Strength Assessment According to the FKM Guideline
Version LIMIT2019
Overview

✦ Motivation

✦ Part I: Strength assessment of non-welded structures
  ▪ Static strength & Workshop 1
  ▪ Fatigue strength & Workshop 2
  ▪ Special topic: Analyzing different loading types in LIMIT & Workshop 3
  ▪ Workshop 4: Assessment of customers structures.....

✦ Part II: Strength assessment of welded structures
  ▪ Stress concepts for welded structures
  ▪ Static strength & Workshop 5
  ▪ Fatigue strength & Workshop 6
  ▪ Weld assessment using effective notch stresses & Workshop 7
  ▪ LIMIT Sensor technology & Workshop 8
  ▪ Workshop 9: Assessment of customers structures.....
Motivation for LIMIT

- Already in the first years of CAE Simulation & Solutions GmbH a large percentage of projects were dealing with the fatigue of welded structures

- We were faced with the following challenges
  - Finding critical loads and load cycle numbers
  - Checking all critical positions
  - Applying different design codes
  - For large problems manual assessment not possible!
Development of LIMIT

- **2004:** start of development: no commercial software was available at that time, covering our needs (DIN15018, DVS-codes)
- **2009:** development of a GUI for LIMIT
  - Easier to use, reduced training period
  - Widespread usage enabled
- **2010:** first commercial installation at Ludwig Engel KG, Austria
- **Current status:**
  - Release 2016
  - Release 2017 Beta
Effects taken into account

- stress gradients normal to surface
- surface factors
- temperature
Assessment of welds with nominal or structural hot spot stresses

a.) complex structures  
b.) simple definition of welds  
c.) visual check of weld geometry
Assessment of welds with nominal or structural hot spot stresses

- static and fatigue assessment
- numerous codes available
- simple post processing

S-N-curve (Wöhler diagram)

- ultimate strength
- yield strength
- finite life fatigue
- infinite life fatigue

\[ D = \sum \frac{n}{N_i} \]

Load cycles \( N \) (log)

\( N_1, N_2, N_{FS}, N_{Cutoff} \)

\( N_{FS} \) - fatigue strength

\( N_{Cutoff} \) - cutoff

\( \sigma_{N1}, \sigma_{N2} \) - stress amplitudes

\( n_1, n_2 \) - load cycles

Wöhler line
LIMIT Within the Simulation Process

Design: 3D-CAD

FE model
Patran, Hypermesh, Abaqus/CAE, ANSYS, NX

Finite Element Input
.bdf, .out, .dat, .inp

FE Solver
Nastran, Abaqus, ANSYS

FE Results
.fil, .odb, .op2, .rst

LIMIT-CAE
Definition of assessments in the GUI

LIMIT-SOLVER
Analysis

LIMIT-VIEWER
Post processing

Global iteration loop, changing geometry

3D-CAD

Mid-surfaces and shell elements

Local loop, e.g. changing weld quality

Degree of utilization in welds
Advantages using LIMIT

✦ Better products
✦ Reduction of time-to-market
✦ Reduction of risk of failure
  ▪ Comprehensive and accurate assessment
  ▪ Assessment quality is improved, especially compared to point-wise assessment
  ▪ Saves money due to less cases of warranty
  ▪ Beneficial for company reputation
✦ Stand alone application, no blocking of other licenses (Ansys, Nastran, Abaqus,..)
✦ Improved assessment documentation

fatigue crack at end of rib
Advantages using LIMIT

- Simple to use for engineers => low costs for training
- Support is provided by experienced engineers of CAE Simulation & Solutions
- Support engineers use LIMIT in everyday customer projects, are thus experts in
  - usage of LIMIT
  - the application of codes and all practical aspects
  - software updates
- LIMIT usage and LIMIT development are closely connected in a small team
  - Features for efficient practical use are constantly added
- Very versatile
  - Numerous design codes
  - Different stress concepts
Strength assessment:

- Investigation whether a structure is fit for design loads.

Why?

- Tech. approval necessary (TUEV, ministry,..)
- Prevention of customer complaints
- Reduction of costs
  - Weight reduction
  - Cheaper manufacturing
  - Material selection,...
Regulated / non regulated fields of mechanical engineering

- **In regulated fields usually special design codes must be met**
  - Railway vehicles: in Germany or Austria mainly: DVS1612 /DVS1608
  - Windpower: approval by German Loyd (GL), on basis of Eurocodes for welded structures, ...
  - Pressure vessels: EN13445, Germany and Austria AD-Guideline, ....
  - ....

- **Non regulated fields / general mechanical engineering**
  - FKM guideline very popular in Germany, Austria and Switzerland
  - Acceptance in regulated field is rising
  - Detailed explanations of assessment procedures for
    - Non welded and welded components
    - Static assessment, fatigue assessment
    - Static and fatigue strength data for many materials
    - Comprehensive
**FKM Guideline:**

**Analytical Strength assessment of components**

- Available since 1994
- Based on
  - former TGL standards from Eastern Germany,
  - VDI2226 and
  - other sources
- Further developed to meet current state of knowledge
- Currently in the 6\textsuperscript{TH} edition, 2012
- Accepted by TUEV
FKM Guideline:

*Analytical strength assessment of components*

- **Static strength assessment**
- **Fatigue strength assessment**
  - Constant amplitude
  - Variable stress amplitude
- **Valid for:**
  - Steel and stainless steel from -40°C to 500°C
  - Cast iron materials from -25°C to 500°C
  - Aluminum materials from -25°C to 200°C
  - Welded steel and welded aluminum
FKM Guideline:

*Organized in Chapters:*

0 General survey

1 Assessment of static strength using nominal stresses

2 Assessment of fatigue strength using nominal stresses

3 Assessment of static strength using local stresses

4 Assessment of fatigue strength using local stresses

5 Annexes

6 Examples

7 Symbols

8 Modifications
Strength Assessment of Non-Welded Structures
Part I
Assessment of static strength using local stresses

Basic procedure

- Non-welded
- FKM, Chapter 3
FKM, Chapter 3.1

Topic: Characteristic service stress

- $\sigma_v$ ... equivalent static stress

Static

- Each relevant static load case gives one dataset of characteristic stresses
- Each stress state is assessed individually
Local stresses:

Typical elements used for Finite Element simulation

- Solid elements (often 10 node tetrahedrons)
  - Machined parts
  - Casted parts
  - Non ductile materials

- Shell elements
  - Thin walled structures
  - Often for welded structures

- Always linear elastic stresses used in FKM-Guideline!!
Stresses

**Nominal stresses**
- Torsion: $\tau_{\text{nom}} = \frac{M_x}{W_p}$
- Bending: $\sigma_{\text{nom}} = \frac{M_z}{W_B}$
- With FE analysis
  - Constant cross section
  - At sufficient distance from boundary conditions or geometric discontinuities

**Local stresses**
- Fine meshes, all notches resolved!
- No sharp notches, model radii > 0!
- Stresses directly used in LIMIT

$\tau_{\text{nom}} = 100 \text{ MPa}$

$\sigma_{\text{nom}} = 150 \text{ MPa}$
Assessment with local stresses

Example, 2D-analysis, :

$R_{0.5}$

$\sigma_{K,\text{max}}$

Tension/Compression
Stresses components used in *LIMIT* for FKM assessments

*Volume elements: FE analysis gives 3D local stress tensors*

1.) FKM: 2D local stresses at surface
   - $\sigma_x, \sigma_y, \tau$
   - Critical plane procedure on surface (default)
   - Stress gradient resolved normal to surface

2.) FKM: Principal stresses
   - $\sigma_1, \sigma_2, \sigma_3$
   - $\sigma_1$ direction of largest absolut principal stress
   - No stress gradient available
Stresses components used in LIMIT for FKM assessments

*Shell elements: FE analysis gives 2D local stress tensors*

1) FKM: 2D local stresses
   - $\sigma_x, \sigma_y, \tau$
   - Critical plane procedure (default)
   - No stress gradient resolved

2) FKM: 2D local stresses in welds
   - $\sigma_{\parallel}$ ... direct stress parallel to weld
   - $\sigma_{\perp}$ ... direct stress transverse to weld
   - $\tau_{\parallel}$ ... shear stress parallel to weld
   - Transformation is performed automatically in weld assessment mode
Stress for assessment, static loading

Assessment is performed using equivalent stresses

- Non-welded components, Chapter 3.1.1
  - Ductile materials => von Mises theory:
  
  \[ \sigma_{VM} = \sqrt{\left(\sigma_x^2 - \sigma_x \sigma_y + \sigma_y^2 + 3\tau_{xy}^2\right)} \]

  - Brittle materials => normal stress hypothesis:
  
  \[ \sigma_{NH} = \text{MAX}\left\{\sigma_1,|\sigma_2|,|\sigma_3|\right\} \]

  - Semiductile materials => superposition:
    
    \[ \sigma_V = q \cdot \sigma_{NH} + (1-q) \cdot \sigma_{VM} \]

    - Steel: q = 0; GJS: q = 0.264; GJM: q = 0.544; GJL: q = 1

  - Multiaxiality:

    \[ h = \frac{\sigma_H}{\sigma_{VM}} = \frac{1}{3} \left(\frac{\sigma_1 + \sigma_2 + \sigma_3}{\sigma_{VM}}\right) \]
FKM, Chapter 3.2, 3.2.1

**Topic: size dependent material strength**
- \( R_m = K_{d,m} \cdot K_A \cdot R_{m,N} \) ... tensile strength
- \( R_p = K_{d,p} \cdot K_A \cdot R_{p,N} \) ... yield strength

**Data and factors**
- Depends on material group
- Standard material values
  - \( R_{m,N}, R_{p,N} \)
- Technological size factor
  - \( K_{d,m}, K_{d,p} \)
- Anisotropy factor: \( K_A \)
- Compression strength factor
- Temperature factor
  - Based on material, temperature \( T \) and duration \( t \)
  - \( K_{T,m} = R_{m,T} / R_m \)
FKM, Chapter 3.2, 3.2.1

Topic: size dependent material strength

\[ R_m = K_{d,m} \cdot K_A \cdot R_{m,N} \] ... tensile strength

\[ R_p = K_{d,p} \cdot K_A \cdot R_{p,N} \] ... yield strength

Case 1:
- Steel: forging, heat treatable, case hardening, GJS, GJM, GJL

Case 2:
- Steel: Non alloyed structural, Fine grain structural, normalized heat treatable, general cast steel
- Aluminum

Source: FKM Guideline, 2003
FKM, Chapter 3.3, 3.3.1

Topic: influence of design characteristics
- \( n_{pl} = \text{MIN}(\sqrt{E \cdot \varepsilon_{ertr}/R_p}; K_p) \) ... section factor
- Double criteria:
  - local material limit + plastic limit load

Data and factors
- \( \varepsilon_{ertr} \) ... critical value of total strain
  - Depends on material group
  - Elongation at break: A
  - Hydrostatic stress state: h
- \( E \) ... Young’s modulus
  - Depends on material group
- \( R_p \) ... yield strength
- \( K_p \) ... plastic notch factor
  - \( K_p = \text{plastic limit load / elastic limit load} \)
FKM, Chapter 3.3, 3.3.1

- **Topic: influence of design characteristics**
  - \( n_{pl} = \text{MIN}(\sqrt{E \cdot \varepsilon_{ertr}/R_p}); K_p) \) ... section factor

- **Data and factors**
  - \( \varepsilon_{ertr} \) ... critical value of total strain
    - Depends on material group
    - Elongation at break: A
    - Hydrostatic stress state: h
  - E ... Young’s modulus
    - Depends on material group
  - \( R_p \) ... yield strength
  - \( K_p \) ... plastic notch factor
    - \( K_p = \text{plastic limit load} / \text{elastic limit load} \)
    - In case of local stress peaks, e.g. holes, only critical strain is relevant. Set \( K_p \) to a large value

Source: Bauteilfließkurve, Dr.-Ing.Hänel, Seminarunterlagen
FKM, Chapter 3.3, 3.3.1

- **Topic: influence of design characteristics**
  - $n_{pl} = \text{MIN}(\sqrt{E \cdot \varepsilon_{ertr}/R_p}); K_p)$ ... section factor

- **Data and factors**
  - $\varepsilon \cdot \sigma = \text{constant}$
  - $\varepsilon_{ertr}$ and $R_p$ are corresponding stress/strain values and mark one critical point on the Neuber-hyperbola (red dot).
  - Using neubers theory the permissible elastic stress can be calculated:
    
    \[
    \sigma_{ertr} = n_{pl} \cdot R_p \\
    \varepsilon_{el} = n_{pl} \cdot R_p / E \\
    n_{pl} \cdot R_p \cdot n_{pl} \cdot R_p / E = R_p \cdot \varepsilon_{ertr} \\
    \Rightarrow n_{pl} = \sqrt{E \cdot \varepsilon_{ertr}/R_p}
    \]

Source: Neuber-Hyperbel, Dr.-Ing.Hänel, Seminarunterlagen
FKM, Chapter 3.3, 3.3.1

**Topic: influence of design characteristics**
- \( n_{pl} = \text{MIN}(\sqrt{E \cdot \epsilon_{ertr}/R_p}); K_p \)  ... section factor

**Examples for \( K_p \)**
- \( K_p \) ... plastic notch factor
  - \( K_p = \) plastic limit load / elastic limit load
  - In case of local stress peaks, e.g. holes, only critical strain is relevant. Set \( K_p \) to a large value

---

**Design parameter, non-welded**

Tension bar with notches:

\( K_p \) ... plastic notch factor:
- \( K_{p,\text{base}} = 1,0 \) ... area without notch
- \( K_{p,\text{notch}} = 3,0 \) ... at notch \( K_t \), sec. 5.2

\( K_p = 1,0 \) ... brittle material
**Static Strength**

**Design parameter, non-welded**

**Bending:**

- \( K_{p,\text{rect}} = 1.5 \) … rectangular section
- \( K_{p,\text{circ}} = 1.7 \) … circular section
- \( K_{p,\text{tw}} = 1.0 \) … thin walled section
- \( K_p = 1.0 \) … brittle material

**Bending: plate with notch**

- \( K_{p,b} = 1.5 \)
- \( K_{t,b} = 3.0 \) (FKM, sec. 5.2)
- \( K_{p,\text{notch}} = 1.5 \times 3.0 = 4.5 \)
- \( K_{p,\text{plate}} = 1.5 \)
- \( K_p = 1.0 \) … brittle material
FKM, Chapter 3.4

**Topic: final strength of the component**

- Double criteria included in $n_{pl}$:
  - Plastic notch factor (plastic limit load)
  - Critical plastic strain (local material limit)
- $\sigma_{SK} = R_p \cdot n_{pl}$ ... component strength
FKM, Chapter 3.5, 3.5.1, 3.5.2

**Topic: definition of safety factors**

- Probability of survival $P_{Ü} = 97.5\%$
- $j_{ges}$ ... total safety factor (equ. 3.5.5):
  - Basic safety factor plus temperature factors
  - Additional partial safety factors
- Basic safety factors
  - $j_m, j_p, j_{mt}, j_{pt}$
  - Can be chosen under consideration of consequences of failure and probability of the occurrence of high loads
- Partial safety factors:
  - $j_G$ ... cast components: 1.4 or 1.25 for tested
  - $\Delta j$ ... non ductile cast components, depends on elongation at break $A$
FKM, Chapter 3.6, 3.5.1, 3.5.2

- **Topic: degree of utilization**
  - $a_{SK} = \frac{\sigma_v}{\sigma_{SK}/j_{ges}} \leq 1$

- **Control of multiaxiality:**
  - $h > h_{max} = 1.333$ ... tension
    - $-a_{SH,Zug} = \frac{\sigma_H}{\sigma_{SH,Zug}/j_{ges}} \leq 1$
  - $h < h_{min} = -1.333$ ... compression
    - $-a_{SH,Druck} = \frac{\sigma_H}{\sigma_{SH,Druck}/j_{ges}} \leq 1$
Workshop 1: Shaft with shoulder

**LIMIT GUI**
- GUI/Menus/Help
- Importing a model
- View manipulations
- Sets and assessment zones

**Assessment of static strength**
- Assigning setups
  - Assignment: Base Material
  - FKM 6\textsuperscript{th} edition
- Defining Jobs
  - Selecting result files
  - Selecting setups
  - Selecting loads
Workshop 1: Shaft with shoulder

- Postprocessing with LIMIT Viewer
  - Basic features
  - Views, coupling views
  - Results
    - Changing legend/show max
    - Searching hot spots
    - Element sets by results
  - Query function
  - Annotation
  - Pictures

- Checking results via text-files
  - Jobname.txt
Assessment of fatigue strength using local stresses

Basic procedure

- Non-welded
- FKM, Chapter 4

4.1 Characteristic service stresses: $\sigma_a, \sigma_m$

4.2 Material properties: $\sigma_{W,zd}$

4.3 Design parameters: $K_{WK}$

4.4.1 Comp. fatigue limit for zero mean stress: $\sigma_{WK}$

4.4.2 Comp. fatigue limit for actual mean stress: $\sigma_{AK}$

4.4.3 Comp. variable amplitude fatigue strength: $\sigma_{BK}$

4.5 Safety factors: $j_D$

4.6 Assessment: $a_{BK}$
FKM, Chapter 4.1

**Topic: Characteristic service stress**
- $\sigma_a$, $\sigma_m$ ... amplitude and mean stress

**Fatigue**
- Stress amplitude and mean stresses are relevant
- At least two load cases are needed
- Each load case must be a relevant service stress state

---

**Service stress, non-welded**

4.1 Characteristic service stresses: $\sigma_a$, $\sigma_m$

4.2 Material properties: $\sigma_{Wzd}$

4.3 Design parameters: $K_{WK}$

4.4.1 Comp. fatigue limit for zero mean stress: $\sigma_{WK}$

4.4.2 Comp. fatigue limit for actual mean stress: $\sigma_{AK}$

4.4.3 Comp. variable amplitude fatigue strength: $\sigma_{BK}$

4.5 Safety factors: $j_D$

4.6 Assessment: $a_{BK}$
Stress for assessment, fatigue

Assessment is performed using stress components

Interaction of components is calculated at the end

فضاء للإجابة

Non-welded components, Chapter 4.1.1

- Surface stresses: $\sigma_x, \sigma_y, \tau$
- Principal stresses: $\sigma_1, \sigma_2, \sigma_3$
Characteristic service stress, fatigue

- Classification of stresses depending on loading condition
  - Proportional stresses
  - Synchronous stresses
  - Non-proportional stresses
    - Simultaneously
    - Time-delayed
    - Uncorrelated in terms of time

- Has impact on
  - Calculation of degrees of utilization
Proportional stresses

- Always when single oscillating load acting on structure
- Directions of principal stresses remain constant in time

\[
F(t) = F_{\text{max}} \sin(\omega t)
\]

Fatigue Stresses

Point of interest
Stress: 2D surface tensor

Signs of stress amplitudes can be taken from FE analysis!

\[
R = \frac{\sigma_m - \sigma_a}{\sigma_m + \sigma_a} = -1 \quad \text{... stress ratio}
\]

LIMIT:

- LC1 .... \( F_{\text{max}} \)
- LC2 .... \(-F_{\text{max}}\)
**Synchronous stresses**
- Amplitudes proportional
- Mean values non proportional
- Directions of principal stresses strictly spoken not constant

Fatigue Stresses

\[ F_1(t) = F_{\text{max}} \ast \sin(\omega t) \]

\[ F_2 \text{ ... constant} \]

Signs of stress amplitudes can be taken from FE analysis!

\[ R = \frac{(\sigma_m - \sigma_a)}{(\sigma_m + \sigma_a)} \quad \text{... stress ratio} \]

**LIMIT:**
- LC1 ... \( F_{\text{max}} + F_2 \)
- LC2 ... \( -F_{\text{max}} + F_2 \)

Point of interest
Stress: 2D surface tensor

---

www.cae-sim-sol.com  LIMIT 2019 – FKM Course
**Non proportional**
- Two or more loads varying in time
- Amplitudes non proportional
- Mean values non proportional
- Directions of principal stresses varying

Point of interest
Stress: 2D surface tensor

No clear interaction of stress components!

Principle stress axes change in time!
Non proportional

- Two or more loads varying in time
- Amplitudes non proportional
- Mean values non proportional
- Directions of principal stresses varying

Fatigue Stresses

LIMIT:  
LC1 \[ M_{B,\text{max}} + M_{T,\text{max}} \]  
LC2 \[ M_{B,\text{max}} - M_{T,\text{max}} \]  
LC3 \[ M_{B,\text{min}} + M_{T,\text{min}} \]  
LC4 \[ M_{B,\text{min}} - M_{T,\text{min}} \]
FKM, Chapter 4.2, 4.2.1

**Topic: strength dependent fatigue limit**
- \( \sigma_{W,zd} = f_{W,\sigma} \cdot R_m \) ... fat. limits rev. stress
- \( \tau_{W,s} = f_{W,\tau} \cdot \sigma_{W,zd} \) ... fat. limits rev. shear

**Data and factors**
- \( R_m \) ... taken from static part, Chapter 3.2
- \( f_{W,\sigma} \) ... Fatigue strength factor for completely reversed stress
  - 0.45 for steel, 0.30 for aluminum
- \( f_{W,\tau} \) ... Fatigue strength factor for completely reversed shear stress
  - 0.577 ductile, 1.0 Brittle
- Temperature factor
  - Based on material group and temperature \( T \)
  - \( K_{T,D} = \sigma_{W,zd,T} / \sigma_{W,zd} \)
FKM, Chapter 4.3, 4.3.1

Topic: influence of design characteristics

- $K_{WK,\sigma} = \frac{1}{n_\sigma} \left[ 1 + \frac{1}{K_f} \cdot \left( \frac{1}{K_R} - 1 \right) \right] \cdot \frac{1}{K_V \cdot K_S \cdot K_{NL,E}}$

- $K_{WK,\tau} = \frac{1}{n_\tau} \left[ 1 + \frac{1}{K_f} \cdot \left( \frac{1}{K_R} - 1 \right) \right] \cdot \frac{1}{K_V \cdot K_S}$

Data and factors

- $n_{\sigma,\tau} \ldots K_t$-$K_f$-ratio, Chapter 4.3.1.3
- $\tilde{K}_f \ldots$ estimate of fatigue notch factor
- $K_R \ldots$ roughness factor
- $K_V \ldots$ surface treatment factor
- $K_S \ldots$ coating factor
- $K_{NL,E} \ldots$ factor for GJL
FKM, Chapter 4.3, 4.3.1

Topic: influence of design characteristics

\[ K_{WK,\sigma} = \frac{1}{n_{\sigma}} \left[ 1 + \frac{1}{\tilde{K}_f} \cdot \left( \frac{1}{K_R} - 1 \right) \right] \cdot \frac{1}{K_V \cdot K_S \cdot K_{NL,E}} \]

\[ K_{WK,\tau} = \frac{1}{n_{\tau}} \left[ 1 + \frac{1}{\tilde{K}_f} \cdot \left( \frac{1}{K_R} - 1 \right) \right] \cdot \frac{1}{K_V \cdot K_S} \]

Data and factors

- \( n_{\sigma,\tau} \) ... Kt-Kf-ratio, Chapter 4.3.1.3
- \( \tilde{K}_f \) ... estimate of fatigue notch factor
- \( K_R \) ... roughness factor
- \( K_V \) ... surface treatment factor
- \( K_S \) ... coating factor
- \( K_{NL,E} \) ... factor for GJL

FKM Guideline 2012, Fig. 4.3-2: Kt-Kf-ratio as function of the related stress gradient G
FKM, Chapter 4.4.1, 4.4.1.1

Topic: component fatigue limit for

- completely reversed stress
- (zero mean stress)
- \( \sigma_{WK} = \sigma_{W,zd} \cdot K_{WK,\sigma} \) ... fat. limits rev. stress
- \( \tau_{WK} = \tau_{W,s} \cdot K_{WK,\tau} \) ... fat. limits rev. stress

4.1 Characteristic service stresses: \( \sigma_a, \sigma_m \)

4.2 Material properties: \( \sigma_{W,zd} \)

4.3 Design parameters: \( K_{WK} \)

4.4.1 Comp. fatigue limit for zero mean stress: \( \sigma_{WK} \)

4.4.2 Comp. fatigue limit for actual mean stress: \( \sigma_{AK} \)

4.4.3 Comp. variable amplitude fatigue strength: \( \sigma_{BK} \)

4.5 Safety factors: \( j_D \)

4.6 Assessment: \( a_{BK} \)
**Component fatigue limit, zero mean stress, non-welded**

**FKM, Chapter 4.4.2, 4.4.2.1**

- **Topic: component fatigue limit as**
  - a function of mean stress $\sigma_m$ and $\tau_m$
  - $\sigma_{AK} = \sigma_{WK} \cdot K_{AK,\sigma}$ ... fat. limits stress
  - $\tau_{AK} = \tau_{WK} \cdot K_{AK,\tau}$ ... fat. limits stress

- **Data and factors**
  - $K_{AK}$ ... mean stress factor

---

**Diagram: Fatigue Strength**

4.1 Characteristic service stresses: $\sigma_a$, $\sigma_m$

4.2 Material properties: $\sigma_{W,zd}$

4.3 Design parameters: $K_{WK}$

4.4.1 Comp.fatigue limit for zero mean stress: $\sigma_{WK}$

**4.4.2 Comp.fatigue limit for actual mean stress: $\sigma_{AK}$**

4.4.3 Comp.variable amplitude fatigue strength: $\sigma_{BK}$

4.5 Safety factors: $j_D$

4.6 Assessment: $a_{BK}$
**Component fatigue limit, non-welded**

**FKM, Chapter 4.4.2, 4.4.2.1**

- **Topic:** component fatigue limit as
  - a function of mean stress $\sigma_m$ and $\tau_m$
  - $\sigma_{AK} = \sigma_{WK} \cdot K_{AK,\sigma}$ ... fat. limits stress
  - $\tau_{AK} = \tau_{WK} \cdot K_{AK,\tau}$ ... fat. limits stress

- **Data and factors**
  - $K_{AK}$ ... mean stress factor
  - $R = (\sigma_m - \sigma_a) / (\sigma_m + \sigma_a)$ ... stress ratio
  - Fields I to IV depend on $R$-value
  - Mean stress sensitivity **material group** dependent
  - Typ of overloading
    - $F1$: the mean stress remains constant
    - $F2$: the stress ratio remains constant (default)
    - $F3$: the minimum stress remains constant
    - $F4$: the maximum stress remains constant

**FKM Guideline 2012: Fatigue limit diagrams (Haigh diagram)**

- $R = -\infty$
- $R = -1$
- $R = 0$
- $R = 0.5$
- $M_\sigma = M_o / 3$
- $M_\sigma = 0$

**Equations:**

- $\sigma_{AK} = \sigma_{WK} \cdot K_{AK,\sigma}$
- $\tau_{AK} = \tau_{WK} \cdot K_{AK,\tau}$

- **Stress ratio:**
  - $R = (\sigma_m - \sigma_a) / (\sigma_m + \sigma_a)$

**Diagram:**

- Fields I to IV
- Mean stress sensitivity
- Stress ratio
- Typ of overloading
**Component fatigue limit, non-welded**

**FKM, Chapter 4.4.2, 4.4.2.1**

**Topic: component fatigue limit as**
- a function of mean stress $\sigma_m$ and $\tau_m$
- $\sigma_{AK} = \sigma_{WK} \cdot K_{AK,\sigma}$ ... fat. limits stress
- $\tau_{AK} = \tau_{WK} \cdot K_{AK,\tau}$ ... fat. limits stress

**Data and factors**
- $K_{AK}$ ... mean stress factor
- $R = (\sigma_m - \sigma_a) / (\sigma_m + \sigma_a)$ ... stress ratio
- Fields I to IV depend on $R$-value
- Mean stress sensitivity **material group** dependent
- Typ of overloading
  - F1: the mean stress remains constant
  - F2: the stress ratio remains constant (default)
  - F3: the minimum stress remains constant
  - F4: the maximum stress remains constant

**FKM Guideline 2012: Fatigue limit diagrams (Haigh diagram)**

\[ R = \frac{\sigma_m - \sigma_a}{\sigma_m + \sigma_a} \]
Component fatigue limit, non-welded

FKM, Chapter 4.4.2, 4.4.2.4

- \( K_{AK} \) ... mean stress factor
  - \( R = (\sigma_m - \sigma_a) / (\sigma_m + \sigma_a) \) ... stress ratio
  - Fields I to IV depend on R-value
  - Mean stress sensitivity material group dependent
  - Typ of overloading
    - F1: the mean stress remains constant
    - F2: the stress ratio remains constant (default)
    - F3: the minimum stress remains constant
    - F4: the maximum stress remains constant

FKM Guideline 2012: Fatigue limit diagrams (Haigh diagrams)
Overloading cases F1 and F2
FKM, Chapter 4.4.3, 4.4.3.1

- **Topic: influence of variable amplitude**
  - variable amplitude fatigue strength factor
    - \( \sigma_{BK} = \sigma_{AK} \cdot K_{BK,\sigma} \)
    - \( \tau_{BK} = \tau_{AK} \cdot K_{BK,\tau} \)

- **Variable amplitude**

\[ K_{BK} = \frac{\sigma_a}{\sigma_{a,1}} \]

\[ K_{BK} = 1 \]

\[ K_{BK} > 1 \]

\[ 10^6 \text{ Number of cycles} \]
**FKM, Chapter 4.4.3, 4.4.3.1**

- **Topic: influence of variable amplitude**
  - variable amplitude fatigue strength factor
  - $\sigma_{BK} = \sigma_{AK} \cdot K_{BK,\sigma}$
  - $\tau_{BK} = \tau_{AK} \cdot K_{BK,\tau}$

- **Variable amplitude**

Source: FKM Guideline 2012

**S-N-curves (Wöhlerlinien), non-welded**

- I ... steel, cast iron
- II ... alu, austenitic steel

Source: FKM Guideline 2012
damage calculation

\[ D = \sum \frac{n_i}{N_i} \]

\[ \sigma_{a1} \]

\[ \sigma_{a2} \]

\[ n_1 \]

\[ n_2 \]

\[ 10^4 \]

\[ N_1 \]

\[ N_2 \]

\[ N_D \]

\[ N_{\text{cutoff}} \]

Wöhler line

Cutoff

Miner elementary
**Component variable amplitude fatigue strength, non-welded**

**FKM, Chapter 4.4.3, 4.4.3.1**

- **Topic: influence of variable amplitude**
  - \( \sigma_{BK} = \sigma_{AK} \cdot K_{BK,\sigma} \)
  - \( \tau_{BK} = \tau_{AK} \cdot K_{BK,\tau} \)

- **Fatigue life curve, non-welded**

**Variable amplitude fatigue**

- \( K_{BK} = \left[ \frac{A_{ele} \cdot N_D \cdot D_m}{\bar{N}} \right]^{1/k} \)

- \( A_{ele} = \frac{1}{\sum_{i=1}^{j} \frac{n_i}{\bar{N}} \cdot \left[ \frac{\sigma_{ai}}{\sigma_{a,1}} \right]^{1/k}} \)

**Data**

- \( \bar{N} \ldots \) required cycle number: \( \Sigma n \)
- \( N_D \ldots \) cycle knee point
- \( A_{ele} \ldots \) dist. Fatigue life curve and const. ampl. S-N curve (Miner elem.)
- \( D_m \ldots \) effective damage sum (4.4.51)
- \( k \ldots \) slope exponent

Source: FKM Guideline 2012
FKM, Chapter 4.4.3, 4.4.3.1

Topic: influence of variable amplitude

- variable amplitude fatigue strength factor
  \[ \sigma_{BK} = \sigma_{AK} \cdot K_{BK,\sigma} \]
  \[ \tau_{BK} = \tau_{AK} \cdot K_{BK,\tau} \]

Maximum values

- \[ \sigma_{BK,\text{max}} = 0.75 \cdot R_p \cdot n_{pl} \]
- \[ \tau_{BK,\text{max}} = 0.75 \cdot f_\tau \cdot R_p \cdot n_{pl} \]

- \( R_p \) ... yield strength
- \( n_{pl} \) ... section factor
- \( f_\tau \) ... shear strength factor, tab. 3.2.5

Fatigue Strength

Component variable amplitude fatigue strength, non-welded
FKM, Chapter 4.4.3, 4.4.3.1

- **LIMIT settings for ASSESSMENT**
  - **FATIGUE_STRENGTH** => $K_{BK} = 1$
    - German: Dauerfestigkeit
    - Number of cycles in spectra is irrelevant!
  - **MINER_ELEMENTARY** => $K_{BK} \geq 1$
    - German: Betriebsfestigkeit
    - Number of cycles:
      » Taken from spectra or
      » Taken from setup: Requ. Num. Of Cycles
FKM, Chapter 4.5, 4.5.1

Topic: definition of safety factors

- \( j_D = j_S \cdot \frac{j_F \cdot j_G}{K_{T,D}} \)

Data and factors

- \( j_S \) ... load safety factor, default 1.0
- \( j_F \) ... material safety factor, tab. 4.5.1
- \( j_G \) ... cast iron factor, tab. 4.5.2
- \( K_{T,D} \) ... temperature factor, chapter 4.2.3
  (depends on material group and temperature)

- In LIMIT safety factors are selected on:
  - Consequence of failure: severe/mean/moderate
  - Regular inspections: yes/no
FKM, Chapter 4.6, 4.6.1

Topic: Calc. of degree of utilization

Individual stress types e.g.: 2D-tensor

- $a_{BK,\sigma_x} = \frac{\sigma_{a,x,1}}{\sigma_{BK,x}/j_D} \leq 1$
- $a_{BK,\sigma_y} = \frac{\sigma_{a,y,1}}{\sigma_{BK,x}/j_D} \leq 1$
- $a_{BK,\tau} = \frac{\tau_{a,1}}{\tau_{BK}/j_D} \leq 1$

Individual stress types

Fatigue Strength

Assessment, non-welded

4.1 Characteristic service stresses: $\sigma_a, \sigma_m$

4.2 Material properties: $\sigma_{W,zd}$

4.3 Design parameters: $K_{WK}$

4.4.1 Comp. fatigue limit for zero mean stress: $\sigma_{WK}$

4.4.2 Comp. fatigue limit for actual mean stress: $\sigma_{AK}$

4.4.3 Comp. variable amplitude fatigue strength: $\sigma_{BK}$

4.5 Safety factors: $j_D$

4.6 Assessment: $a_{BK}$
FKM, Chapter 4.6, 4.6.2

Topic: Calc. of degree of utilization

Combined types of stress

- \( a_{BK,\sigma_v} = q \cdot a_{NH} + (1 - q) \cdot a_{GH} \leq 1 \)

Data and factors

- \( a_{NH} = 0.5 \cdot \{ | a_{BK,\sigma_x} + a_{BK,\sigma_y} | + \sqrt{(a_{BK,\sigma_x} - a_{BK,\sigma_y})^2 + 4 \cdot a_{BK,\tau}^2} \} \)
- \( a_{GH} = \sqrt{(a_{BK,\sigma_x}^2 + a_{BK,\sigma_y}^2 - a_{BK,\sigma_x} \cdot a_{BK,\sigma_y} + a_{BK,\tau}^2)} \)

- \( q \) ... depends on ductility of material:
  - Steel, wrought aluminum: \( q = 0 \)
  - GJS: \( q = 0.264 \)
  - GJM: \( q = 0.544 \)
  - GJL: \( q = 1 \)
FKM, Chapter 4.6, 4.6.2

Topic: Calc. of degree of utilization

Combined types of stress

\[ a_{BK,\sigma_v} = q \cdot a_{NH} + (1 - q) \cdot a_{GH} \leq 1 \]

Data and factors

\[ a_{NH} = 0.5 \cdot \{ | a_{BK,\sigma_x} + a_{BK,\sigma_y} | + \sqrt{(a_{BK,\sigma_x} - a_{BK,\sigma_y})^2 + 4 \cdot a_{BK,\tau}^2} \} \]

\[ a_{GH} = \sqrt{a_{BK,\sigma_x}^2 + a_{BK,\sigma_y}^2 - a_{BK,\sigma_x} \cdot a_{BK,\sigma_y} + a_{BK,\tau}^2} \]

\[ q \ldots \text{depends on ductility of material:} \]
- Steel, wrought aluminum: \( q = 0 \)
- GJS: \( q = 0.264 \)
- GJM: \( q = 0.544 \)
- GJL: \( q = 1 \)

Assessment, non-welded

Signs for combined stresses

Procedure within LIMIT

- Check if same load pair responsible for \( a_{BK,\sigma_x}, a_{BK,\sigma_y} \)
- If different load pairs are involved, the signs are set for maximum value of \( a_{BK,\sigma_v} \)

Proportional/synchronous stresses

- Signs taken directly from FEA
- Combined D.o.U.: AUTO

Non-proportional loads, see later chapter
Combined Degree of Utilization

GUI: Edit: Setup
Assignment: Fatigue
Combined D.o.U

- **AUTO** (default): In this case LIMIT checks, whether the signs of individual stress amplitudes can be used or not. This is done on the basis of the load cases responsible for each amplitude. If normal stresses origin from the same load cases, signs are taken as calculated by FEA.
- **FKM_MAX_ALG**: will give highest possible degree of utilization after altering signs. i.e. worst case with respect to signs.
- **OFF**: deactivates combined criteria
- **LIN**: linear summation of all DoU (CAE add-on, not part of FKM)
FKM, Chapter 4.6, 4.6.2

- Topic: Calc. of degree of utilization
- Check results in Job.txt-file!

4.1 Characteristic service stresses: $\sigma_a$, $\sigma_m$

4.2 Material properties: $\sigma_{W,zd}$

4.3 Design parameters: $K_{WK}$

4.4.1 Comp. fatigue limit for zero mean stress: $\sigma_{WK}$

4.4.2 Comp. fatigue limit for actual mean stress: $\sigma_{AK}$

4.4.3 Comp. variable amplitude fatigue strength: $\sigma_{BK}$

4.5 Safety factors: $j_D$

4.6 Assessment: $a_{BK}$
Strength Assessment of Non-Welded Structures

Overview of Assessments
Base material assessment using local stresses

- **GUI: Edit: Setup**
- **Assignment: Base Material**
- **Material group:**
  - CASE_HARDENING_STEEL
  - STAINLESS_STEEL
  - FORGING_STEEL
  - STEEL
  - GS, GJS, GJM, GJL
  - WROUGHT_ALUMINIUM
  - CAST_ALUMINIUM
- **All assessment types supported:**
  - Static strength
  - Fatigue strength
  - And mixed types
Workshop 2: Shaft with shoulder

- Assessment of fatigue strength

  - Defining Loads
    - Proportional / synchronous
    - Defining spectra
  
  - Assigning setups
    - Assignment: Base Material
    - FKM 6th edition
  
  - Defining Jobs
Workshop 2: Shaft with shoulder

- **Postprocessing with LIMIT Viewer**
  - Basic features
  - Views, coupling views
  - Results
    - Changing legend/show max
    - Searching hot spots
    - Element sets by results
  - Query function
  - Annotation
  - Pictures

- **Checking results via text-files**
  - Jobname.txt
Special topic: Analyzing different loading types in LIMIT

- Proportional stresses
- Synchronous stresses
- Non-proportional stresses

Fatigue Stresses
Proportional stresses

- Always when single oscillating load acting on structure
- Directions of principal stresses remain constant in time

\[ F(t) = F_{\text{max}} \cdot \sin(\omega t) \]

Point of interest
Stress: 2D surface tensor

Fatigue Stresses

Signs of stress amplitudes can be taken from FE analysis!

\[
R = \frac{\sigma_m - \sigma_a}{\sigma_m + \sigma_a} = -1 \quad \text{... stress ratio}
\]

LIMIT:
LC1 = \( F_{\text{max}} \)
LC2 = \(- F_{\text{max}} \)
**Synchronous stresses**

- Amplitudes proportional
- Mean values non proportional
- Directions of principal stresses strictly spoken not constant

![Graph of synchronous stresses](image)

**Fatigue Stresses**

\[
F(t) = F_{\text{max}} \cdot \sin(\omega t)
\]

**LIMIT:**

- \(LC1 = F_{\text{max}} + F_2\)
- \(LC2 = -F_{\text{max}} + F_2\)

**Stress: 2D surface tensor**

\(\sigma_{x}, \sigma_{y}, \tau_{xy}\)

**Signs of stress amplitudes can be taken from FE analysis!**

\[R = \frac{\sigma_{m} - \sigma_{a}}{\sigma_{m} + \sigma_{a}}\] ... stress ratio
Forcing synchronous or proportional loading

- Two ways of always forcing synchronous or proportional scenarios:
  - Only two load cases used
Forcing synchronous or proportional loading

- E.g. synchronous torsion and bending of a shaft
- Following steps in the LoadManager are possible:
  - Create FE Results
    - Two individual FE load cases
    - Torsion and Biegung
  - Create Loads
    - Linear combination of two FE Results
    - TB1 and TB2
    - This way limit will always assume synchronous loads

\[ F(t) = F_{\text{max}} \times \sin(\omega t) \]
Forcing synchronous or proportional loading

Two ways of always forcing synchronous or proportional scenarious:

- Only two load cases used or
- Activating option Criteria = CRIT_LCPAIR in JobManager
  - In this case all loads are assessed pair wise
  - Will take longer, but all stress components will result from same two loads!
  - Not as conservative as default setting (Criteria = SPECTRUM).
Fatigue Stresses

Non proportional

- Two or more loads varying in time
- Amplitudes non proportional
- Mean values non proportional
- Directions of principal stresses varying

LIMIT:

LC1 .... \( M_{B,max} + M_{T,max} \)
LC2 .... \( M_{B,max} - M_{T,max} \)
LC3 .... \( M_{B,min} + M_{T,min} \)
LC4 .... \( M_{B,min} - M_{T,min} \)

Conservative approach: maximum amplitudes simultaneous!
Non proportional loads

*Further types of non-proportional loading, FKM Chapter 4.6.2.2*

- Simultaneous occurrence of maximum amplitudes
- Time-delayed occurrence of maximum amplitudes
- Occurrence of maximum amplitudes uncorrelated in terms of time
Non proportional loads

*Simultaneous occurrence of maximum amplitudes*

- FKM Chapter 4.6.2.2
- Define a spectrum for each non proportional load group
- Select the spectra in the JobManager and introduce the flag *NON_PROPORTIONAL_X=1.0
- LIMIT will perform separate fatigue assessments for all spectra and will add the combined degrees of utilization over all spectra (see next page).
- E.g. text output for the critical element (last lines):

```plaintext
FKM-GUIDELINE:
LIST OF COMBINED DEGREES OF UTILIZATION OF NON-PROP. LOADS
ASSESSMENT POSITION:  1
(SPECTRUM_#,   DoU):
  1,  0.71511
  2,  0.61119
  3,  0.98258

TOTAL DoU:   2.3089
```
Non proportional loads

*Simultaneous occurrence of maximum amplitudes*

- JobManager
- Loads > Use Spectra
- Place 
  
  *NON_PROPORTIONAL

  after each spectrum
- Run the analysis
Non proportional loads

*Time delayed occurrence of maximum amplitudes*

- FKM Chapter 4.6.2.2
- Define a spectrum for each non proportional load group
  - Constant amplitude spectrum
  - Variable amplitude spectrum
- Select MINER_ELEMENTARY in Edit:Setup
- Select all spectra in the JobManager (see next slide)
- Load spectra are added with respect to load cycles
- Run the analysis
Non proportional loads

*Time delayed occurrence of maximum amplitudes*

- JobManager
- Loads > Use Spectra
- Run the analysis
Non proportional loads

*Occurrence of maximum amplitudes uncorrelated in terms of time*

- Conservative approach: sum of combined degrees of utilization over all spectra
- Since LIMIT2015: rain flow counting, critical section plane and scaled normal stress
Workshop 3

*Special topic: Analyzing different loading types in LIMIT*

- Proportional stresses
- Synchronous stresses
- Non-proportional stresses
Further important chapters in FKM guideline

**FKM Chapter 5**
- 5.1 Material tables
- 5.2 Stress concentration factors
- 5.3 Fatigue notch factors
- 5.4 Fatigue classes for welded components

**FKM Chapter 6**
- Various examples
Workshop Part 4:

Assessment of customers structures......
Strength Assessment of Welded Structures

Part II
Stress Concepts for Welded Structures
Characteristic stress in welded structures

- **Crack initiation**
  - Stress amplitude and number of cycles relevant
  - Cracks start at local stress peaks (holes, notches,...)
  - Local stress peaks must be taken into account!
Weld Analysis with LIMIT

- Single sided fillet weld
  - Fillet throat critical => stresses in throat needed!
  - A.) Using section forces from shell model
  - B.) Using section forces from solid model & LIMIT sensors
  - C.) R1-effective notch

Load

Cracks

no singularities

Sensors
Weld Analysis with LIMIT

- Double sided fillet weld
  - Weld toes critical => simpler approach
    A.) Shell stresses can be used
    B.) Solid model & LIMIT sensors
    C.) CAB-method (structural stress at transition lines)

Load ➔ Cracks

\[ r = \sqrt{2 \times a}, \text{ avoids singularities} \]
Weld Analysis with LIMIT

Example: Solid modeling & weld assessment with sensors
Strongly mesh dependent results:
Stress concepts for welded structures

- **Nominal stress**
  - classic concept

- **Notch stress**
  - (peak stress)

- **Structural hot spot stress** (IIW)
Nominal stresses

✦ Stresses relating to nominal section

✦ Permissible stresses include:
  ▪ Stress increase due to change in stiffness (I)
  ▪ Local notch effect through weld root or weld toe (II)

<table>
<thead>
<tr>
<th>Kerbfall</th>
<th>Konstruktionsdetail</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>$L \leq 50\text{mm}$</td>
</tr>
<tr>
<td>71</td>
<td>$50 &lt; L \leq 80\text{mm}$</td>
</tr>
<tr>
<td>63</td>
<td>$80 &lt; L \leq 100\text{mm}$</td>
</tr>
<tr>
<td>58</td>
<td>$L &gt; 100\text{mm}$</td>
</tr>
</tbody>
</table>

Source: EC3
Nominal stress concept in LIMIT

- **FEA mesh size**
  - Fine mesh
  - Element size near thickness or even finer
  - Higher order elements: 8-node quadrilaterals
  - Stress extraction to avoid singularities
    - D ... at ends of welds (e.g. 2.0 x t)
    - d ... transverse to weld (e.g. 1.5 x t, see DVS1612)
**Structural hot spot stress**

- According to IIW (International Institute of Welding)
- Stresses include structural effect (I)
- Permissible values include notch of weld (II)

### Table: Structural Hot Spot Stress

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>100</strong></td>
<td><img src="image1.png" alt="Image 1" /> 4) Unbelastete Kehlnähte.</td>
</tr>
<tr>
<td><strong>100</strong></td>
<td><img src="image2.png" alt="Image 2" /> 5) Enden von Anschlussblechen und Längsteilen.</td>
</tr>
<tr>
<td><strong>100</strong></td>
<td><img src="image3.png" alt="Image 3" /> 6) Enden von Gußlamellen und ähnliche Anschlüsse.</td>
</tr>
</tbody>
</table>

Source: FKM Guideline 2012
Effective notch stress according to Radaj

- Toes and roots modeled with radius 1mm
- Linear elastic FE analysis
- Stresses include all effects
- Structural steel: FAT 225 (2 Mio)
- Only efficient for details
Weld Analysis with LIMIT

- **Basic features of LIMIT**
  - Automated detection of elements along welds based on different shell properties for flange and web
  - Visualization of weld details relative to local weld direction
Weld Analysis with LIMIT

Basic features of LIMIT

- Checking all critical points (red circles)
  - Base material
  - Weld section
  - Toes and Roots
Local Shell Element Coordinate Systems

- **Element coordinate systems not aligned with weld direction**
  - Abaqus default: local 1-axis in general parallel to global x-axis
  - Ansys or Nastran default: local 1-axis depends on node numbering and interpolation functions

- **Transformation to local weld coordinate system**

  ![Diagram of Local Shell Element Coordinate Systems](image)
Different Ways to Use Stresses

- **Offset by a certain distance (see i.e. DVS 1612)**
  - for “nominal stress concepts”
  - taken at i.e. 1,5 x thickness
  - green points are stress extraction locations (can be visualized in LIMIT Viewer).
  - Stress interpolation within the target element using stresses at corners
  - directions taken from weld orientation
  - See also additional Information in document: LIMIT-Defining_Offset_Endings_Directions.pdf

![Diagram showing stress directions and weld orientation](image-url)
**Different Ways to Use Stresses**

- **Stress extrapolation**
  - for “IIW structural hot spot stress”
  - IIW reference points at distance of
    - IIW, IIW_A: 0,5 x thickness and 1,5 x thickness or
    - IIW_B: 5mm and 15mm
  - Local stresses defined relative to extrapolation direction
    - Extrapolation direction = transverse
    - Longitudinal = transverse to extrapolation dir.
Assessment Points and Stresses

- Double sided fillet weld
- $a = t/2$
- P5, P6 ... shell stresses transformed to local directions ($\parallel, \perp$)

$$\begin{align*}
(\sigma_\parallel, \sigma_\perp, \tau_\parallel)_{\text{Top}, P6} \\
(\sigma_\parallel, \sigma_\perp, \tau_\parallel)_{\text{Top}, P5} \\
(\sigma_\parallel, \sigma_\perp, \tau_\parallel)_{P1} \\
(\sigma_\parallel, \sigma_\perp, \tau_\parallel)_{P2} \\
(\sigma_\parallel, \sigma_\perp, \tau_\parallel)_{P3} \\
(\sigma_\parallel, \sigma_\perp, \tau_\parallel)_{P4}
\end{align*}$$

Shell normal
Assessment Points and Stresses

- Single sided fillet weld
- $a = 0.7 \, t$
- Excentricity

Stresses and Section Forces

- $\sigma_{\|}$, $\sigma_{\perp}$, $\tau_{\|}$ at $P_6$
- $\sigma_{\|}$, $\sigma_{\perp}$, $\tau_{\|}$ at $P_4$
- $\sigma_{\|}$, $\sigma_{\perp}$, $\tau_{\|}$ at $P_3$
Single sided fillet weld, Stresses in P6

- \( t \) ... sheet thickness
- Continuously welded
- \( P6 \) ... stresses calculated for sheet thickness

Stress longitudinal to weld direction:

\[
\sigma_{\|,6} = \sigma_{\|,\text{Top}}
\]

Stress lateral to weld direction:

\[
\sigma_{\perp,P6} = \frac{n_{\perp}}{t} + \left( m_{\perp} + n_{\perp} e_{\text{EXC}} \right) / \left( t^2/6 \right)
\]

\( e_{\text{EXC}} = e_{\text{SSW}} \) ... free (FKM)
\( e_{\text{EXC}} = e_{\text{SSW}}/2 \) ... constrained

Shear in weld (in plane):

\[
\tau_{\|,P6} = \frac{s_{\|}}{t}
\]
Assessment of static strength using local stresses

Basic procedure

- Welded
- FKM, Chapter 3
- Assignment: WELD
- Local stresses
  - Local nominal stresses
  - Structural hot spot stresses
  - Effective notch stresses

3.1 Characteristic service stresses: $\sigma_v$

3.2 Material properties: $R_m, R_p$

3.3 Design parameters: $n_p, \alpha_W, \rho_{wez}$

3.4 Component strength: $\sigma_{SK}$

3.5 Safety factors: $j_{ges}$

3.6 Assessment: $a_{SK}$
FKM, Chapter 3.0

Assessment of welded components

- **Sheet / Base material, LIMIT: P5, P6**
  - Stress on top and bottom of shell
  - Relevant dimension: shell thickness
  - Weld toes/base material
  - Softening HAZ (heat affected zone)

- **Weld section, LIMIT: P1 to P4**
  - Relevant dimension: cross section of weld
  - Weld toes/root
  - Weld factor and softening in HAZ

<table>
<thead>
<tr>
<th>$t$ [mm]</th>
<th>$b_{WEZ}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 6$</td>
<td>20</td>
</tr>
<tr>
<td>$\leq 12$</td>
<td>30</td>
</tr>
<tr>
<td>$\leq 25$</td>
<td>35</td>
</tr>
<tr>
<td>$&gt; 25$</td>
<td>40</td>
</tr>
</tbody>
</table>

Source: FKM Guideline 2012
FKM, Chapter 3.1

Topic: Characteristic service stress

\( \sigma_{VW} \) ... equivalent static stress

Static

- Each relevant static load case gives one dataset of characteristic stresses
- Each stress state is assessed individually
- Most unfavourable load case stored
Stress for assessment, static loading

Assessment is performed using an equivalent stresses

- **Welded components, Chapter 3.1.2**
  - Base material and heat affected zone as non-welded materials
  - Weld section, only transverse and shear, according to DIN18800:
    \[
    \sigma_{VW} = \sqrt{\left(\sigma_{\perp}^2 + \tau_{\parallel}^2\right)}
    \]
  - Effective notch concepts: similar to base material, Chapter 3.1.2.2
    - Effective stress: \(\sigma_{VMwK}\)
    - Multiaxiality: \(h_{wK}\)
    - \(wK\)...weld Kerb
3.2 Material properties, welded

FKM, Chapter 3.2, 3.2.2

_topic: Strength data for welds
- Rp .... yield strength
- Rm .... tensile strength

_steel_
- Table 5.1.24

_aluminum_
- Table 5.1.25 and 5.1.26
FKM, Chapter 3.3, 3.3.2

- **Topic: influence of design characteristics**
  - Full penetration welds
  - Welded both sides, covering whole cross section
- **Steel**
  - \( n_{pl} = \text{MIN}(\sqrt{E \cdot \varepsilon_{ertr}/R_p}; K_p) \) ... section factor
- **Aluminum**
  - \( n_{pl} = \text{MIN}(\sqrt{E \cdot \varepsilon_{ertr}/(\rho_{wez} R_p)}); K_p) \) ... section factor
- **Data and factors**
  - \( \varepsilon_{ertr} \) ... depends on material group, tab. 3.3.3
  - \( E \) ... Young’s modulus
  - \( R_p \) ... yield strength, tab. 5.1.24, 5.1.25
  - \( \rho_{wez} \) ... softening factor tab. 5.1.25
  - \( K_p \) ... plastic notch factor
3.3 Design parameter, welded

FKM, Chapter 3.3, 3.3.2

Topic: Weld factor $\alpha_W$

 Depends on
  - Material
    - Type (Steel, Alu)
    - Strength
    - Filler material
    - Weld type
    - Weld quality
    - Stress type
      » Compressen, tension, shear

 Steel
  - $\alpha_W$ ... according to tab. 3.3.5
  - Values derived by LIMIT automatically

 Aluminum
  - $\alpha_W$ ... according to tab. 5.1.25

3.1 Characteristic service stresses: $\sigma_Y$

3.2 Material properties: $R_{mv}, R_p$

3.3 Design parameters:
  $n_{pl}, \alpha_W, \rho_{wez}$

3.4 Component strength: $\sigma_{SK}$

3.5 Safety factors: $j_{ges}$

3.6 Assessment: $a_{SK}$
Topic: Weld factor $\alpha_W$

Depends on
- Material
  - Type (Steel, Alu)
  - Strength
- Filler material
- Weld type
- Weld quality
- Stress type
  » Compressen, tension, shear

Steel
- $\alpha_W$ ... according to tab. 3.3.5
- Values derived by LIMIT automatically

Aluminum
- $\alpha_W$ ... according to tab. 5.1.25

### Table 3.3.5: Weld factor $\alpha_W$ for steel

<table>
<thead>
<tr>
<th>Weld</th>
<th>Weld quality $\perp_1$</th>
<th>Stress type</th>
<th>S235 GS200</th>
<th>GS240 G17Mn5+ QT</th>
<th>S275 P275</th>
<th>S355 P355 G20Mn5+N</th>
<th>S420 0 S460 0 S460 0</th>
<th>S690 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>full penetration weld or with back weld</td>
<td>all compression</td>
<td>compression</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>verified</td>
<td>not verified tension or shear</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>partial penetration or fillet weld</td>
<td>all compression/tension or shear</td>
<td></td>
<td>0.95</td>
<td>0.85</td>
<td>0.8</td>
<td>0.7</td>
<td>0.55</td>
<td></td>
</tr>
</tbody>
</table>

*$\perp_1$ The weld quality is verified if testing of 10% of the welds by radiographic or ultrasound test does not result in any failures.

Source: FKM Guideline 2012
FKM, section 3.4

Topic: final strength of the component

Sheet:
- Base material or non-softening material
  \[ \sigma_{SK} = R_p \cdot n_{pl} \] ... component strength
- Heat affected zone, softening material, (HAZ)
  \[ \sigma_{SK} = R_p \cdot \rho_{wez} \cdot n_{pl} \] ... component strength

Weld section:
- Steel or non-softening materials
  \[ \sigma_{SK,w} = R_p \cdot \alpha_W \cdot n_{pl} \] ... component strength
- Softening aluminium materials
  \[ \sigma_{SK,w} = R_p \cdot \alpha_W \cdot \rho_{wez} \cdot n_{pl} \] ... component strength

3.1 Characteristic service stresses: \(\sigma_y\)
3.2 Material properties: \(R_m, R_p\)
3.3 Design parameters: \(n_{pl}, \alpha_W, \rho_{wez}\)
3.4 Component strength: \(\sigma_{SK}\)
3.5 Safety factors: \(j_{ges}\)
3.6 Assessment: \(a_{SK}\)
FKM, Chapter 3.5, 3.5.1, 3.5.2

**Topic: define safety factors**

- Probability of survival $P_U = 97.5\%$
- $j_{ges}$ ... total safety factor (equ. 3.5.5):
  - Basic safety factor plus temperature factors
  - additional partial safety factors
- Basic safety factors
  - $j_m, j_p, j_{mt}, j_{pt}$
  - Can be chosen under consideration of consequences of failure and probability of the occurrence of high loads
- Partial safety factors:
  - $j_G$ ... cast components: 1.4 or 1.25 for tested
  - $j_w$ ... partial safety factor welded, alu: 1.13
  - $\Delta j$ ... non ductile cast components, depends on elongation at break $A$
FKM, Chapter 3.6, 3.6.2

- **Topic: degree of utilization**
  - \( a_{SK} = \frac{\sigma_v}{\sigma_{SK}/j_{ges}} \leq 1 \)

- **Assessment for all critical points**
  - Sheet metal: Points P5, P6
  - Weld section: Points P1 to P4
Workshop 5: Beam with box section

✦ Assessment of static strength

- Weld sets
  - By property
  - By part
  - By feature
  - By hand

- Assignments: WELD

- Defining Jobs
  - Selecting result files
  - Selecting setups
  - Selecting loads
Workshop 5: Beam with box section

- **Postprocessing with LIMIT Viewer**
  - Basic features
  - Views, coupling views
  - Results
    - Changing legend/show max
    - Searching hot spots
    - Element sets by results
  - Query function
  - Annotation
  - Pictures

- **Checking results via text-files**
  - Jobname.txt
Report Generator

- Automated Documentation of every individual weld
  - load cases or load spectra
  - weld geometry
  - notch cases / FAT classes
  - used stress concept or extrapolation
  - required safety factors
  - individual assessment results
  - ...

- Report as well structured HTML-File
  - open file format
  - importable in many other documentation software
  - easy operability of every report picture
  - ...
Assessment of fatigue strength using local stresses

Basic procedure

- Welded
- FKM, Chapter 4
- Assignment: WELD/WELD_GLOBAL

Local stresses
- Local nominal stresses
- Structural hot spot stresses
- Effective notch stresses

FKM Introduction, Fatigue

4.1 Characteristic service stresses: \( \sigma_a, \sigma_m \)

4.2 Material properties: \( \sigma_{W,zd} \)

4.3 Design parameters: FAT, \( f_{\text{FAT}}, f_V, K_V, K_{NL,E} \)

4.4.1 Comp.fatigue limit for zero mean stress: \( \sigma_{WK} \)

4.4.2 Comp.fatigue limit for actual mean stress: \( \sigma_{AK} \)

4.4.3 Comp.variable amplitude fatigue strength: \( \sigma_{BK} \)

4.5 Safety factors: \( j_0 \)

4.6 Assessment: \( a_{BK} \)
FKM, Chapter 4.1

Topic: Characteristic service stress

- $\sigma_a$, $\sigma_m$ ... amplitude and mean stress

Fatigue

- Stress amplitude and mean stresses are relevant
- At least two load cases are needed
- Each load case must be a relevant service stress state

4.1 Characteristic service stresses: $\sigma_a$, $\sigma_m$

4.2 Material properties: $\sigma_{W,zd}$

4.3 Design parameters: FAT, $f_{\text{FAT}}$, $f_v$, $K_V$, $K_{NL,E}$

4.4.1 Comp.fatigue limit for zero mean stress: $\sigma_{WK}$

4.4.2 Comp.fatigue limit for actual mean stress: $\sigma_{AK}$

4.4.3 Comp.variable amplitude fatigue strength: $\sigma_{BK}$

4.5 Safety factors: $j_D$

4.6 Assessment: $a_{BK}$
Stress for assessment, fatigue

Assessment is performed using stress components

Interaction of components is calculated at the end

Welded components, Chapter 4.1.2

- $\sigma_{\parallel}$ ... direct stress parallel to weld
- $\sigma_{\perp}$ ... direct stress transverse to weld
- $\tau_{\parallel}$ ... shear stress parallel to weld
FKM, Chapter 4.2, 4.2.3

Topic: Temperature Factor

- Temperature factor
  - Based on material group and temperature T
  - $K_{T,D} = \frac{\sigma_{W,zd,T}}{\sigma_{W,zd}}$

4.1 Characteristic service stresses: $\sigma_a$, $\sigma_m$

4.2 Material properties: $\sigma_{T,D}$

4.3 Design parameters: FAT, $f_{FAT}$, $f_V$, $K_V$, $K_{NL,E}$

4.4.1 Comp.fatigue limit for zero mean stress: $\sigma_{WK}$

4.4.2 Comp.fatigue limit for actual mean stress: $\sigma_{AK}$

4.4.3 Comp.variable amplitude fatigue strength: $\sigma_{BK}$

4.5 Safety factors: $j_D$

4.6 Assessment: $a_{BK}$
FKM, Chapter 4.3, 4.3.2

Topic: characteristic permissible stress

- FAT-class ... fatigue strength at 2 mio. cycles
- $f_{\text{FAT}}$ ... conversion factor, S-N-curve
- $f_t$ ... thickness factor
- $K_V$ ... Surface treatment factor, tab.4.3.7
  - LIMIT: Input currently over increased FAT class
- $K_{NL,E}$ ... non-linear elastic stress GJL, tab.4.3.5
FKM, Chapter 4.3, 4.3.2

Topic: characteristic permissible stress

- FAT-class ... fatigue strength at 2 mio. cycles
  - Notch type
  - Stress type (normal, shear)
  - Stress concept: nominal, structural, notch

- Example for longitudinally loaded welds
  - Nominal stress
  - Double sided fillet weld: FAT 100

### Source:

FKM 2012
FKM, Chapter 4.3, 4.3.2

- **Topic: characteristic permissible stress**
  - Example for welds loaded in transverse direction, nominal stress
    - Double sided fillet weld, toe: FAT 63
    - Double sided fillet weld, root: FAT 36

---

**Table 5.4.1 Fatigue classes for nominal stress (normal stress), continued page 4 of 10**

<table>
<thead>
<tr>
<th>No.</th>
<th>Structural detail</th>
<th>Description</th>
<th>FAT Steel</th>
<th>FAT Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>331</td>
<td>Longitudinally loaded welds</td>
<td>Joint at stiffened knuckle of a flange to be assessed according to Nos. 411 – 414, depending on type of joint. Stress in stiffener plate: ( \sigma = 2 \cdot \sin \alpha \cdot \sigma_1 \cdot A_1 / A_S ) Stress in weld: ( \sigma_S = 2 \cdot \sin \alpha \cdot \sigma_1 / 2A_W ) ( A_S = ) area of stiffener ( A_W = ) area of weld throat.</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>332</td>
<td>Unstiffened curved flange to web joint, to be assessed according to Nos. 411 – 414, depending on type of joint. Stress in web plate: ( \sigma = F_y / (t - 1) ) Stress in weld: ( \sigma = F_y / (2a) ) ( F_y = ) axial force in flange ( t = ) thickness of web plate ( a = ) weld.</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>411</td>
<td>Cruciform joint or T-joint, K-butt welds, full penetration, weld toes ground, no lamellar tearing, misalignment ( e &lt; 0.15 \cdot t ), toe crack. Misalignment ( e &lt; 0.15 \cdot t ) No misalignment.</td>
<td>80</td>
<td>90</td>
<td>28</td>
</tr>
<tr>
<td>412</td>
<td>Cruciform joint or T-joint, K-butt welds, full penetration, no lamellar tearing, misalignment ( e &lt; 0.15 \cdot t ), toe crack. Misalignment ( e &lt; 0.15 \cdot t ) No misalignment.</td>
<td>71</td>
<td>80</td>
<td>25</td>
</tr>
<tr>
<td>413</td>
<td>Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds, no lamellar tearing, toe crack. Misalignment ( e &lt; 0.15 \cdot t ) No misalignment.</td>
<td>63</td>
<td>71</td>
<td>22</td>
</tr>
<tr>
<td>414</td>
<td>Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds including toe ground joints, root crack. Analysis based on stress in weld ( \sigma = F_y (a - 1) / t ) length of the weld joint ( a = ) short metal thickness</td>
<td>36</td>
<td>40</td>
<td>12</td>
</tr>
</tbody>
</table>
FKM, Chapter 4.3, 4.3.2

**Topic: characteristic permissible stress**

- FAT-class ... permissible stress range at 2 mio. cycles
  - FAT classes compatible to IIW, EC3!
  - \( \sigma_{AC} = \frac{\text{FAT}}{2} \)

- Fatigue strength
  - At 5 mio. cycles!
  - LIMIT will calculate factor for transition from 2 mio. to 5 mio. (100 mio) cycles.

- \( \sigma_{AK} = \frac{\text{FAT} \sigma}{2} \cdot \left( \frac{N_C}{N_{D,\sigma}} \right)^{1/3} = \frac{\text{FAT} \sigma}{2} \cdot f_{\text{FAT},\sigma} \)

- \( \tau_{AK} = \frac{\text{FAT} \tau}{2} \cdot \left( \frac{N_C}{N_{D,\tau}} \right)^{1/5} = \frac{\text{FAT} \tau}{2} \cdot f_{\text{FAT},\tau} \)

Source: FKM Guideline 2012
FAT classes, but weld:

- Typical FAT values, both shell sides

Nominal stress, root:
- $FAT_{||} = 100$
- $FAT_{\perp} = 36 \ldots \text{w/o backing}$
- $FAT_{\perp} = 71 \ldots \text{w. backing, NDT}$
- $FAT_\tau = 80$

Structural stress, toe (IIW):
- $FAT_{||} = 100$
- $FAT_{\perp} = 100$
- $FAT_\tau = 80$

Nominal stress, toe:
- $FAT_{||} = 100$
- $FAT_{\perp} = 80$
- $FAT_\tau = 80$

Structural stress, toe (IIW):
- $FAT_{||} = 100$
- $FAT_{\perp} = 100$
- $FAT_\tau = 80$
FAT classes, one sided fillet weld:

**Typical values:**

![Diagram of a fillet weld with stress components](image)

**Nominal stress, toe:**
- \( \text{FAT}_\parallel = 100 \)
- \( \text{FAT}_\perp = 71 \div 80 \)
- \( \text{FAT}_\tau = 80 \)

**Structural stress, toe (IIW):**
- \( \text{FAT}_\parallel = 100 \)
- \( \text{FAT}_\perp = 100 \)
- \( \text{FAT}_\tau = 80 \)

**Only nominal stress, root:**
- \( \text{FAT}_\parallel = 100 \)
- \( \text{FAT}_\perp = 36 + \text{Excentricity} \)
- \( \text{FAT}_\tau = 80 \)
FAT classes, double sided fillet weld:

* Typical values: *

- **Nominal stress, toe:**
  - $FAT_{||} = 100$
  - $FAT_{\perp} = 71 \div 80$
  - $FAT_\tau = 80$

- **Structural stress, toe (IIW):**
  - $FAT_{||} = 100$
  - $FAT_{\perp} = 100$
  - $FAT_\tau = 80$

- **Only nominal stress, toe:**
  - $FAT_{||} = 100$
  - $FAT_{\perp} = 71$
  - $FAT_\tau = 80$

- **Only nominal stress, root:**
  - $FAT_{||} = 100$
  - $FAT_{\perp} = 36$
  - $FAT_\tau = 80$
FAT classes, strong discontinuity:

✧ Typical values:

<table>
<thead>
<tr>
<th>Kerfbal</th>
<th>Konstruktionsdetail</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>( L \leq 50) mm</td>
</tr>
<tr>
<td>71</td>
<td>( 50 &lt; L \leq 80) mm</td>
</tr>
<tr>
<td>63</td>
<td>( 80 &lt; L \leq 100) mm</td>
</tr>
<tr>
<td>56</td>
<td>( L &gt; 100) mm</td>
</tr>
</tbody>
</table>

Nominal stress, toe:
- \( \text{FAT}_{||} = 100 \Rightarrow 56 \)
- \( \text{FAT}_{\perp} = 71 \div 80 \)
- \( \text{FAT}_\tau = 80 \)
- LIMIT: 100(56),71,80

Structural stress, toe:
- \( \text{FAT}_{||} = 100 \)
- \( \text{FAT}_{\perp} = 100 \)
- \( \text{FAT}_\tau = 80 \)

Source: EC3
FAT classes, overlap weld:

- **Typical values:**

  Only nominal stress, toe:
  
  \[
  \text{FAT}_{\parallel} = 100 \\
  \text{FAT}_{\perp} = 71 \\
  \text{FAT}_{\tau} = 80
  \]

  Nominal stress, toe:
  
  \[
  \text{FAT}_{\parallel} = 100 \\
  \text{FAT}_{\perp} = 45 \div 56 \\
  \text{FAT}_{\tau} = 80
  \]

  Structural stress, toe (IIW)
  
  \[
  \text{FAT}_{\parallel} = 100 \\
  \text{FAT}_{\perp} = 100 \\
  \text{FAT}_{\tau} = 80
  \]

  Only nominal stress, toe:
  
  \[
  \text{FAT}_{\parallel} = 100 \\
  \text{FAT}_{\perp} = 36, \text{ deactivate eccentricity in LIMIT} \\
  \text{FAT}_{\tau} = 80
  \]
FAT classes, intermittent weld, if not modeled:

Typical values:

Weld seam stress:

Effective weld factor:

\[ f_{wl} = \frac{4 \times l_w}{L} \]

\[ \sigma_{\perp,\text{effective}} = \frac{\sigma_{\perp}}{f_{wl}} \]

\[ \tau_{\text{effective}} = \frac{\tau}{f_{wl}} \]

\[ \text{FAT}_{\parallel} = 36 \div 80 \]

\[ \text{FAT}_{\perp} = 71 \ldots \text{toe} \]

\[ \text{FAT}_{\perp} = 36 \ldots \text{root} \]

\[ \text{FAT}_\tau = 80 \]
FKM, Chapter 4.3, 4.3.2

Topic: characteristic permissible stress

- $f_t$ ... thickness factor
  - According to IIW, Fall A:
    » Correction for sheet thickness $t \geq 25$ mm: $f_t = (25 \text{mm}/t)^n$
    » $n$ ... according to tab. 4.3.6, LIMIT: selection of type of weld joint required!
  - According to DVS 1612, 1608: Fall B

Source: FKM Guideline 2012
FKM, Chapter 4.3, 4.3.2

Topic: characteristic permissible stress

- $K_V$ ... Surface treatment factor, tab.4.3.7
- LIMIT: Input currently over modified FAT class

4.1 Characteristic service stresses: $\sigma_{a}$, $\sigma_{m}$

4.2 Material properties:

4.3 Design parameters: FAT, $f_{FAT}$, $f_{V}$, $K_{V}$, $K_{NL,E}$

4.4.1 Comp.fatigue limit for zero mean stress: $\sigma_{WK}$

4.4.2 Comp.fatigue limit for actual mean stress: $\sigma_{AK}$

4.4.3 Comp.variable amplitude fatigue strength: $\sigma_{BK}$

4.5 Safety factors: $j_{D}$

4.6 Assessment: $a_{BK}$
FKM, Chapter 4.4.1, 4.4.1.2

- Topic: component fatigue limit for
  - completely reversed stress
  - (zero mean stress)
  - \[ \sigma_{WK,\parallel} = FAT_{\parallel} \cdot f_{FAT,\sigma} \cdot f_t \cdot K_V \cdot K_{NL,E} \]
    ... fat. limits rev. stress
  - \[ \sigma_{WK,\perp} = FAT_{\perp} \cdot f_{FAT,\sigma} \cdot f_t \cdot K_V \cdot K_{NL,E} \]
    ... fat. limits rev. stress
  - \[ \tau_{WK} = FAT_\tau \cdot f_{FAT,\tau} \cdot f_t \cdot K_V \]
    ... fat. limits rev. stress
Component fatigue limit, zero mean stress, welded

FKM, Chapter 4.4.2, 4.4.2.2

Topic: component fatigue limit as
- a function of mean and residual stress
- \( \sigma_{\text{AK},\parallel} = \sigma_{\text{WK},\parallel} \cdot K_{\text{AK},\parallel} \cdot K_{\text{E},\sigma} \) … longitudinal
- \( \sigma_{\text{AK},\perp} = \sigma_{\text{WK},\perp} \cdot K_{\text{AK},\perp} \cdot K_{\text{E},\sigma} \) … lateral
- \( \tau_{\text{AK}} = \tau_{\text{WK}} \cdot K_{\text{AK},\tau} \cdot K_{\text{E},\tau} \) … shear

Data and factors
- \( K_{\text{AK}} \) … mean stress factor, tab. 4.4.2
- \( K_{\text{E}} \) … residual stress factor, tab. 4.4.2
  - high/moderate/low
- Typ of overloading (see base material!)
  - F1: the mean stress remains constant
  - F2: the stress ratio remains constant (default)
  - F3: the minimum stress remains constant
  - F4: the maximum stress remains constant
Component variable amplitude fatigue strength, welded

FKM, Chapter 4.4.3, 4.4.3.2

Topic: influence of variable amplitude

- variable amplitude fatigue strength factor
  - $\sigma_{BK,II} = \sigma_{AK,II} \cdot K_{BK,II}$
  - $\sigma_{BK,\perp} = \sigma_{AK,\perp} \cdot K_{BK,\perp}$
  - $\tau_{BK} = \tau_{AK} \cdot K_{BK,\tau}$

Variable amplitude

4.1 Characteristic service stresses: $\sigma_a, \sigma_m$

4.2 Material properties: $\sigma_{W,zd}$

4.3 Design parameters: $\text{FAT, } f_{\text{FAT}}, f_{V}, K_V, K_{NL,E}$

4.4.1 Comp.fatigue limit for zero mean stress: $\sigma_{WK}$

4.4.2 Comp.fatigue limit for actual mean stress: $\sigma_{AK}$

4.4.3 Comp.variable amplitude fatigue strength: $\sigma_{BK}$

4.5 Safety factors: $j_D$

4.6 Assessment: $a_{BK}$

5 x $10^6$ Number of cycles

$K_{BK} = 1$

$K_{BK} > 1$
**FKM, Chapter 4.4.3, 4.4.3.2**

**Topic: influence of variable amplitude**
- variable amplitude fatigue strength factor
  - $\sigma_{BK,II} = \sigma_{AK,II} \cdot K_{BK,II}$
  - $\sigma_{BK,I} = \sigma_{AK,I} \cdot K_{BK,I}$
  - $\tau_{BK} = \tau_{AK} \cdot K_{BK,\tau}$

**Maximum values**
- $\sigma_{BK,\text{max,II}} = 0.75 \cdot R_p \cdot \alpha_w \cdot \rho_{wez} \cdot n_{pl}$
- $\sigma_{BK,\text{max,I}} = 0.75 \cdot R_p \cdot \alpha_w \cdot \rho_{wez} \cdot n_{pl}$
- $\tau_{BK,\text{max}} = 0.75 \cdot R_p \cdot \alpha_w \cdot \rho_{wez} \cdot n_{pl}$

- $R_p$ ... yield strength
- $n_{pl}$ ... section factor
- $\alpha_w$ ... weld factor
- $\rho_{wez}$ ... softening factor

**Component variable amplitude fatigue strength, welded**

4.1 Characteristic service stresses: $\sigma_a, \sigma_m$

4.2 Material properties: $\sigma_{W,zd}$

4.3 Design parameters: FAT, $f_{FAT}, f_V, K_V, K_{NL,E}$

4.4.1 Comp. fatigue limit for zero mean stress: $\sigma_{WK}$

4.4.2 Comp. fatigue limit for actual mean stress: $\sigma_{AK}$

4.4.3 Comp. variable amplitude fatigue strength: $\sigma_{BK}$

4.5 Safety factors: $j_D$

4.6 Assessment: $a_{BK}$
FKM, Chapter 4.5, 4.5.2

Topic: definition of safety factors

- $j_D = j_S \cdot \frac{j_F \cdot j_G}{K_{T,D}}$

Data and factors

- $j_S$ ... load safety factor, default 1.0
- $j_F$ ... material safety factor, tab. 4.5.3
- $j_G$ ... cast iron factor, tab. 4.5.2
- $K_{T,D}$ ... temperature factor, chapter 4.2.3
  (depends on material group and temperature)

In LIMIT safety factors are selected on:
- Consequence of failure: severe/mean/moderate
- Regular inspections: yes/no

4.1 Characteristic service stresses: $\sigma_a$, $\sigma_m$

4.2 Material properties: $\sigma_{W,zd}$

4.3 Design parameters: FAT, $f_{FAT}$, $f_U$, $K_V$, $K_{NL,E}$

4.4.1 Comp. fatigue limit for zero mean stress: $\sigma_{WK}$

4.4.2 Comp. fatigue limit for actual mean stress: $\sigma_{AK}$

4.4.3 Comp. variable amplitude fatigue strength: $\sigma_{BK}$

4.5 Safety factors: $j_D$

4.6 Assessment: $a_{BK}$
FKM, Chapter 4.6, 4.6.1

Topic: Calc. of degree of utilization

Individual stress types e.g.: 2D-tensor

- $a_{BK,\parallel} = \frac{\sigma_{a,\parallel,1}}{\sigma_{BK,\parallel}/j_D} \leq 1$
- $a_{BK,\perp} = \frac{\sigma_{a,\perp,1}}{\sigma_{BK,\perp}/j_D} \leq 1$
- $a_{BK,\tau} = \frac{\tau_{a,1}}{\tau_{BK}/j_D} \leq 1$

Individual stress types
Assessment, welded

FKM, Chapter 4.6, 4.6.2

- Topic: Calc. of degree of utilization
- Combined types of stress
  - For welds: normal stress criteria!
  - \( a_{BK,\sigma v} = 0.5 \cdot \left\{ | a_{BK,\|} + a_{BK,\perp} | + \sqrt{(a_{BK,\|} - a_{BK,\perp})^2 + 4 \cdot a_{BK,t}^2} \right\} \)

Signs for combined stresses

- Procedure within LIMIT
  - Check if same load pair responsible for \( a_{BK,\|} \cdot a_{BK,\perp} \)
  - If different load pairs are involved, the signs are set for maximum value of \( a_{BK,\sigma v} \)

- Proportional/synchronous stresses
  - Signs taken directly from FEA
  - Combined D.o.U.: AUTO

- Non-proportional loads, see base material

- Recommendations IIW
Recommendations of IIW

- Non-proportional bending and shear

Criteria in IIW

- \((a_{BK,\perp}^2 + a_{BK,t}^2) \leq CV\)
- Material dependent:
  - Steel: \(CV = 0.5\)
  - Aluminium: \(CV = 1.0\)

Since LIMIT 2015

- IIW (optional)
  - \(a_{BK,VM} = \sqrt{(a_{BK,ll}^2 + a_{BK,\perp}^2 - a_{BK,ll}a_{BK,\perp} + a_{BK,t}^2)}\)
  - \(a_{BK,VM}^2 \leq CV \Rightarrow a_{BK,VM} \leq \sqrt{CV}\)
  - \(a_{BK,VM}/\sqrt{CV} \leq 1\)
  - \(a_{BK,IIW} = a_{BK,VM}/\sqrt{CV} = a_{BK,VM} \cdot 1.41\)

- For welds also normal stress criteria!
  - \(a_{BK,ov} = 0.5 \cdot \{ |a_{BK,ll}| + a_{BK,\perp} | + \sqrt{|(a_{BK,ll} - a_{BK,\perp}) + 4 \cdot a_{BK,t}|} \}\)

Activation of IIW criteria

- JobManager / Edit / Multiaxial-Nonprop-IIW: YES
Combined degree of utilization

GUI: Edit: Setup
Assignment: Fatigue
Combined D.o.U

- **AUTO** (default): In this case LIMIT checks, whether the signs of individual stress amplitudes can be used or not. This is done on the basis of the load cases responsible for each amplitude. If normal stresses origin from the same load cases, signs are taken as calculated by FEA.
- **FKM_MAX_ALG**: will give highest possible degree of utilization after altering signs. i.e. worst case with respect to signs.
- **OFF**: deactivates combined criteria
- **LIN**: linear summation of all DoU (CAE add-on, not part of FKM)
FKM, Chapter 4.6, 4.6.2

- Topic: Calc. of degree of utilization
- Check results in Job.txt-file!

4.1 Characteristic service stresses: $\sigma_a$, $\sigma_m$

4.2 Material properties: $\sigma_{Wzd}$

4.3 Design parameters: $K_{WK}$

4.4.1 Comp. fatigue limit for zero mean stress: $\sigma_{WK}$

4.4.2 Comp. fatigue limit for actual mean stress: $\sigma_{AK}$

4.4.3 Comp. variable amplitude fatigue strength: $\sigma_{BK}$

4.5 Safety factors: $j_D$

4.6 Assessment: $a_{BK}$
Workshop 6: Beam with box section

Assessment of fatigue strength of welded structures

- Weld sets
- Assignments: WELD, WELD_GLOBAL
  - FKM 6th edition
  - Defining weld types
  - Selecting FAT-classes
  - Choosing a stress concept
- Defining Jobs
  - Selecting result files
  - Selecting setups
  - Selecting loads
Workshop 6: Beam with box section

Postprocessing with LIMIT Viewer

- Basic features
- Views, coupling views
- Results
  - Changing legend/show max
  - Searching hot spots
  - Element sets by results
- Query function
- Annotation
- Pictures

Checking results via text-files

- Jobname.txt
Strength Assessment of Welded Structures

✦ Overview of Assessments
Assessment of welded structures using local stresses

- GUI: Edit: Setup
- Assignment: Base Material
- Material group:
  - WELDED_STEEL or
  - WELDED_ALUMINIUM
- Submodus:
  - EFFECTIVE_NOTCH_STRESS_R=1.0
  - EFFECTIVE_NOTCH_STRESS_R=0.05
  - FICTICIOUS_NOTCH_Ktfiktiv=1.6
  - FICTICIOUS_NOTCH_Ktfiktiv=4.5
  - WELDED_FAT100
  - WELDED_FAT90
  - WELDED_FAT40
  - WELDED_FAT36
  - DEFAULT
Submodus:

Valid selections for **WELDED_STEEL:**

- **EFFECTIVE_NOTCH_STRESS_R=1.0**
  - Effective notches modeled with radius 1mm
  - Assessments: Static and Fatigue (FKM Sec.3.3.2, Sec.5.4.3)

- **EFFECTIVE_NOTCH_STRESS_R=0.05**
  - Effective notches modeled with radius 0.05mm for thin sheets
  - Assessments: **only** Fatigue (Sec.5.4.3)
Submodus:

Valid selections for **WELDED_STEEL**: 

- **FICTICIOUS_NOTCH_Ktfiktiv=1.6**
  - Assumes mild notches in combination with FAT class 225/160
  - Assessments: *only* Fatigue (Sec.5.4.3)
  - Reduces the permissible values by the global factor of 1.6
  - Can be used to assess areas where the solid element results represent structural stresses

- **FICTICIOUS_NOTCH_Ktfiktiv=4.5**
  - Assumes mild notches in combination with FAT class 630/250
  - Assessments: *only* Fatigue (Sec.5.4.3)
  - Reduces the permissible values by the global factor of 4.5
  - Can be used to assess areas where the solid element results represent structural stresses

- **WELDED_FAT100 and WELDED_FAT90**
  - Can be used to assess areas where the solid element results represent structural stresses (Tab. 5.4.3)
Submodus:

Possibilities for **WELDED_ALUMINIUM**:

- **EFFECTIVE_NOTCH_STRESS_R=1.0**
  - Effective notches modeled with radius 1mm
  - Assessments: only Fatigue (Sec.5.4.3)

- **EFFECTIVE_NOTCH_STRESS_R=0.05**
  - Effective notches modeled with radius 0.05mm for thin sheets
  - Assessments: only Fatigue (Sec.5.4.3)

- **FICTICIOUS_NOTCH_Ktfiktiv=1.6**
  - Assumes mild notches in combination with FAT class 71/63
  - Assessments: only Fatigue (Sec.5.4.3)
  - Reduces the permissible values by the global factor of 1.6
  - Can be used to assess areas where the solid element results represent structural stresses

- **FICTICIOUS_NOTCH_Ktfiktiv=4.5**
  - Assumes mild notches in combination with FAT class 180/90
  - Assessments: only Fatigue (Sec.5.4.3)
  - Reduces the permissible values by the global factor of 4.5
  - Can be used to assess areas where the solid element results represent structural stresses

- **WELDED_FAT40 and WELDED_FAT36**
  - Can be used to assess areas where the solid element results represent structural stresses (Tab. 5.4.3)
Assessment of weld structures using nominal or structural stresses

- STEEL
- GUI: Edit: Setup
- Assignment: WELD or WELD_GLOBAL
- Material group: STEEL
- Push bar next Select
- Choose a material from table (see FKM, Tab. 5.1.24)
Assessment of weld structures using nominal or structural stresses

- **ALUMINIUM**
- **GUI: Edit: Setup**
- **Assignment: WELD or WELD_GLOBAL**
- **Material group: ALU**
- **Push bar next Select**
- **Choose a material from table** (see FKM, Tab. 5.1.25)
- **Press OK and choose filler material** (see FKM, Tab. 5.1.26)
Workshop 7: effective notch stress

- Assessment using local stresses
  - Assignments: BASE
    - FKM 6th edition
    - WELDED STEEL
    - SUB MODUS: EFFECTIVE_NOTCH_STRESS
  - Defining Jobs
    - Selecting result files
    - Selecting setups
    - Selecting loads
LIMIT Sensor Technology
Structural Hot Spot Stresses for Solid Elements

- Sensors embedded within the solid model
- Extracting structural stresses for weld toes
- Linear extrapolation scheme according to IIW
- Averaged stress data comparable to shell results
Structural Hot Spot Stresses for Solid Elements

- Generation of sensors with LIMIT SensorManager
Structural Hot Spot Stresses for Solid Elements

- Sensors: definition of welds in the same way as for shells
Workshop 8: Sensors

Assessment using sensors

- Preparing the model for sensor generation
- Generating sensors
- Assignments: WELD
  - FKM 6th edition
  - Defining weld types
  - Selecting FAT-classes
  - Choosing a stress concept
- Defining Jobs
  - Selecting result files
  - Selecting setups
  - Selecting loads
Workshop 8: Sensors

- **Postprocessing with LIMIT Viewer**
  - Basic features
  - Views, coupling views
  - Results
    - Changing legend/show max
    - Searching hot spots
    - Element sets by results
  - Query function
  - Annotation
  - Pictures

- **Checking results via text-files**
  - Jobname.txt
Workshop 9:

- Assessment of welded customers structures......