

**Zeitschrift:** IABSE reports = Rapports AIPC = IVBH Berichte  
**Band:** 37 (1982)

**Artikel:** Fatigue assessment according to Eurocode 3 (steel structures)  
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**DOI:** <https://doi.org/10.5169/seals-28900>

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## Fatigue Assessment According to Eurocode 3 (Steel Structures)

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

Betriebsfestigkeitsnachweis für Stahlbauten nach Eurocode 3

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### 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  $\beta_T$ , not falling below a minimum value  $\min \beta$ , if possible and also not exceeding a maximum value  $\max \beta$  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.

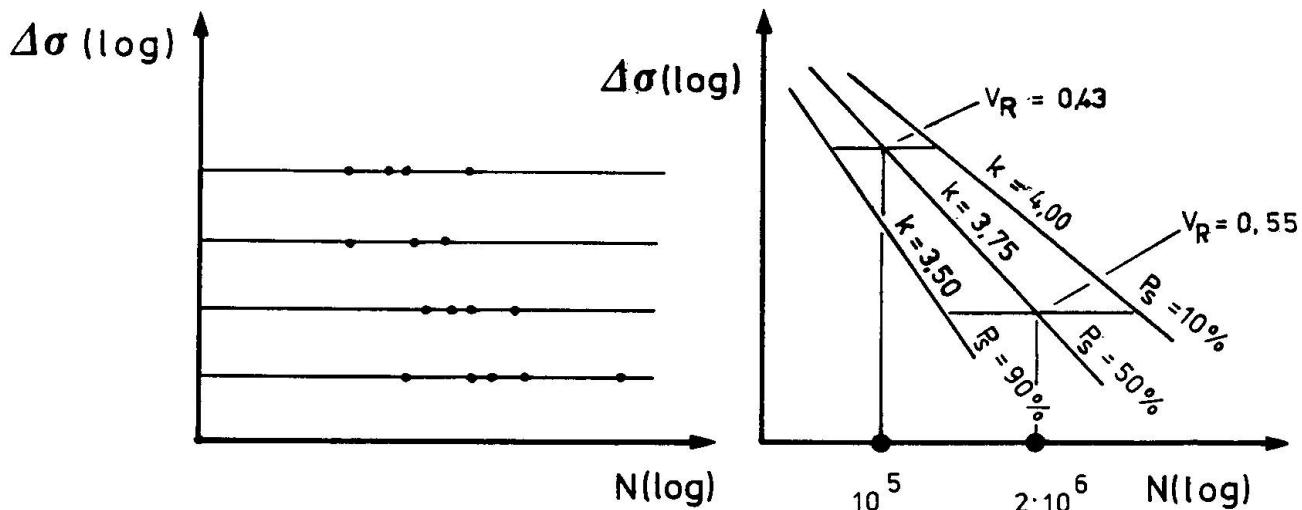


Fig. 1: Scatter-band of fatigue test results

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

$$g(X_i) = N_i - n_i = 0 \quad (1)$$

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

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

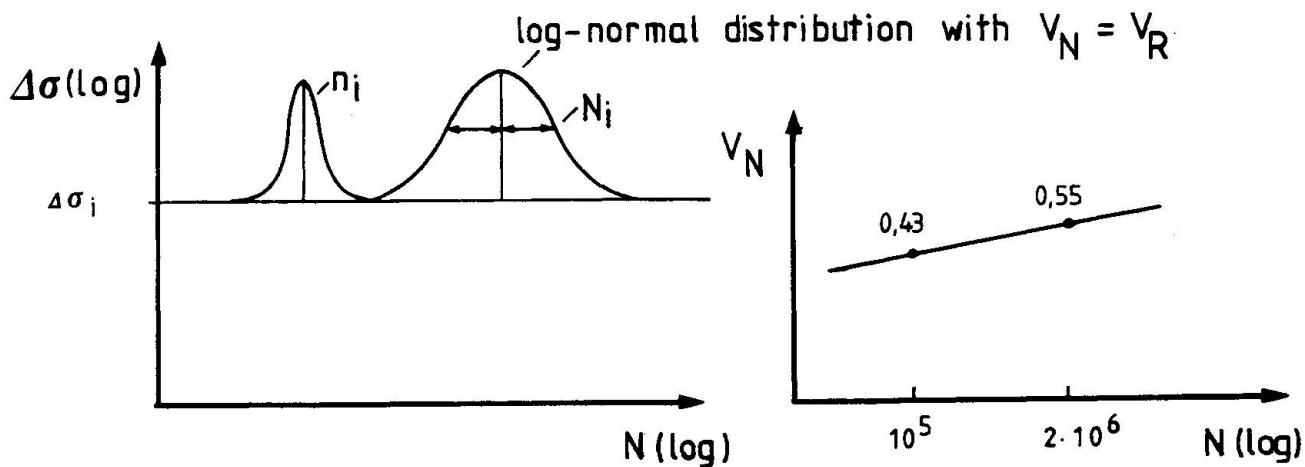
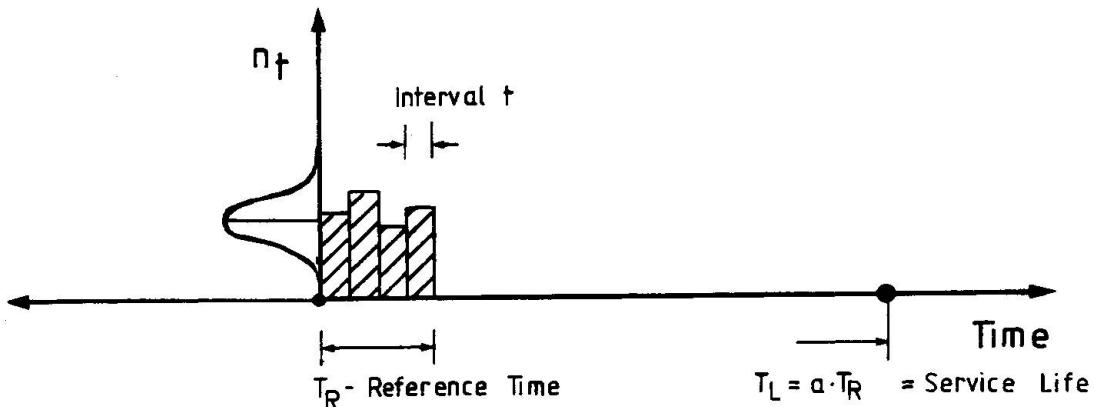
Fig. 3: Distributions of  $N$  and  $n$ .Fig. 4: Variation coefficient  
( $N$ -log normal)

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/

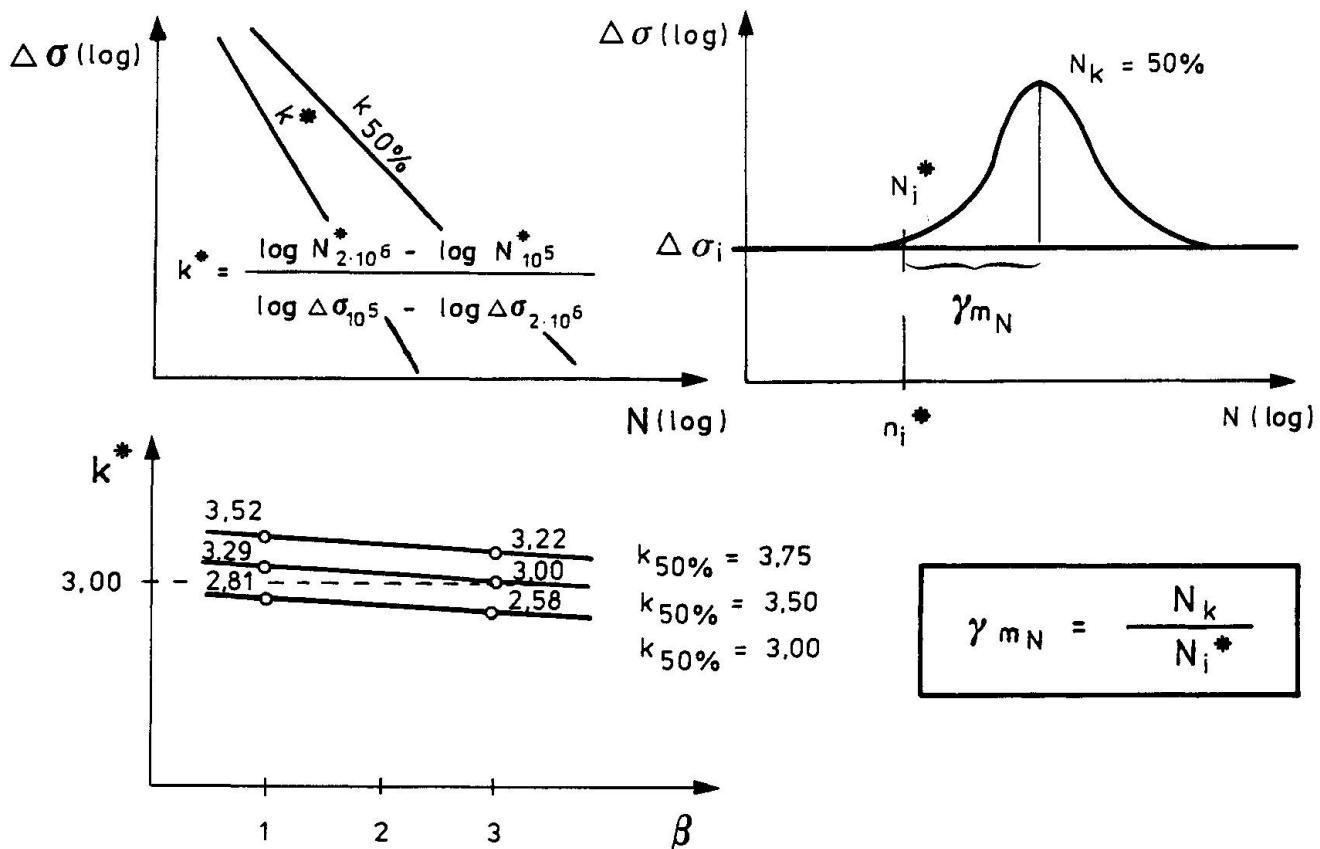
$$\left. \begin{aligned} N_i^* &= m_N \exp (-\alpha_R \beta V_R - \frac{1}{2} V_R^2) && \text{with } \alpha_R = 1,0 \\ n_i^* &= m_n (1 + \alpha_S \beta V_S) = m_n && \text{due to } \alpha_S = 0 \end{aligned} \right\} \quad (3)$$

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  $\beta$ , the assumed variation coefficient and by the slope of the 50 %-S-N-line, see fig. 6.

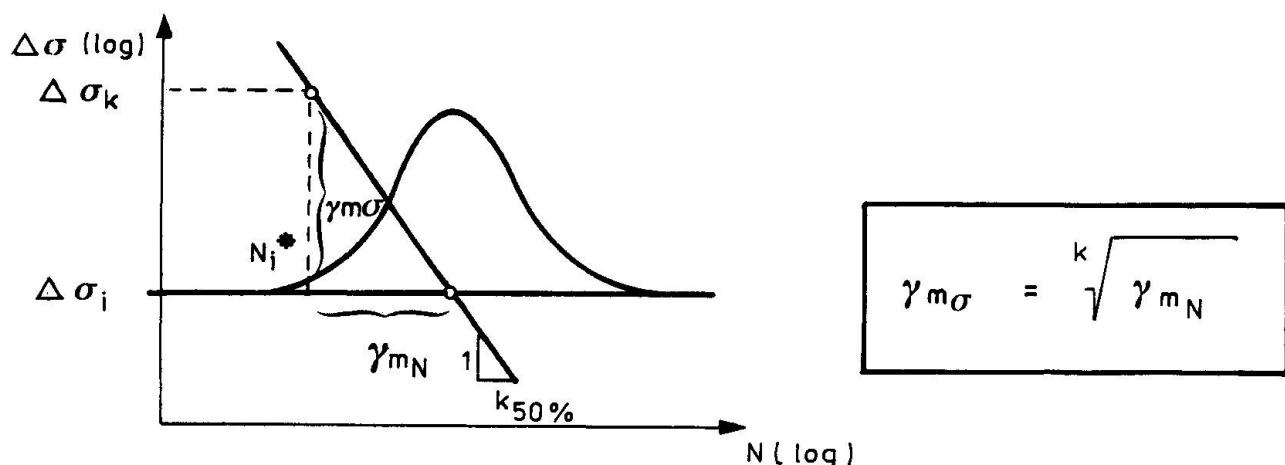
For target values  $\beta_T$  of the order of 2 the slope is  $k^* = 3,0$ . This value is also obtained in tests with full scale structural components for which the variation coefficients are smaller and the scatter-bands are more parallel as compared with the test results obtained with small test-specimens.



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



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.



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

**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.

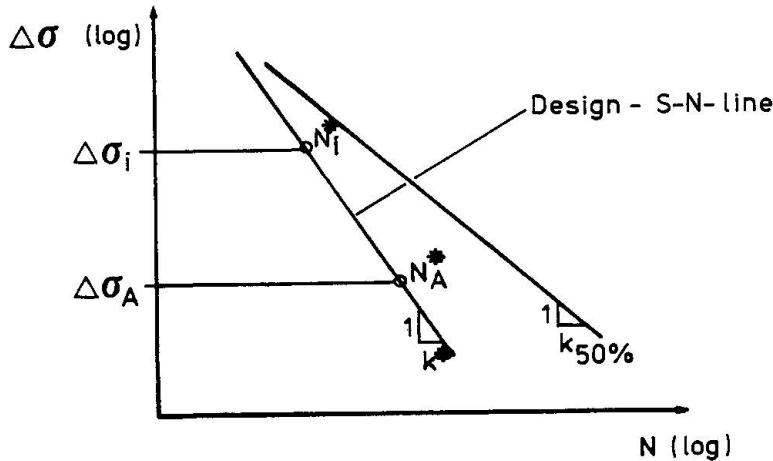


Fig. 9: Design-S-N-line.

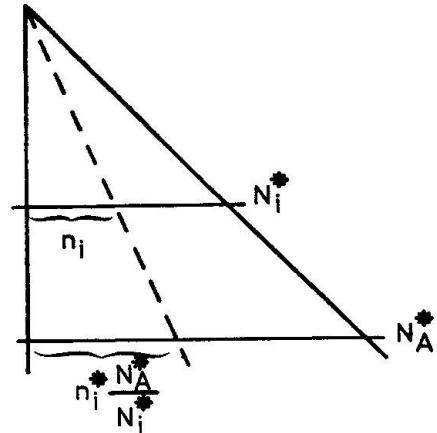


Fig. 10: Equivalent-damage stress cycles on different levels of stress range.

$$n_e^* = \sum n_i^* \frac{N_A^*}{N_i^*} \quad (4)$$

Considering the equation of the S-N\*-line

$$\Delta\sigma_i^{k^*} \cdot N_i^* = \Delta\sigma_A^{k^*} \cdot N_A^* \quad (5)$$

it follows from (4)

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

The design-equation is then

$$g(X_i^*) = N_A^* - n_e^* = 0 \quad (7)$$

or using characteristic values and safety factors, fig. 11

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

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.

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

the equivalent-damage stress range.

$$n_e = n_1 + n_2 !$$

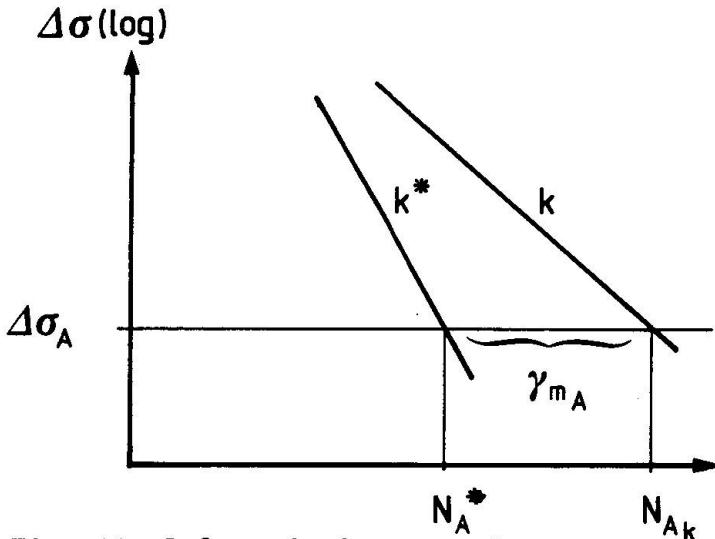


Fig. 11: Safety check on a reference stress range level  $\Delta\sigma_A$ .

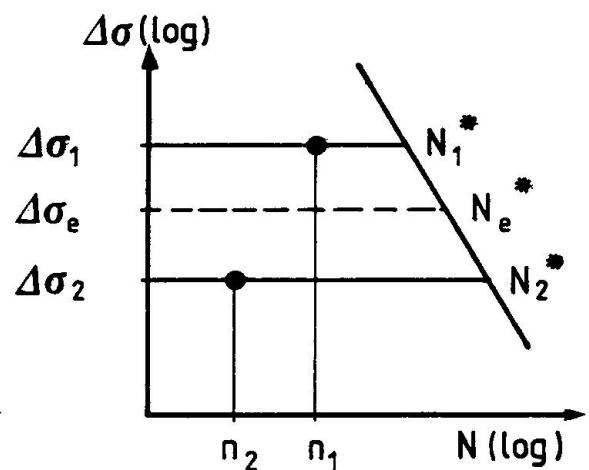


Fig. 12: Safety check on the equivalent-damage stress range level  $\Delta\sigma_e$ .

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

follows and the verification is performed by

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

The equivalent verification in terms of stresses can be carried out using  $\gamma_m \sigma$  according to fig. 13.

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

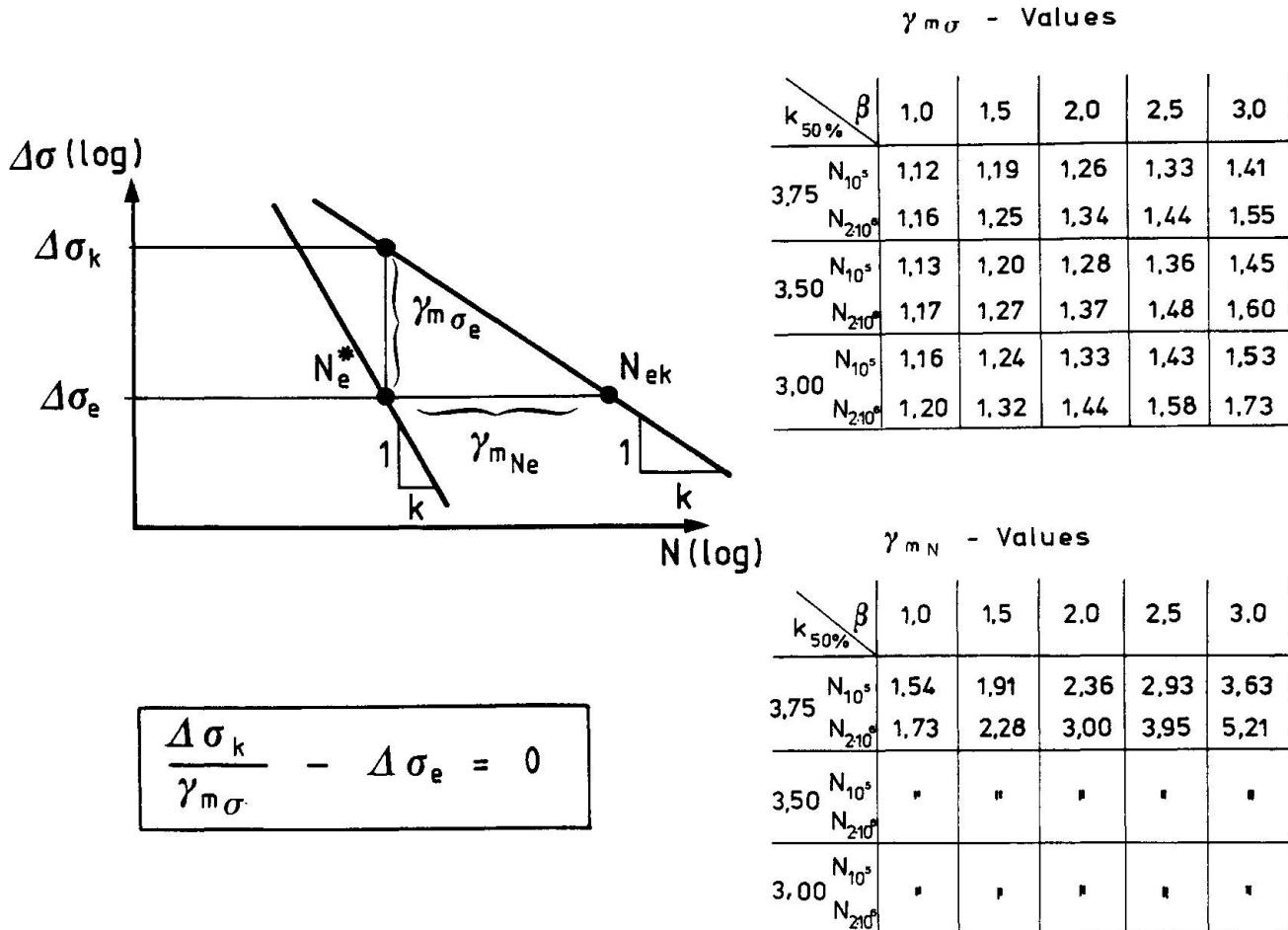


Fig. 13: Safety check in  $\Delta\sigma$  scale with equivalent-damage stress range  $\Delta\sigma_e$ .

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

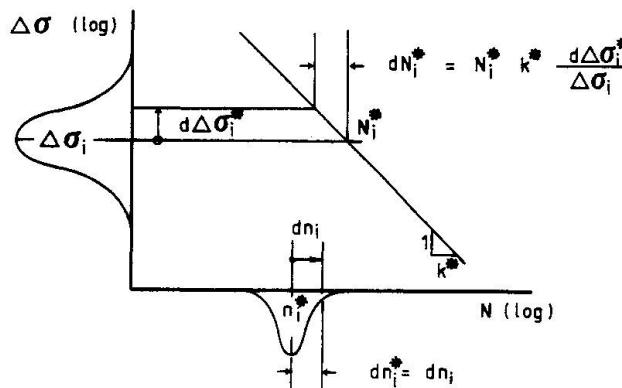
#### 4. ASSESSMENT WITH VARYING $\Delta\sigma_i$ -LEVEL AND VARYING NUMBERS OF CYCLES $n_i$

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  $a_i$  for all variables can be derived from the characteristic equation in fig. 15 using

$$a_i = \frac{\frac{\partial g}{\partial x_i} s_i}{\sqrt{\sum_j \left( \frac{\partial g}{\partial x_j} s_j \right)^2}} \quad (12)$$

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

The  $\gamma_m$ -values and  $\gamma_{sys}$ -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 data :  $N_{50\%} = 2 \cdot 10^6$ ;  $V_N = 0,55$ ;  $\sigma_N = 1,1 \cdot 10^6$

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

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

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

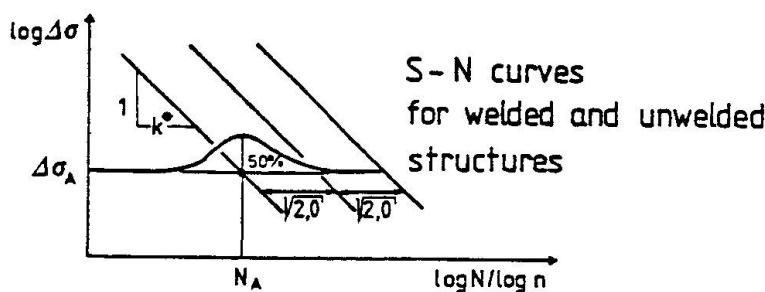
Sensitivity factors :

$$\alpha_N \sim 1,0 \quad ; \quad \alpha_{\Delta\sigma} \sim -0,30 \quad ; \quad \alpha_{n_i} \sim 0 \quad ; \quad \alpha_{dn_i} \sim -0,10$$

Overall Sensitivity factors :

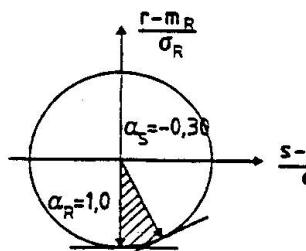
$$\alpha_R \sim 1,0 \quad ; \quad \alpha_S \sim -0,30$$

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
$\gamma_{m_N}$	2,30	3,00	4,00	5,20
$\gamma_{sys_N}$	1,15	1,20	1,25	1,30
$\gamma_{Glob_N}$	2,65	3,60	5,00	6,80

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

β	1,5	2,0	2,5	3,0
$\gamma_{m_\sigma}$	1,30	1,45	1,60	1,75
$\gamma_{sys_\sigma}$	1,05	1,06	1,08	1,09
$\gamma_{Glob_\sigma}$	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 Eurocode 3 the S-N-lines have been defined as  $(m - 2s)$ -values so that  $\gamma_m$ , 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.

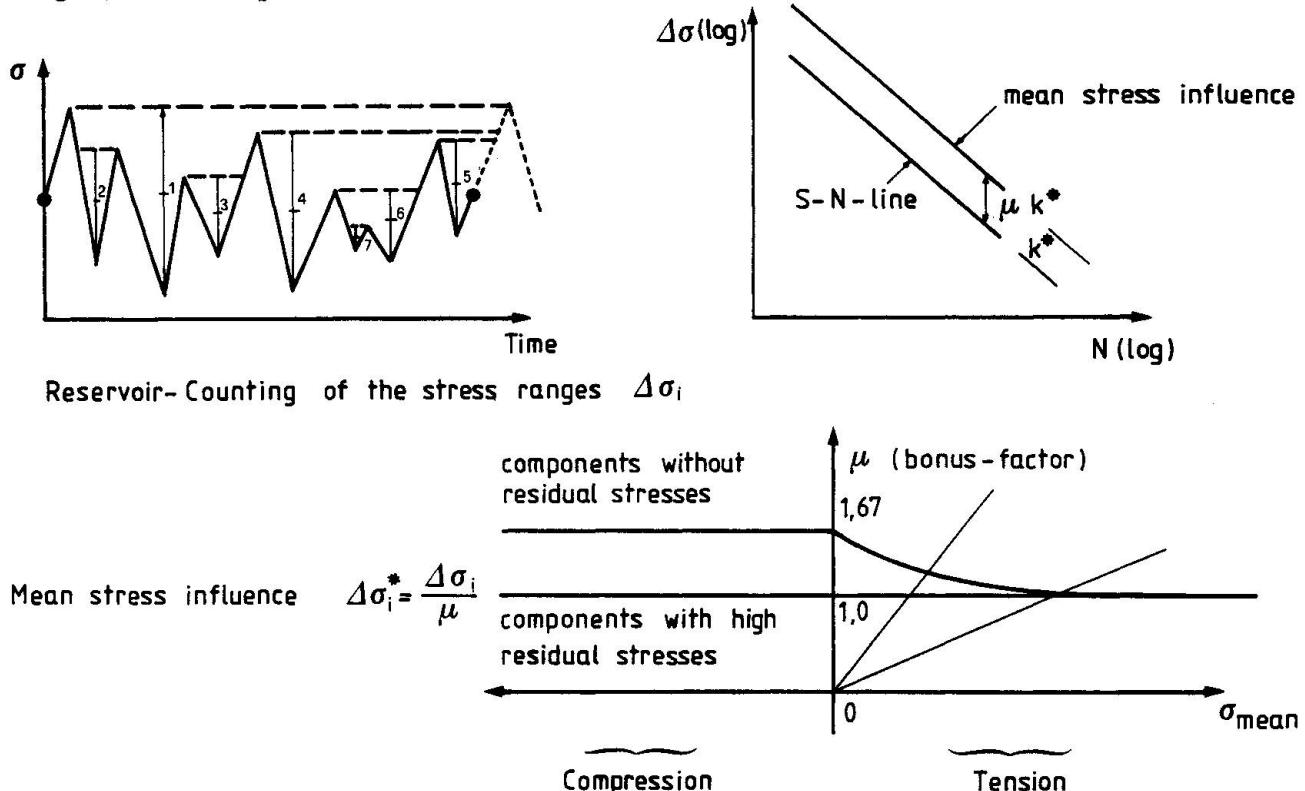


Fig. 17: Bonus factor for mean-stress-influence.

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