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Fatigue of Concrete Structures

Fatigue dans les structures en béton

Ermüdungsverhalten von Betonelementen

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SUMMARY
The paper presents a general view of fatigue failures of concrete structures and discusses the object and scope of RILEM activities. The RILEM Committee report on "Long Term Random Loading" of concrete structures, completed in 1981, is summarised. This includes comments on fatigue life, fatigue strength, accumulated damage, analytical service-life functions and the results of both experiments and analyses.

RESUME
L'article présente une vue générale des cas de rupture par fatigue des structures en béton et discute les buts et la portée des activités de la RILEM. Le rapport du comité de la RILEM sur "les charges de longue durée aléatoires" dans les structures en béton a été achevé en 1981 et est résumé dans cet article. Il traite de la durée de vie, de la résistance à la fatigue, de dommages accumulés, des fonctions analytiques de durée de service et des résultats tant expérimentaux qu'analytiques.

ZUSAMMENFASSUNG
Ein allgemeiner Überblick über das Ermüdungsverhalten von Betonelementen ist in diesem Artikel gegeben; zugleich werden die Zielsetzungen und der Umfang der Aktivitäten des RILEM vorgestellt. Der Kommissionsbericht "Long Term Random Loading" von Betonelementen, welcher 1981 fertiggestellt worden ist, wird in zusammengefasster Form präsentiert. Dieser Bericht enthält Kommentare über das Ermüdungsverhalten, die Ermüdungsfestigkeit und die Schadensakkumulation sowie über analytische Funktionen für die Lebensdauer. Zudem werden Resultate von Experimenten und Analysen diskutiert.

1. INTRODUCTION

Fatigue of concrete structures never created the widespread interest as has been the case for steel structures. While fatigue failures of steel structures have caused catastrophic failures, no such fatigue failure has been reported for concrete structures, although there have been speculations in some cases whether the failure might be due to fatigue. Minor damage to concrete supporting machinery is not included. Research on concrete, however, indicates that the effect of repeated loading may be more damaging to concrete structures than realized at present. The interest for fatigue of concrete structures has also increased in recent years because of a higher degree of utilisation of the capacity of the materials, which increases the stress-variations and brings the working stress range closer to the failure stress.

2. FATIGUE PROPERTIES OF REINFORCED CONCRETE

The fatigue properties of reinforced concrete are related to the component materials, reinforcement and concrete. The bond between the components may be the critical factor for the fatigue life of a structure. During fatigue loading the structure undergoes local and overall deformations which leads to a continuous redistribution of stresses. In a structural member, concrete in compression may be critical at static load and at a few repeated loads, while many repeated, smaller loads relieve the concrete stresses and the final failure may be due to fatigue of reinforcement |19|. This illustrates the complexibility of the problem, which is significantly increased by the fact that the variable loads are usually stochasticly distributed in time.

From experimental investigations, considerable information has been achieved on the fatigue of steel and also steel reinforcement. Some knowledge is also available on fatigue of concrete. Several proposals for mathematical expressions of the fatigue life have been presented. Realizing that these formulae give inaccurate results, new research programs have been initiated to find better correlation between theory and test results. Gradually, better results have been obtained for the components of reinforced concrete. These results from research on steel bars and plain concrete are basic factors in systematic investigations of the combined response of the the components of a structural member subjected to fatigue loading. Such comprehensive investigations are not carried out to such an extent that the lifetime of a structure can be predicted with a degree of accuracy that may be said to be satisfactory.

3. FATIGUE FAILURE MODES OF STRUCTURAL MEMBERS

Shear failure may occur with the same mode of failure as observed at static tests. However, in some cases, beams which have failed in shear after repeated loadings would have failed in bending under static load, |1,22|. Fig. 1 compares test results of beams without shear reinforcement subjected to a dominant bending moment or shear force.

Interesting observations are indicated in |2|. A beam is such loaded that the shar force is approximately constant between supports and loading points. The shear reinforcement is not strained according to the shear force, but according to the crack-formation. Repeated loadings lead to the shear force, but according to the crack-formation. Repeated loadings lead to a greater crack zone and wider cracks. The strains in the stirrups increase irregulatly. Further loadings increases the bond slip, which results in greater deformations. Finally the compression zone of the concrete may fail, or it may happen that the repeated stresses in the stirrup bends have increased so that the stirrups fail in fatigue, or the wide cracks crossing the longitudinal bars introduce local repeated bending of the bars until they fail. All these failure developments have been reported.

Bond properties are also of major importance at overlapped spliced bars and for anchoring capacity of bars. Again there are two aspects involved: bond fatigue capacity and deformations resulting from the repetitions of loadings. The latter may cause fatal stress-redistribution in the member. Some observations from investigations |3| are illustrated in Fig. 2.

The fact that we are far from having a general, reliable, analytical model for estimating the fatigue life of a reinforced concrete structure, should not prevent steps towards such a model. A model requires knowledge of the properties of each of the components of the composite reinforced material under repeated random loadings. In addition, the interaction properties of the components are needed. Deformations during the loading period and the fatigue capacity are equally important.

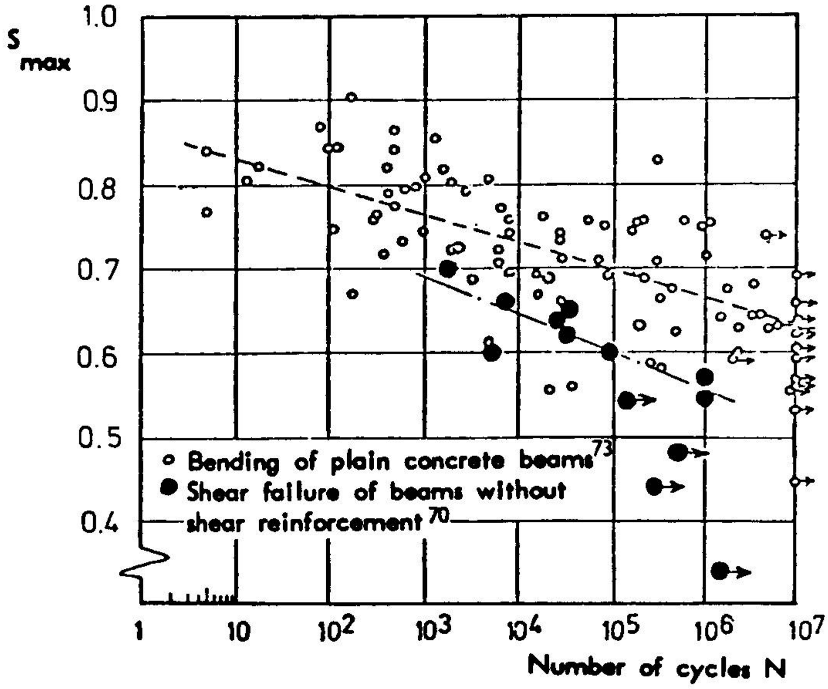


Fig. 1 Comparison between strength in shear of beams without shear reinforcement and fatigue strength in bending of plain concrete beams

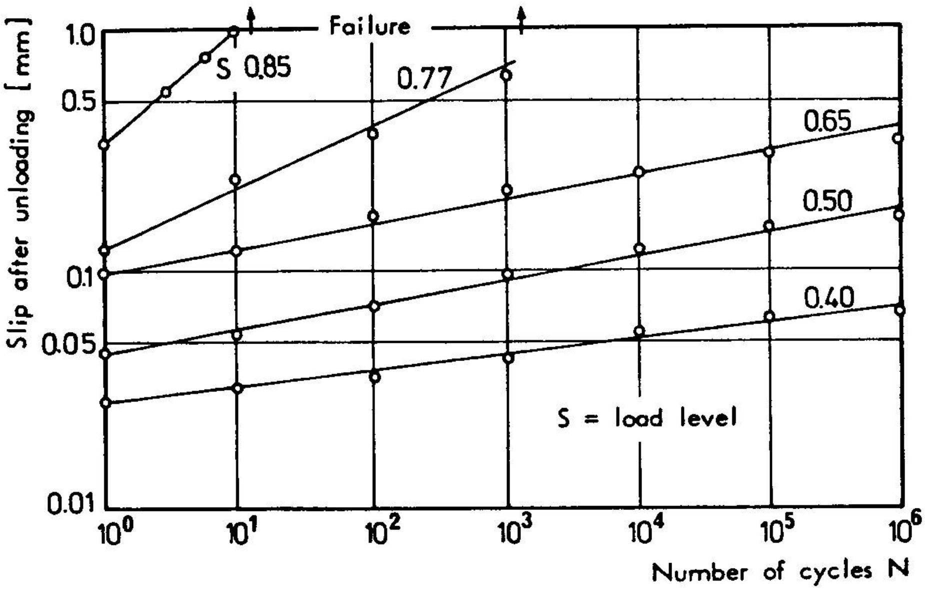


Fig. 2 Increase of slip at the free bar end during cyclic load as a function of the number of load reversals n(f_c = 23.5 MPa, d = 14mm, bond length 30d)

4. BRIEF COMMENTS ON REINFORCEMENT

Reinforcement steel is relatively well covered due to the extensive research on fatigue of steel within mechanical, naval and aeronautical engineering |4,5,6,7,8,9,10,11,12,13,14,15,19|. This paper will primarily deal with fatigue of concrete. Because the investigations and discussions on fatigue of concrete have followed the same lines as for steel, some main properties of steel bars subjected to fatigue loading will be briefly mentioned. It is important to be aware of both similarities and differences between steel and concrete.

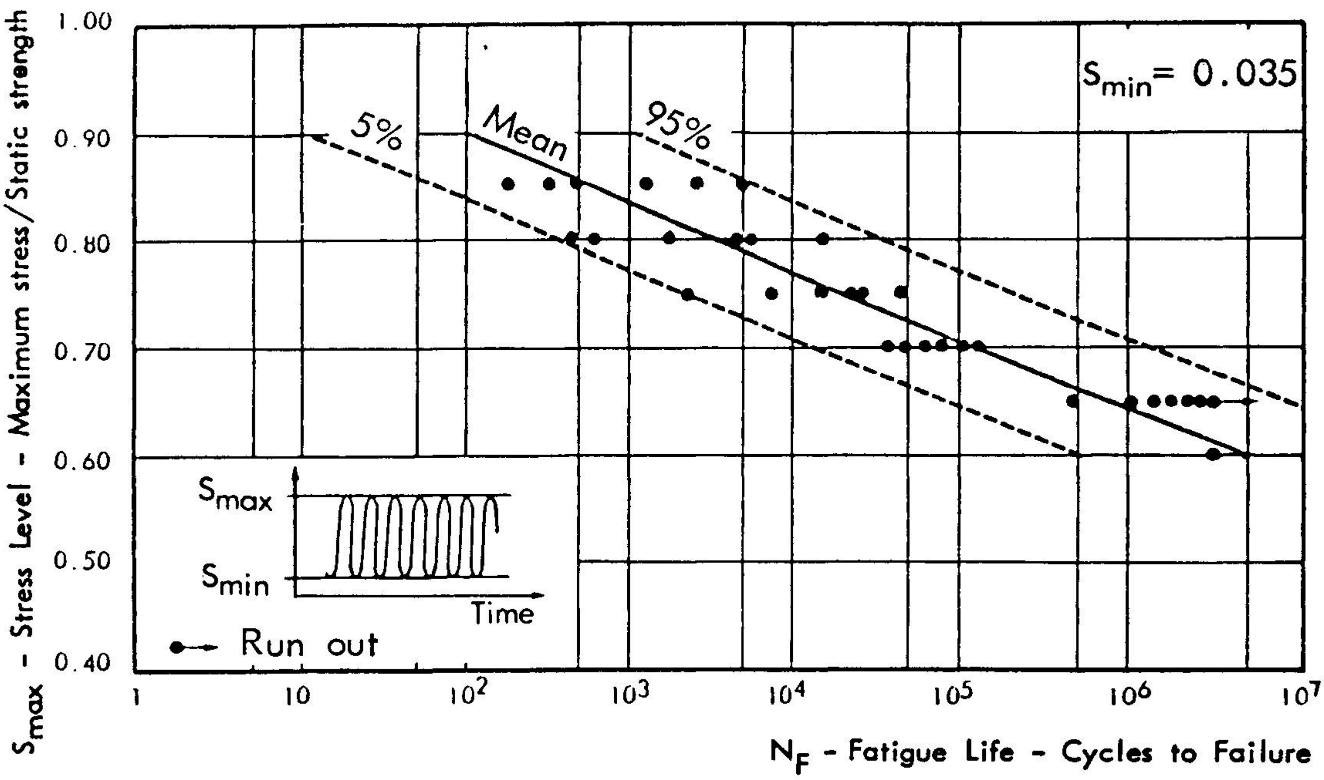


Fig. 3 Typical S-N relationship for concrete i compression

The surface geometry of the steel bar has a marked influence, for instance the shape of the ribs |10,11,12|. The effect of the concrete surrounding the reinforcement has been investigated in a number of projects with contradicting results. A reasonable conclusion is that reinforcement bars in a structure have approximately the same fatigue life as the twin naked bars although the scatter of the test results is greater in the first case. Bent reinforcement bars can have a drastic reduction of fatigue strengh compared with straight bars |16,17,18,22|. In relation to the pin diameter, P, and the bar diameter, d, it is reported that the fatigue strengh of a 45^0 bend is reduced with 1/5 to 2/3 as the ratio D/d is decreased from 15 to 5.

5. CONCRETE UNDER COMPRESSION

For concrete, there is a better correlation between the ratio max. stress/ static strength and the fatigue strength, than between stress range and fatigue strength, as experienced with steel. Therefore the S-N-diagram for concrete is presented as shown in Fig. 3. The minimum stress of the load cycle, or in other words the stress range, is also significant for fatigue of concrete. Examination of fatigue of concrete requires that many factors should be considered, such as: aggregates and proportions of concrete, humidity and temperature conditions, stress rate and load frequency, tri-axial conditions, stress gradient and eccentric loading - and other factors |20|.

In the following the load aspect will be given most attention. The results reported are primarily generated in a recent investigation at our research institute |21|.

Previously it has been reported a significantly greater scatter of fatigue testing than at static testing. However, the mean standard deviation, expressed in units of stress, is not significantly different for static strength and for fatigue strength. This is also reported in a research paper by TNO in Delft |23|. It might be added that an extrapolation of the S-N-

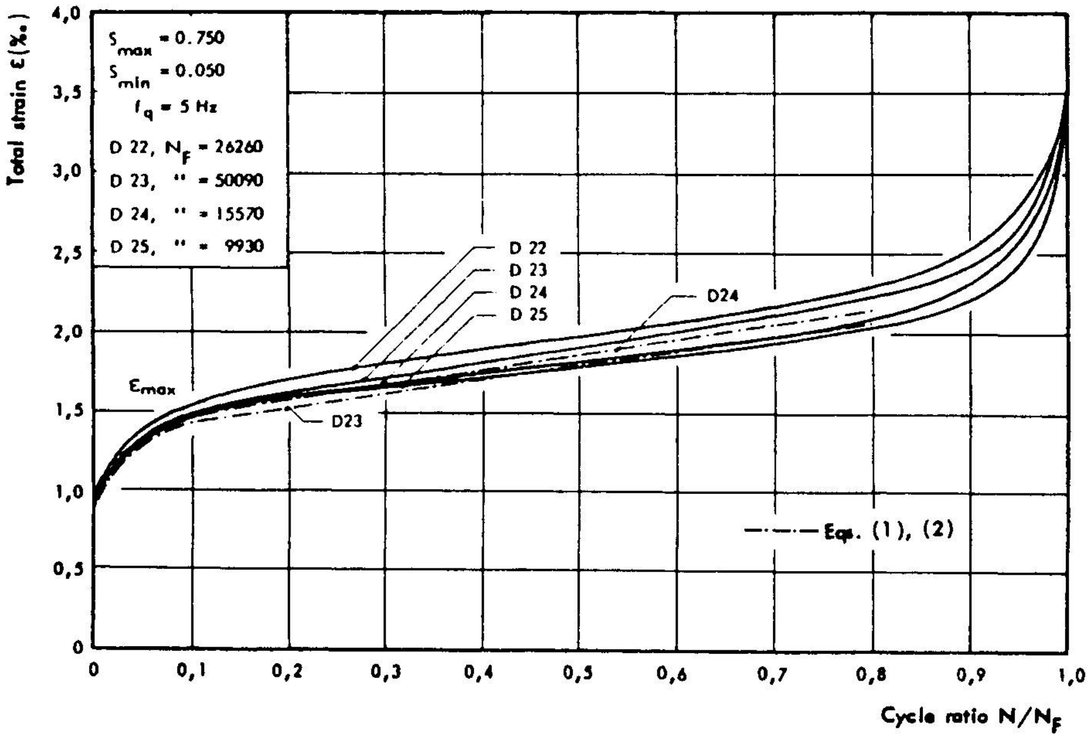
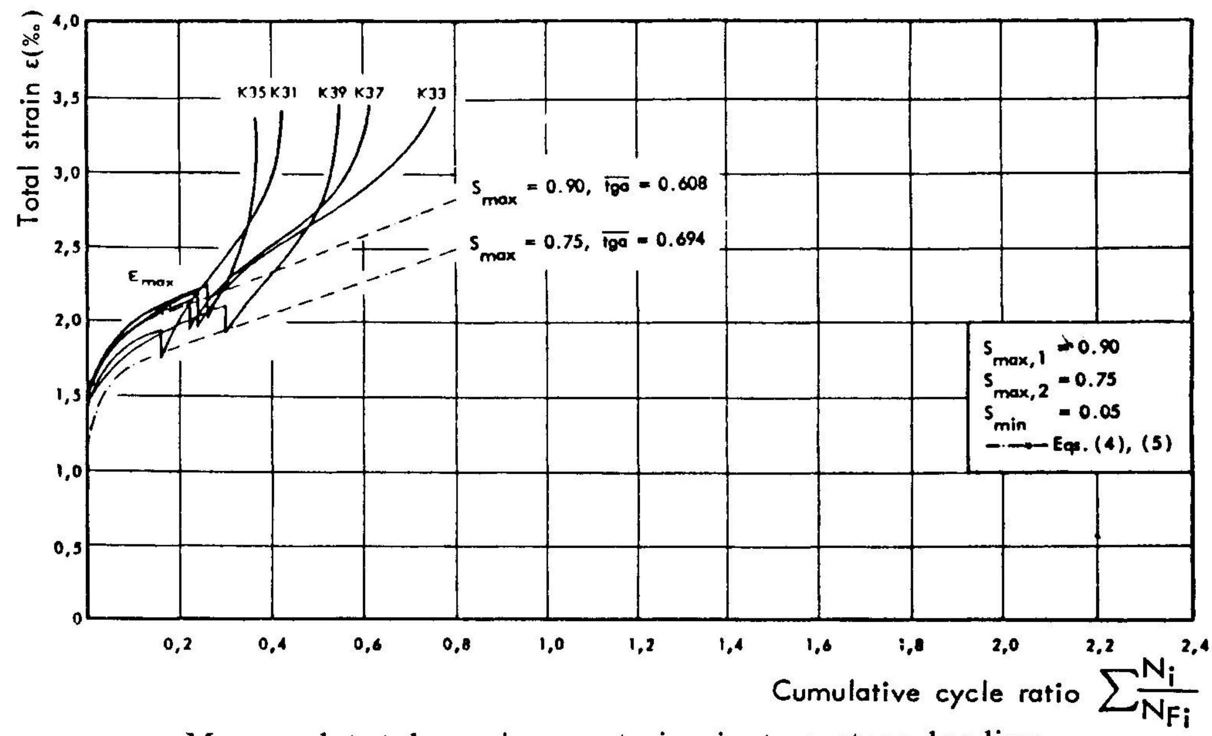
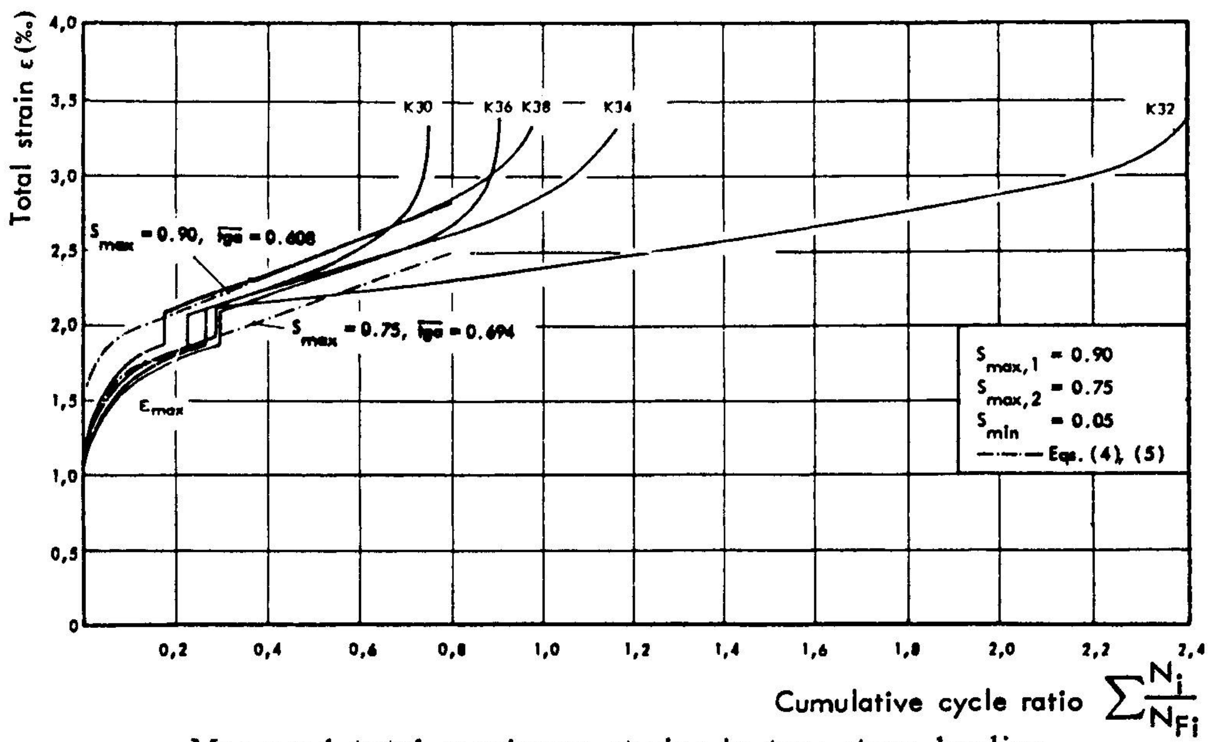


Fig. 4 Measured and calculated variation of total maximum strain with the cycle ratio



Measured total maximum strains in two stage loading compared with eqs. (4), (5)



Measured total maximum strains in two stage loading compared with eqs. (4), (5)

Fig. 5

curve in Fig. 3 towards a smaller number of loadings would give a strength higher than the static strength. It has to be noted that the rate of the dynamic loading in this case is approximately 2000 times higher than the prescribed rate for the static tests. According to other tests, an increase of approximately 25% in "static" strength is to be expected by such a high rate of loading as mentioned above |23|.

The importance of the deformation during the fatigue loading has been more and more realized. In Fig. 4 typical test results from tests of short duration are shown |19|. The trend is the same for all test specimens. The first loadings greatly increase the deformation. After a while the increase in deformation is reduced and the specimen enters a more stabilized period until an excessive deformation starts a short while before the final failure - if the specimen fails in fatigue. The relation between the number of loadings and the strain can, according to the experiments, be expressed by

$$0 < \frac{N}{N_F} \leqq 0{,}1:$$

$$\varepsilon_{e_1} = \operatorname{cotan}\alpha(3.76-2.18\ S_{max})\sqrt{\frac{N}{N_F}} \qquad (1)$$

$$0.10 < \frac{N}{N_F} < 80:$$

$$\varepsilon_{e_2} = \operatorname{cotan}\alpha(1.11+0.75\ \frac{N}{N_F}) \qquad (2)$$

where: ε_e = total maximum strain (o/oo)

ε_0 = total maximum strain in the first cycle (o/oo)

S_{max} = maximum stress/static ultimate strength

$\operatorname{cotan}\alpha = \varepsilon_0/S_{max}$

The α-value is to be considered as a material property. The strain or the deformation at constant amplitude loading is dependent on the fatigue life, N_F, of the concrete at that loading. Since N_F is not directly known, the equations 1 and 2 may not be practical for estimating the strain. However, if a specimen is subjected to fatigue loading and the strain and number of loadings are recorded, the remaining fatigue life can be found.

For dynamic loading with long duration a part of the total strain is due to the dynamic action, and the other part is due to creep of the same nature as for long time static load. Many proposals have been presented for a representative creep function, mostly for static permanent load. For alternating loads with long duration, tests indicate that the creep is higher than for a permanent static load equal to the average alternating loads. For creep calculations under alternating loads the so-called RMS-value, root mean square-value, seems to be a good equivalent permanent load

$$RMS = \sqrt{\frac{1}{T_0} \int_0^{T_0} x^2(t)dt}$$

where $x(t)$ = alternating stress

T = total time, duration of the cyclic loading

This RMS-value is also used for random loading. The mean stress level plus the RMS-value is called the characteristic stress level, S_c. The equations 1 and 2 are extended to include the creep:

$0 \leq \frac{N}{N_F} < 0.10$:

$$\varepsilon_{max} = \cot\alpha(3.76-2.18\ S_{max})\sqrt{\frac{N}{N_f}} + 0.143\ S_c^{1.184} \ln(t+1) \qquad (4)$$

$0.1 < \frac{N}{N_F} < 0.80$:

$$\varepsilon_{max} = \cot\alpha(1.11+0.75\ \frac{N}{N_F})+0.143\ S_c^{1.184} \ln(t+1) \qquad (5)$$

where $S_c = S_m$+RMS

S_m = mean stress

t = duration of alternating load in hours

The simple time-dependent creep function proved suitable for the laboratory climate.

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