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콘크리트의 손상모델에 관한 실험적 연구

Experimental Study on the Damage Model of Concrete

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Abstract

The concept of damage is all-pervasive in structural engineering. It can be considered a state variable and defined to vary from 0(no damage) to 1(failure). Thus, the factor of safety against failure, the most important aspect of a structure, cannot be assessed without evaluating the damageability of a structure under load.

It is the objective of the research reported herein to study the behavior of concrete under repeated load applications. Concrete is known to deteriorate under such loading, i. e., it suffers damage of increasing degree. Its response to future loading is a function of the amount of damage sustained during previous load exposures. The same can be said about reinforced concrete members and entire structures, but here we wish to consider only plain concrete and express some of its material properties as functions of the degree of sustained damage. The work described herein is based on the stipulation that the energy dissipation capacity of plain concrete is a material property and the damage accumulates in direct proportion to the degree to which the energy dissipation capacity is being exhausted, in some analogy to both high—and low—cycle failure behavior of materials.

요 지

콘크리트는 고응력 범위에서 적은 반복횟수에 의해서도 파괴에 도달할 수 있고 소성변형에 의한 콘크리트 손상이 심각하다. 본 연구에서는 반복하중하에서의 콘크리트의 손상과정에 관하여 실험적으로 연구하였고 에너지개념에 의한 소상모델을 개발하였다.

실험은 일축압축상태의 무근콘크리트에 대해서 변위제어상태하에서 수행하였다. 콘크리트의 파괴시점은 잔여강도가 존재하지 않은 상태까지로 가정하였고, 손상도는 실험적으로 파괴시까지 구해진 에너지 발산량과 주어진 횟수의 반복하중에 의한 에너지 발산량의 비로 정의하였다. 고응력 범위에서 손상도는 변형량의 비선형함수로 누적되며, 손상비율은 초기에 높고 파괴상태에 가까울수록 점차적으로 감소하였다.

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1. INTRODUCTION

The increased use of concrete in complex structures requires the development of accurate models to predict their fatigue behavior or rather their damage accumulation under repeated load applications. The last decade has brought considerable progress in the development of concrete models, but most of these are of limited use.

Most of the models proposed so far do not consider the strain softening behavior of concrete, because fatigue behavior and damage are typically considered functions of stress. The important post-failure regime can be modeled only by taking the strains as independent variables. A versatile model should be capable of simulating the fatigue behavior and damageability of concrete under multiaxial stress states and repeated load applications, and its validity should be substantiated by test data covering the important variables such as strength properties, stress ratios, and load histories. This study therefore addresses both aspects of an experimental testing program to develop an appropriate damage model for concrete, and here we wish to consider only the uniaxial state as a basis of further research.

The damage theory to be selected is based on the premise that damage is proportional to the dissipated energy relative to the total energy dissipation capacity of the material and that it is a measure of the material's residual capacity to resist further loading. Since we are dealing with stress states for which the constitutive behavior of concrete exhibits considerable nonlinearity, this approach basically considers damage as a low-cycle fatigue phenomenon. The energy dissipation capacity of concrete per unit volume is a material property which is influenced by a large number of factors, among them the loading history. It is objective of the testing propram to establish the main variables that influence this important material property.

2. LOW-CYCLE FATIGUE AND CONCRETE DAMAGE

The fatigue strength of concrete is influenced by the range of loading, rate of loading, load history, material properties and environmental conditions. The influence of loading range or amplitude is illustrated by the S-N curve. According to several investigations, the rate of loading has little effect on fatigue strength for levels lower than about $0.75f'_c$, whereas a significant influence has been observed for stress levels higher than that [1, 2]. The load history effect is typically accounted for by Miner's rule or some modified form of it. The fatigue strength is also influenced by various material properties such as cement content, water-cement ratio, curing conditions, age at loading, amount of entrained air, type of aggregates [3]. Knowledge of the effect of environmental conditions on the fatigue strength of concrete is still limited.

Reinforced and prestressed concrete structures subjected to a relatively small number of load cycles of high amplitude may suffer severe damage or even failure. These are generally characterized as low-cycle high-amplitude failures. Under such loading the material undergoes a rapid physical deterioration, as each load cycle inflicts a certain amount of irreversible damage. However, limited information is available on this damage accumulation and how the concrete "remembers" the amount of damage sustained in all preceding load cycles. It is helpful to define damage of plain concrete to signify a certain degree of physical deterioration with precisely defined consequences regarding the capacity to resist further load. Similiarly, failure should be defined as a specific level of damage, which is equivalent to a certain(negligible) amount of residual capacity to resist further load. Several important points are illustrated in Fig. 1, which shows the behavior of plain concrete under cyclic compressive loading[5].

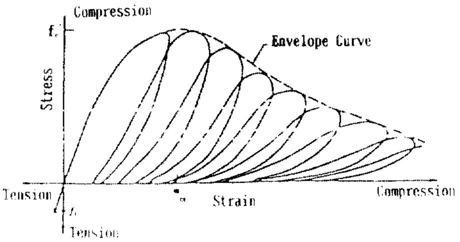

Fig. 1 Response of concrete to uniaxial loading

The envelope curve bears a strong resemblance to the stress-strain curve for monotonic loading. For low stress amplitudes not shown here, the hysteresis curves appear as closed loops with near-linear branches. On the other hand, the hysteresis loops for the high stress cycles shown in Fig. 1 seem to incorporate the horizontal axis to signify additional residual inelastic strains accumulated during each load cycle. With increasing numbers of cycles the slopes of the hysteresis curves decrease(stiffness degradation) and the dissipated energies as measured by the enclosed areas decrease.

Experimental research on concrete subjected to cyclic loading has been reported in [6, 7, 8]. Test results obtained from these experiments indicate that the stress-strain curves for cyclic compressive load histories describe an envelope as shown in Fig. 1, which may be considered unique and identical to the stress-strain curve obtained from monotonically increasing strain. These studies underscore the important role of microcracking [9], which accelerates crack propagation and failure at stress levels in excess of approximately 75% of the ultimate strength [6].

3. EXPERIMENTAL STUDY

Experimental Setup

Loading Frame. -A 200kip capacity automatic materials testing machine(MTS) with accompanying PDP-11 computer was used for applying vertical loads. The load frame consists of four smooth vertical columns joined by two stiff structural cross members : a movable crosshead and a fixed platen. The crosshead is vertically adjustable to accomodate specimens of different lengths. The symmetrical four-column construction of the load frame provides a rigid testing unit with close tolerances and excellent axial alignment. Swivel mechanisms utilizing steel ball bearings facilitate proper alignment of the applied loads.

Friction Reducing Scheme.—In order to assure a uniform state of stress throughout the specimen, measures have to be taken to reduce or eliminate the effect of friction between the specimen and the loading platen. Following a suggestion by Shah [10], two sacrificial specimens were inserted between the actual test specimen and the top and bottom loading platens, Fig. 2. The three concrete specimens were separated by polyethylene sheets of 0.0005 inch thickness. The concrete surfaces to be in contact with the loading platens were capped with gypsum plaster.

Load and Displacement Measurements.—For-

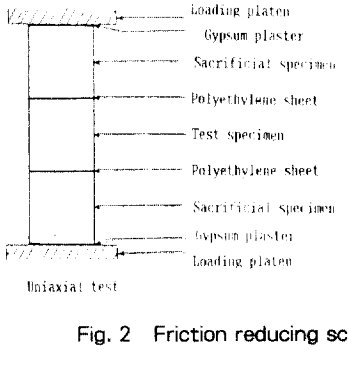

Fig. 2 Friction reducing scheme

ces were measured by means of loadcells and acquired with Digital-to-Analog(D/A) Converters and interpreted by the built-in PDP-11 computer. Deformations were measured by means of Linear Variable Differential Transducers (LVDT) attached to the loading frame. These were likewise acquired by D/A converters and interpreted by the PDP-11 computer. An MTS X-Y recorder was used to monitor and plot the experimental data.

Definition of Failure Criterion. —Fatigue failure of metal specimen or concrete specimen loaded in tension is sudden and complete. In contrast, failure in compression under repeated load application is progressive and cannot be related to a specific event comparable to complete fracture. In fact, loading could conceivably continue indefinitely, as the material is pound into dust. For this reason it is essential that a rational failure criterion be defined as opposed to some arbitrary failure definition.

The failure criterion developed herein is based on the attainment of a near-horizontal slope of the stress-strain curve during a strain controlled test, Fig. 3.

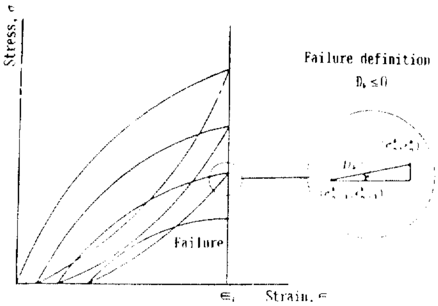

Fig. 3. Definition of failure criterion

This definition assures that there are no more strength reserves left in the material at the time of test termination. During the test, the tangent is computed in real time as,

$$D_k = \frac{\sigma_n^k - \sigma_{n-1}^k}{\epsilon_n^k - \epsilon_{n-1}^k}$$

where k signifies the load cycle number, and n-1 and n two successive data points. The test is terminated when

$$\frac{D_k}{D_1} < e$$

where e is predetermined tolerance. This criterion covers the case that D_k becomes negative.

Test Control.—All tests were conducted under displacement control. Load was applied to the specimen without interruptions, while the measuring divices were scanned at prescribed intervals and the data processed and stored in the computer. In this fashion, the complete load-displacement histogram could be recorded. The control circuit contained an electronic and a hydraulic part, including the servohydraulic actuator of the MTS machine. The test could easily be controlled with proper BASIC program commands entered into the PDP-11 computer.

Scope of Experimental Program

Test Specimen. Two identical batches of concrete were mixed and designated as M and C. Batch M was used for specimens tested with monotonic loading only, while the specimens of batch C were loaded cyclically. The mix design was based on a target strength of 3000psi at 28days. The concrete mix proportions are given in Table 1. The maximum size of the aggregate was 0.25 in. (6.35mm) and the coarse aggregate was sandstone. Portland cement Type I was used in the mix.

Table 1. Concrete mix proportions

Water	9.4	Percent by weight
Portland cement, Type I	13.7	〃
Sand	36.0	〃
Aggreate	40.9	〃

All specimens used in this test program were 2 in.(50.8mm) cubes. Seven molds for three cubes each were available. Each batch thus produced a total of twenty-one cubes plus two standard cylinders for the determination of the standard compressive strength. The production and compaction of the cubes and cylinders followed standard ASTM procedures [2]. The compressive strengths determined from the cylinders are summarized in Table 2. The surfaces in contact with the polyethylene sheets of both the test specimen and the sacrificial specimens were ground, as were the surfaces of specimens with strain gauges.

Table 2. Concrete strength at 28 days

Batch	Cube strength(psi)	Control cylinder strength(psi)
M	3125	2570
C	2990	2370

Test Procedure.—All tests were conducted under displacement control. Load cycles in all tests were of ramp-form type and of 10sec duration. Aside from the test to determine the effectiveness of the friction reduction scheme, monotonic and cyclic uniaxial load tests were performed. The monotonic tests served to determine the compressive strength f'_c and the associated ultimate strain $\in_f$ for both batches. In the cyclic load tests the strain level was defined as the ratio of axial strain $\in_f$. In this study, tests were conducted with strain levels, 0.75, 0.85, 0.90, and 0.95.

Results And Interpretation

The LVDT and loadcell output was stored in the PDP-11 computer and subsequently plotted. The output was calibrated and converted to stresses and strains. The data were then read from the computer and tabulated for use in subsequent analysis, such as the computation of the dissipated energy.

Cyclic Stress-Strain Curves.—Loads were cycled from near zero to a predetermined compression strain level, $\in_i$, and were applied at a frequency of six cycles per minute. The recorded stress-strain curves exhibit an initial stiffening effect before displaying the expected softening behavior. It is suspected that the cause for this abnormal behavior is related to the loading mechanism. This will be explored until a satisfactory answer is obtained so that corrective measures can be taken.

Fatigue Strength. —In this study, the fatigue strength of concrete is defined as the energy dissipation capacity for a given strain level Plotting the experimental results as relating the strain level, $\in_i$, to the number of cycles to failure, N_f, is plotted on a logarithmic scale, Fig. 4.

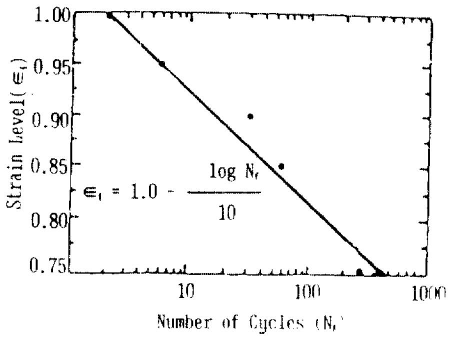

Fig. 4. $\in_i - N_f$ curve

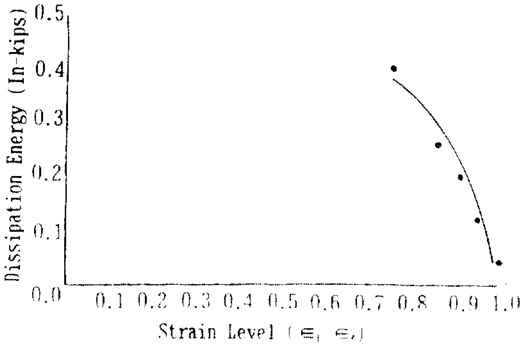

Fig. 5. Energy dissipation capacity versus strain level

On the other hand, if the total energy dissipation capacity is plotted as a function of strain level normalized to $\in_f$, the strain associated with peak stress in a monotonic load test, then the relationship of Fig. 5 is obtained. This result confirms the intuitive expectation that the total energy dissipation capacity increases as the strain level decreases[11]—up to a point. Where this point of optimum energy dissipation capacity or damageability is remains to be determined. Table. 3 summarizes the results for four specimens with constant amplitude cyclic loading and for a monotonically loaded specimen.

Table 3. Number of cycles and dissipated energy at each strain level

Strain Level	Num. of Cycles	Dissipated Energy(In-Kips)
1.00	1	0.0492
0.95	5	0.1259
0.90	20	0.2117
0.85	45	0.2638
0.75	162	0.3976

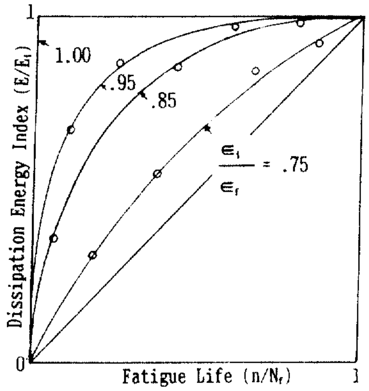

Fig. 6. Damage curves for different strain levels

Damage Accumulation.—Fig. 6 illustrates for four of the five tests the damage accumulation as measured by the energy dissipated after n cycles, where $n=1, ---, N_f$. Both variables are normalized, i. e., E_i with respect to E_i, and n with respect to N_f. As can be seen in all curves, damage accumulates at a faster rate during the earlier load cycles, and the change of damage accumulation rate with continued loading is the more pronounced the higher the strain level. In the extreme case of monotonic loading, the entire energy dissipation capacity is exhausted in the first and only load cycle. If the material were not to degrade under cyclic loading, the dissipated energy $E(\in_i)$, would be exactly proportional to the number of applied load cycles. In reality, however, the amount of energy dissipated in each load cycle decreases with progressive damage, until failure has been reached. This phenomenon of large change increments in the early life of the material can be related to the extent of cracking sustained in each load cycle.

4. NEW DAMAGE MODEL FOR CONCRETE

Many damage theories have been developed for prediction the cumulative damage of plain concrete under variable-amplitude loading. Most of these are based on the Palmgren-Miner rule, i. e., they do not consider the nonlinearity of the damage accumulation rate as function of stress or strain amplitude and load sequence, which can be observed in concrete. A new damage model shall be proposed based on the limited experimental results, which does consider this nonlinear relationship betweem damage accumulation, strain-level, and variable amplitude cyclic loading.

The relationship between stress level S or strain $\in$ and N_f, the number of cycles to failure, is traditionally expressed as a linear function between S and log N. In agreement with other studies, the data shown in Fig. 5 seem to fit closely the function,

$$\in_i = 1.0 - \frac{\log N_f}{10}$$

In this study, the dissipated energy E_i and strain level $\in_i$ are used as variables. Fig. 6 shows the damage index or energy ratio E/E_i, plotted as a function of the cycle ratio, n/N_f. In spite of the limited range of these data it is apparent that this relationship is nonlinear, and presumably has a strain level at which the energy dissipation capacity of the material is a maximum.

The damage index proposed herein was developed to satisfy the following criteria :

a) The energy index, E/E_i, is adopted as the measure of damage.

b) The damage D, for constant amplitude cyclin loading, is a nonlinear function of the cyclic ratio, n/N_f, and the strain level, $\in_i$. D is zero at the start of loading and equal to 1 at failure.

c) The rate of damage accumulation decreases as a function of n/N_f

d) The New material constant, μ, shall be calibrated so that it fits our experimental data.

The new damage index, D_i, is defined as follows :

$$D_i = \frac{E(\in_i)}{\bar{E}(\in_i)}$$

Where

$E(\in_i)$: energy dissipated at the i-th strain level

$\bar{E}(\in_i)$: total energy dissipation capacity at the i-th strain level

For constant amplitude cycling the damage index can be expressed as a power function of the cycle ratio, n/N_f,

$$D_i = \left(\frac{n}{N_f}\right)^{\mu_i}, \qquad \mu_i > 1$$

where $\mu_i = f(\in_i)$ is a material property which increases in value as the strain level increases. Table 4 contains numerical values determined from the test results.

Table. 4 Material parameter

strain level	μ
0.75	2.5
0.85	3.5
0.90	5.0
0.95	11.0

5. CONCLUSIONS

The work described herein was prompted by a scarcity of information on a low""cycle fatigue behavior of plain concrete. A experimental investigation was performed in order to appreciate the effects of the important variables involved. Damage is defined herein as the energy dissipated by the material, normalized with respect to the total energy dissipation capacity for a given strain level. The experimental data clearly show that damage accumulates as a nonlinear function of strain amplitude. The rate of damage accumulation is highest at the early life and decreases gradually as failure is approached.

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