SP 41-1

Strength And Deformation Characteristics of Plain Concrete Subjected to High Repeated and Sustained Loads

By
M.E. Award and H.K. Hilsdorf

Synopsis: 300 concrete prisms were subjected to high repeated or sustained compressive loads with maximum stresses ranging from 80 to 95 percent of their short time compressive strength. Stress range was varied between zero and 95 percent of the compressive strength. Speed of testing was varied between 600 and 60,000 psi/min (42-4200 kgf/cm^2/min). Specimens were tested at an age of 3; 7 or 90 days. The results indicate that concrete response to high repeated loads is to a large extent controlled by the duration of time during which the concrete has to resist stresses higher than its sustained load strength. Therefore, the speed of testing has a substantial influence on the fatigue life of concrete: A decrease of rate of loading by one order of magnitude results in a decrease of the number of cycles to failure by almost one order of magnitude. For young concrete the continued hydratation may partially or completely offset the damage caused by high loads. An analytical procedure was developed to predict the number of cycles to failure for concrete subjected to various stress ranges at various rates of loading.

Keywords: age; compression tests; compressive strength; concretes; cyclic loads; deformation; fatigue (materials); hydration; loading rate; loads (forces); strength; stress-strain relationships.

Mohamed E. Awad is a research officer and head, Materials Department, National Building Research Station, University of Khartoum, Sudan, He also lectures at the Faculty of Engineering, University of Khartoum. Dr. Awad was formerly a graduate research assistant, Department of Civil Engineering, University of Illinois, Urbana.

Hubert K. Hilsdorf is Professor of Building Materials, University of Karlsruhe, Germany. He was previously Professor of Civil Engineering, University of Illinois, Urbana. Dr. Hilsdorf is author of numerous papers on concrete research and is a member of ACI 104, Notations; ACI 201, Durability; and ACI 215, Fatigue.

INTRODUCTION

Under extreme conditions reinforced concrete structures may be exposed to a small number of high overloads approaching the ultimate load carrying capacity of a structural member. Such conditions may arise when a structure is exposed to earthquakes, high winds or blasts. They are also of significance for young concrete structures which may have to sustain heavy loads during construction, and for the application of limit analysis to the design of reinforced concrete structures. However, only limited information is available on the behavior of concrete subjected to repititions of high stresses, often referred to as low cycle fatigue (1-3).

In the prediction and evaluation of the low cycle fatigue behavior of concrete particular attention has to be given to the fact that the repeatedly applied stresses may be larger than the sustained load strength of the concrete. Under such conditions the period of time during which concrete has to resist stresses larger than the sustained load strength may be as significant as the number of applied cycles. Then, concrete response is both cycle and time dependent, and the frequency at which the repeated loads are applied may become a major parameter affecting the fatigue behavior of concrete.

The objective of this study was to investigate the strength and deformation characteristics of plain concrete subjected to repeatedly applied high compressive stresses. Particular emphasis was placed upon studies of the role of time during which concrete is subjected to high stresses. Analytical procedures were developed to predict concrete response under such loading conditions.

EXPERIMENTAL PROGRAM

Approximately 300 prismatic specimens, 4 by 4 by 12 in, were subjected to concentric compression. The investigation was limited to one type of concrete with a cylinder strength of 4000 psi (280 kgf/cm^2) after 28 days. The specimens were either loaded to failure at a constant strain rate or subjected to sustained or repeated loads. In the fatigue tests the specimens were loaded or unloaded with a constant stress rate, $\pm \dot{f}$, so that a saw-tooth loading pattern was obtained, as shown in the top right corner of Fig. 1.

To correlate the results obtained from all batches, the maximum and minimum stresses in a fatigue test are given as a ratio of the static strength of companion specimens, f_{cup}, hereafter referred to as the stress levels, σ_{max} and σ_{min}. The stress level in a sustained load test is referred to as σ_{sus}.

The test program was divided into three phases: In Phase One 133 specimens were subjected to high repeated or sustained loads. The maximum stress level, σ_{max}, and the stress range $R = \sigma_{max} - \sigma_{min}$ were the parameters in the repeated load tests. Four levels of maximum stress, σ_{max} = 0.80; 0.85; 0.90 or 0.95 were investigated. The stress range, R was varied between 0.05 and the level of the maximum stress ($\sigma_{min} = 0$). In the sustained load studies three levels of sustained stress, σ_{sus} = 0.85; 0.90 or 0.95 were studied. In both repeated and sustained load tests the concrete age at initial load application was 7, 28 or 90 days, respectively.

Phase Two was concerned with the effect of stress rate and frequency of testing on concrete response to high repeated loads. Stress rates of $\dot{f} = \pm$ 600 (42) and $\pm$ 60,000 psi/min. (4200 kgf/cm^2/min), were chosen to supplement the data obtained in Phase One where a stress rate of $\pm$ 6,000 psi/min. (420 kgf/cm^2/min) was used in all tests. A maximum stress level σ_{max} = 0.90 and stress ranges R = 0.10; 0.50 and 0.90 were investigated. Note that the frequency of testing (cycles/min) was different for the same maximum stress level but varying stress ranges whenever the stress rate (stress/min) was kept constant. The age of concrete at the time of loading was 28 days.

In Phase Three the extent of damage caused by high sustained or repeated loads which did not as yet cause failure was investigated. The specimens were loaded to 30; 60 or 90 percent of their predicted lives. Then the compressive strength of the preloaded specimens, hereafter referred to as the reloading strength, was determined and compared with the strength of companion specimens without previous load history. One level of sustained stress, σ_{sus} = 0.90, and two levels of repeatedly applied stresses, σ_{max} = 0.90 and 0.95, ($\sigma_{min} = 0$) were chosen. The age of concrete at the time of loading was 28 days.

In all tests longitudinal and lateral concrete strains were observed. Further details of experimental procedures, tests results and their evaluation are given in (4).

TESTS RESULTS

Effect of Maximum Stress Level and Range of Stress

Strength data--In Fig. 1 the relationship between the maximum stress level, σ_{max}, and the number of cycles to failure, n_u, for a constant stress range, R, are given. Each data point corresponds to the logarithmic average of between three and seven individual tests. As is true for most fatigue data, the number of cycles to failure increases with decreasing maximum stress level and with decreasing stress range. The effect of stress range becomes even clearer in Fig. 2. There, the relation between the stress range, R, and the number of cycles to failure, n_u, is given for constant maximum stress levels. For maximum stress levels below the sustained load strength of concrete the relationship between R and n_u should approach the n_u-axis asymptotically giving a value of $n_u \rightarrow \infty$ for R = 0. According to Fig. 2, however, these relationships become almost vertical particularly for σ_{max} = 0.95 and R < 0.50. At these stress levels the maximum stress is well above the sustained load strength so that the total time of testing or the time during which a specimen has to sustain high stresses becomes more significant than the number of applied cycles. Therefore, further reduction of the stress range R does not result in a significant increase of the number of cycles to failure, n_u.

A sustained load test may be considered a limiting case of fatigue loading where R = 0. Therefore, the fatigue tests were supplemented by tests on concrete under sustained loads. The results of these studies are summarized in Fig. 3. There, the relationship between the level of sustained stress, σ_{sus}, and the time to failure, t_u, is given for specimens loaded at an age of 7, 28 or 90 days respectively. Similar to the results from previous investigations (5) the time to failure increases with decreasing sustained stress level. For high stress levels causing failure after less than 500 min (σ_{sus} > 0.90), old concrete is more resistant to sustained loads than young concrete. At lower stress levels causing failure after more than 1000 min, this trend is reversed: The time to failure for concrete loaded at an age of 7 days is larger than it is for older concrete. It was shown in (5) that this is due to continued hydration occuring while the specimen is under load. Such hydration may partially or completely offset the damage caused by high sustained loads. Hydration under load is insignificant at high stresses when failure occurs already after a few hours. However, it becomes significant for low stress levels when the time to failure may be several days.

Strain data--In Fig. 4 the longitudinal and lateral strains observed on specimens which were subjected to repeated loads are given as a function of the number of cycles to failure. Similar to the behavior of concrete under sustained loads both longitudinal and lateral strains increase with increasing number of cycles. The strains at failure are the larger the lower the applied maximum stress level or the longer the time to failure. In Fig. 5 the failure strains obtained for the various loading conditions and stress ranges are summarized. In this diagram the dashed line gives the stress-strain diagram under static loading as determined in a short time test in which the specimens were loaded at a constant strain rate of 10^{-5} in./in./sec. The failure strains observed on specimens which were subjected to repeated loads fall between two limits: For a given maximum stress level the upper strain limit is given by the failure strains observed in sustained load tests (R = 0). The lower limit is given by the descending portion of the static stress strain relationship. As the stress range decreases also the influence of the time under load becomes more significant and the failure strains increase.

Effect of Stress Rate and Frequency of Testing

In Fig. 6 the relationship between the stress rate, in psi/min and the number of cycles to failure, n_u, is given for three different stress ranges, R. In the same diagram also the frequency of testing in cycles/min is given for each data point. According to Fig. 6 an increase of the stress rate by one order of magnitude leads to an increase of the number of cycles to failure by almost one order of magnitude. This effect is most pronounced for small stress ranges.

The effect of frequency of loading is likely to diminish with decreasing maximum stress level, and other investigators have, in deed, reported that the frequency of testing has little influence on the fatigue behavior of concrete when subjected to comparatively low stresses (6). This may be explained by the accumulation of both cycle and time dependent damage caused by fatigue loading at high stresses and will be discussed further in the evaluation of the rest results.

Reloading Strength

For the evaluation of the experimental data an estimate of the accumulation of damage which occurs during a repeated or sustained load test was needed. It was assumed that the reloading strength as defined earlier would give such an estimate. The results of this investigation are given in Fig. 7. There, the reloading strength expressed as a fraction of the short-time static strength of companion specimens is given as a function of the life ratio which is the fraction of the total life to which a specimen was subjected. According to Fig. 7 repeated or sustained loads cause a reduction of the reloading strength below the static strength only after 3o to 7o percent of the total life of the specimen had been applied. For smaller life ratios even a slight strength increase was observed.

EVALUATION OF TEST RESULTS

The purpose of the evaluation of the experimental results was to develop an analytical procedure by which the fatigue behavior of concrete under high compressive loads can be predicted for various stress ranges, frequency of testing and other load history parameters. The derivations given in the following are based upon the principles of cumulative fatigue damage. Their application to the behavior of concrete is discussed e.g. in (7). In these derivations the following assumptions were made:

a) Damage in concrete caused by repeated loads can be seperated in a time dependent and a cycle dependent part.

b) The cycle dependent as well as the time dependent damage are linear functions of the number of applied cycles or of the time under sustained load, respectively.

c) Time dependent damage accumulates only above a certain thresh hold stress σ_{sh}. It is equal to the sustained load strength of concrete if the minimum stress level in a fatigue test is less than σ_{sh}. For minimum stress levels larger than the sustained load strength $\sigma_{sh} = \sigma_{min}$.

d) The total damage in a fatigue test can be determined by arithmetic addition of the cycle and the time dependent damage.

In the following, damage, D, is defined such that failure of the specimen will occur if D = 1.o. Assuming linear damage accumulation, the cycle dependent damage, D_n, can be expressed by:

$$D_n = \frac{n}{n_o} \tag{1}$$

where n = number of applied cycles

n_o = number of cycles to failure under pure fatigue conditions ($\overset{o}{f} \to \infty$) for a given σ_{max} and R

Assuming linear damage accumulation the time dependent damage in a sustained load test, can be expressed by:

$$D_t = \frac{t}{t_u} \tag{2}$$

where t = duration of loading under a constant stress level, σ

$t_u = f(\sigma)$ = time of failure under a constant stress level, σ

Using eq. (2) the time dependent damage caused by one load cycle may be expressed by:

$$D_{t1} = 2 \int_{\sigma_{sh}}^{\sigma_{max}} \frac{dt}{t_u}$$

Then, the total time dependent damage after n cycles is:

$$D_t = 2n \int_{\sigma_{sh}}^{\sigma_{max}} \frac{dt}{t_u} \tag{3}$$

Since the loads are applied at a constant stress rate $d\sigma/dt$ = $\dot{f}/f_{cup}$ = β we can transform eq. (3) to:

$$D_t = \frac{2n}{\beta} \int_{\sigma_{sh}}^{\sigma_{max}} \frac{d\sigma}{t_u} \tag{4}$$

From the experimental data of this investigation as well as the data given in (5) the following approximation for $t_u = f(\sigma)$ was derived by curve fitting:

$$t_u = 240 \left(\frac{1 - \sigma}{\sigma/\sigma_s - 1}\right)^2 \tag{5}$$

with $\sigma_s = 0.70$ and t_u in minutes.

After substituting eq. (5) in eq. (4) and integrating, the time damage can be expressed as follows:

$$D_t = K_1 \cdot \frac{n}{\beta} \tag{6}$$

where

$$K_1 = \frac{1}{120\sigma_s^2}\left[\frac{(\sigma_{max} - \sigma_s)^2}{1 - \sigma_{max}} - \frac{(\sigma_{sh} - \sigma_s)^2}{1 - \sigma_{sh}} + 2\,(\sigma_{max} - \sigma_{sh}) + 2\,(1 - \sigma_s)\log_e \frac{1 - \sigma_{max}}{1 - \sigma_{sh}}\right] \tag{7}$$

Then, the total damage after n cycles, D_{tn} is:

$$D_{tn} = D_n + D_t = \frac{n}{n_o} + K_1 \cdot \frac{n}{\beta}$$

By definition, failure will occur if D_{tn} = 1.0 and $n = n_{uc}$. With these conditions we obtain for the calculated number of cycles to failure, n_{uc}:

$$n_{uc} = \frac{n_o}{1 - K_1 \cdot \frac{n_o}{\beta}} \tag{8}$$

To evaluate eq. (8) the number of cycles to failure for pure fatigue conditions, n_o, have to be known. Therefore, eq. (8) was rearranged to calculate values for n_o from the experimental data which had been obtained for the fastest stress rate. Then, values for n_{uc} for other stress rates were calculated from eq. (8).

Since the agreement between calculated and experimental values was not satisfactory, eq. (8) had to be further modified. Two additional assumptions were made:

a) Damage starts to accumulate only after an initial life ratio η, has been applied. This assumption is in agreement with the experimental data shown in Fig. 7 which indicate, that the strength of concrete drops below its initial value only for $0.30 < \eta < 0.70$.

b) If the strength of the concrete falls below its initial value, then time dependent damage may also be caused at stresses below the sustained load strength. This is of particular significance when R is large. Therefore, it was assumed that the thresh hold stress σ_{sh} decreases with increasing stress range, R. With these assumptions eq. (8) was modified to

$$n_{uc} = \frac{n_o}{1 + K_2(R) \cdot (1 - \eta) \cdot \frac{n_o}{\beta}} \tag{9}$$

There, $K_2(R)$ is equal to K_1 (eq. 7) except that σ_{sh} is not constant but stress range dependent. Eq. (8) was evaluated using the following values for σ_{sh}

$R = 0.10$ $\quad\quad$ $\sigma_{sh} = \sigma_{min} = 0.80$

$R = 0.50$ $\quad\quad$ $\sigma_{sh} = 0.65$

$R = 0.90$ $\quad\quad$ $\sigma_{sh} = 0.55$

In Fig. 8 experimental and calculated values for n_u as well as a relation for the pure fatigue failure cycles n_o are given. The agreement between experimental and calculated results is satisfactory. Fig. 8 clearly shows the expected trends:

a) The pure fatigue failure cycles n_o approach a value of $n_o \rightarrow \infty$ for $R = 0$.

b) The higher the stress range the larger the cycle dependent damage. Therefore, at high stress rates the observed failure cycles are close to the estimated values for pure fatigue conditions.

c) For small stress ranges and low stress rates the time dependent damage dominates. This is evidenced by the small increase in failure cycles with a reduction of the stress range.

The values for n_o are also dependent on the maximum stress level, however, no reliable values for n_o at stress levels $\sigma_{max} = 0.95$ and 0.85 can be given since for these stress levels only one stress rate was investigated.

CONCLUSIONS

The results from this investigation may be summarized as follows:

a) When concrete is subjected to high repeated compressive stresses, a decrease in either the maximum stress level or the stress range results in an increase of the number of cycles to failure. The increase in failure cycles with decreasing stress range becomes insignificant at high maximum stress levels and small stress ranges.

b) At high stresses, a reduction in the speed of testing results in a significant reduction of the fatigue life of concrete.

c) Under repeated loads the failure strains of concrete increase with decreasing stress level or decreasing range of loading.

d) High repeated or sustained loads may cause a significant strength decrease only after 30 to 70 percent of the number of cycles causing failure have been applied.

e) Damage caused by high repeated loads depends both on the number of applied cycles and the total time concrete has to sustain high stresses. Based upon this observation an analytical procedure was developed which allows the prediction of the fatigue properties of concrete for various stress ranges and stress rates.

REFERENCES

(1) Sinha, B.P.; Gerstle, K.H. and Tulin, L.G., "Stress-Strain Relations for Concrete Under Cyclic Loading," Journal, ACI, Proc., Vol. 61, No. 2, February 1964, pp. 195-212.

(2) Shah, S.P. and Winter, G., "Response of Concrete to Repeated Loading," Paper Submitted to the RILEM International Symposium on the Effects of Repeated Loading on Materials and Structural Elements, September 1966, Mexico, D. F.

(3) Karsan, D.; Jirsa, J., "Behavior of Concrete Under Compressive Loadings," Journal, Structural Division, ASCI, Proc., Vol. 95, 1969, pp. 2543-2563.

(4) Awad, M.E.; Hilsdorf, H.K., "Strength and Deformation Characteristics of Plain Concrete Subjected to High Repeated and Sustained Loads," Civil Engineering Studies, SRS No. 372, University of Illinois, Urbana, Illinois, February 1972, pp. 266.

(5) Rüsch, H., "Research Towards a General Flexural Theory for Structural Concrete," Journal, ACI, Proc. No. 57, No. 1, July 196o, pp. 1-28.

(6) Kesler, C.E., "Effect of Speed of Testing on Flexural Fatigue Strength of Plain Concrete," Highway Research Board, Proc. 32, 1953, pp. 251-258.

(7) Hilsdorf, H.K. and Kesler, C.E., "Fatigue Strength of Concrete Under Varying Flexural Stresses," Journal, ACI, Proc. Volume 63, No. 1o, October 1966.

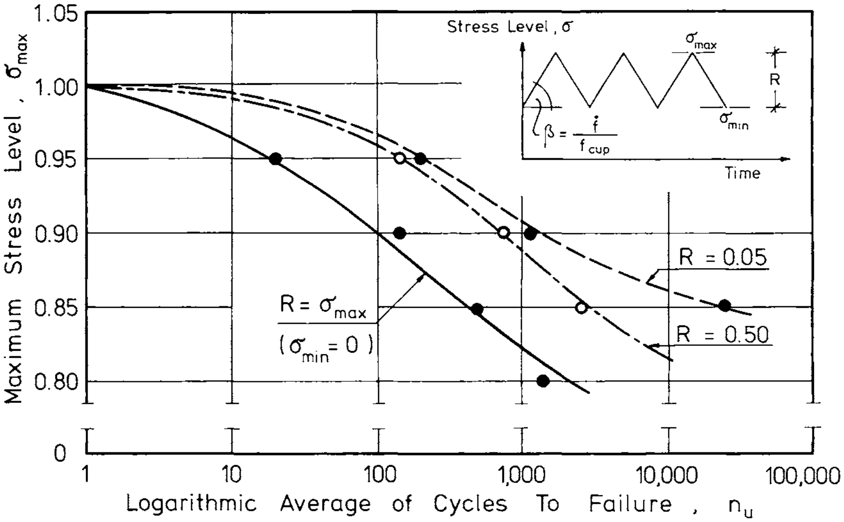

Fig. 1-Relation between maximum stress level and number of cycles to failure for different stress ranges

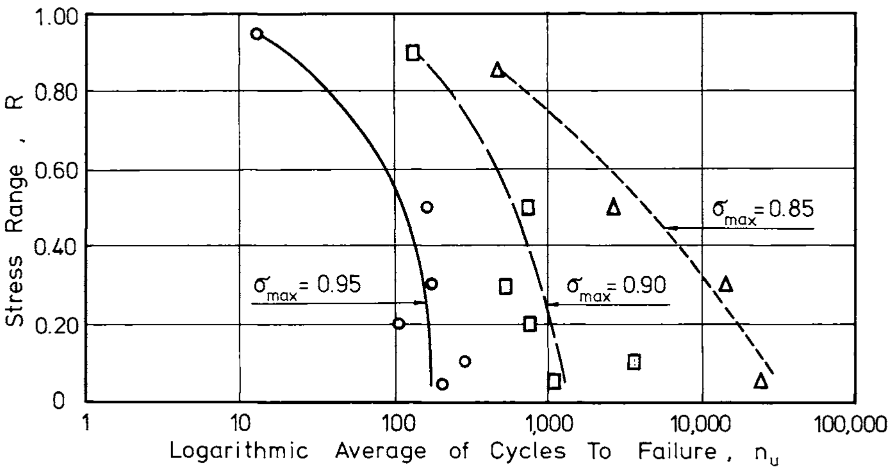

Fig. 2-Relation between stress range and number of cycles to failure for different maximum stress levels