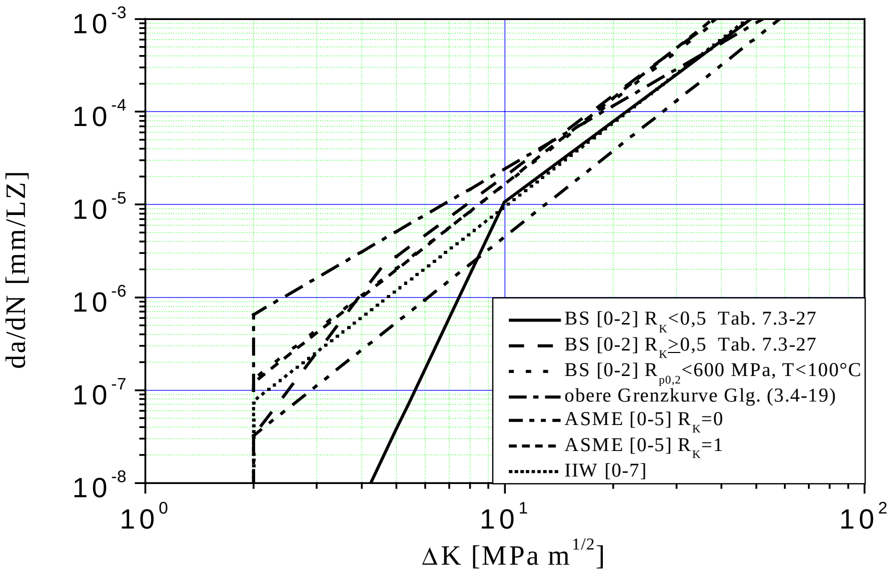

Figure 6: Compilation of crack growth rates for steels in air from other standards and guidelines.

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