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Statistical Interpretation of the Miner-number using an Index of Probability of Total Damage

Interprétation statistique du nombre de Miner au moyen d'un indice de probabilité de dommage total

Statistische Interpretation der Miner-Zahl mit Hilfe eines Indexes der Wahrscheinlichkeit einer Totalschädigung

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SUMMARY
The use of the Miner-number, M, as an index of probability of total damage rather than as a measure of the partial damage is proposed for fatigue limit state design of concrete structures. The method is checked by introducing a second logarithmic index, D, more compatible with the logarithmic abscissa commonly adopted for the Wöhler-curve.

RESUME
Pour le calcul à l'état-limite de fatigue des structures en béton armé ou précontraint, on propose l'utilisation du nombre de Miner domme indice de probabilité de dommage total plutôt que comme mesure du dommage partiel. Cette méthode est complétée par l'introduction d'un deuxième indice logarithmique D et elle est ainsi en accord avec la représentation logarithmique de Wöhler.

ZUSAMMENFASSUNG
Die Verwendung der Miner-Zahl wird als Index der Wahrscheinlichkeit einer Totalschädigung anstatt als Mass der teilweisen Schädigung für die Bemessung von Stahlbeton- und Spannbetontragwerken im Grenzzustand der Ermüdung vorgeschlagen. Das Verfahren basiert auf der Einführung eines zweiten logarithmischen Indexes D. Dieser steht im Einklang mit der allgemein angenommenen logarithmischen Darstellung der Wöhler-Kurve.

1. INTRODUCTION

The cumulative damage concept proposed by Miner maintains that the damage can be expressed in terms of the number of cycles applied at a given stress level divided by the number needed to produce failure for the same stress level. When the summation of these "increments of damage" at several stress levels becomes unity, failure occurs. After its formulation, this hypothesis was repeatedly tested for different materials under multi-step or variable amplitude loading programs. Its practical applicability to the design of concrete structures, however, was often questioned because of the unsatisfactory experimental evidence.

Recently, Van Leeuwen and Siemes [1], [2] contucted series of tests on plain concrete and interpreted the scatter of the Miner-number M by deducing theoretical expressions for the mean and standard deviation values of M from the Wöhler curve. These formulae, derived initially for the simple case of constant amplitude cycling, were then extended to the case of general loading. They showed that the Miner-number at failure is a stochastic variable with an approximate logarithmic normal distribution and emphasized the importance of the study of the scatter of the Wöhler curve for constant amplitude cycling.

From this it follows that the Miner-number can be used to ascertain the probability of failure (as a more suitable design criterion) rather than as a measure of a problematic and abstract "degree of damage". It can then be taken as a basis for a consistent life prediction in fatigue design, in accordance with the consideration of fatigue failure as the third limit state.

2. PREDICTION OF THE CENTRAL VALUES OF M

Let us conduct n one-step tests for a given stress-range $\Delta\sigma_I$ (Fig.1) and evaluate the corresponding M-number for each of the specimens. If N_i is the number of cycles to failure in test i, the general expression for the Miner-number is

$$M_i = \frac{N_i}{N_I}\,, \tag{1}$$

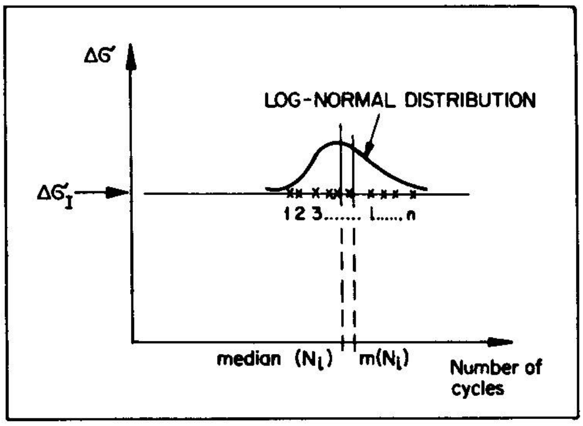

Fig.1 Distribution of N_i for a one-step test at level I (normal scale)

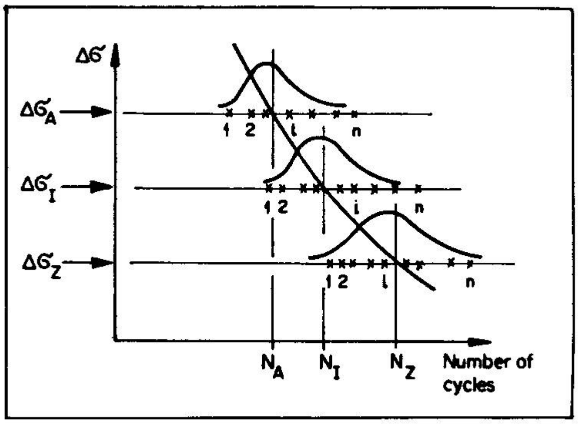

Fig.2 Distribution of N_i for a one-step test at several levels (normal scale)

where N_I is a representative value for the number of cycles to failure for the n tests, normally given by the median value

$$N_I = \text{median } (N_i) \text{ at level } I\,.$$

Hence, the median of M_i

$$\text{median } (M_i) = \frac{\text{median } (N_i)}{N_I} = \frac{\text{median } (N_i)}{\text{median } (N_i)} = 1 \tag{2}$$

and the mean is

$$m(M_i) = \frac{m(N_i)}{N_I} = \frac{m(N_i)}{\text{median}(N_i)} = \frac{10^{m(\log N_i)+1.1513\cdot s^2(\log N_i)}}{10^{m(\log N_i)}} = 10^{1.1513\cdot s^2(\log N_i)}, \tag{3}$$

where s(log N_i) is the standard deviation of log N_i, and assuming a log-normal distribution for the results of the n tests.

From

$$\log(M_i) = \log(N_i) - \log(N_I) = \log(N_i) - \text{const.}$$

and taking the standard deviation

$$s(\log(M_i)) = s(\log(N_i) - \text{const}) = s(\log(N_i)) . \tag{4}$$

Since N_i is a random variable with an assumed logarithmic normal distribution, it follows from Eq. (1) that for one-step tests the M-number also has a log-normal distribution, whose median value becomes 1, Eq. (2), and whose standard deviation is related to the standard deviation of the Wöhler curve, Eq. (4).

For the more general case of multi-step loading with Z different stress ranges $\Delta\sigma_I$ we must first determine the characteristic values N_I (median values) for each level. The multi-step test will then be repeated n times in order to establish the Miner-number for which we assume the existence of "isodamage lines", i.e. lines along which the fatigue damage is the same independent of the stress level as

$$\frac{n_A}{N_A} = \frac{n_B}{N_B} = \ldots\ldots = \frac{n_I}{N_I} = \ldots\ldots\ldots = \frac{n_Z}{N_Z} . \tag{5}$$

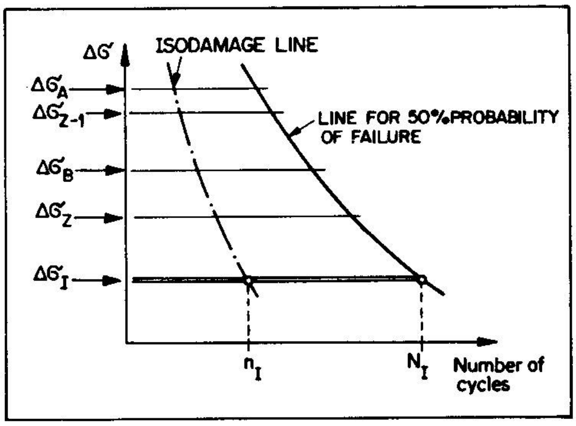

Fig.3 Representation of isodamage lines (normal scale)

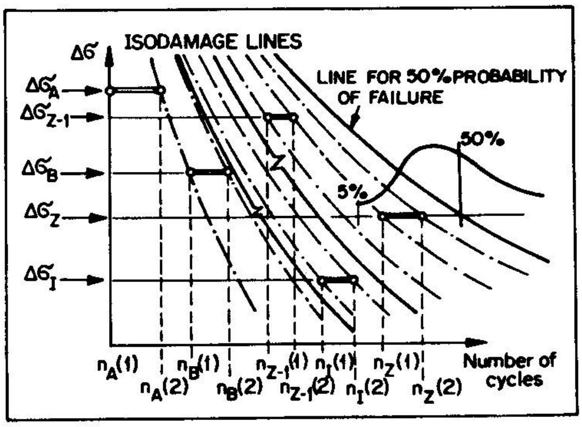

Fig.4 Diagramatic representation of the progress of a multi-step test using isodamage lines (normal scale)

This assumption enables the multi-step loading to be handled in the same way as a one-step test. At the end of each stress level, $\Delta\sigma_{I-1}$, the current number of cycles is replaced (by following the isodamage lines) by the equivalent number of cycles at level $\Delta\sigma_I$ as if the loading had been maintained at $\Delta\sigma_I$ from the start of the test.

The conversion of the number of cycles for the test shown in figure 4 is given in table 1.

LOAD LEVEL	NUMBER OF CYCLES (START)	NUMBER OF CYCLES (END)
A	$n_A(1)=0$	$n_A(2)=n_A$
B	$n_B(1)=n_A(2)\frac{N_B}{N_A}=n_A\frac{N_B}{N_A}$	$n_B(2)=n_A\frac{N_B}{N_A}+n_B$
I	$n_I(1)=n_A\frac{N_I}{N_A}+n_B\frac{N_I}{N_B}+\dots n_{I-1}\frac{N_I}{N_{I-1}}$	$n_I(2)=N_I\sum_{I=A}^{I-1}\left(\frac{n_I}{N_I}\right)+n_I$
Z-1	$n_{Z-1}(1)=\sum_{I=A}^{Z-2}\left(n_I\frac{N_{Z-1}}{N_I}\right)$	$n_{Z-1}(2)=\sum_{I=A}^{Z-2}\left(n_I\frac{N_{Z-1}}{N_I}\right)+n_{Z-1}$
Z	$n_Z(1)=\sum_{I=A}^{Z-1}\left(n_I\frac{N_Z}{N_I}\right)$	$n_Z(2)=\sum_{I=A}^{Z-1}\left(n_I\frac{N_Z}{N_I}\right)+n_Z$

Table 1 Conversion of the number of cycles for a multi-step test at each level (normal scale)

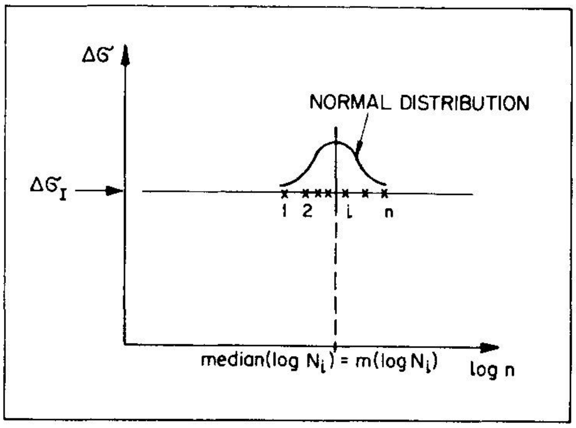

Fig.5 Distribution of N_i for a one-step test at level I (log. scale)

The Miner-number for specimen i failing on stress level Z is given by the expression

$$M_i = \frac{n_Z(2)}{N_Z} = \frac{\sum_{I=A}^{Z-1}\left(n_I \frac{N_Z}{N_I}\right) + n_Z}{N_Z} = \sum_{I=A}^{Z-1}\left(\frac{n_I}{N_I}\right) + \frac{n_Z}{N_Z} = \sum_{I=A}^{Z}\left(\frac{n_I}{N_I}\right) . \tag{6}$$

As can be seen, the treatment of a multi-step loading as a one-step test by means of conversions using the isodamage lines defined by the condition (5) leads to the same results for the Miner-number as the classical formulation. Consequently, Eqs. (2), (3) and (4) hold for the multi-step loading case as well. However, it cannot be accepted that for the multi-step test the scatter of the Miner-number is related only to the scatter of the Wöhler curve at whatever level Z the specimen happens to break. Therefore, an equivalent standard deviation s $(\log N_i)$ must be proposed for any level of the Wöhler curve. Eq. (4) becomes

$$s(\log M_i) = s_{eq}(\log N_i) = \frac{\sum_{I=A}^{Z} \left(s_I(\log N_i)\right) \frac{n_I}{N_I}}{\sum_{I=A}^{Z} \frac{n_I}{N_I}} . \tag{7}$$

In the case of repeated loading blocks Z is the number of levels within each. Eq. (7) assumes that the contribution of the scatter at each level to the equivalent standard deviation is proportional to the ratio of the number of cycles conducted at this level to the number of cycles to failure at the same level (i.e. proportional to its contribution to the Miner-number). Accordingly the scatter of the standard deviation of the Miner-number depends only on the composition of the loading blocks and not on the loading sequence.

3. INDEX OF TOTAL DAMAGE PROBABILITY D AND PREDICTION OF ITS CENTRAL VALUES

As usual in the representation of fatigue results (Wöhler curve) the number of cycles is plotted on a logarithmic scale on the abscissa. Let us define therefore a new index D, given for the constant cycle tests by the logarithmic ratio

$$D = \frac{\log n_I}{\log N_I} \tag{8}$$

In order to deduce the nature of the frequency distribution of D as well as its central values we carry out one-step tests on n specimens with a stress range $\Delta\sigma_I$ as in section 2 (Fig. 5). The general expression for the new index D for test i at failure is given by

$$D_i = \frac{\log N_i}{(\log N)_I} , \qquad (9)$$

where $(\log N)_I$ is a representative value of the fatigue lines for the n tests, normally equal to the median and in this case also equal to the mean.

The values for m(D) and s(D) can be found as follows

$$m(D_i) = \frac{m(\log N_i)}{(\log N)_I} = \frac{m(\log N_i)}{m(\log N_i)} = 1 \qquad (10)$$

$$s(D_i) = \frac{s(\log N_i)}{(\log N)_I} = \frac{s(\log N_i)}{m(\log N_i)} = v(\log N_i) , \qquad (11)$$

where $v(\log N_i)$ is the coefficient of variation of $\log N_i$ at level I.

As $\log N_i$ is assumed to be a stochastic variable with a Gaussian frequency distribution, D_i must have a normal distribution as well, Eq. (9), whose mean value will be 1, Eq. (10), and whose standard deviation is given by the coefficient of variation of $\log N_i$ at the level $\Delta\sigma_I$.

As in section 2 we can now consider the general multi-step loading by first obtaining the basic information for the component levels in the loading blocks (as indicated in Fig. 2, i.e. $m_A(\log N_i)$, $m_B(\log N_i)$, ..., $m_I(\log N_i)$, ..., $m_Z(\log N_i)$) and then repeating the multi-step block n-times.

In order to evaluate the index D for each test (Fig. 6) we again assume the existence of isodamage lines but using this time for the abscissa a logarithmic scale

$$\frac{\log n_A}{(\log N)_A} = \frac{\log n_B}{(\log N)_B} = \ldots = \frac{\log n_I}{(\log N)_I} = \ldots \frac{\log n_Z}{(\log N)_Z} \qquad (12)$$

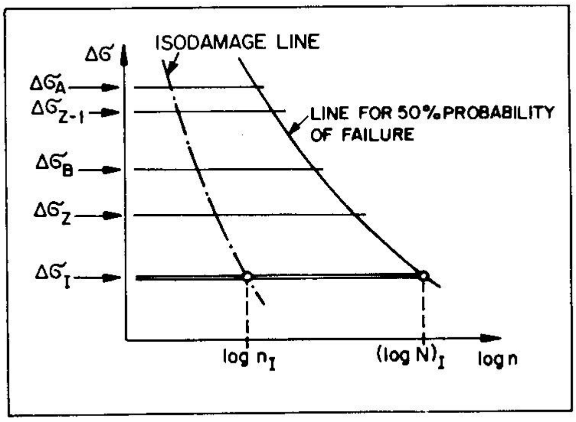

Fig.6 Representation of isodamage lines (log. scale)

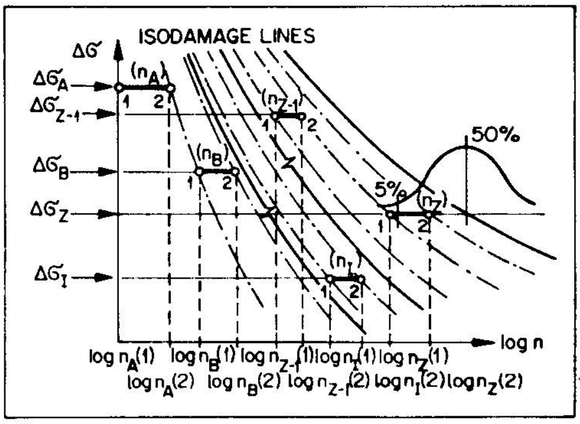

Fig.7 Diagramatic representation of the progress of a multi-step test using isodamage lines (log.scale)

This assumption again allows a reduction from the multi-step test to the one-step test to be made as for the Miner-number Fig. 7, and after changing the stress range from the I-1 to the I-level the index D is evaluated as if the test had been conducted from the beginning on the level I. However, the calculation of D, unlike the Miner-number, requires a reconversion of the number of cycles to the normal (non log) scale at the beginning of each new step, Table 2.

LOAD LEVEL	NUMBER OF CYCLES AT THE START OF EACH LEVEL	NUMBER OF CYCLES AT THE END OF EACH LEVEL	D AT THE END OF EACH LEVEL
A	$n_A(1) = 0$	$n_A(2) = n_A(1) + n_A = n_A$	$\log n_A(2) / \log N_A$
B	$n_B(1) = \text{antilog}\left(\log n_A(2) \cdot \frac{\log N_B}{\log N_A}\right)$	$n_B(2) = n_B(1) + n_B$	$\log n_B(2) / \log N_B$
I	$n_I(1) = \text{antilog}\left(\log n_{I-1}(2) \cdot \frac{\log N_I}{\log N_{I-1}}\right)$	$n_I(2) = n_I(1) + n_I$	$\log n_I(2) / \log N_I$
Z−1	$n_{Z-1}(1) = \text{antilog}\left(\log n_{Z-2}(2) \cdot \frac{\log N_{Z-1}}{\log N_{Z-2}}\right)$	$n_{Z-1}(2) = n_{Z-1}(1) + n_{Z-1}$	$\log n_{Z-1}(2) / \log N_{Z-1}$
Z	$n_Z(1) = \text{antilog}\left(\log n_{Z-1}(2) \cdot \frac{\log N_Z}{\log N_{Z-1}}\right)$	$n_Z(2) = n_Z(1) + n_Z$	$\log n_Z(2) / \log N_Z$

Table 2 Conversion of the number of cycles for a multi-step test at each level (log. scale)

Because of the above conversion expressions (10) and (11) which apply to the one-step case are also valid for the multi-step case. However, a similar expression to Eq. (7) for $v(\log N_i)$ must be used in Eq. (11), that is

$$s(D_i) = v_{eq}(\log N_i) = \frac{\sum_{I=A}^{Z} \left(v_I(\log N_i) \frac{n_I}{N_I}\right)}{\sum_{I=A}^{Z} \left(\frac{n_I}{N_I}\right)} \quad . \tag{13}$$

For concrete for which $v_I(\log N_i) \simeq$ const. along the Wöhler curve

$$v_{eq}(\log N_i) \simeq v_I(\log N_i) \simeq \text{const.} \tag{14}$$

4. PREDICTION OF NUMBER OF CYCLES TO FAILURE FOR A GIVEN PROBABILITY P%

The probability of fatigue failure can now be used for the prediction of fatigue life for the general case of loading, since this can be treated as a simple one-step loading, and the mean and standard deviation values M and D can be forecast for the latter.

Using Eqs. (2) and (7), it is possible to calculate the value of the Miner-number corresponding to any given probability of failure P% with the following well-known statistical relationship

$$\log(M(P\%)) = m(\log M) - k(P\%) \cdot s(\log M) \ , \tag{15}$$

where k(P%) is the one-sided statistical tolerance limit for a standardized confidence level, normally taken as the value of the standardized normal distribution, i.e. $n \to \infty$. The corresponding number of cycles can be found from

$$M(P\%) = \frac{n_I}{N_I} \ , \tag{16}$$

that is

$$n_I = N_I \left[\text{antilog}\left(m(\log M) - k(P\%) \cdot s_{eq}(\log N)\right)\right] \ . \tag{17}$$

Similarly, with Eqs. (10) and (13)

$$D(P\%) = m(D) - k(P\%)\cdot s(D) = m(D) - k(P\%)\cdot v_{eq}(\log N) \tag{18}$$

and using

$$D(P\%) = \frac{\log \Sigma n_I}{(\log N)_I} , \tag{19}$$

$$\Sigma n_I = \text{antilog}\ [(\log N)_I\cdot[m(D) - k(P\%)\cdot v_{eq}(\log N)]] , \tag{20}$$

where Σn_I is the total number of cycles "equivalenced" to level I. The correspondence between Eqs. (17) and (20) is illustrated in Fig. 8.
It should be mentioned that when v(log N) = const. the isodamage lines coincide with the lines showing the same probability of failure.

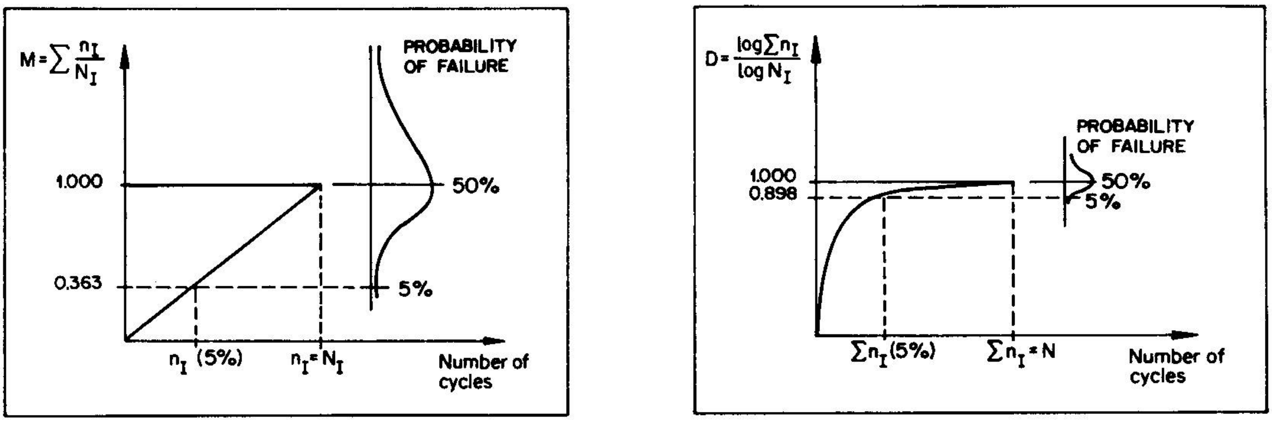

Fig.8 Interpretation of the correspondence between n(5%) using M and D for one test of [2]

5. CASE OF STOCHASTIC LOADING

When a continuous load collective is used for fatigue design it may be discretized as a histogram and handled as a multi-step load sequence. The smaller the volume of the basic loading block the better is the agreement of the predicted number of cycles obtained using M and D and the better is the simulation of the random nature of the load.

The evaluation of the fatigue results reported in [3] for concrete in compression with stochastic load simulation gives a very good agreement between predicted and measured values of s(D). On the contrary, the predicted mean value of D differs clearly from the mean value derived from the results, probably due to the interaction of the various levels present in a stochastic load. However, if the mean value of D at failure could be determined empirically (as Holmen [3] suggests for the mean value of log M, Fig. 9) then the prediction of D (5%) for design would be more reliable. The same applies for M.

Since the number of cycles required for 5% probability of failure,predicted using M and using D,are in very good correspondence (for stochastic load as well) it follows that the initial hypothesis, Eq. (5) or Eq. (12), influences only the type of the frequency distribution obtained (in this case log-normal and normal, respectively).However, with appropriate treatment both lead to the same prediction. Furthermore, because of the good agreement between P(5%) obtained using M and D, it follows that the loading sequence (which must be considered in the derivation of D, but is ignored for M) has a negligible influence on D and M, provided the basic loading block is small and must be repeated many times before the value of D or M corresponding to the 5% probability of failure is reached.

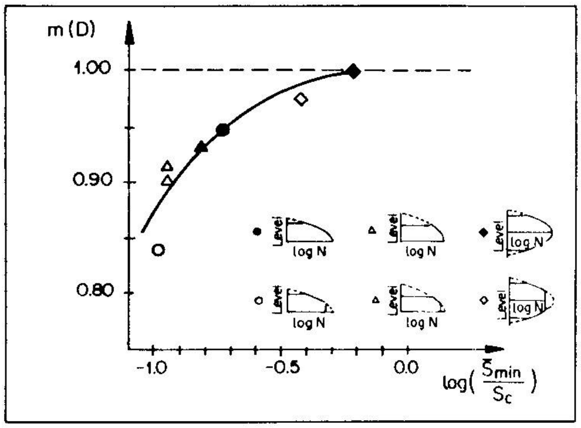

Fig.9 Variation of m(D) for various load collectives determined empirically (adapted from Holmen [3])

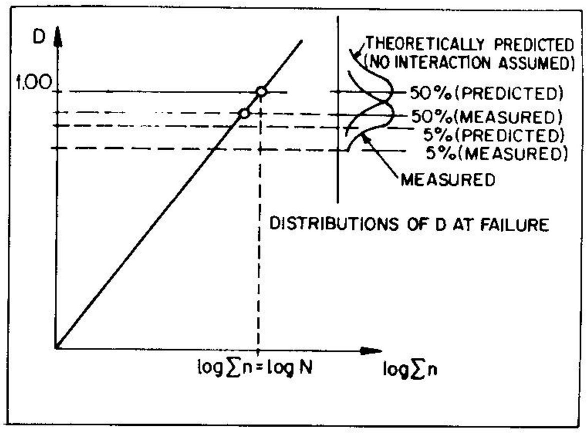

Fig.10 Diagramatic representation of the shift of the distribution of D for stochastic loading due to the interaction between the load levels

Despite the fact that neither D nor M can take into account the interaction of the different participant load levels, Eqs. (17) and (20) can still be used for design on condition that the frequency distribution is suitable adjusted (empirically) to account for the different mean value.

The difference can be merely considered as a displacement of the distribution of D from the theoretical positions as shown in Fig. 10. The type of the frequency distribution function (Gaussian) and the shape (standard deviation) of D remain the same, and analogous to M.

6. REFLECTIONS ABOUT A POSSIBLE COMPARISON BETWEEN M OR D AND THE ACTUAL DEVELOPMENT OF DAMAGE IN CONCRETE

The good agreement between the physical quantities such as ultrasonic pulse velocity [4] acoustic emission [5] and longitudinal strain [3] measured during concrete fatigue tests suggests that they can be identified with actual fatigue damage. This has sometimes led investigators to compare the development of this "physical" damage (as a function of the cycle ratio to failure) with the development of the Miner-number, and to the conclusion that the M-method represents an unsafe prediction of "damage" at the start and end, and the contrary in the middle of the fatigue life, Fig. 11. The same can be said for D, where D could be

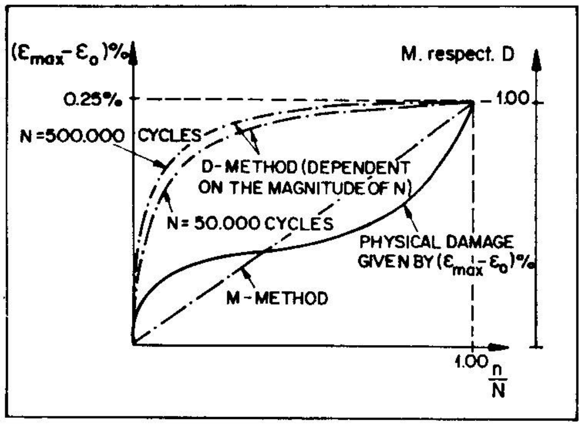

Fig.11 Comparison between the development of M and D and fatigue damage as measured by longitudinal strain

SPECIMEN NR.	M_{Rk}(5%)	D_{Rk}(5%)	M_{Sk} AT FAILURE	D_{Sk} AT FAILURE	γ_{Gl} FROM(24) WITH η_M=1	γ_{Gl} FROM(21) WITH η_D=1
4	0.202	0.868	0.091	0.817	0.450	0.941
11	0.231	0.868	0.223	0.865	0.965	0.997
5	0.286	0.868	0.203	0.891	0.710	1.026
1	0.270	0.868	0.363	0.899	1.344	1.036
2	0.253	0.868	0.399	0.913	1.577	1.052
7	0.226	0.868	0.413	0.924	1.827	1.065
3	0.218	0.868	0.583	0.956	2.674	1.101
6	0.264	0.868	0.701	0.968	2.655	1.115
9	0.293	0.868	0.644	0.975	2.198	1.123
12	0.209	0.868	0.846	0.993	4.048	1.144
8	0.205	0.868	2.218	1.087	10.820	1.252
10	0.273	0.868	2.417	1.094	8.853	1.262

Table 3 Comparison of various quantities for tests of [2]

regarded as a unsafe estimate of partial damage over the whole range of cycle ratios, except close to start. In our opinion such a comparison is based on a wrong concept. The Miner-number and D represent a measure of the probability of failure and do not give any indication of the degree of fatigue damage as is supposed in the above comparisons. The physical quantities measured by the three authors mentioned above can be considered as actual "damage" but their use in design requires further information regarding the scatter associated with the "damage" curve. The statistical analysis of M and D on the other hand shows that scatter information is an integral part of the Miner- (or D-) methods, which gives no information about the degree of damage, only the probability of failure.

7. SAFETY FACTOR ANALYSIS AFTER D

Due to the interaction between fatigue strength resistance (Wöhler curves) and the applied load, in order to calculate the fatigue life of a structure, a measure of the damage must be taken for safety considerations. The probability of total damage seems to be the most reliable unit of reference for defining the safety factor.

A process similar to that adopted by Van Leeuwen and Siemes [1] for the calculation of the safety factor from M can also be applied to D, the only difference being the Gaussian nature of the latter.

According to the CEB Model Code [6] the condition

$$S_d(F_k \cdot \gamma_f) \leq R_d(f_k/\gamma_m) \tag{21}$$

must be satisfied, i.e. at any section the action, in general, of the loading must be less than the corresponding resistance of the structure. In the case of fatigue, Eq. (21) takes the form

$$D_{Sd} = D_{Sk} \cdot \gamma_f \leq D_{Rd} = D_{Rk}/\gamma_m \tag{22}$$

and the safety factor

$$\eta_D = \frac{D_{Rk}/\gamma_m}{D_{Sk} \cdot \gamma_f} = \frac{D_{Rk}}{D_{Sk}} \cdot \frac{1}{\gamma_{Gl}} , \tag{23}$$

where D_{Rk} = Value of the Index D, computed at a section for the loading history considered and corresponding to a probability of failure of 5% (normally less than unity)

γ_m = Reduction factor, which reduces the probability of failure below 5%

D_{Sk} = Value of the Index D, computed at a section for the characteristic loading collective for the structure for the return period considered

γ_f = Magnification factor, which results in a probability of failure greater than that corresponding to D_{Sk}

γ_{Gl} = Global factor equal to $\gamma_m \cdot \gamma_f$.

Hence, two probabilities of failure (represented by two different values of D) are compared. The first corresponds to 5% (less due to γ_m), while the second (increased by γ_f) depends on the loading collective, the Wöhler curve and the chosen return period.

Given in table 3 are the γ_{Gl} values necessary to transform D_{Sk} at failure to $D_{Rk}(5\%)$ (Eq.(23), assuming η_D = 1.0), and the values of γ_{Gl} calculated from

$$\eta_M = \frac{10^{m(\log M) - k(5\%) \cdot s(\log M)}}{\gamma_{Gl} \cdot M_{(failure)}} \tag{24}$$

proposed by Van Leeuwen and Siemes necessary to transform M_{Sk} at failure to M(5%) (assuming η_M = 1.00), for the results for tests of [2].

As can be seen from table 3 the qualitative agreement between the values of $\gamma_{G1}(M)$ and $\gamma_{G1}(D)$ for each specimen is quite good with the exception of tests 5 and 8 in which the influence of the loading sequence and the use of few loading blocks to failure can be seen. Quantitatively, however, it is evident that the range of variation for $\gamma_{G1}(M)$ is disproportionate and shows no correspondence with the common static safety factor.

8. CONCLUSIONS

A new way of looking at fatigue seems necessary for a consistent limit state design. The fundamentals of such a new approach are outlined.

A new index for the probability of total damage (failure) D using a logarithmic scale is introduced.

The assumption of the existence of isodamage lines not only for the Miner-number M, but also for D, allows the reduction of the multi-step to a one-step loading, and the prediction of the central values for both.

The two different relationships for the definition of isodamage lines (normal respectively logarithmic scale) lead to the same qualitative and quantitative fatigue life predictions in spite of the different distributions which result for M and D at failure.

A comparison of the probability of failure for stochastic loads using M and D shows very good accordance and demonstrates the validity of these indices in fatigue life prediction provided a reliable empirically mean value of M and D at failure can be determined.

For concrete the isodamage lines coincide with the isoprobabilistic lines (lines representing equal probability of failure), since the coefficient of variation v(log N) is constant.

Finally, it is shown that statistical treatment of the Miner-number is necessary to be used in limit state design.

A detailed description of the proposed method can be found in a report that is currently being drawn up.

REFERENCES

1 Van Leeuwen J., Siemes A.J.M.: "Miner's rule with respect to plain concrete", Heron vol. 24, No 1, 1979.

2 Van Leeuwen J., Siemes A.J.M.: "Fatigue of concrete", Report No B 76-443/04.2.6013, Tables, TNO-IBBC Delft, 1977.

3 Holmen J.O.: "Fatigue of concrete by constant and variable amplitude loading", Institutt for Betongkonstruksjoner, Norges Tekniske Høgskole, Universitet i Trondheim, 1979.

4 Jinawath P.: "Cumulative fatigue damage of plain concrete in compression", PhD Thesis, University of Leeds, 1974.

5 Klausen D.: "Festigkeit und Schädigung von Beton bei häufig wiederholter Beanspruchung", Dissertation, Technische Hochschule Darmstadt, 1978.

6 CEB/FIP Mustervorschrift für Tragwerke aus Stahlbeton und Spannbeton. Band II, 3. Ausgabe 1978.

Notation

M	Miner-number
M_i	Miner-number calculated in test i at failure (i = 1, 2....n)
$M(P\%)$	Miner-number corresponding to a probability of failure P%
$m(M_i)$	Mean value of M_i
$median(M_i)$	Median value of M_i
$m(\log M_i)$	Mean value (equal to the median value) of $\log M_i$
$s(\log M_i)$	Standard deviation of $\log M_i$
D	Index of probability of total damage (failure) defined in a logarithmic scale
D_i	D calculated in test i at failure (i = 1, 2,...n)
$m(D_i)$	Mean value of D_i
$s(D_i)$	Standard deviation of D_i
n	Number of specimens pertaining to a sample
n_I	Number of cycles conducted at level I
Σn_I	Total number of cycles 'equivalenced' to level I
N_i	Number of cycles to failure in test i (i = 1, 2,...n)
N_I	Representative value for the number of cycles to failure for a sample at level I, normally given by the median value
$(\log N)_I$	Representative value of log N for the logarithm of the number of cycles to failure for a sample at level I, normally taken as the mean value
$m(N_i)$	Mean value of N_i
$median(N_i)$	Median value of N_i
$m(\log N_i)$	Mean value of $\log N_i$
$s(\log N_i)$	Standard deviation of $\log N_i$
$v(\log N_i)$	$= s(\log N_i)/m(\log N_i)$: Coefficient of variation of $\log N_i$
$median_I(N_i)$	Median value of N_i at level I
$m_I(\log N_i)$	Mean value of $\log N_i$ at level I
$s_I(\log N_i)$	Standard deviation of $\log N_i$ at level I
$v_I(\log N_i)$	Coefficient of variation of $\log N_i$ at level I
$k(P\%)$	one-sided statistical tolerance limit for a given confidence level

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