Fatigue assessment according to Eurocode 3 (steel structures)

Fatigue Assessment According to Eurocode 3 (Steel Structures)

Vérification à la fatigue selon l'Eurocode 3 (constructions métalliques)

Betriebsfestigkeitsnachweis für Stahlbauten nach Eurocode 3

G. SEDLACEK
Professor
Rheinisch-Westfälische Technische Hochschule
Aachen, BRD

SUMMARY
The fatigue assessment of steel structures according to the limit state equation of Eurocode 3 is defined in terms of service life (number of cycles). The safety factors are derived from the "Level II" method of constant sensitivity factors.

RESUME
Les états limites considérés dans l'Eurocode 3 pour la vérification de la sécurité à la fatigue des constructions métalliques sont définis sur l'axe des durées de vie. Les facteurs de sécurité à utiliser pour la vérification sont déterminés selon la procédure issue des théories de "Level II" et faisant intervenir des facteurs de sensibilités constants.

ZUSAMMENFASSUNG
Für den Betriebssicherheitsnachweis für Stahlbauten nach Eurocode 3 werden der Grenzzustand in der Achse der Lebensdauer definiert und nach dem aus der Level II-Methode abgeleiteten Verfahren der konstanten Wichtungsfaktoren die Sicherheitsfaktoren für den Nachweis abgeleitet.

1. GENERAL

The calculative safety assessment for the fatigue behaviour of dynamically loaded steel structures should be carried out in a way to attain as often as possible a target reliability expressed by the safety index β_T, not falling below a minimum value min β, if possible and also not exceeding a maximum value max β for economic reasons.

The justification for a proposal for the determination of the safety elements is developed in the following using the procedure of global sensitivity factors which is derived from the Level II method /3/.

2. ASSESSMENT FOR A DETERMINED $\Delta\sigma$-LEVEL AND A DETERMINED NUMBER OF CYCLES n

Fig. 1 demonstrates a scatter-band of test results from fatigue tests with a component with a critical detail for different levels of damaging stress ranges $\Delta\sigma$, which are calculated as nominal stresses for measured test loads.

As a resistance model the S-N-lines for defined survival probabilities can be illustrated in double logarithmic scale as for instance fig. 2.

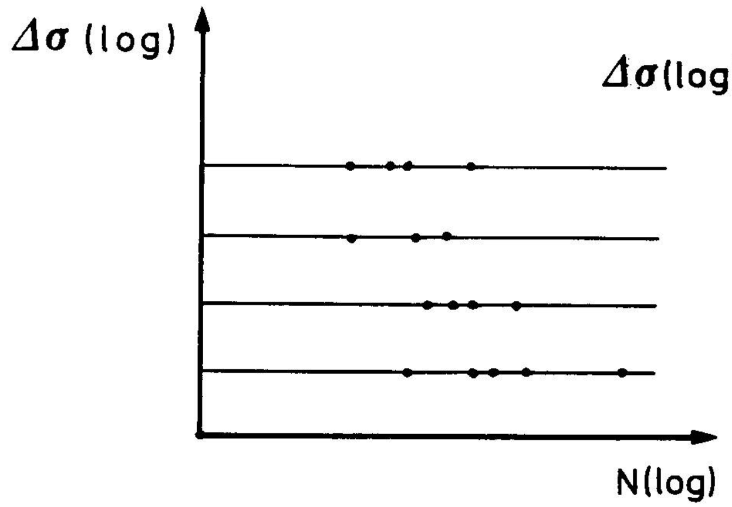


Fig. 1: Scatter-band of fatique test results

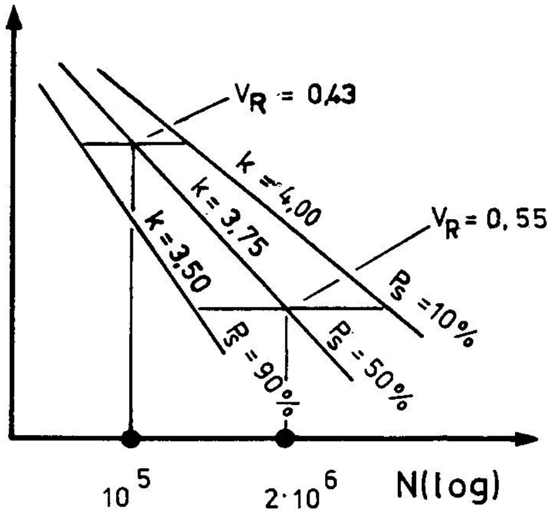


Fig. 2: S-N-lines for small test specimens

The safety assessment should be carried out for a structural component designed in the same way as the test elements.

The limit state equation for fatigue for the stress range level $\Delta\sigma_i$ is then

$$g\ (X_i) = N_i - n_i = 0 \tag{1}$$

see fig. 3.

Here a log-normal distribution with the variation coefficient V_R - for instance for small components according to fig. 4 - is assumed for the basic variable for the "resistance" N_i, and for the "action" n_i the sum of the cycles of all measuring time intervals is extrapolated over a designed service life and defined as, fig. 5

$$n_i = \sum_{T_L} n_t \quad . \tag{2}$$

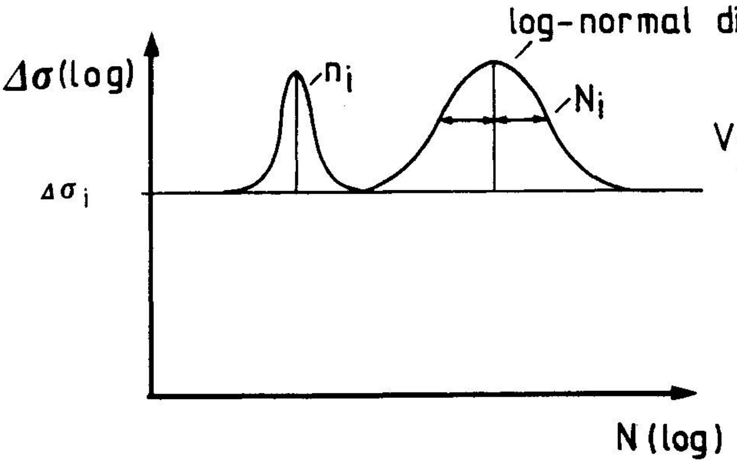


Fig. 3: Distributions of N and n

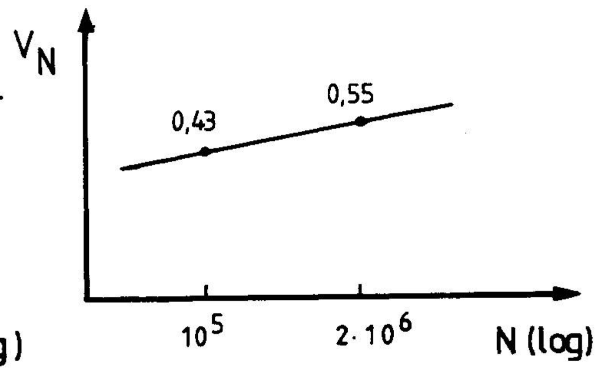


Fig. 4: Variation coefficient (N-log normal)

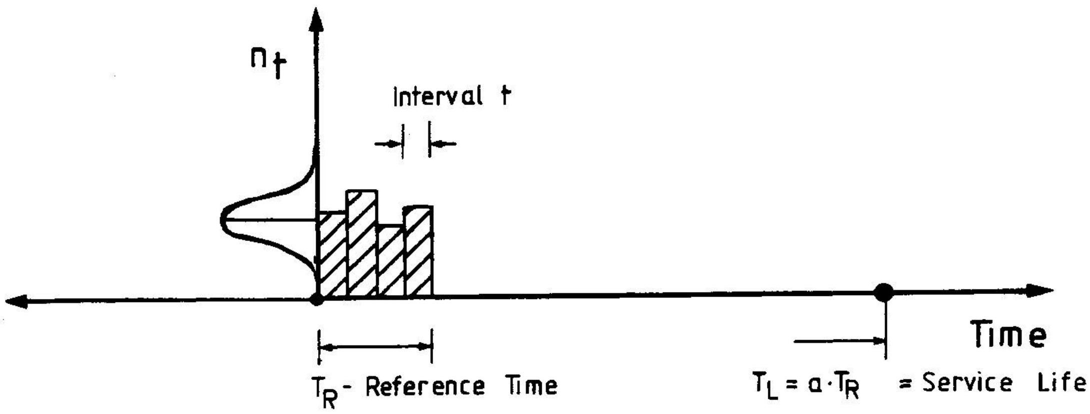


Fig. 5: Number of stress range cycles

If a symmetrical density distribution of the numbers of cycles is assumed over the measuring time intervals within service life, then the variation coefficient for n_i is zero.

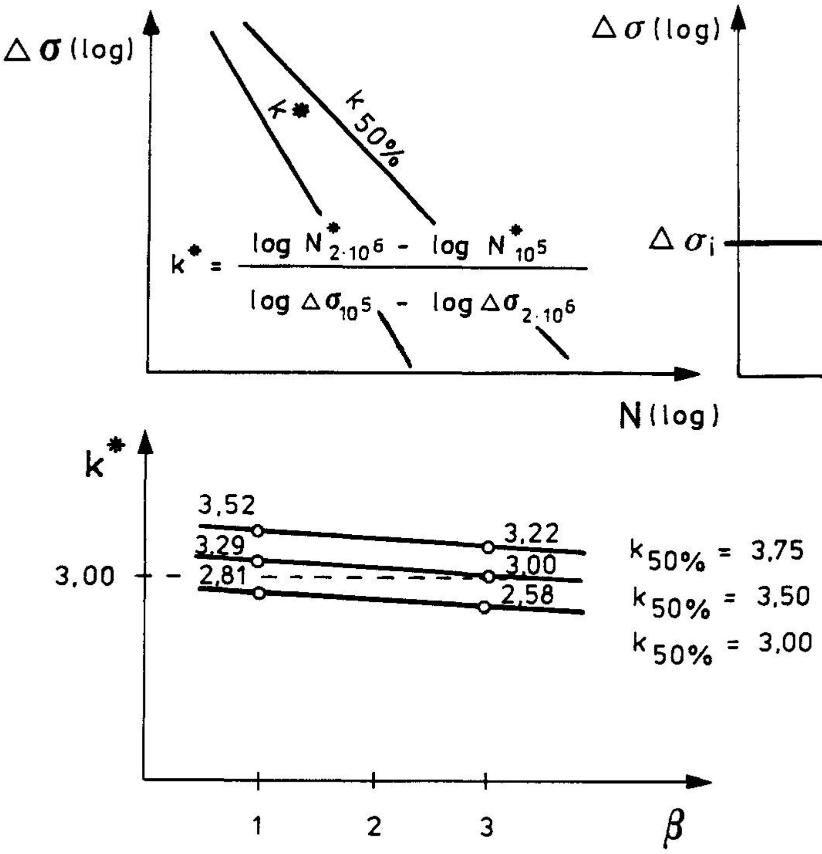
The design values N_i^* and n_i^* can be expressed according to /4/

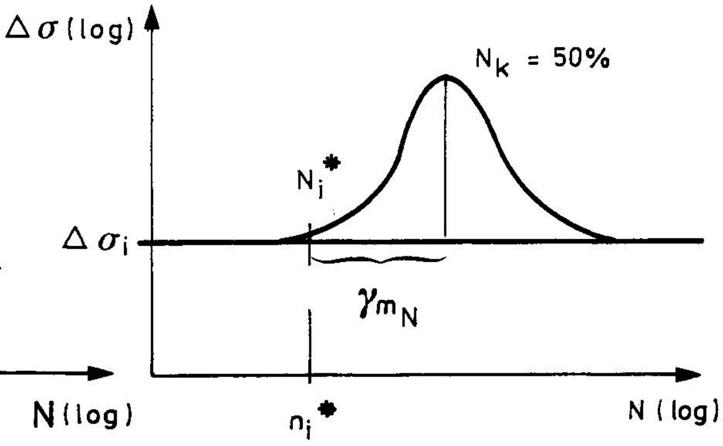
$$\left. \begin{array}{lll} N_i^* = m_N \exp\left(- \alpha_R \beta V_R - \frac{1}{2} V_R^2\right) & \text{with} & \alpha_R = 1{,}0 \\ n_i^* = m_n \left(1 + \alpha_S \beta V_S\right) = m_n & \text{due to} & \alpha_S = 0 \end{array} \right\} \tag{3}$$

The design values N_i^* for various stress levels $\Delta\sigma_i$ will then lie on the design S-N-curve with the slope k* which is influenced by β, the assumed variation coefficient and by the slope of the 50 %-S-N-line, see fig. 6.

For target values β_T of the order of 2 the slope is k* = 3,0. This value is also obtained in tests with full scale structural components for which the variation coefficients are smaller and the scatter-bands are more parallel as compared with the test results obtained with small test-specimens.

The safety verification for a deterministically given stress range can now be carried out in the time scale with γ_{mN}, with reference to the characteristic values N_k (for example $N_k = N_{50\,\%}$) according to fig. 7.



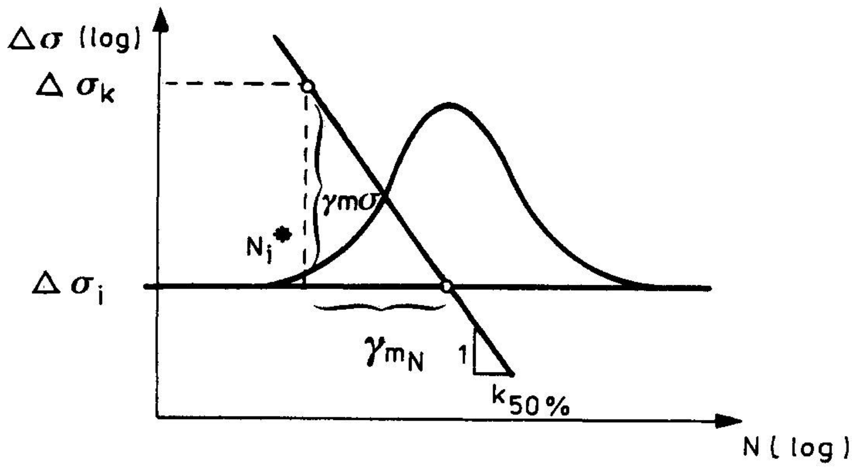


$$\gamma_{mN} = \frac{N_k}{N_i^*}$$

Fig. 6: Design values for the slope k*.

Fig. 7: Safety factor in N-scale.

An equivalent verification with respect to the stress range scale is performed with the slope k of the characteristic S-N-line according to fig. 8.



$$\gamma_{m\sigma} = \sqrt[k]{\gamma_{mN}}$$

$$\frac{\log N_k - \log N_i^*}{\log \Delta\sigma_k - \log \Delta\sigma_i} = \frac{\log \gamma_{mN}}{\log \gamma_{m\sigma}} = k$$

Fig. 8: Safety factor in $\Delta\sigma$-scale.

3. ASSESSMENT FOR SPECTRA WITH VARIOUS DETERMINED $\Delta\sigma_i$-LEVELS AND VARIOUS DETERMINED NUMBERS OF CYCLES n_i

If according to fig. 9 the stress ranges $\Delta\sigma_i$ are acting at different levels, for example $\Delta\sigma_i$ with n_i and $\Delta\sigma_A$ with n_A, the equivalent-damage stress range cycles n_e at the reference level $\Delta\sigma_A$ can be expressed using Miner's rule, fig. 10.

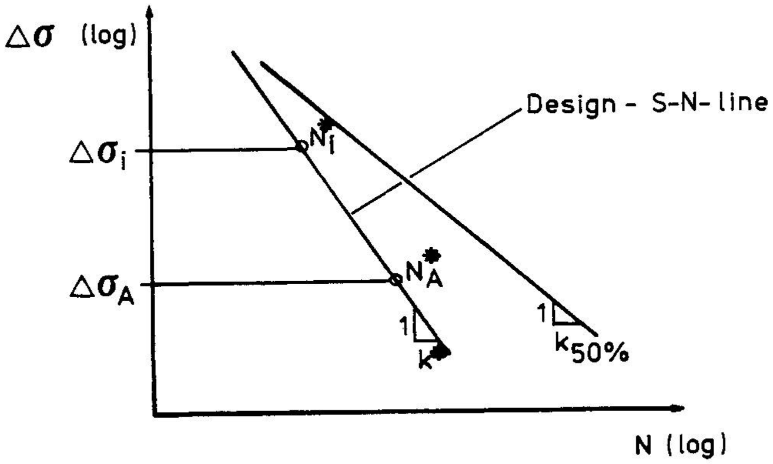


Fig. 9: Design-S-N-line.

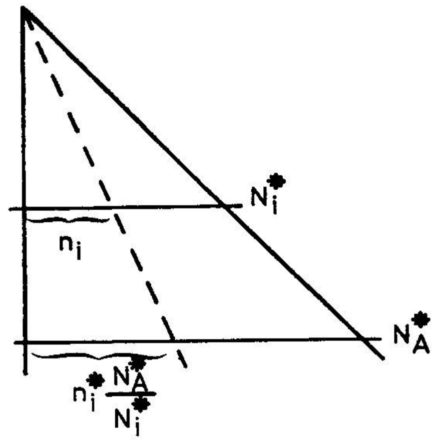


Fig. 10: Equivalent-damage stress cycles on different levels of stress range.

$$n_e^* = \sum n_i^* \frac{N_A^*}{N_i^*} \tag{4}$$

Considering the equation of the S-N*-line

$$\Delta\sigma_i^{k^*} \cdot N_i^* = \Delta\sigma_A^{k^*} \cdot N_A^* \tag{5}$$

it follows from (4)

$$n_e^* = \sum n_i^* \left(\frac{\Delta\sigma_i}{\Delta\sigma_A}\right)^{k^*} \tag{6}$$

The design-equation is then

$$g(X_i^*) = N_A^* - n_e^* = 0 \tag{7}$$

or using characteristic values and safety factors, fig. 11

$$\frac{N_{Ak}}{\gamma_{mNA}} - n_e = 0 \qquad (8)$$

By defining the reference level $\Delta\sigma_A$ as the level of the equivalent-damage stress range $\Delta\sigma_e$ for the number of load cycles $\sum n_i$, fig. 12.

$$n_e^* = \sum n_i^* \left(\frac{\Delta\sigma_i}{\Delta\sigma_e}\right)^k = \sum n_i \qquad (9)$$

the equivalent-damage stress range.

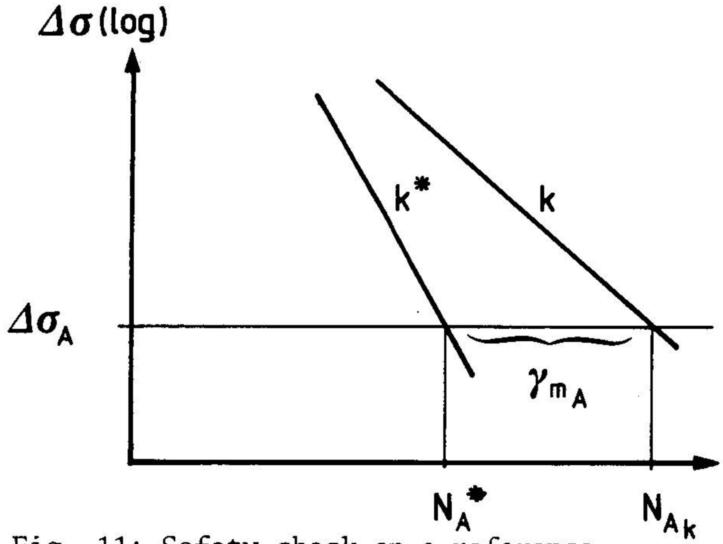


Fig. 11: Safety check on a reference stress range level $\Delta\sigma_A$.

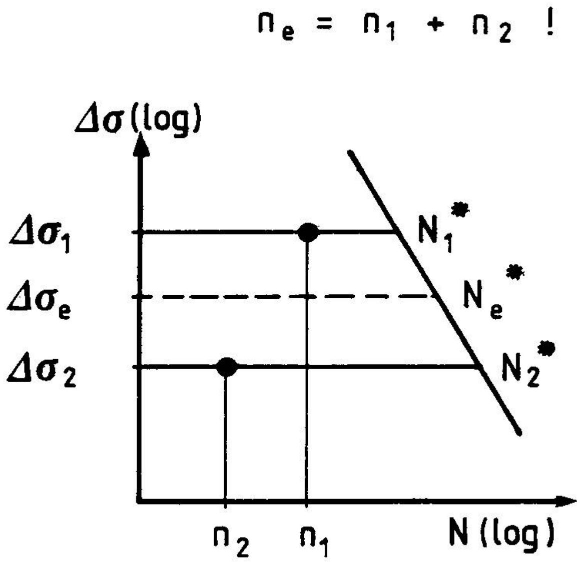


Fig. 12: Safety check on the equivalent-damage stress range level $\Delta\sigma_e$.

$$\Delta\sigma_e = \left(\frac{\sum n_i \Delta\sigma_i^{k^*}}{\sum n_i}\right)^{\frac{1}{k^*}} \qquad (10)$$

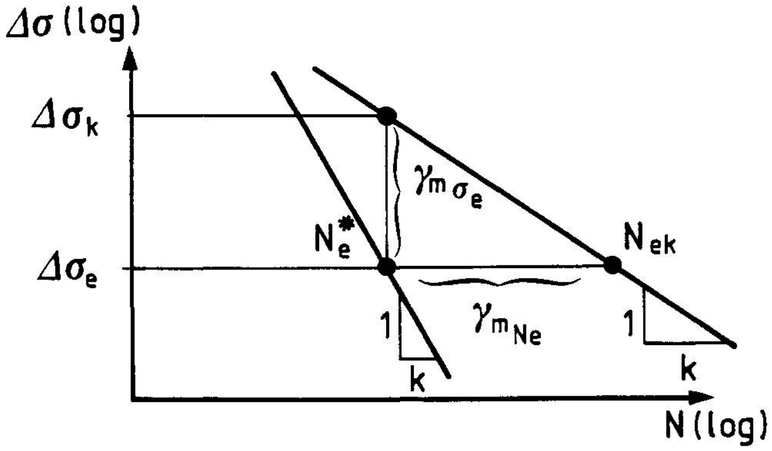
follows and the verification is performed by

$$N_e^* - \sum n_i = 0 \qquad (11)$$

The equivalent verification in terms of stresses ca be carried out using $\gamma_{m\sigma}$ according to fig. 13.

In fig. 14 γ_{mN} - values and $\gamma_{m\sigma}$ - values related to the 50 %-S-N-lines given as characteristic values are specified for different slopes and β-values.

For steel structures $\beta = 2{,}0$ is considered to be sufficient, if the appropriate values for $\Delta\sigma_i$ and n_i are correct.



$$\frac{\Delta\sigma_k}{\gamma_{m\sigma}} - \Delta\sigma_e = 0$$

Fig. 13: Safety check in $\Delta\sigma$ scale with equivalent-damage stress range $\Delta\sigma_e$.

$\gamma_{m\sigma}$ - Values

$k_{50\%}$ \ β		1.0	1.5	2.0	2.5	3.0
3.75	N_{10^5}	1.12	1.19	1.26	1.33	1.41
	$N_{2\cdot10^6}$	1.16	1.25	1.34	1.44	1.55
3.50	N_{10^5}	1.13	1.20	1.28	1.36	1.45
	$N_{2\cdot10^6}$	1.17	1.27	1.37	1.48	1.60
3.00	N_{10^5}	1.16	1.24	1.33	1.43	1.53
	$N_{2\cdot10^6}$	1.20	1.32	1.44	1.58	1.73

γ_{mN} - Values

$k_{50\%}$ \ β		1.0	1.5	2.0	2.5	3.0
3.75	N_{10^5}	1.54	1.91	2.36	2.93	3.63
	$N_{2\cdot10^6}$	1.73	2.28	3.00	3.95	5.21
3.50	N_{10^5} / $N_{2\cdot10^6}$	"	"	"	"	"
3.00	N_{10^5} / $N_{2\cdot10^6}$	"	"	"	"	"

Fig. 14: γ_m-values for safety checks in N-scale or $\Delta\sigma$-scale using 50 % values as characteristic values

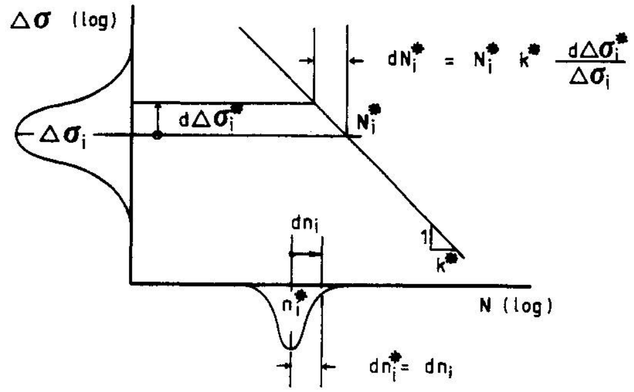
4. ASSESSMENT WITH VARYING $\Delta\sigma_i$-LEVEL AND VARYING NUMBERS OF CYCLES n_i

Assuming that the values of $\Delta\sigma_i$ and n_i are only correct in the mean of all design cases and that they vary with $d\Delta\sigma_i$ and dn_i around the correct mean value with the variation coefficients 0,10 (which corresponds to the variance of specified dead loads), the sensitivity factors α_i for all variables can be derived from the characteristic equation in fig. 15 using

$$\alpha_i = \frac{\frac{\partial g}{\partial x_i} \; s_i}{\sqrt{\sum_j \left(\frac{\partial g}{\partial x_j} \cdot s_j\right)^2}} \qquad (12)$$

These sensitivity factors can be combined into α_R = 1,0 for the "resistance model" and α_S = -0,30 for the "acting model".

The γ_m-values and γ_{SYS}-values for verifications in terms of time or stresses using the 50 %-S-N-lines as characteristic values are illustrated in fig. 16.



characteristic equation:

$$N_i^* - N_i^* k^* \frac{d\Delta\sigma_i^*}{\Delta\sigma_i} - n^* - dn^* = 0$$

Estimated datas:

$N_{50\%} = 2 \cdot 10^6$; $V_N = 0{,}55$; $\sigma_N = 1{,}1 \cdot 10^6$

$d\Delta\sigma_{50\%} = 0$; $\sigma_{\Delta\sigma} = 0{,}10\ \Delta\sigma_i$

$n_{i50\%} = n_i$; $V_n = 0$; $\sigma_n = 0$

$dn_{i50\%} = 0$; $\sigma_{dn} = 0{,}10\ n_i$

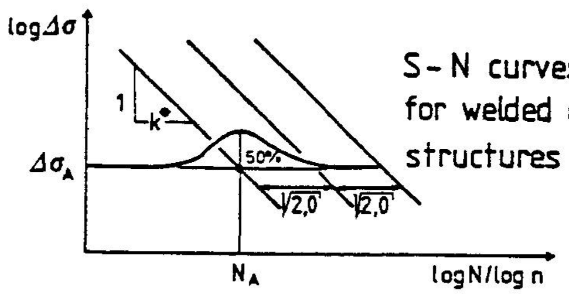
Sensivity - factors:

$\alpha_N \sim 1{,}0$; $\alpha_{\Delta\sigma} \sim -0{,}30$; $\alpha_{ni} \sim 0$; $\alpha_{dni} \sim -0{,}10$

Overall Sensivity factors:

$\alpha_R \sim 1{,}0$; $\alpha_S \sim -0{,}30$

Fig. 15: Consideration of a scatter for $\Delta\sigma_i$ and n_i.



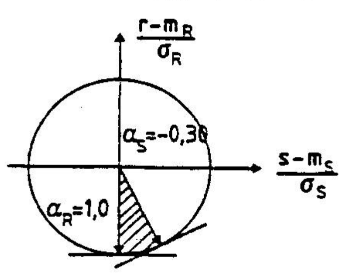
$$N_R^* \geq n_S^*$$

$$N_A \exp(-\alpha_R \beta V_R - 0{,}5\, V_R^2) \geq \sum_j n_j \left(\frac{\Delta\sigma_j\,(1-\alpha_S\,\beta\, V_S)}{\Delta\sigma_A}\right)^{K^*}$$

$$\frac{N_A}{\gamma_{m_N} \cdot \gamma_{sys_N}} \geq n_e = \sum n_j \left(\frac{\Delta\sigma_j}{\Delta\sigma_A}\right)^{K^*}$$

For $K^* = 3{,}0$; $V_R = 0{,}55$; $V_S = 0{,}10$

β	1,5	2,0	2,5	3,0
γ_{m_N}	2,30	3,00	4,00	5,20
γ_{sys_N}	1,15	1,20	1,25	1,30
γ_{Glob_N}	2,65	3,60	5,00	6,80



$V_R \geq 0{,}50$

$V_S \leq 0{,}10$

$$\frac{\Delta\sigma_K}{\gamma_{m_\sigma} \cdot \gamma_{sys_\sigma}} \geq \Delta\sigma_e = \left[\frac{\sum n_j\ \Delta\sigma_j^{K^*}}{\sum n_j}\right]^{1/K^*}$$

β	1,5	2,0	2,5	3,0
γ_{m_σ}	1,30	1,45	1,60	1,75
γ_{sys_σ}	1,05	1,06	1,08	1,09
γ_{Glob_σ}	1,40	1,55	1,75	1,90

Fig. 16: Safety check for fatigue taking into account of a scatter for $\Delta\sigma_i$ and n_i.

In the Euorcode 3 the S-N-lines have been defined as (m - 2s)-values so that γ_m, may be defined, $\gamma_m = 1{,}0$.

5. MEAN STRESS INFLUENCE

The mean stress influence in Eurocode 3 is generally considered to be negligible; if the mean stress influence is significant, for instance for small welded elements or stress relieved components with minor residual stresses, the verification according to Eurocode 3 is on the safe side. In addition the mean stress influence can be considered by taking into account a bonus factor for the stress-ranges, which depends on the mean stress according to fig. 17.

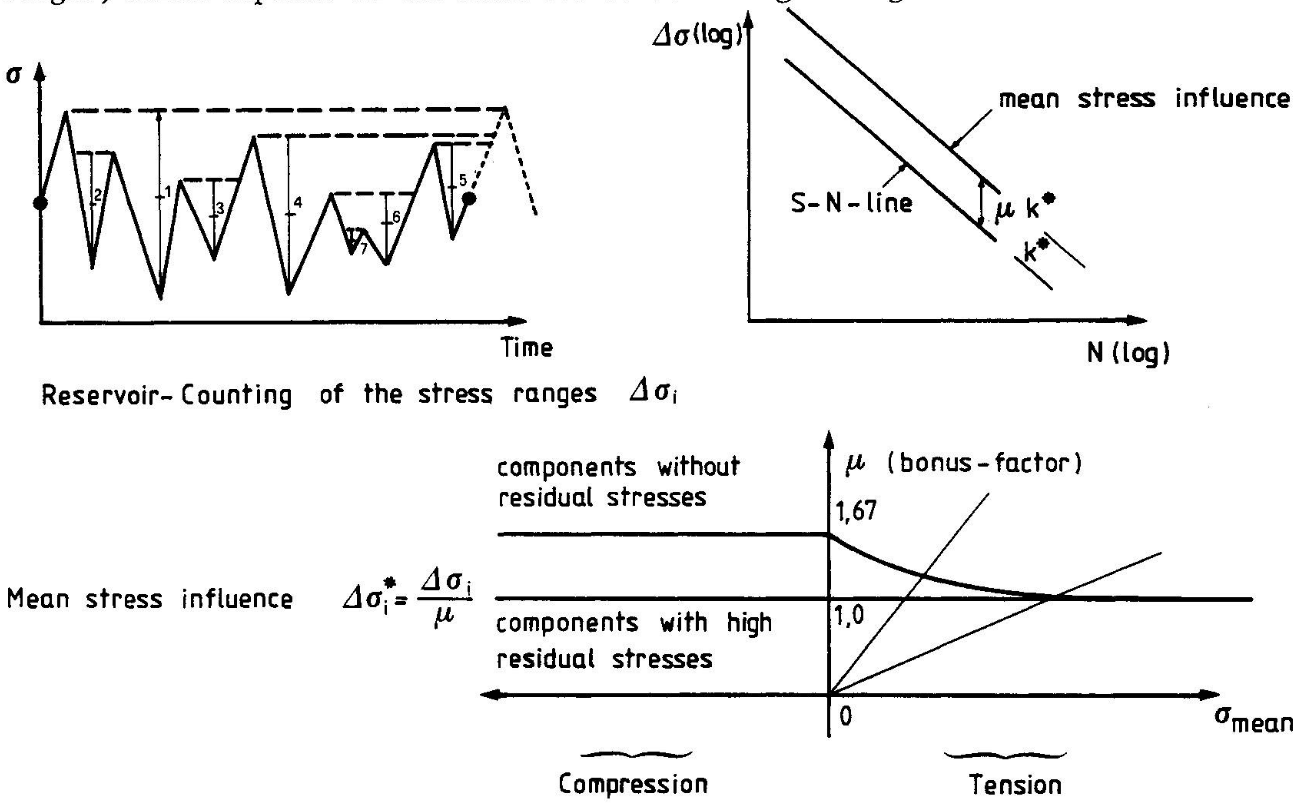


Fig. 17: Bonus factor for mean-stress-influence.

REFERENCES

/1/ Eurocode 1, Draft August 1981

/2/ Eurocode 3, Draft August 1981

/3/ NABau-Arbeitsausschuß-Sicherheit von Bauwerken: Grundlagen für die Festlegung von Sicherheitsanforderungen für bauliche Anlagen

/4/ König, Hosser, Schobbe: Herleitung von Sicherheitselementen für die praktische Bemessung

/5/ Poussett,Sedlacek: The Application of Safety-Concepts to Steel Structures, 3rd International ECCS-Symposium, London 1981

/6/ EKS-TC6 (Fatique): Recommendations for the Fatique Design of Structures

/7/ Sedlacek, Schlesiger: Sicherheitsnachweis für Ermüdung, 1981, unveröffentlicht.

/8/ Olivier, Ritter: Wohlerlinienkatalog für Schweißverbindungen aus Baustählen; Deutscher Verband für Schweißtechnik e.V. 1979

Leere Seite
Blank page
Page vide