SLIP INCREASE UNDER CYCLIC AND LONG TERM LOADS

ZUNAHME DER RELATIVVERSCHIEBUNG UNTER SCHWING- UND DAUERBEANSPRUCHUNG

AUGMENTATION DE GLISSEMENT SOUS CHARGES CYCLIQUES ET À LONG TERME

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SUMMARY

Test results of an ongoing research project on the interactional behavior between steel reinforcing bars and concrete subjected to long term or constant amplitude cyclic loads are presented. The load levels varied between 30 to 80 percent of the monotonic pull-out strength. The fitting of measurements resulted in slightly higher coefficients of the bond creep function than included in the CEB-FIP Model Code 1990. Another fitting curve was also proposed which is able to distinguish slip increases with or without pull-out failure.

ZUSAMMENFASSUNG

Versuchsergebnisse eines laufenden Forschungsprojektes über das Verbundverhalten zwischen Bewehrungsstählen und Beton unter Dauerlast oder Schwinglast mit konstanter Amplitude sind dargestellt. Die Belastungshorizonte betrugen 30 bis 80 %, bezogen auf die statische Verbundfestigkeit. Die Annäherungen der Meßergebnisse haben für die Verbundkriechfunktion etwas höhere Koeffizienten erbracht, als die der CEB-FIP Mustervorschriften von 1990. Eine andere Annäherung wurde auch vorgeschlagen, die die Entwicklung der Relativverschiebung, sowohl mit als auch ohne Ausziehen, berücksichtigen kann.

RÉSUMÉ

Les résultats d'essai d'un recherches en cours concernant le comportement d'adherence entre les aciers d'armement et le béton sous charge à long terme ou charge cyclique avec amplitude constante sont représentés. Les niveaux de chargement varient entre 30 à 80 % de la force d'adhérence statique. Les approches des résultats de mesure ont donné des coéfficients de fluage d'adhérence légèrement plus élevés que le code modèle CEB-FIP de 1990. Une autre approche a été également proposée qui est en mesure de tenir compte des augmentations de glissement avec et sans arrachement.

Keywords: cyclic load, long term load, creep, cyclic creep, pull-out test, slip, fitting

1. INTRODUCTION

For reinforced concrete structures the bearing capacity under monotonic loading has been widely studied within the past years. For the two constituent materials – reinforcing steel and concrete – in addition to the load-deformation characteristics, also the behavior under long term and cyclic loading has been intensivly investigated. The interaction between these two materials, however, shows some gap of knowledge concerning realistic loading cases. The German Research Society (DFG), therefore, introduced a special research program concerning the behavior of reinforced concrete elements in service conditions. As a part of this program one project deals with the bond behavior in order to determine the stress-slip relationship under different non-monotonic loadings [1], [2]. In this paper selected test results of the ongoing project are presented as a contribution to a better understanding of the bond behavior under cyclic and long term loading. These results will be extended with measurements on low load levels.

2. EXPERIMENTAL STUDIES

2.1 Test specimen

The tests for this program were performed as centric pull-out tests with 5·Ø bond length and an other 5·Ø unbonded length on both sides of the specimen (**Fig.1**). The reinforcing bars were cast in the concrete prism in horizontal position in order to have similar bond conditions also for reversed loading although the results presented herein deal only with unidirectinal tensile loading.

The sizes of the specimen were derived from the RILEM pull-out specimen [4] with the exception unbonded parts on both sides of the bond length. This was also chosen to cover the planed reversed loading cases. No additional transverse reinforcement was supplied to prevent splitting of the concrete cover.

All tests presented in this paper were performed with a reinforcing bar of 16 mm diameter (f_y=500 N/mm^2) and a concrete grade of B 25 according to the DIN 1045. To avoid significant strength increase of the concrete during the cyclic or long term loading, the loading started at an age of the concrete of about 10 weeks to decrease the influence of the strength development of concrete.

2.2 Test procedure

Cyclic and long term tests run simultaneously.

2.2.1 Cyclic tests

The cyclic tests were carried-out in a load frame with a hydraulic 100 kN actuater which was controlled by a computer [3] to produce the load and to make the data registrations (**Fig.1.a**). The relative displacement (slip) between steel and concrete war registered by an LVDT at the unloaded end of the reinforcing bar. In addition to the slip, the actual load and the number of load cycles were automaticaly registered at given load cycles and selected slip values.

The cyclic tests began with a monotonic loading of 300 N/s rate up to the middle value of cyclic load. The sinusoidal cyclic load was then applied with a frequency of 4 s^{-1}. Depending on the magnitude of the amplitude, about 10 cycles were necessary to reach the full value of the amplitude. The cyclic tests run fully automatically until either to a pull-out of the reinforcing bar or to $2 \cdot 10^6$ load cycles being the usual technical limit.

The upper value of cyclic load was chosen as a percentage of the monotonic pull-out strength, determined by three displacement controlled static tests. The lower value of cyclic load was always 10 % of the upper value. The investigated load levels and the number of tests are given in **Tab.1**.

2.2.2 Long term tests

The long term tests were carried out in a test frame with weight loading having a lever arm of 1 to 14 (**Fig.1.b**). The slip was measured by a mechanical dial gauge at the unloaded end of the reinforcing bar, related to the

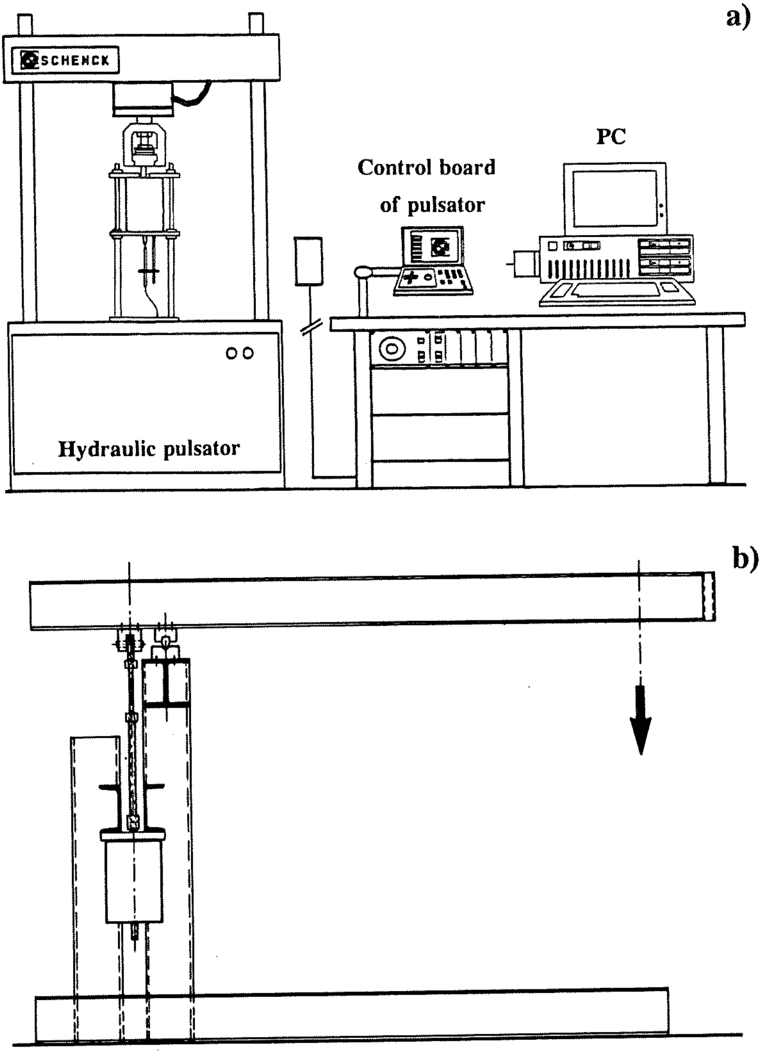

Fig.1 Test setup
a) Cyclic tests
b) Long term tests

end face of the concrete prism. The load was applied approximately with the same rate as by the beginning of cyclic tests.

The time at reaching the required load level was regarded as the start (t=0) for the long term loading with an entire loading time of 1008 hours (6 weeks). The time limit of 1008 hours was taken as a compromise between realistic long term loads (several years, appr. 100 000 h) and a reasonable testing time.

The slip readings were taken at different intervals to follow the expected deformation rate. The load limits were also chosen as a percentage of the pull-out strength (**Tab.1**).

Tab.1 Applied load levels together with the number of tests

Nr.	τ_b/τ_{bu} $\tau_{b,max}/\tau_{bu}$ [-]	Number of tests	
		cyclic load	long term load
1	0.20	1	-
2	0.30	2	6
3	0.35	2	-
4	0.40	5	6
5	0.50	5	6
6	0.55	1	-
7	0.60	7	6
8	0.70	5	6
9	0.75	2	-
10	0.80	5	4
11	0.90	1	-

3. TEST RESULTS

The test results are presented in this chapter. Their fitting with two different funktions together with further comparisons are given in chapter 4.

3.1 Slip increase under long term loads

The observed slip increase as a function of the duration of load and that of the load level is plotted in **Fig.2** in logarithmic scale. A comparison of the same results in linear scale is provided by **Fig.3**. Pull-out failure did not occur during the loading period of 1000 hours on a load level of 30 to 70 % related to the pull-out load and only in some cases up to 80 %.

The results indicate that the higher the load level the higher the initial slip and the slip increase. The slip increase related to the final slip value after 1000 hours loading $[(s_{1000}-s_0)/s_{1000}]$ was between 50 and 80 % having a mean value of 62 %. The initial slip values at reaching the total long term load are summarized in Fig.9.

3.2 Slip increase under cyclic loads

The observed slip increase as a function of the number of load cycles and that of the load level is plotted in **Fig.4** in logarithmic scale.

The higher load levels (60, 70 and 80%) generally produced pull-out failure in less then $2 \cdot 10^6$ load cycles (**Fig.5**), however, lower load levels (30, 40 and 50%) did not produce failure (Fig.4.d, e and f). That means, that none of the specimens failed up to 50 % relative load level to $2 \cdot 10^6$ load cycles,

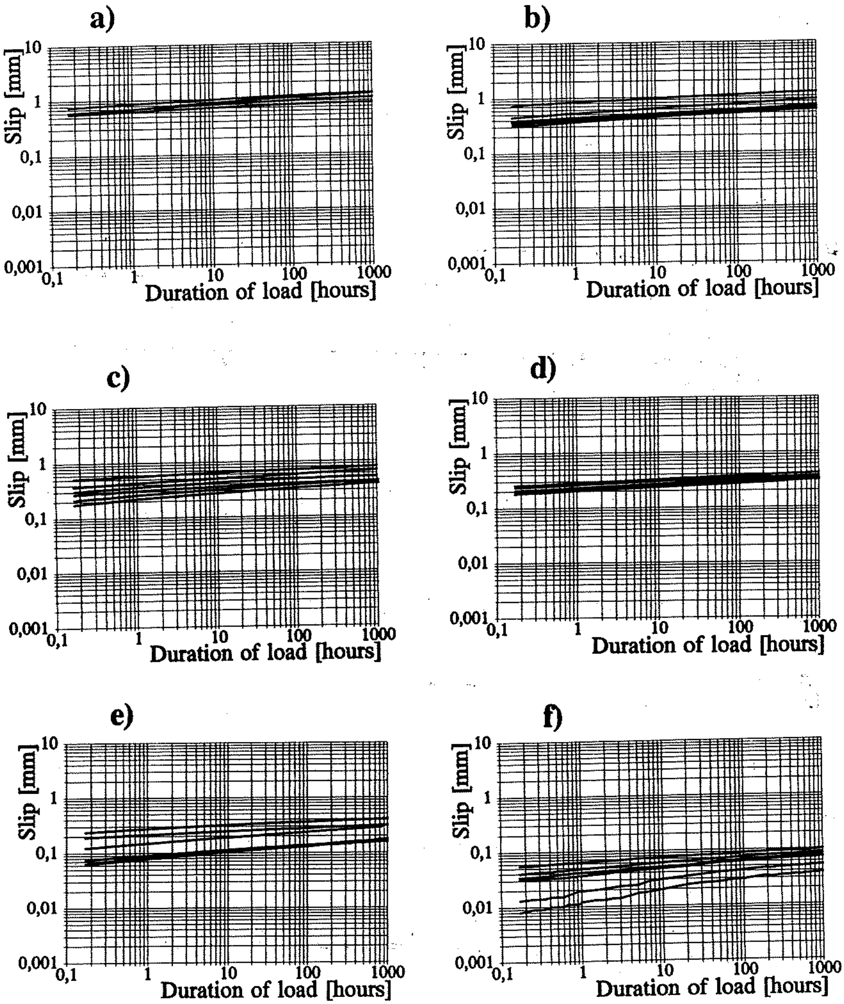

Fig.2 Slip increase under long term loads (logarithmic representation of the test results), Ø16, $\alpha_{sb}=0.065$, $f_y=500$ N/mm^2, $f_c=30$ N/mm^2

a) $\tau_b/\tau_{bu}=80$ % **b)** $\tau_b/\tau_{bu}=70$ %

c) $\tau_b/\tau_{bu}=60$ % **d)** $\tau_b/\tau_{bu}=50$ %

e) $\tau_b/\tau_{bu}=40$ % **f)** $\tau_b/\tau_{bu}=30$ %

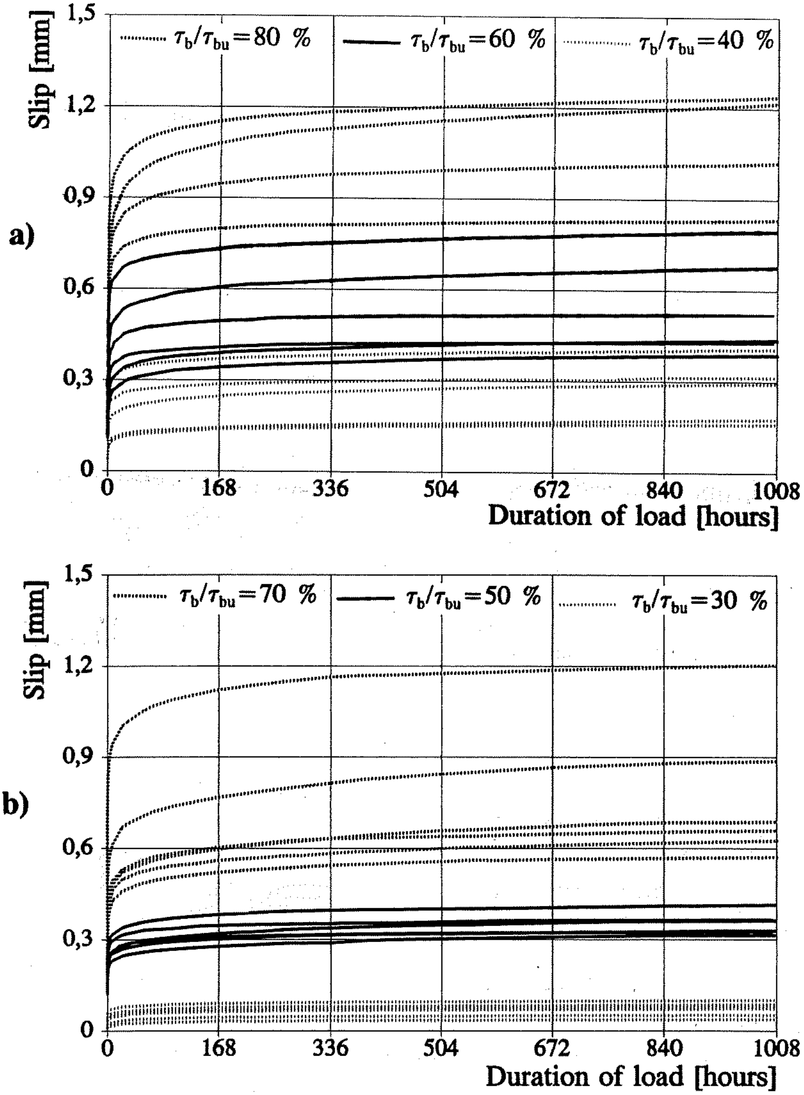

Fig.3 Comparison of long term test results in linear scale, Ø16, α_{sb}=0.065, f_y=500 N/mm^2, f_c=30 N/mm^2
a) τ_b/τ_{bu}=40 %, 60 % and 80 % **b)** τ_b/τ_{bu}=30 %, 50 % and 70 %

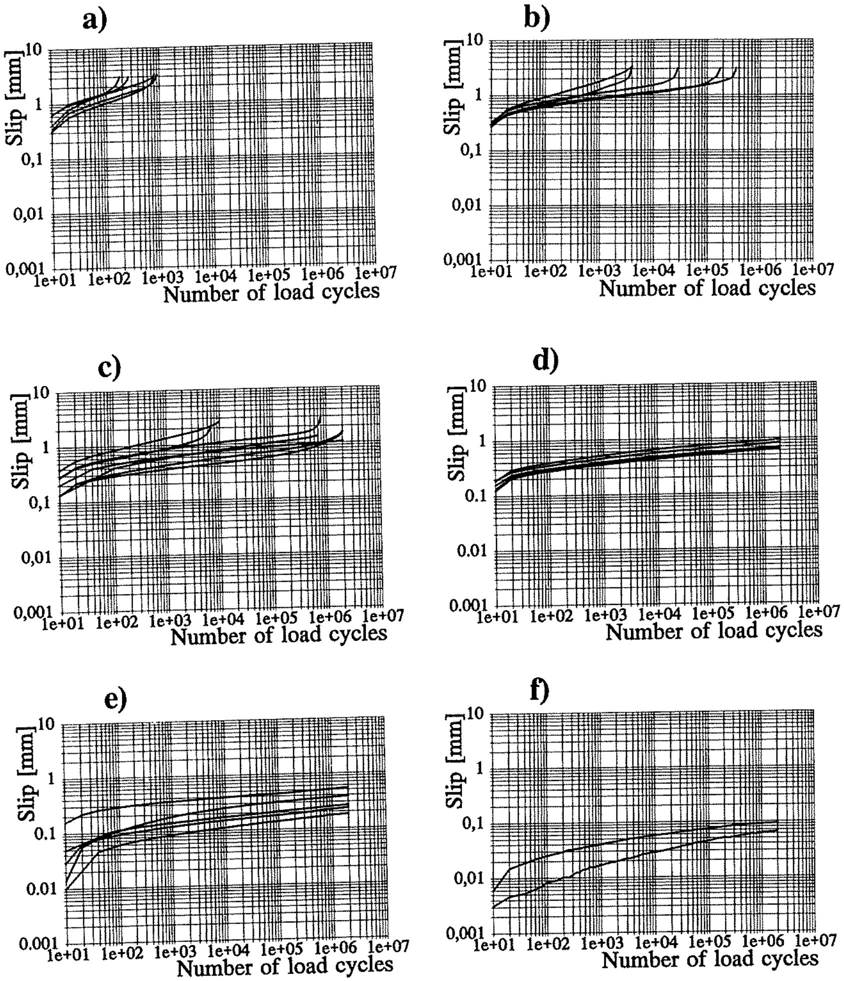

Fig.4 Slip increase under cyclic loads (logarithmic representation of the test results), Ø16, $\alpha_{sb}=0.065$, $f_y=500$ N/mm^2, $f_c=30$ N/mm^2

a) $\tau_b/\tau_{bu}=80$ %
b) $\tau_b/\tau_{bu}=70$ %
c) $\tau_b/\tau_{bu}=60$ %
d) $\tau_b/\tau_{bu}=50$ %
e) $\tau_b/\tau_{bu}=40$ %
f) $\tau_b/\tau_{bu}=30$ %

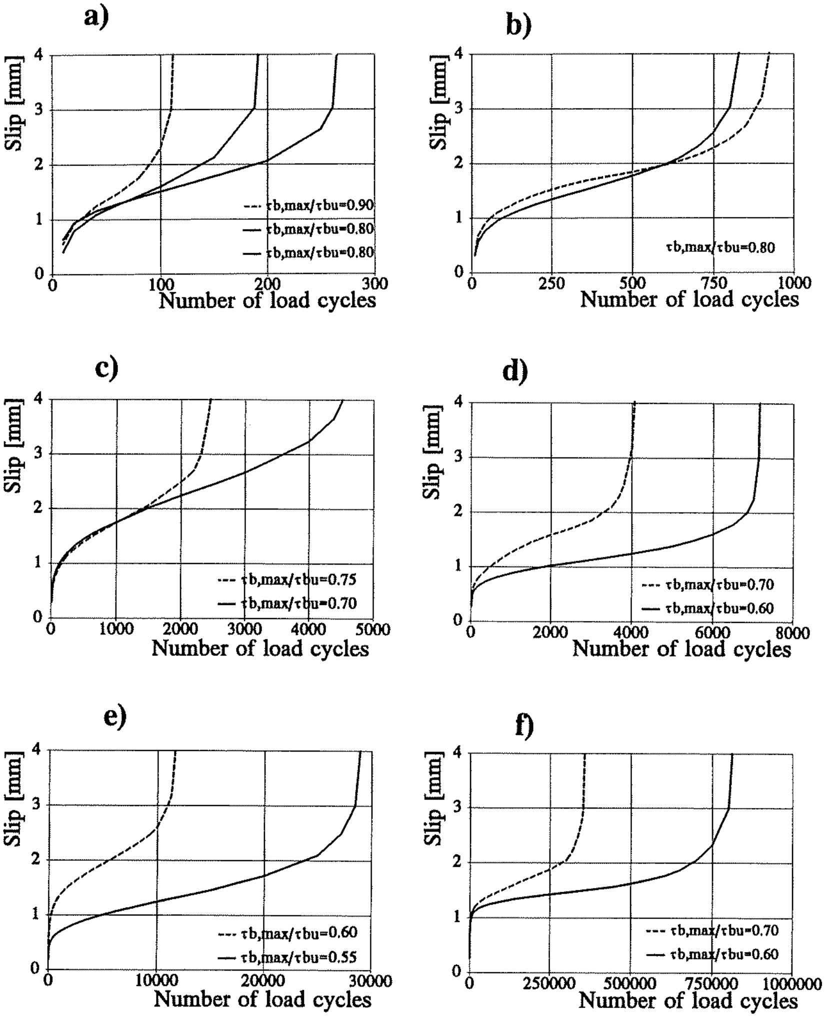

Fig.5 Cyclic test results with pull-out failure in linear scale, Ø16, $\alpha_{sb}=0.065$, $f_y=500$ N/mm^2, $f_c=30$ N/mm^2 (load levels are indicated in each diagram)

otherwise all of the specimens failed by pull-out for loads 70 % or higher. *The higher the load level the shorter the fatigue life or the smaller the number of load cycles needed to produce a given slip.*

In case of a pull-out failure, the typical three phases of the fatigue process (presented in the form of a slip versus number of load cycles diagram) observed in previous studies [5] were observed here as well independently on the load level: *first decreasing slip rate, then a practically constant slip rate, finally increasing slip rate.*

4. APPROACHES

Above test results are fitted using the method of least squares and compared to the CEB-FIP Model Code 1990 proposal.

4.1 Comparisons with the CEB-FIP Model Code 90 proposal

Based on comparisons by Rehm and Eligehausen [6], the CEB-FIP Model Code 1990 [7] proposes the same type of relationship to consider the slip increase both under long term and cyclic loads, respectively:

$$s_t = s_0(1+k_t) \tag{1a}$$

$$s_n = s_0(1+k_n) \tag{1b}$$

Based on test results by Franke [8] as well as by Rostásy and Kepp [9], *the creep factor* is given as:

$$k_t=(1+10\cdot t)^{0.080}-1 \tag{2}$$

where **t** is the duration of load in hours.

In case of cyclic loads, based on test results by Rehm and Eligehausen [6], *the cyclic creep factor* is:

$$k_n=(1+n)^{0.107}-1 \tag{3}$$

where **n** is the number of load cycles.

Eqs.(1) to (3) are valid only for the ascending branch of the bond stress-slip relationship.

4.1.1 Analysis of CEB-FIP Model Code 90 proposal

The CEB-FIP Model Code 90 proposal gives a *linear slip increase* under long term and cyclic loads considering the logarithm of both the slip and the duration of load or the number of load cycles. The slope of the lines for cyclic loading is, however, 34% higher predicting a faster slip increase for cyclic loads (**Fig.6.a**). (The multiplicators of time and number of load cycles are also different: see Eqs.(2) and (3).)

The creep coefficients have a point of intersection at appr. 900 hours or number of load cycles (**Fig.6.b**). $k_n=k_t=1$ for $t=579$ hours or $n=650$ load cycles and $k_n=k_t=2$ for $t=92048$ hours or $n=28778$ load cycles.

$$s_n = s_0(1+k_n) \qquad k_n = (1+n)^{0.107} - 1$$

$$s_t = s_0(1+k_t) \qquad k_t = (1+10 \cdot t)^{0.080} - 1$$

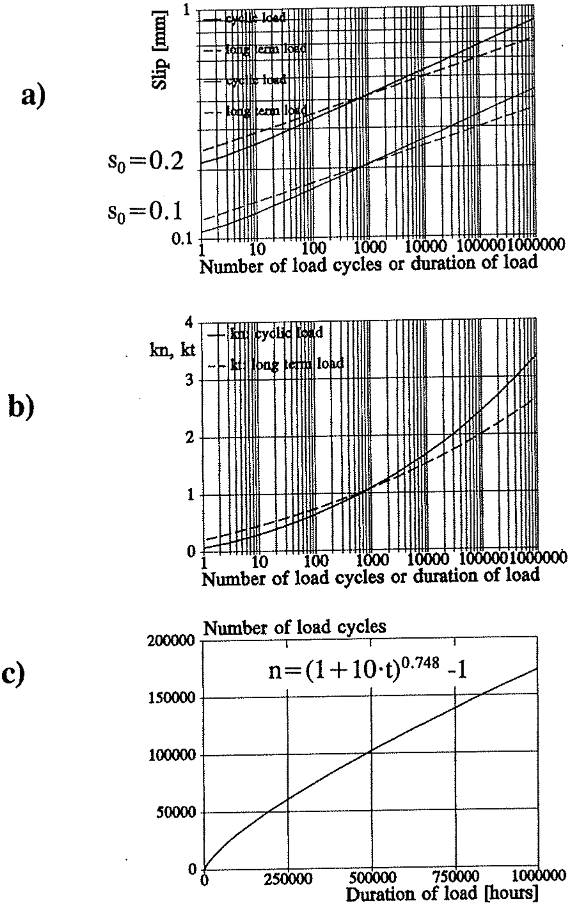

Fig.6 Analysis of the CEB-FIP Model Code 90 [2] proposal

a) Slip increse in logarithmic scale

b) Creep coefficients

c) Number of load cycles versus time relationship

A parabolic equation may be obtained for the relationship between the time and the number of load cycles considering the same initial slip, taking $s_n = s_t$ and expressing the number of load cycles (**Fig.6.c**):

$$n=(1+10\cdot t)^{0.080/0.107}-1=(1+10\cdot t)^{0.748}-1$$

The creep coefficients and therefore the predicted slip values are independent of the *frequency of the load.*

4.1.2 Comparisons for long term loads

Figs.7 and 8 show the fitting of our test results to Eq.(1a) using the method of minimum squares and considering both the initial slip $\mathbf{s_0}$ and the power **b** as parameters in $s=s_0(1+10\cdot t)^b$. Fig.7.a indicates three typical test results and Fig.7.b presents the average curves of measurements to the different load levels compared to Eq.(1a).

The results of fitting indicate an almost linearly decreasing tendency of the *power b* depending on the load in the range of 30 to 50 % relative load levels, then it may be considered to be constant being approximately 0.066 (Fig.8.a). It means that the average s versus n diagrams are parallel in logarithmic scale for 50 to 80 % load levels, however, they have slightly higher tangents for 30 and 40 % load levels, respectively. The average of fittings in groups for the different load levels on the entire 30 to 80 % range is **b=0.077** which is close to 0.080 given by Eq.(2). (The average of fittings to every single result gives b=0.076.)

The results of fitting gives slightly higher *initial slip* (s_0) values than the

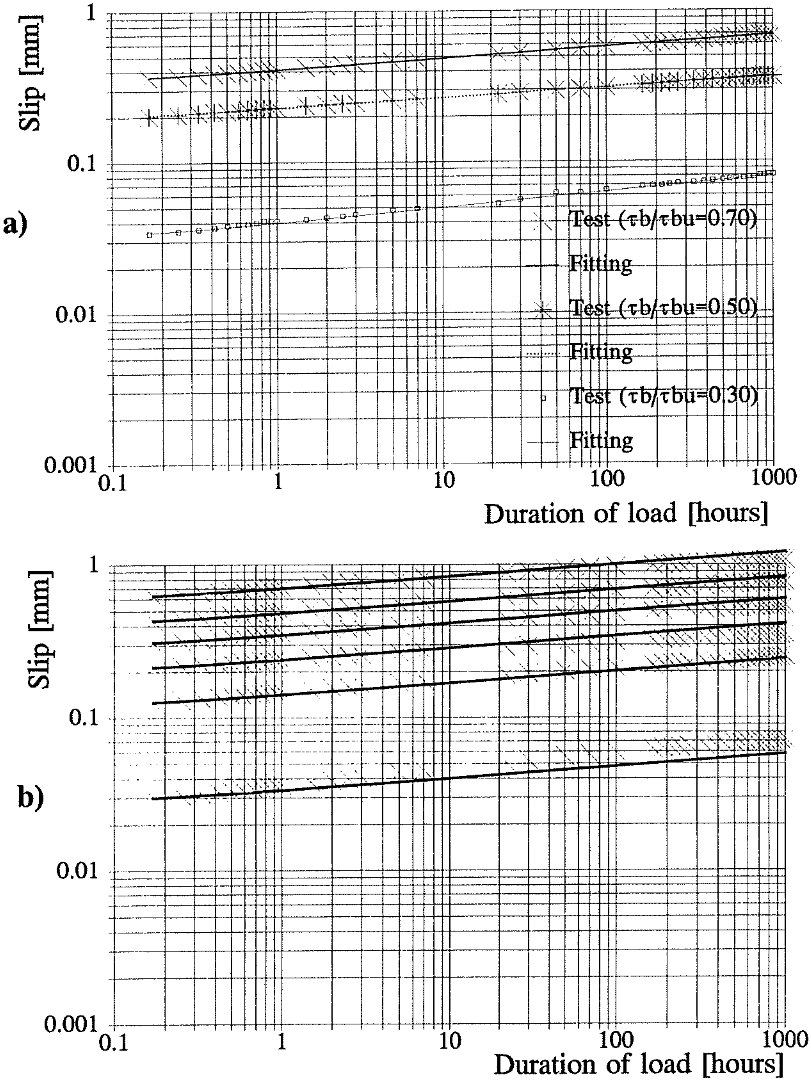

Fig.7 Comparisons for long term loads

a) Single results : $\tau_b/\tau_{bu}=30$ %, 50 % and 70 % with the fitting curves

b) Average of results together with the MC 90 proposal considering the same measured and calculated values at 10 minutes (0.17 hours)

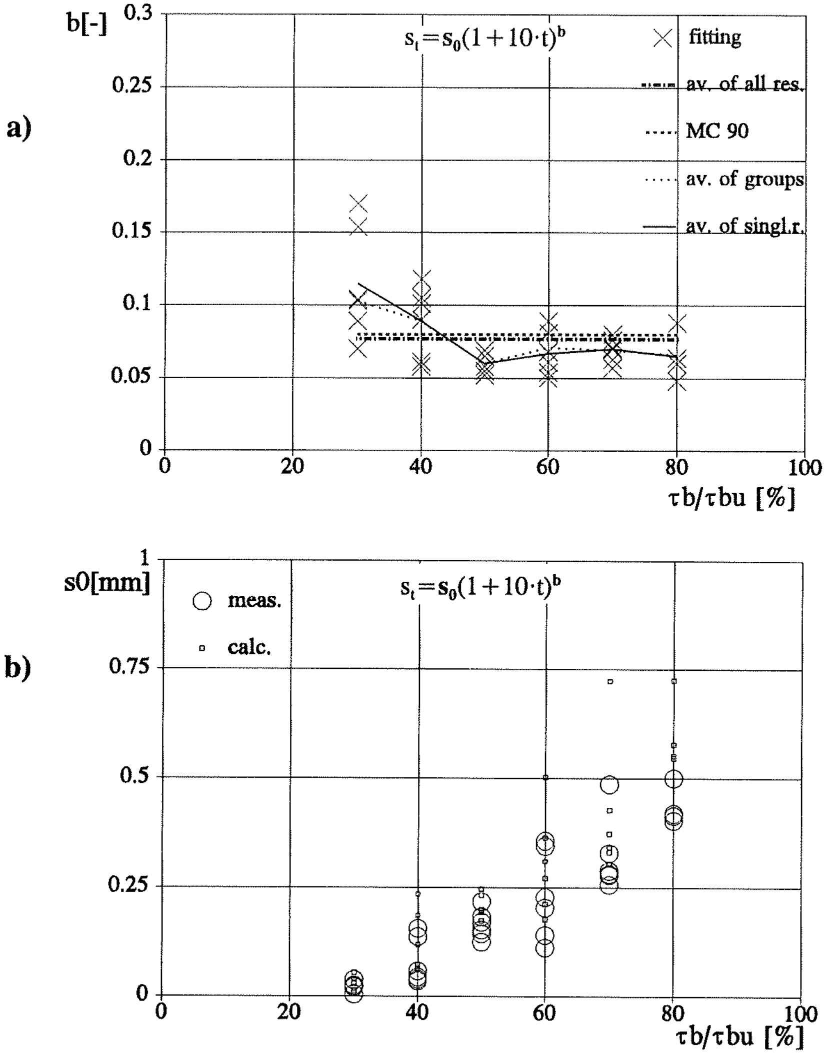

Fig.8 Coefficients of $s=s_0(1+10\cdot t)^b$ obtained by the method of minimum squares in case of long term loads

a) power **b** **b)** initial slip s_0

measured initial slip values at t=0 (Fig.8.b).

Considering only the power **b** of Eq.(1a) as a variable and substituting the measured s_0 values, the obtained powers are considerably higher but show the same tendency as observed by Fig.8.a. The average value of fittings in groups for the different load levels on the entire 30 to 80 % loading range is **b=0.123** (Fig.9). The average of all single results gives b=0.124.

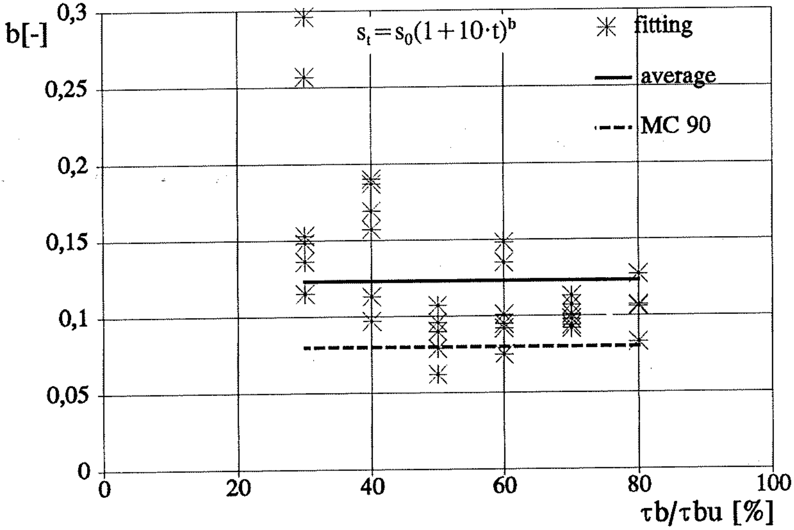

Fig.9 Power b of $s=s_0(1+10t)^b$ obtained by fitting in case of long term loads. s_0 was considered as the measured value.

4.1.3 Comparisons for cyclic loads

Figs.10 and 11 show the fitting of our test results to Eq.(1b) considering number of load cycles $10 \leq n \leq 2\cdot10^6$ and slips $s \leq 1.5$ mm. Load cycles

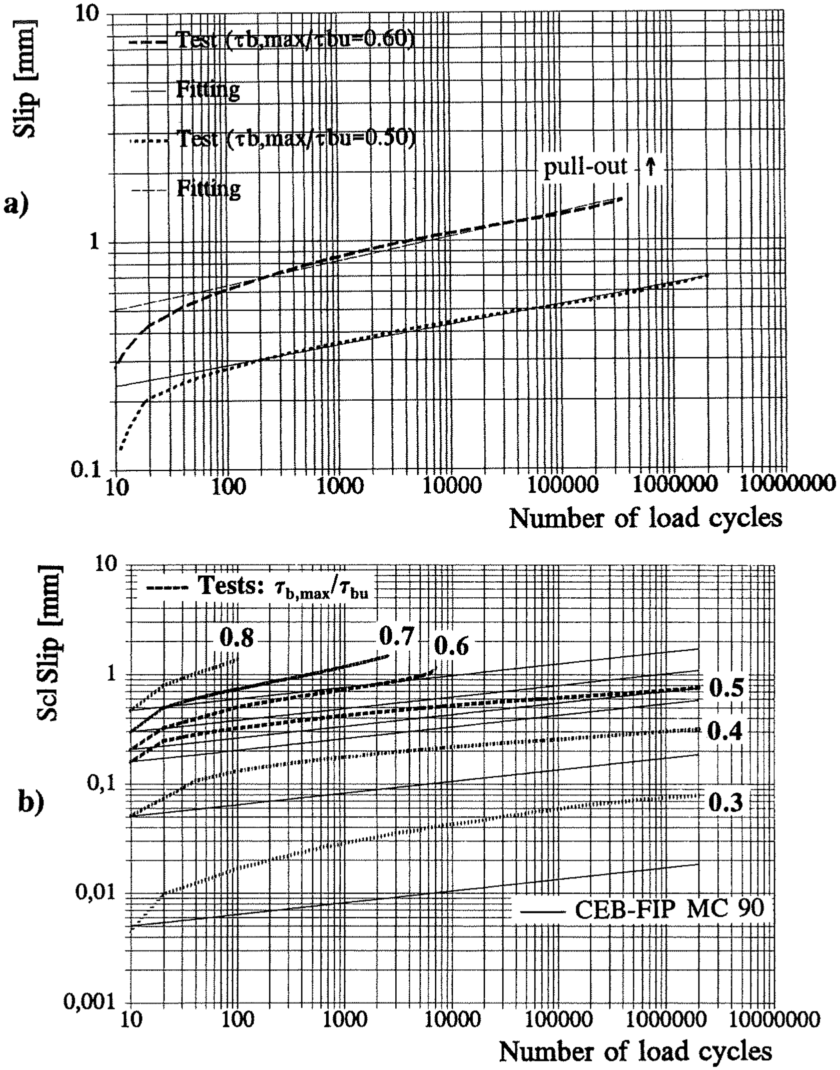

Fig.10 Comparisons for cyclic loads

a) Test results: $\tau_{b,max}/\tau_{bu}=50$ % and 60 % together with the fitting curves

b) Average of results to the different load levels (---) together with the CEB-FIP Model Code 90 proposal (—)

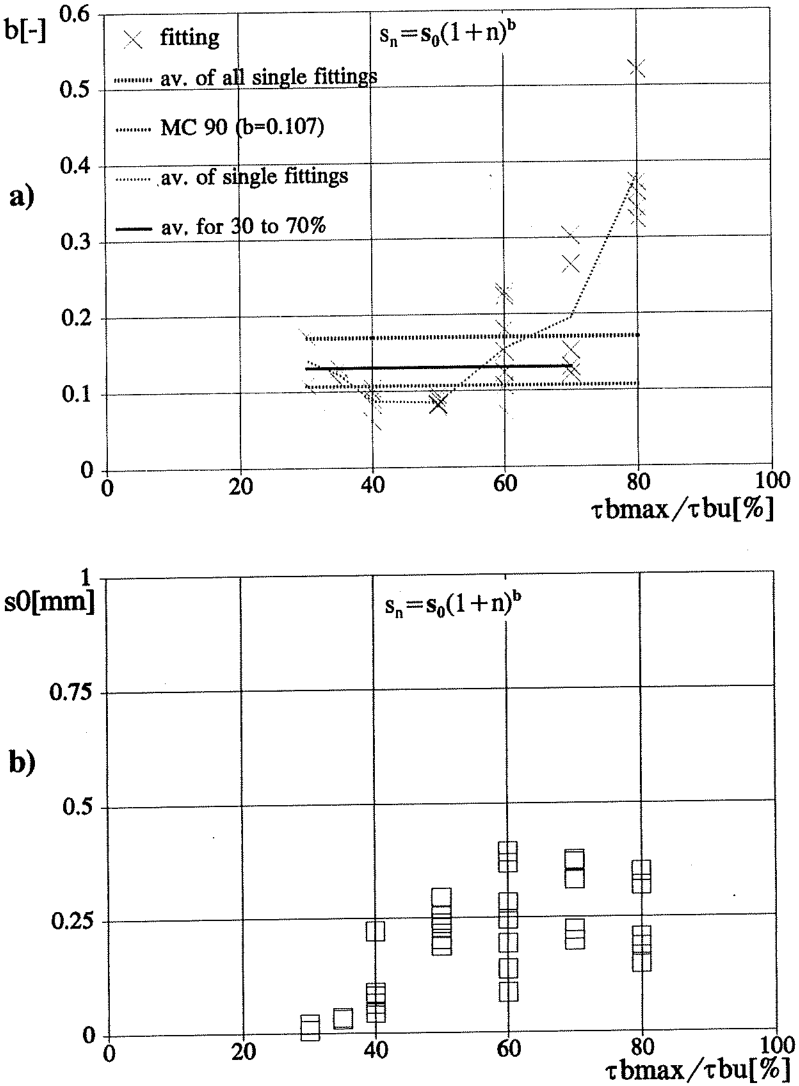

Fig.11 Coefficients of $s=s_0(1+n)^b$ obtained by the method of minimum squares in case of cyclic loads

a) power **b** **b)** initial slip s_0

smaller than 10 were unconsidered because approximately 10 load cycles were needed to reach the complete amplitude of loading. Slip values higher than 1.5 mm generally fall on the failing branch of the slip versus number of load cycles diagramm which would make the fitting for the entire curve unreasonable.

Fig.10.a shows two typical test results with and without pull-out failure. Fig.10.b indicates the average curves of measurements together with Eq.(1b) having the same initial values at n=10 load cycles as the test results. Comparing the measurements to the lines provided by Eq.(1a), differences may be observed in the course of diagrams and in the inclination of them.

Considering both power **b** and initial slip $\mathbf{s_0}$ as fitting parameters in $s=s_0(1+n)^b$, the smallest powers (b=0.078 to 0.104) are obtained for 40 and 50 % load levels and considerably higher values for the lower and the higher load levels (Fig.11.a). The averege of single fittings for 30 to 70 % load levels is **b=0.131**. The averge of single fittings for the entire 30 to 80 % loading range is **b=0.170.**

Fig 11.b indicates the initial slip values obtained by the fitting.

Considering only the power **b** of Eq.(1b) as a variable and substituting the s_0 values obtained at t=0 by the long term tests, the obtained powers show an increasing tendency with incresing load and the average value of fittings in groups for the different load levels on the entire loading range is **b=0.148 (Fig.12)**.

4.2 Fitting with or without failure branch

Another logarithmic function is able to distinguish the slip increases with or without pull-out failure:

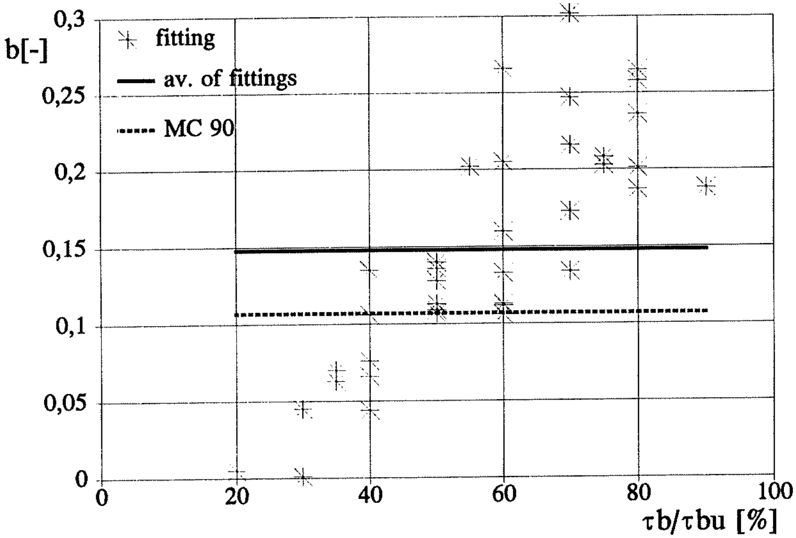

Fig.12 Power b of $s=s_0(1+n)^b$ obtained by fitting in case of cyclic loads. s_0 was considered as measured at the long term tests.

$$s_t=k_1+k_2\cdot\ell n(k_3+t)+k_4\cdot\ell n(k_5\text{-}t) \qquad t>k_5 \qquad (4a)$$

or

$$s_n=k_1+k_2\cdot\ell n(k_3+n)+k_4\cdot\ell n(k_5\text{-}n) \qquad n>k_5 \qquad (4b)$$

$k_4=0$ without pull-out failure

$k_4\neq0$ with pull-out failure

Fig.13 indicates the fitting coefficients of Eq.(4a) obtained by the method of minimum squares for the long term test results without pull out failure. The additive term, k_1 and the tangent, k_2 show increasing tendencies with increasing

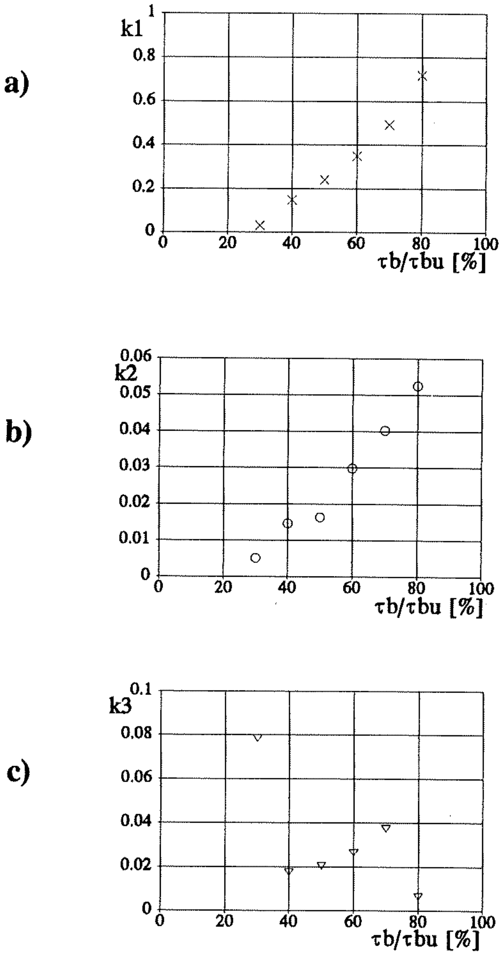

Fig.13 Coefficients of the fitting curve $s=k_1+k_2 \cdot \ell n(k_3+t)$ obtained by the method of least squares in case of long term loading

load levels. The corresponding fitting curves together with the average of measurements on the various load levels are presented in **Fig.14.**

In case of a pull-out failure there is a final rapid slip increase, therefore, the third term should be incorporated providing a point of inflexion and a vertical asympthot.

Further evaluation is needed for a complete comparison.

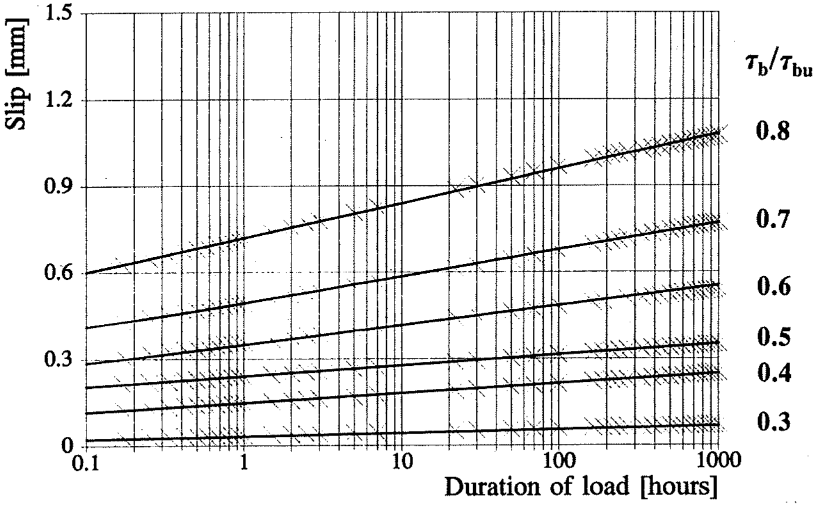

Fig.14 Comparison of the average of measurements and the fitting curves: $s = k_1 + k_2 \cdot \ell n(k_3 + t)$

5 COMPARISON OF LONG TERM AND CYCLIC BOND BEHAVIOUR

Based on comparisons of test results, Rehm and Eligehausen [6] concluded that the repeated loading may be assumed as a time accelerator compared to the long term loading. Otherwise the behaviors are similar and the slip increase under long term and repeated loads may be expressed in the same mathematical form.

A possible way of comparison of long term and cyclic test results is based on the analysis of deformations during the same time which is, however, dependent on the frequency of the cyclic load. Considering the applied frequency of 4 s^{-1}, the cyclic tests run 139 hours up to $2 \cdot 10^6$ load cycles.

The comparison of long term and cyclic test results up to 139 hours together with a comparison in the early period of loading (0.25 hours = 3600 load cycles) are given in **Fig.15**. The slip values obtained in our tests indicate a non-linear increase as a function of the load level.

Relating the average slip values at the different load levels under cylic and long term loads, the ratios show an increasing tendency with increasing load level (**Fig.16**). This slip ratio increases from **1.16** to **3.85** between 30 to 70 % load levels in case of 3600 load cycles (i.e. 0.25 hours) and from **1.36** to **2.37** between 30 to 50 % load levels in case of $2 \cdot 10^6$ load cycles (i.e. 139 hours), respectively. The slip ratio is slightly higher for higher number of load cycles (or time) and goes to infinity for load levels producing failure with the cyclic load.

Substituting above values in the CEB-FIP Model Code 1990 formulas:

$$s_n/s_t=(1+n)^{0.107} \;/\; (1+10\cdot t)^{0.080}$$

the slip ratio is **2.17** for 3600 load cycles and **2.65** for $2 \cdot 10^6$ load cycles independently on the load level and the frequency of cyclic load. These values approximately agree with our test results at 50 % load level.

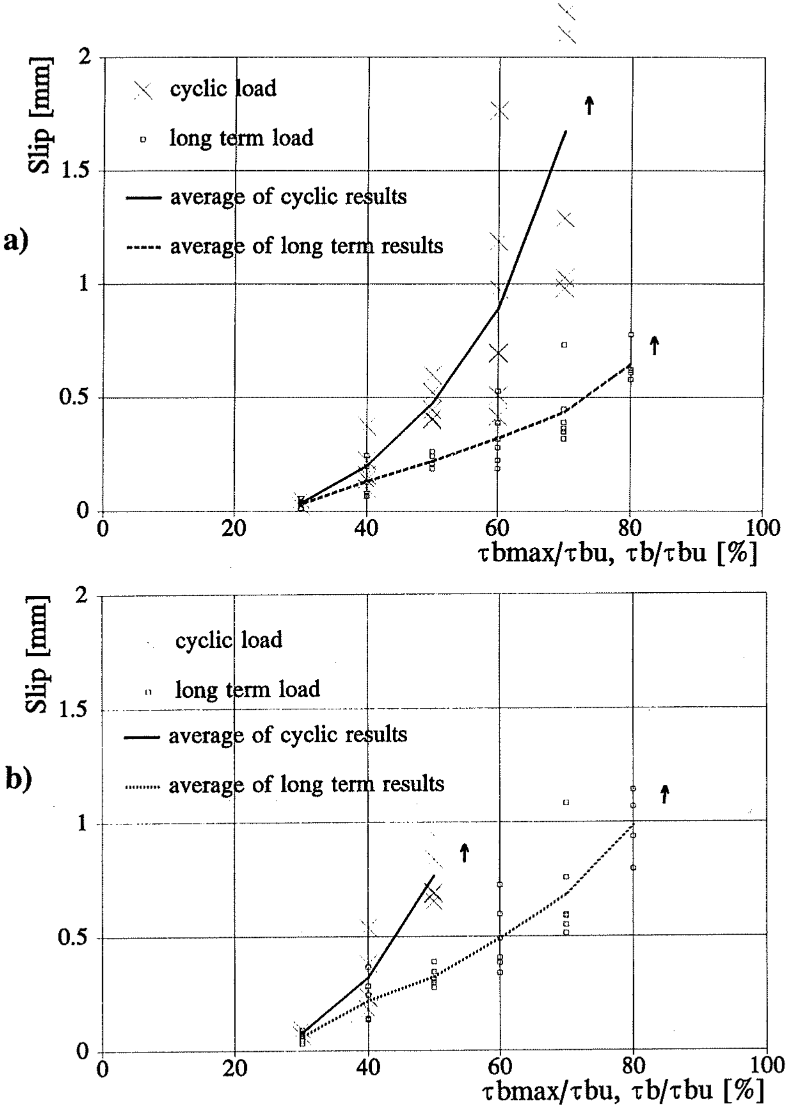

Fig.15 Comparison of slip increases under cyclic and long term loads
a) after 3500 load cycles or 0.25 hours, resp. (↑: pull-out failure
b) after $2 \cdot 10^6$ load cycles or 139 hours, resp. in cyclic tests)

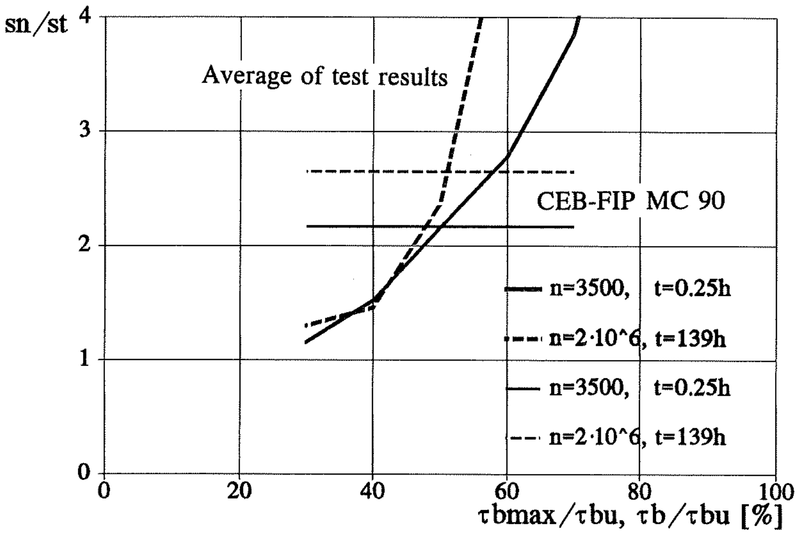

Fig.16 Ratio of slips under cyclic and long term loads

The numerical approximation to Eqs.(4a) and (4b) allows an analytical comparison of slip values produced by cyclic or long term loads, respectively. Under the same loading (which means the upper load limit for the cyclic test and the constant load for the long term test), those *t* and *n* combinations can be calculated which produce the same slip value. The result of this calculation is plotted in **Fig.17**. For higher load levels all results are close to each other and can be represented by:

$$\ell og\ t = -5.8 + 4 \cdot \ell og\ n$$

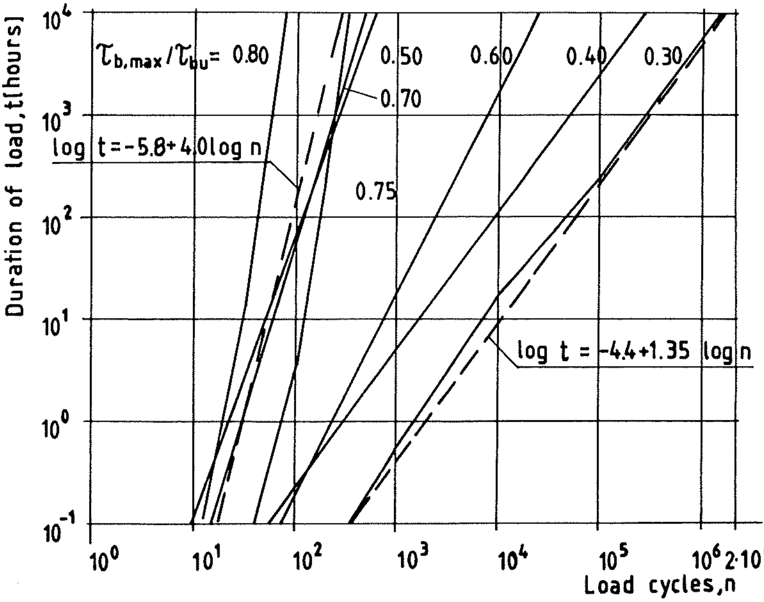

Fig.17 Relationship of the duration of load and the number of load cycles in long term and cyclic tests

For the lower load levels, this line is more shifted to the n - axis:

$$\ell og\ t = -4.4 + 1.35 \cdot \ell og\ n$$

This comparison was carried out with the upper load for the cyclic test and not for the amplitude (being 90 % of the maximum value cyclic load for this tests). Further analysis – including different ratios of the amplitude and the maximum value of cyclic load — is needed to decide which loading parameter is important to compare results of cyclic and long term tests.

6. CONCLUSIONS

The following conclusions can be drawn from the analysis of 70 pull-out test results with long term and constant amplitude cyclic loads applying 30 to 80% load levels related to the monotonic pull-out strength:

a) *Considerable slip increase* is observed both under long term and cyclic loads. 1000 hours long term load up to 70 % load level did not produce failure, however, specimens under cyclic load above 60 % load level and some of them on 60 % load level failed by pull-out within $2 \cdot 10^6$ load cycles.

b) The average slip increase related to the final slip value after 1000 hours *long term loading* was 62%.

c) The power of the creep function for *long term loads*, fitted in the form of $s=s_0(1+10\cdot t)^b$, is found to be practically constant for the 50 to 80 % load levels but it is slightly increasing for lower load levels. The average of all results in the entire 30 to 80 % loading range fitting with two parameters b and s_0 resulted in a power $b=0.077$ value similarly to the CEB-FIP Model Code 90 proposal ($b=0.080$). The obtained average power substituting the measured s_0 values is, however, $b=0.124$.

d) The fitting of *long term test* results in the form of $s=k_1+k_2\cdot \ell n(k_3+t)$ gave increasing tangents with increasing load levels.

e) A complete slip versus number of load cycles (or time) diagram can be obtained in the following form providing even a vertical asympthote by pull-out failure: $s_n=k_1+k_2\cdot \ell n(k_3+n)+k_4\cdot \ell n(k_5-n)$.

f) The power of the *cyclic creep function*, fitted in the form of $s=s_0(1+n)^b$, is found to be higher than the CEB-FIP Model Code 90 proposal ($b=0.107$) and dependent on the load level. The average of our fitting in the 30 to 70 %

loading range provided b=0.131 and on the entire 30 to 80 % loading range b=0.170. Considering only the power b as a varibale and substituting the s_0 values obtained at t=0 by the long term tests, the average power on the entire loading range is b=0.148.

g) The *ratio of slip* reached during the same time by cyclic or by long term loads has a strongly increasing tendency as a function of the load level. This ratio approximately agrees with the ratio provided by the CEB-FIP Model Code 90 at about 50% load level.

h) A relationship between the duration of load and the number of load cycles can be obtained producing the same slip by long term and cyclic loads, respectively.

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NOTATIONS

f_c	mean value of concrete strength at testing measured on cubes of 150 side lengths	N/mm^2

f_y	characteristic value of yield strength of reinforcing bar	N/mm^2
k_n	cyclic creep factor for slip	-
k_t	creep factor for slip	-
s	relative displacement	mm
s_n	slip under cyclic load	mm
s_t	slip under long term load	mm
s_0	initial slip by applying long term or cyclic loads	mm
t	duration of load	hours
α_{sb}	related rib area	-
τ_b	bond stress	N/mm^2
τ_{bu}	bond strength obtained by monotonic load	N/mm^2
$\tau_{b,max}$	maximum value of cyclic load	N/mm^2
$\tau_{b,min}$	minimum value of cyclic load	N/mm^2
τ_b/τ_{bu}	load level at long term load	%
$\tau_{b,max}/\tau_{bu}$	load level at cyclic load	%
Ø	nominal diameter of reinforcing bar	mm

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