Effects of Thermal Loads to Stress Analysis and Fatigue Behaviour

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ABSTRACT

Technical codes and standards used for the construction, design and operation of nuclear components and systems provides the materials data required, detailed stress analysis procedures and a design philosophy which guarantees a reliable behaviour of the structural components and systems throughout the specified lifetime. For cyclic stress evaluation the different codes and standards provides fatigue analyses to be performed considering the various loading histories (mechanical and thermal loads) and geometric complexities of the components. In order to fully understand the background of the fatigue analysis included in the codes and standards as well as of the fatigue design curves used as a limiting criteria (fatigue life usage factor), it is important to understand the history and the methodologies available for the design engineers are discussed in the following.

Using design by analysis (DBA) in the nuclear codes and standards a simplified elastic plastic fatigue analysis is recommended when the range of primary plus secondary stress intensity exceeds the $3S_m$ limit. For that case the fictitious alternating stress amplitude S_a is calculated by multiplying the range of primary plus secondary plus peak stress intensity S_n with the stress dependent plastification factor K_e. In different nuclear and non nuclear codes and standards different plastification factor values are available. The safety margins of this simplified elastic plastic fatigue analysis was studied by using experimental and numerical results.

Most of the fatigue relevant stresses in piping systems are caused by thermal loading. The difference between the density of the fluid caused by the temperature gradient from bottom to top of the pipe cross section combined with low flow rates can result in thermal stratification in the horizontal portions of a piping system. The hot and cold fluid levels of the stratified flow conditions are separated by an interface or mixing layer. On the other hand high flow rates can cause a temperature gradient in pipe longitudinal direction (jump of temperature) and result in a thermal shock loading on the inside pipe surface constant throughout the pipe cross section. These loading conditions impact the secondary stresses and the fatigue usage analysis typically performed for piping components by equations in the technical codes and standards. Thermal stratification in piping system causes an cirumferentially varying temperature distribution in the pipe wall resulting in local through wall axial stresses (through wall radial temperature gradient) and global bending stresses in the piping system (axial expansion forces and thermal moments). Maximum local thermal stress is found when a thin interface (mixing) layer occurs in the upper or lower parts of the pipe cross section. Maximum global thermal bending stress is found when a thin interface layer occurs in the middle of the pipe cross section. The rules included in the technical codes and standards to calculate thermal stresses may not be completely applicable for the thermal stratification loading, the rules to calculate thermal stresses are applicable for the thermal shock loading.

INTRODUCTION

Technical codes and standards like ASME-Code Section III [1], French RCC-M Code [2], British Standard BS 5500 [3] or German KTA Safety Standards [4] are the basis for construction, design and operation of nuclear components and systems. The general philosophy in the design of components and structures is to demonstrate that the function and the integrity is guaranteed throughout the lifetime. It is important that the design concept accounts for most possible failure modes and provides rational margins of safety against each type of failure mode. Some of the potential failure modes which component and structure designers should take into account are for example:

- Excessive elastic deformation including elastic instability,
- Excessive plastic deformation,
- Brittle fracture,
- Fatigue,
- Corrosion.

During design stage a complete picture of the state of stresses within the component, structure or system obtained by calculation or measurement of both mechanical and thermal stresses during transient and steady state operation has to be created. It has to be demonstrated that all stresses (primary, secondary) as well as environmental loading are within the allowable stress limits given by the codes and standards, and the usage factor developed by a fatigue analysis (peak stresses) is well below the limiting value (cumulative fatigue life usage factor U).

It is possible to prevent failure modes caused by fatigue by imposing distinct limits on the peak stresses at the highest loaded regions of the component and structure since fatigue failure is related to and initiated by high local stresses or by reducing the load cycles. The design rules according to the technical codes and standards [1,2,3,4] provides for explicit consideration of cyclic operation, using design fatigue curves of allowable alternating loads (allowable stress or strain amplitudes) vs. number of loading cycles (S/N-curves), specific rules for assessing the cumulative fatigue damage caused by different specified or monitored load cycles. The influence of different factors like welds, environment, surface finish, temperature, mean stress and size must be taken into consideration in an appropriate way.

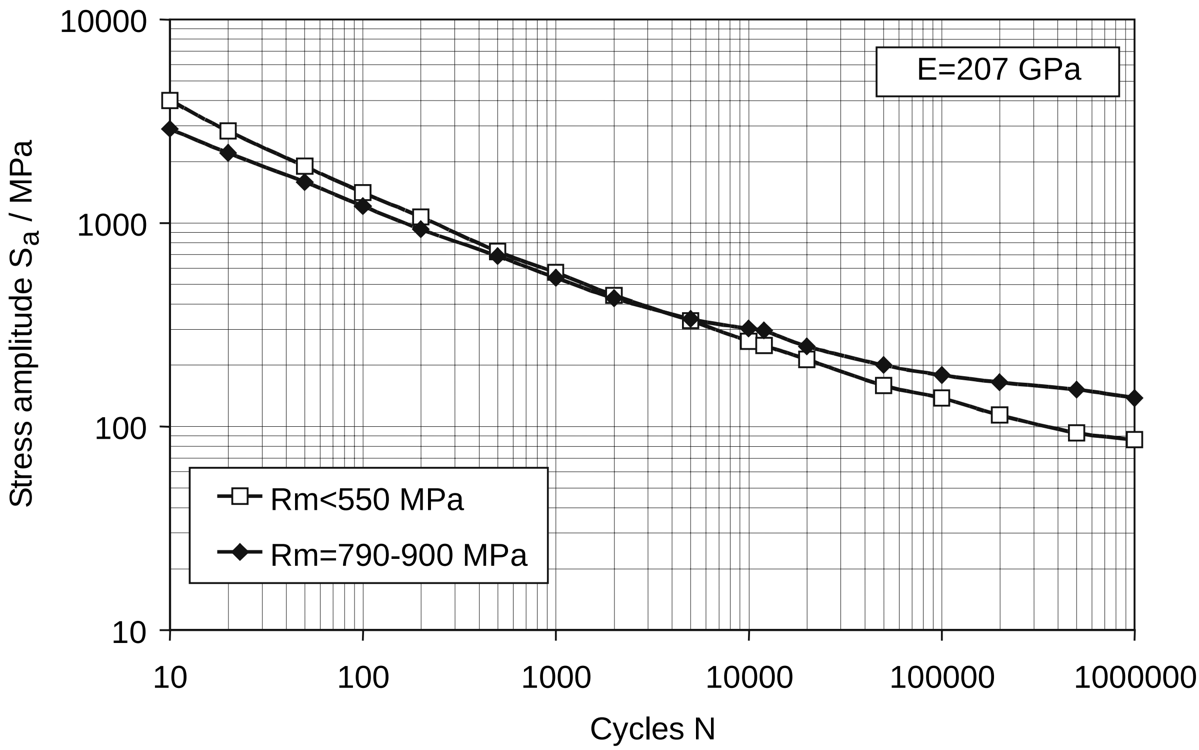

Figure 1: Design fatigue curve for ferritic material according to KTA 3201.2 [4]

USE OF DESIGN FATIGUE CURVES

Reviewing fatigue analyses for nuclear pressure vessels and piping it becomes apparent that the majority is similar to or identical with those in the ASME-Code Section III [1], like the German KTA Standards [4]. The ASME design fatigue curves for carbon and low alloy steels as well as austenitic stainless steels are based on stress amplitude and cycles to failure data which were obtained from small smooth-machined specimens tested under strain controlled loading, mainly in bending in room temperature and air environment [5,6,7]. The design curves were derived by introducing factors of 2 on stress and 20 on cycles, whichever gave the lowest curve and is meant to account for real effects (size, environment, surface finish, scatter of data) occuring during plant operation. The fatigue design curve in the British Standard BS 5500 [3] was derived from fatigue test data obtained under axial load from welded specimens. The reason therefore was that the presence of a weld could reduce fatigue strength because of the inevitable presence of weld defects. But all of the pressure vessel and piping fatigue design rules are based essentially on the same approach based on data from primarily low-cycle fatigue (LCF) tests carried out on machined specimens, mainly with plain unwelded specimens tested under strain control. Conservative S/N-curves are developed and used for the fatigue analysis in conjunction with stress concentration factors K_t or fatigue strength reduction factors K_f to take into account the structural discontinuities in the components and structures including welds [8].

Different procedures exist in the German technical rules for pressure vessels AD-Merkblatt [9] and the European Standard EN 13445 [10] for unfired pressure vessels. The approach uses also S/N-curves with stress concentration factors like the ASME Code but much more advice is given about the use of the stress concentration factors to be adopted for weld details. Additional explicit factors in form of an equation or a curve are given to account for the influence of temperature, surface finish and weldment, size and mean stresses. Further German codes and rules used in mechanical engineering and machinery are the FKM-Guidelines [11] and the RKF-Guidelines [12] with detailed requirements for the determination of alternating stress amplitudes.

Fatigue data are generally obtained from unwelded specimens at room temperature and are plotted in the form of nominal stress amplitude S_a vs. number of cycles to failure. The total strain range $\Delta\varepsilon_t$ obtained from the tests is converted to nominal stress range by multiplying the strain range by the room temperature modulus of elasticity E

$$\mathbf{S_a = E \cdot \frac{\Delta\varepsilon_t}{2}} \tag{1}$$

Most of the S/N-curves given in the codes and standards are to be applied for specific steels (e.g. distinguish between steels of different ultimate tensile strength R_m).

Influence of Temperature

The use of fatigue design curves is restricted in the nuclear codes and standards to a specific maximum temperature below the creep range. Using design fatigue curves it is necessary to adjust the allowable stresses if the modulus of elasticity E at operating temperature is different from the one used for the design curves. The stress amplitude S_a must be multiplied by the ratio of the modulus of elasticity given by the design fatigue curve to the value of the modulus of elasticity used in the analysis. Another approach is given in the German AD S2 rules [9] and the European Standard EN 13445 [10] where the influence of temperature must be adjusted by a cycle depending factor f_T.

Influence of Surface Finish and Welds

Design curves in the nuclear codes include a factor of 2 on stress or 20 on cycles relative to the mean of the test data to account for differences between specimen test conditions and real vessels and piping. This includes effects of surface finish and welds. Furthermore there are in the nuclear codes specific requirements concerning the surface finish of components especially for welded regions and for different vessel and piping products and different joints. Stress indices are available for use of the code equations determining the stress amplitudes.

A special regard to the influence of surface finish depending upon peak-to-valley height R_z and number of cycles is given in German AD S2 rule. The influence of the surface finishing is described by the surface factor which is defined by

$$\mathbf{f_o = \frac{\sigma_{a,f}(R_z)}{\sigma_{a,f}(R_z < 6\,\mu m)}} \tag{2}$$

where $\sigma_{a,f}$ is the sustainable stress amplitude for different R_z values. The requirements for determining f_o according to AD S2 for a material with ultimate tensile strength of 500 MPa are shown in Fig. 2.

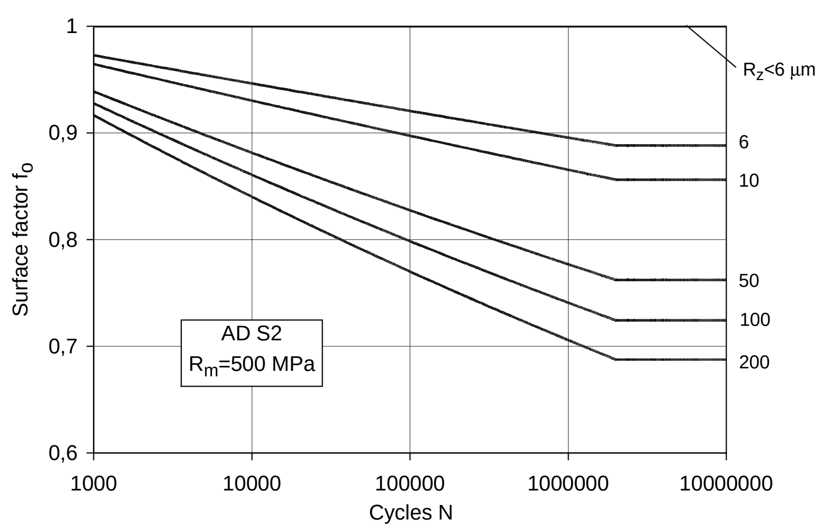

Figure 2: Influence of surface finish according to AD S2 [9]

Experimental values for surface factors f_o derived by specimens with different R_z values are shown in Fig. 3. The experimental data has been evaluated for the endurance limit ($N=2\cdot10^6$) of different materials.

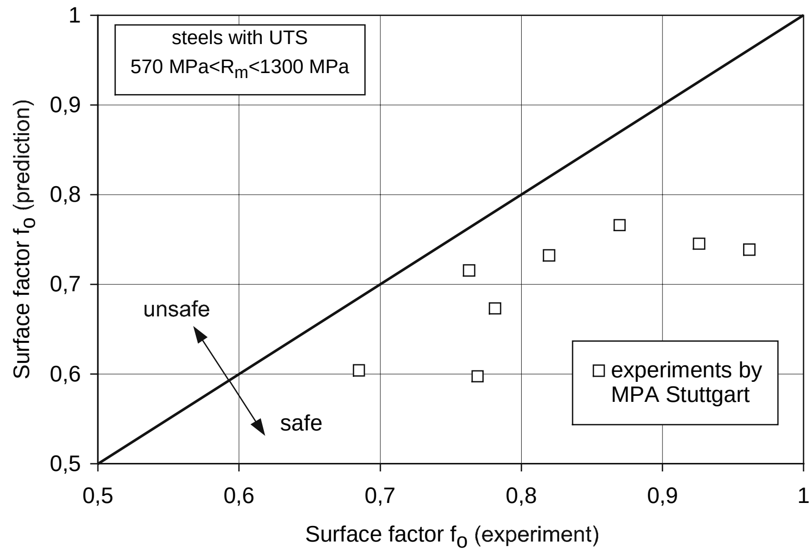

Figure 3: Surface finish factor f_o for the endurance limit of stress (fatigue strength)

Influence of Size

Most of the material and failure behaviour has been determined using small laboratory specimens. However failure stress amplitudes are lower for components because of size effects caused by different stress gradients or statistical effects of material characteristics. Size effects are covered in the nuclear codes [1,4] by the factors 2 on stress or 20 on cycles. A different approach is included in German AD S2 rule, Fig. 4

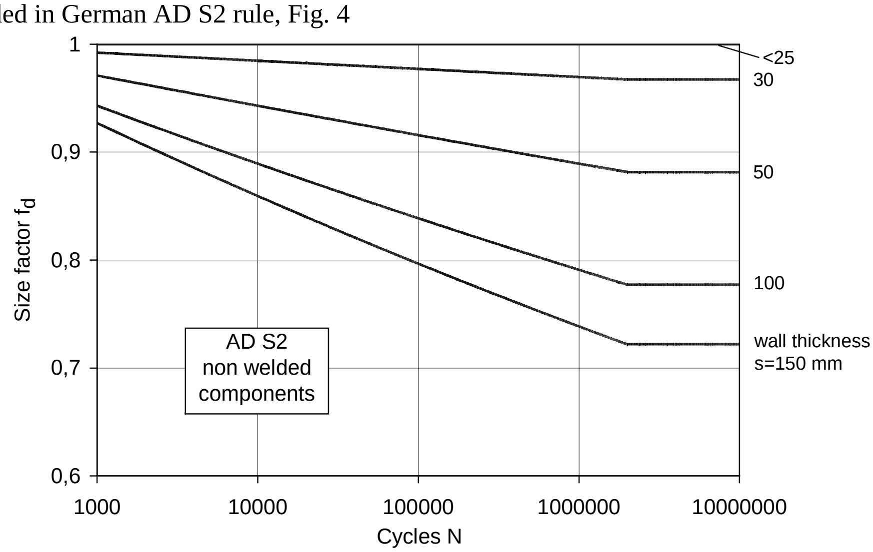

Figure 4: Influence of size according to AD S2 [9]

Experimental data concerning the influence of size are available from [13], Fig. 5. It is evident that comparatively large scatter emerge, especially for the tests with larger specimens.

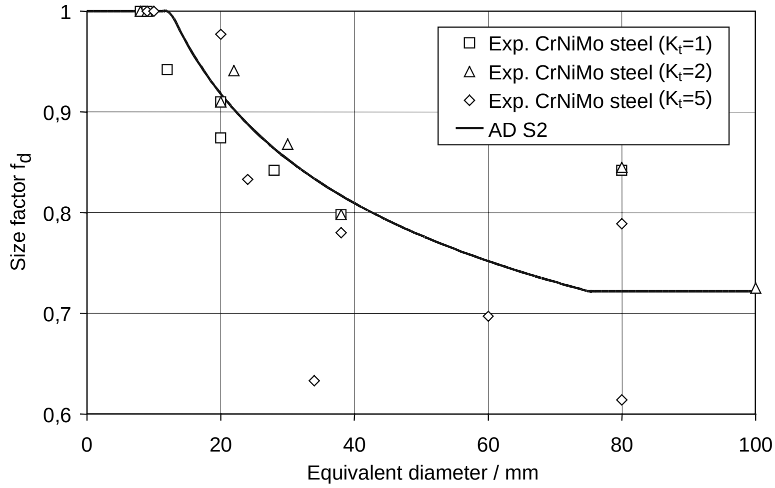

Figure 5: Size factor f_d for the fatigue strength of round solid specimens under repeated (reversed) bending stresses [13] depending upon the equivalent diameter (for pipes: equivalent diameter = t/2)

Influence of Mean Stress

If a component is stressed by an alternating stress greater than the yield strength $R_{p0,2}$ of the material, it makes no difference whether there is a present nominal mean stress σ_m or not. In this stress state the true mean stress always will be zero. Therefore the fatigue design curves are adjusted to include the maximum effect of the mean stress by the Langer-Goodman Diagram only in the part of the fatigue curve lying below an alternating stress amplitude $\sigma_a = R_{p0,2}$ .In all the ASME-based codes and standards the fatigue design curves are plotted in terms of stress amplitude independent of mean stress, the curves are showing already the full effect of maximum mean stress. The evaluation of the effect of mean stresses is accomplished by use of the modified Langer-Goodman Diagram, where mean stress is plotted as the abscissa and the amplitude of the alternating stresses is plotted as the ordinate. Thus, for the adjusted fatigue curve there should not be any mean stress present which will cause fatigue failure in less than the given cycles.

In non-nuclear codes the influence of mean stresses is taken into account individually. A simple equation was proposed by Wellinger and Dietmann [14]

$$\sigma_{a,f}(R) = \sigma_{a,f}(R=-1) \cdot \sqrt{1 - \frac{\sigma_m}{R_m}} \qquad (3)$$

with R as the stress ratio. The influence of mean stresses in the FKM-Guidelines [11] is described by the mean stress sensitivity M_σ which was introduced by Schütz [15] as

$$M_\sigma = \frac{\sigma_{a,f}(R=-1) - \sigma_{a,f}(R=0)}{\sigma_{a,f}(R=0)} \qquad (4)$$

If there is no experimental data available, the mean stress sensitivity for steels can approximately be determined by the equation

$$M_\sigma = 0.00035 \cdot R_m - 0.1 \, , \qquad (5)$$

with R_m in dimension MPa. Eq. (5) is illustrated in Fig. 6. For the endurance limit of stress (fatigue strength) the mean stress effect on the alternating stress amplitude $\sigma_{a,f}$ can be adjusted by the Haigh's diagram. Fig. 7 shows the proposal by [11] and [14] compared with experimental data for a high strength low alloy rotor CrMoV-steel.

Influence of Environment

Despite of the factors 2 and 20 there have been relatively few corrosion fatigue failures in carbon or low-alloy steel components in LWR's and quite a lot of discussions are under way concerning the influence of environment to the fatigue design curves (crack initiation and crack growth under environmental conditions). Data from specimens testing indicated that fatigue life shorter than the fatigue design curve values are possible, if the tests are carried out under low frequency loading conditions in oxygenated water environment at elevated temperatures [16,17], but up to now there is no clear picture about the necessity to change the fatigue design curves. The investigations performed to determine corrosion-assisted crack growth rates for pressure boundary materials exhibit a big scatter [18].

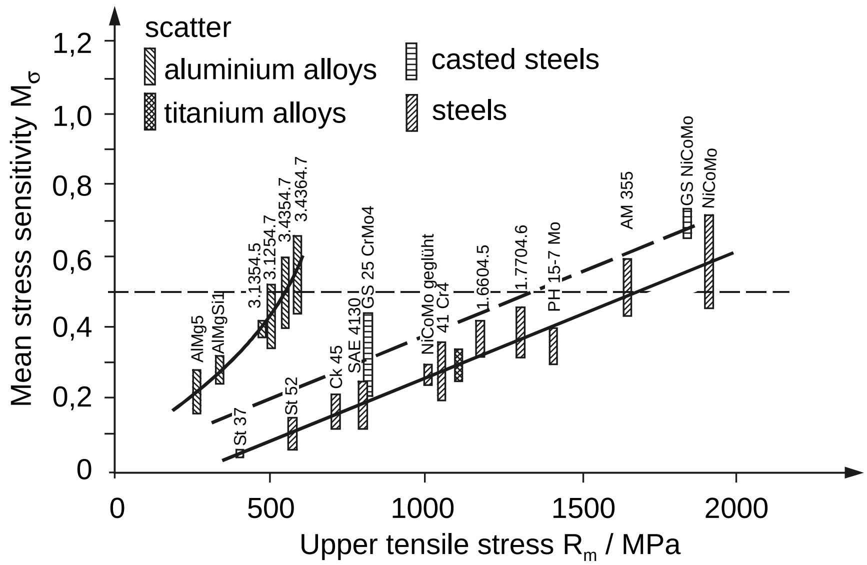

Figure 6: Mean stress sensitivity M_σ versus ultimate tensile strength [15]

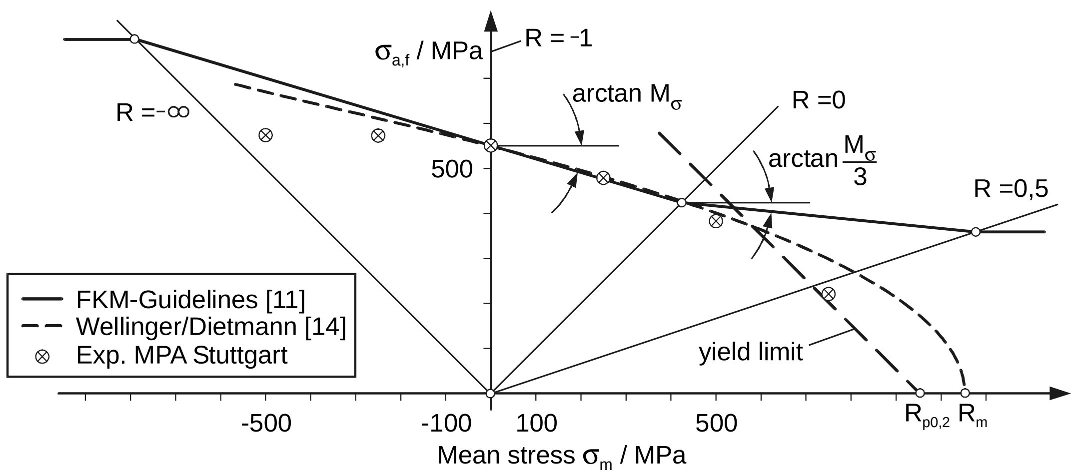

Figure 7: Influence of mean stress according to the fatigue strength diagram (Haigh's diagram)

CALCULATION OF STRESS INTENSITY RANGE

The four equations used for Class 1 piping to calculate the stress intensity are the Code Eq. (9) [1] addressing primary stress margins

$$B_1 \frac{pD_o}{2t} + B_2 \frac{D_o M_i}{2I} \le 1{,}5 \cdot S_m \qquad (6)$$

(primary stress limit for design conditions), the Code Eq. (10) addressing the shake down stress limit

$$S_n = C_1 \frac{p_o D_o}{2t} + C_2 \frac{D_o M_i}{2I} + \text{Thermal Stress Range } (\Delta T_m) \le 3 \cdot S_m \qquad (7)$$

(limit for the primary + secondary stress intensity range) and the Code Eq. (11) defining the peak stress range for fatigue analysis

$$S_p = K_1 C_1 \frac{p_o D_o}{2t} + K_2 C_2 \frac{D_o M}{2I} + \text{Thermal Stress Range } (\Delta T_m, \Delta T_1, \Delta T_2) \qquad (8)$$

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[1] Code Eq. referes to [1] ASME-Code, Sedtion III, NB3600 equations

with the stress amplitude

$$S_a = \frac{S_P}{2} \tag{9}$$

Research is still under way concerning the categorization of the stresses directly influencing the result of a fatigue analysis.

Thermal Stresses

Most of the fatigue relevant stresses in piping systems are caused by thermal loading. The difference between the density of the fluid caused by the temperature gradient from bottom to top of the pipe cross section (eg. pressurizer coolant and that of the somewhat cooler hot leg coolant) combined with low flow rates can result in thermal stratification in the horizontal portions of a piping system. The hot and cold fluid levels of the stratified flow conditions are separated by a interface or mixing layer. On the other hand high flow rates can cause a temperature gradient in pipe longitudinal direction (jump of temperature) and result in a thermal shock loading on the inside pipe surface constant throughout the pipe cross section. To calculate thermal stresses in pipes the Code Eq. 10 and 11 are available.

Thermal stratification

Thermal stratification in piping system causes an cirumferentially varying temperature distribution in the pipe wall resulting in local through wall axial stresses (through wall radial temperature gradient) and global bending stresses in the piping system (axial expansion forces and thermal moments). Maximum local thermal stress is found when a thin interface layer occurs in the upper or lower parts of the pipe cross section. Maximum global thermal bending stress is found when a thin interface layer occurs in the middle of the pipe cross section.

The ASME-Code Section III [1] or KTA Standards [4] rules calculating thermal stresses may not be completely applicable for the thermal stratification loading. Also analytical approaches may be highly conservative compared to detailed finite element (FE) calculations as demonstrated for a straigth pipe with nominal diameter DN400 and wall thickness 12 mm under thermal transient loading of ΔT=100 K, Fig. 8 to 11.

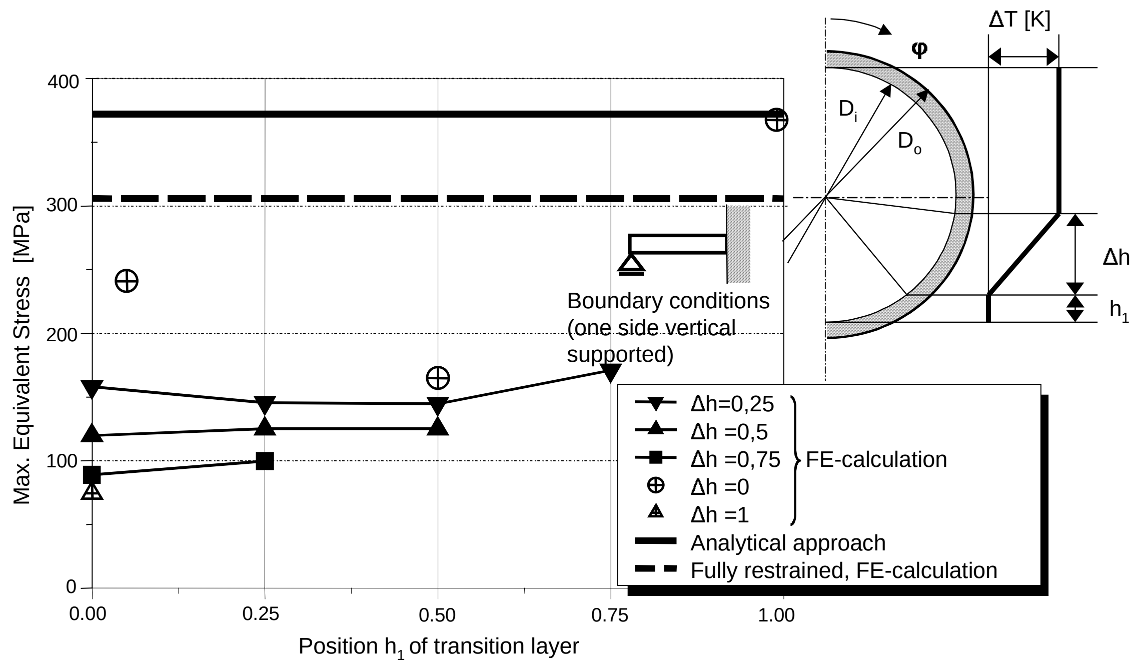

Figure 8: Maximum equivalent stress resulting from different thermal transient (stratification) loading

Thermal shock

The ASME-Code Section III [1] or KTA Standards [4] rules calculating thermal stresses are applicable for the thermal shock loading.

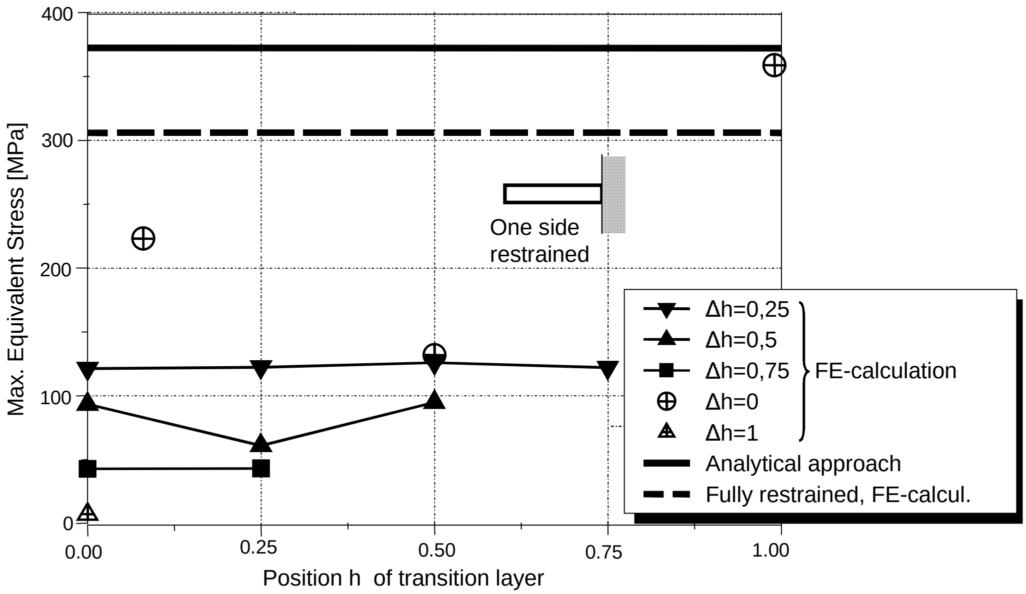

Figure 9: Maximum equivalent stress resulting from different thermal transient (stratification) loading

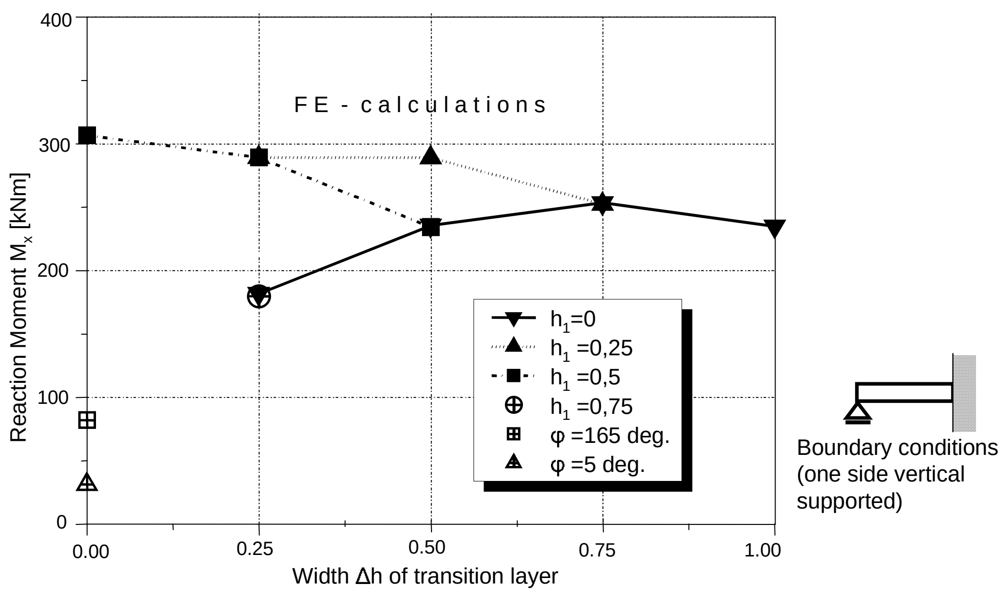

Figure 10: Maximum reaction moment resulting from different thermal transient (stratification) loading

Plastification Factor K_e

For nuclear power plant components which are subjected to cyclic loading a fatigue analysis in accordance with the codes and standards [1-3] has to be performed. If elastic-plastic deformation is to be expected then generally costly non-linear FE-calculations have to be carried out. However under specific conditions a simplified elastic-plastic fatigue analysis may also be performed using plastification factors K_e . This is considerably simpler since it is based on linear elastic material behaviour. The determination of K_e values according to the German KTA safety rules, which have been largely adopted from the ASME code is shown in the following.

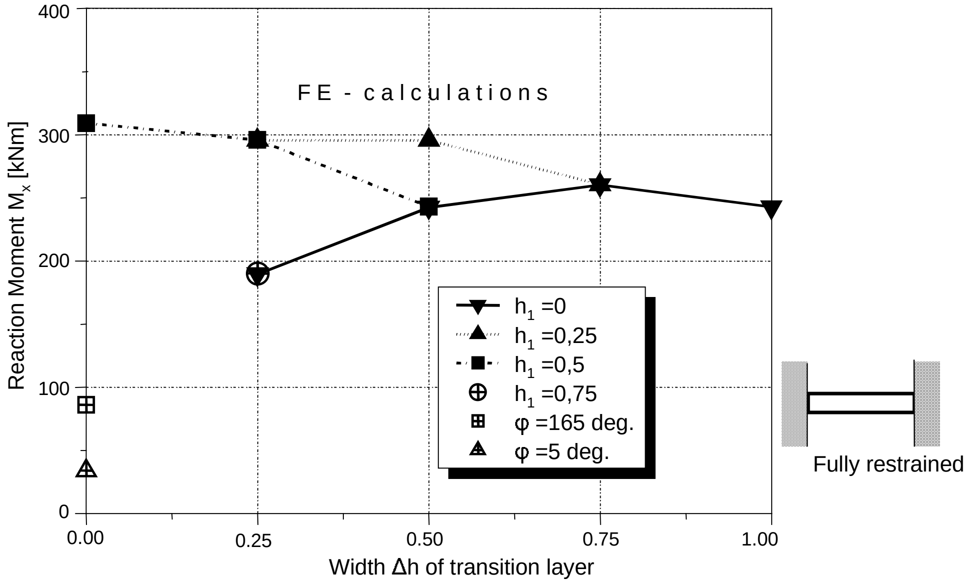

Figure 11: Maximum reaction moment resulting from different thermal transient (stratification) loading

Characteristic stresses and strains are represented by a hysteresis loop during a cycle, Fig. 12. The fictive elastic strains $\Delta\varepsilon_{el}$ are brought into line with the actual, elastic-plastic strain $\Delta\varepsilon_t$ by multiplying them by the plastification factor K_e which is defined by

$$\mathbf{K_e} = \frac{\Delta\varepsilon_t}{\Delta\varepsilon_{el}} \quad . \tag{10}$$

According to KTA 3201.2, Section 7.8.4 the plastification factor has to be calculated as follows:

$$\mathbf{K_e} = \begin{cases} \mathbf{1} & \textbf{for } \mathbf{0 \le \frac{S_n}{S_m} \le 3} \\ \mathbf{1 + \frac{1-n}{n\,(m-1)} \cdot \left[\frac{S_n}{3\,S_m} - 1\right]} & \textbf{for } \mathbf{3 < \frac{S_n}{S_m} < 3m} \\ \mathbf{\frac{1}{n}} & \textbf{for } \mathbf{\frac{S_n}{S_m} \ge 3m} \end{cases} \tag{11}$$

with S_m as design stress intensity value for the material used.
For example, for ferritic respectively martensitic steels the characteristic material value S_m is calculated as

$$\mathbf{S_m = Min\left\{\frac{R_{p0,2T}}{1,5}; \frac{R_{mT}}{2,7}; \frac{R_{mRT}}{3,0}\right\}} . \tag{12}$$

S_n is the fictive elastic equivalent stress range of primary and secondary stresses. The value of the material parameters m and n are to be taken from Tab. 1.

Table 1: Material parameters

Material	Group	m	n	T_{max} [°C]
low alloy carbon steel, martensitic stainless steel	1	2,0	0,2	370
unalloyed carbon steel, austenitic stainless steel	2	3,0	0,2	370
nickel-based alloy	3	1,7	0,3	425

In Fig. 13 the dependence of of the plastification factor K_e on the load proportional reference magnitude S_n/S_m is shown for various material groups according to the nuclear codes and standards. An evaluation of experimental results from LCF tests with smooth specimens (K_t = 1) for group 1 materials (ferritic and martensitic steels) is shown in Fig. 14. It's obvious that the scatter is according to the available wide scale of different heat treatments and strengths relatively small. The calculation of K_e values according to ASME/KTA is evidently very conservative.

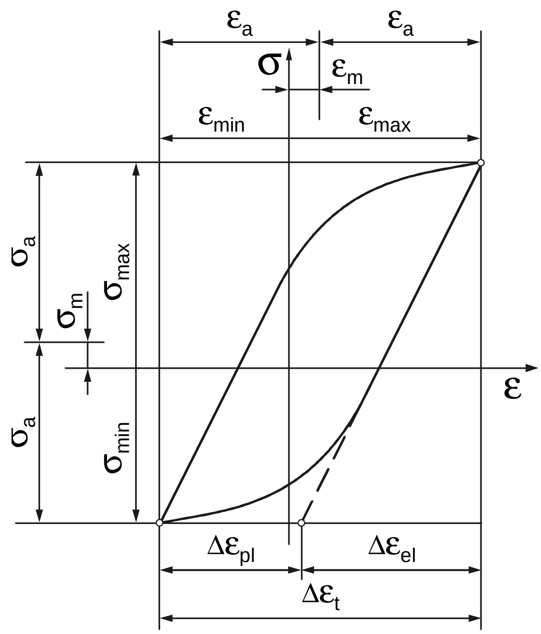

Figure 12: Hysteresis loop

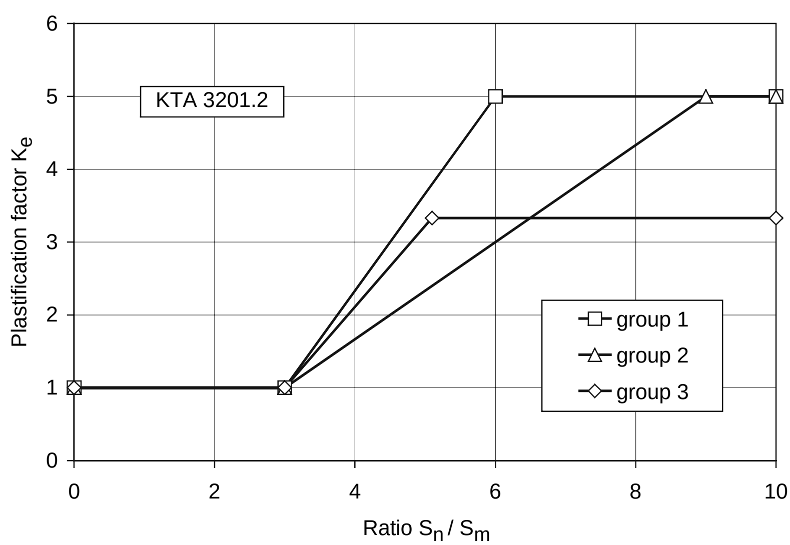

Figure 13: K_e factors according to ASME [1] and KTA [4]

CONCLUSIONS

Fatigue is a potential failure mode for components and structures of nuclear power plants. For the explicite consideration of cyclic operational loads (mechanical, thermal) in different technical codes and standards specific fatigue analysis methods are available. As for the nuclear codes and standards the following conclusions can be drawn:

- The influence of temperature is adequate addressed by considering the ratio of the modulus of elasticity using the S/N-curves.

- The design curves were derived by introducing factors of 2 on stress and 20 on cycles to account for real effects (size, environment, surface finish, scatter of data) occuring during plant operation. This implies that during manufacturing and design the specific requirements are met and during plant operation the conditions for environmental effects are monitored and controlled.
- To account for thermal stresses within a fatigue analysis the code equations may not be completely applicable for the thermal stratification loading
- Compared to experimental data the calculation of the plastification factor K_e according to ASME/KTA is evidently very conservative.

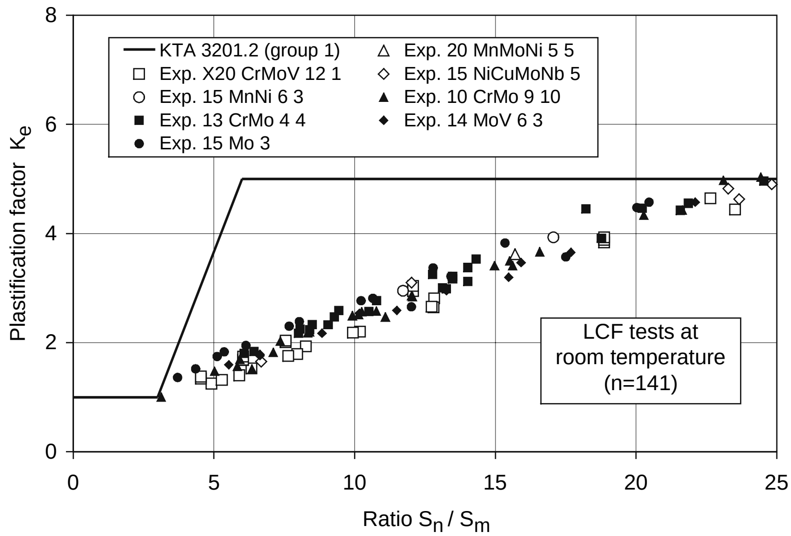

Figure 14: K_e factors from LCF tests compared with the values of KTA [4]

NOMENCLATURE

f_d	=	size factor
f_o	=	surface factor
f_T	=	temperature factor
m, n	=	material parameters
t	=	wall thickness
B_1, B_2	=	primary stress indices
C_1, C_2	=	secondary stress indices
D_i	=	inside pipe diameter
D_o	=	outside pipe diameter
E	=	Young's modulus
I	=	moment of inertia
K_e	=	plastification factor
K_f	=	fatigue strength reduction factor
K_t	=	stress concentration (notch) factor
M_i	=	resultant moment
K_1, K_2	=	local stress indices
M_σ	=	mean stress sensitivity
N	=	number of cycles
R	=	stress ratio
R_m	=	ultimate tensile strength
$R_{p0.2}$	=	yield strength
R_z	=	peak-to-valley high
S_a	=	alternating stress amplitude
S_m	=	allowable design stress intensity value

S_n	=	primary plus secondary stress intensity value
S_p	=	peak stress intensity value
T	=	temperature
U	=	cumulative usage factor
ΔT_m	=	range of average temperature
ΔT_1, ΔT_2	=	absolute value of temperature range
ε	=	strain
$\Delta\varepsilon$	=	strain range
σ	=	stress
σ_a	=	stress amplitude
σ_m	=	mean stress

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