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# EXPERIMENTAL STUDY OF THE FATIGUE BEHAVIOR OF HIGH STRENGTH CONCRETE

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**ABSTRACT**

In this study, cylindrical concrete specimens with various strength levels were tested to investigate the fatigue behavior of concrete in compression. Selected test variables were compressive strength with 4 levels (26 Mpa, 52 Mpa, 84 Mpa, 103 Mpa) and maximum stress with 4 levels (75%, 80%, 85%, 95%), 160 specimens ($\phi$ 100 × 200 mm) were cast for the test. The reference for the fatigue strength was the ultimate static strength acquired just before the fatigue testing. The moisture contents of specimens were preserved during the fatigue testing. In fatigue tests, the first cycle of loading was loaded at standard rate, and the other cycles were loaded in the frequency of 1 Hz. Test results show that the fatigue life decreased with increasing the concrete strength, and a model for $S_{max}$-$N_f$ relationship considering the effect of the concrete strength was proposed. While fatigue strain of high strength concrete was smaller than that of low strength concrete, the rate of fatigue strain increment of high strength concrete was greater than that of low strength concrete. 

## Introduction

In recent years, there has been more interest in the fatigue behavior of high strength concrete subjected to fatigue loading because of its increased use in structures such as long-span bridges, offshore structures and reinforced concrete pavements. At present, it is generally accepted that the relationship between maximum stress level and fatigue life ($S_{max}$-$N_f$ relationship) is not affected by strength level and that the variables which affect static strength also influence fatigue strength in a similar proportionate manner[1]. However in the report of CEB[2], the reduced relative fatigue strength for high strength concrete was indicated. Considerably less work has been done for the effects of strength level on the fatigue behavior, and studies to date have produced conflicting results[2-4].

Fatigue failure occurs when a concrete structure fails catastrophically at less than design load after being exposed to a large number of stress cycles. The fatigue strength of concrete is defined as a fraction of the static strength that it can support repeatedly for a given number of cycles[1]. Fatigue strength is influenced by concrete composition, environmental conditions, loading conditions and mechanical properties. Kleiber and Lee[3] reported that the fatigue behavior of plain concrete in flexure was somewhat affected by the water-cement ratio of concrete, and the fatigue strength was decreased for a low water-cement ratio concrete. Bazant and Schell[5] reported that high strength concrete was more brittle than normal strength concrete under fatigue loading.

Fatigue is a process of progressive and permanent internal damage in a material subjected to repeated loading. This is attributed to the propagation of internal microcracks which results in a significant increase of irrecoverable strain. Hence in addition to fatigue strength, deformation properties of the concrete were investigated.

One objective of this investigation was to provide more data for the fatigue strength of high strength concrete and to compare the results with those of normal strength concrete. The other objective was to find out the fatigue deformation characteristics of high strength concrete.

## Experimental Program

Test Variables. Generally, fatigue tests have been carried out for a given constant minimum stress or for a constant ratio between the minimum and maximum stress level. In this study, a constant minimum stress level of 25 percent of the static uniaxial compressive strength was maintained. The cyclic tests were carried out at maximum stress levels ranging from 75 to 95 percent of the static strength. The compressive strength with 4 levels was selected for these tests. Frequency of loading was 1 Hz, and loading was applied sinusoidally with time, as shown in FIG. 1. TABLE 1 gives the test variables.

Materials. A single source of Type I portland cement was used. Crushed stone of maximum size of 13 mm and natural river sand was used as coarse and fine aggregates, respectively. Fineness moduli of the fine and coarse aggregates were 2.89 and 6.08, respectively. A superplasticizer with retarder which meets ASTM C 494 requirements for Type F admixture was used in the mix to give good workability, and also the silica fume produced by Elkem Microsilica (powder) was used for the high strength concrete of 84 and 103 MPa.

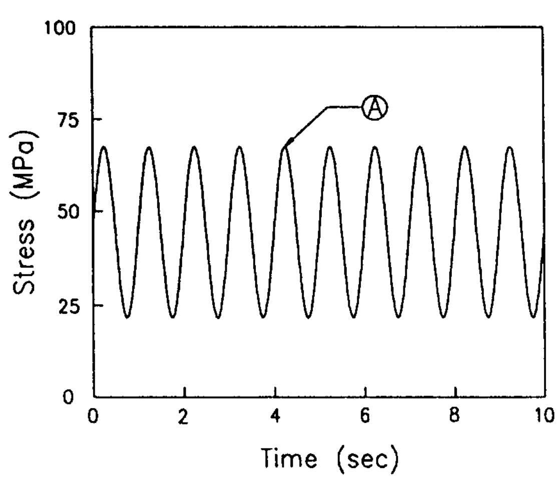


FIG. 1.
Loading history ($f'_c$=84MPa, $S_{max}$=85% , $S_{min}$=25%).

TABLE 1

Variables for Test

| | |
|---|---|
| Maximum stress level (%) | 95, 85, 80, 75 |
| Compressive strength (MPa) | 26, 52, 84, 103 |

Mix Proportions. The mix proportions were selected to achieve an optimal balance of compressive strength, and moderately high workability. Four different mixes shown in TABLE 2 were designed with target strengths of 25, 50, 80, and 100 MPa, and mix batches of LS, MS, HS, and VHS were corresponding to each of strength levels. Concrete MS2 was slightly different from MS1 in mix proportions. All concrete was mixed in 40 liter batches in a forced mixing type mixer.

Specimens Preparation. All specimens were cast in ϕ 100 × 200 mm steel cylinder molds. Slump tests were done according to ASTM 143 on each batch, as it was taken out from the mixer. Specimens were cured in a moisture room (98±1% R.H.) at 20±3°C during the required periods.

Testing Procedure. A total of 160 specimens was cast, of which 57 specimens were tested monotonically and 103 specimens were tested for fatigue. 75 specimens were tested for the relationships between stress level, number of cycles to failure and static strength level. 28 specimens were tested for the deformation characteristics of concrete subjected to fatigue loading.

The median age of the specimens at the time of test was 30 days. Specimens tested monotonically just before and just after the fatigue testing exhibited little strength gain. The stress levels were based on ultimate static strength measured just before the fatigue testing.

Static and fatigue tests were made in an Instron-8506 2500 kN Closed-Loop Servo-Hydraulic Dynamic Materials Testing System. The faces of the cylinders were polished smoothly by using a MARUI-196-1-74 grinder in order to secure the parallelism of the end-planes. In fatigue tests, the first cycle was loaded at standard rate, and the other loading cycles were made with the frequency of 1 Hz. Fatigue strength of concrete is influenced by

TABLE 2

Mix Proportions

| Mix | Cement ($kg/m^3$) | S.F.* ($kg/m^3$) | Water ($kg/m^3$) | Fine agg. ($kg/m^3$) | Coarse agg. ($kg/m^3$) | Admix-ture (%) | Slump (mm) |
|---|---|---|---|---|---|---|---|
| LS | 320 | - | 218 | 717 | 931 | - | 61 |
| MS1 | 450 | - | 156 | 698 | 1047 | 3.0 | 81 |
| MS2 | 480 | - | 168 | 677 | 1016 | 2.0 | 208 |
| HS | 442 | 78 | 156 | 633 | 1032 | 2.0 | 169 |
| VHS | 488 | 162 | 124 | 533 | 1082 | 5.0 | 141 |

* dry weight

moisture condition, therefore the cylinders of fatigue life test were wrapped in wet coverings to preserve the moisture content.

As studying the fatigue deformation characteristics, specimens air-dried for 12 hours were tested for measuring fatigue strains, and the three foil strain gages were used for each specimen. Fatigue strains were measured by TEAC MR-30 Portable Cassette Data Recorder.

In addition, a series of tests was carried out for 32 cylinders in order to study the strain rate effect. The selected strain rates are standard rate ($2\times10^{-5}$/sec) and fatigue rate ($2\times10^{-3}$/sec). Standard and fatigue rate are corresponding to the rate of static and fatigue loading in this study, respectively.

## Results and Discussions

Static Tests. Static test results obtained before fatigue testing are presented in TABLE 3. The mean values of compressive strengths are close to the target strengths. Standard deviations for strengths are less than 2.5 MPa, showing a good confidence of the static test results.

Relationships Between Maximum Stress Level and the Number of Cycles to Failure ($S_{max}$-$N_f$ Relationships). TABLE 4 shows test results of the relationship between stress level and fatigue life. Under the same stress levels, fatigue life decreases as the concrete strength increases, and then the fatigue resistance of high strength concrete seems to be inferior to that of low strength concrete.

General methods to determine $S_{max}$-$N_f$ relationships are derived on the assumption that $S_{max}$-$N_f$ curve consists of the slope part and the horizontal part on a semi-log scale[6]. It is well known that $S_{max}$-$N_f$ curve for concrete is approximately linear ranging from 102 to 107 cycles. Since the fatigue lives in this study belonged to the slope part, the following equation was fitted to the data for each strength level.

$$S_{max} = \beta_0 + \beta_1 \log N_f \quad (1)$$

As can be seen in TABLE 5, the slope of $S_{max}$-$N_f$ curve ($\beta_1$) increases with the strength of concrete and the intercepts on vertical axis ($\beta_0$) are almost constant to be about 110. Since the correlation coefficients ($r$) of each strength level are distributed from 0.94 to 0.98, the relationships can be acceptable for the practical point of view. $S_{max}$-$N_f$ relationships with the test data are shown in FIG. 2.

TABLE 3

Static Test Results (Tested Before Fatigue Testing)

| Mix | Age (days) | Number of specimens | Compressive strength (MPa) | Standard deviation (MPa) |
|---|---|---|---|---|
| LS | 30 | 3 | 26 | 0.85 |
| | 30 | 3 | 26 | 0.72 |
| MS1 | 29 | 4 | 50 | 1.03 |
| MS2 | 29 | 3 | 55 | 0.92 |
| HS | 29 | 4 | 84 | 1.32 |
| | 30 | 4 | 84 | 0.97 |
| VHS | 29 | 4 | 102 | 2.27 |
| | 29 | 3 | 104 | 1.39 |

TABLE 4

Fatigue Test Results

| Mix | Compressive strength (MPa) | Maximum stress level $S_{max}$ (%) | Number of specimen | Average fatigue life $(N_f)_{avg}$ |
|---|---|---|---|---|
| LS | 26 | 95 | 6 + 2* | 123 |
| | | 85 | 5 + 2* | 1363 |
| | | 80 | 5 + 2* | 5738 |
| | | 75 | 3 + 2* | 55739 |
| MS | 52 | 95 | 5 + 2* | 100 |
| | | 85 | 6 + 2* | 968 |
| | | 80 | 6 + 2* | 2528 |
| | | 75 | 5 + 2* | 10117 |
| HS | 84 | 95 | 4 + 2* | 58 |
| | | 85 | 6 + 2* | 1045 |
| | | 75 | 6 + 2* | 1644 |
| | | 70 | 4 + 2* | 3484 |
| VHS | 103 | 95 | 4 + 1* | 46 |
| | | 85 | 4 + 1* | 481 |
| | | 75 | 3 + 1* | 1419 |
| | | 70 | 4 + 1* | 3394 |

* : number of cylinders used for fatigue deformation tests

In determining the $S_{max}$-$N_f$ curve, $S_{max}$ was nondimensionalized with respect to the average static strength that had been obtained by standard rate (SR, $2\times10^{-5}$/sec) testing. Since fatigue test was carried out by fatigue rate (FR, $2\times10^{-3}$/sec), the starting point of the regression lines, i.e., the intercept on vertical axis would move to higher value[7]. TABLE 6 shows the strength ratios ($R_f$) which are the test results for the strain rate effect. $R_f$ corresponds to $S_{max}$ for the fatigue life of 1 cycle, that is, $\beta_0$ in eq.(1).

As can be seen in TABLE 6, $R_f$ values are distributed from 110 to 120, and the values decrease with increasing the concrete strength. According to the test results of Su and Hsu[8], the fatigue life was about 10 and 3~4 cycles when $S_{max}$ was 100 and 110%, respectively. Sparks and Menzies[9] found that fatigue life was enhanced by the increase in the rate of loading when using the static strength at the same rate as the reference strength of fatigue. The tendency that $R_f$ decreases with increasing the concrete strength is similar to the results of other researchers[10-11].

A mathematical expression was suggested in order to describe the trends that $\beta_1$ in TABLE 5 and $R_f$ in TABLE 6 vary with the strength of concrete. The equation expresses the $S_{max}$-$N_f$ relationship considering the effects of the concrete strength as follows.

TABLE 5

The Results of Regression Analysis

| Mix | $\beta_0$ | $\beta_1$ | $r$ |
|---|---|---|---|
| LS | 108.87 | -7.428 | 0.966 |
| MS | 114.25 | -9.907 | 0.983 |
| HS | 113.74 | -10.34 | 0.935 |
| VHS | 111.14 | -10.07 | 0.952 |

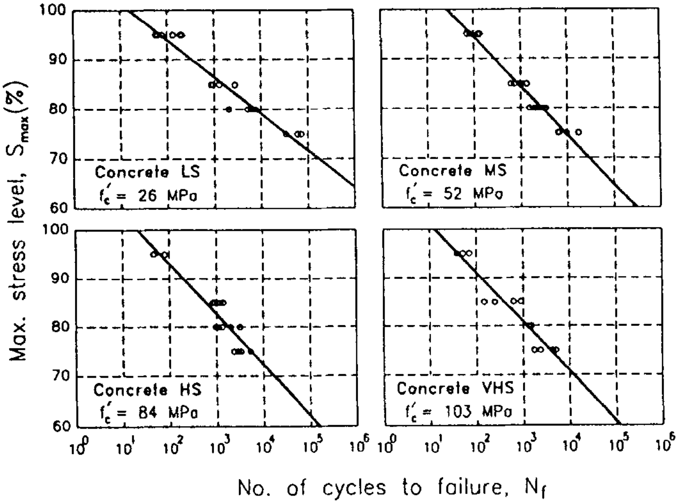


FIG. 2.
$S_{max}$-$N_f$ relationships

$$S_{max} = k_1\left(\frac{f_c'}{f_1}\right)^n log\, N_f + k_2\left(\frac{f_c'}{f_1}\right)^m \tag{2}$$

where $f_1$ is 1.0 MPa , and $k_1$, $k_2$, n and m are parameters, which are evaluated as follows.

1. Parameter $k_1\left(f_c'/f_1\right)^n$ is the slope of $S_{max}$-$N_f$ curve of the linear relation. The effect of the concrete strength is represented by parameter *n*.
2. Parameter $k_2\left(f_c'/f_1\right)^m$ is the intercept on vertical axis of $S_{max}$-$N_f$ curve, and is $S_{max}$ for the fatigue life of 1 cycle. The effect of the concrete strength is represented by parameter *m*.

TABLE 6

The Results of the Strain Rate Test

| Mix | Strength Ratio* (%) | Standard deviation (%) |
|---|---|---|
| LS | 117 | 1.3 |
| MS | 118 | 3.5 |
| HS | 114 | 1.2 |
| VHS | 110 | 2.5 |

$* : R_f = \frac{(f_c')\text{ by FR}}{(f_c')\text{ by SR}} \times 100$

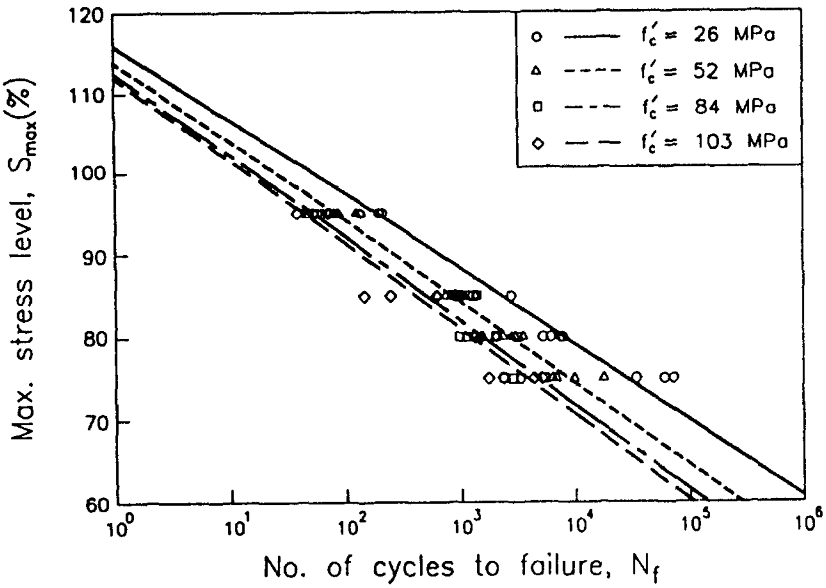


FIG. 3.
Test data with curves fitted.

The four parameters in eq.(2) were evaluated by the results of fatigue and strain rate test. The resulting $S_{max}$-$N_f$ relationship is as follows.

$$S_{max} = -7.6\left(\frac{f_c'}{f_1}\right)^{0.066} log\,N_f + 126\left(\frac{f_c'}{f_1}\right)^{-0.025} \qquad (3)$$

Eq.(3) is plotted in FIG. 3 with the data of fatigue test.

Fatigue Deformation Characteristics. As described earlier, three foil strain gages(gage length 67mm) were attached to cylinders to measure the axial strain. Firstly the axial strain was measured by a Cassette Data Recorder in a analogue type. Thereafter the analogue signals were converted to the digital values by A/D converter. The fatigue strains plotted herein are the measured values at maximum stress level which corresponding to the strains at point A in FIG. 1. The typical history of fatigue behavior of concrete in compression is shown in FIG. 4. In this study, the measured axial strains were divided into the three types. The initial strain $\varepsilon_i$ and the total strain $\varepsilon_t$ are corresponding to the strains of maximum stress level at first loading cycle and at a certain loading cycles respectively as shown in FIG. 4. Subtracting total strain to initial strain, the fatigue strain $\varepsilon_f$ is calculated.

The cycle ratio which is defined as the ratio of cycle number N to cycle number until failure $N_f$ is used for the analysis of fatigue deformation characteristics. Generally, it is well known that the fatigue strain gradually increases with an increase in the number of cycles. The fatigue strain development consists of three stages : stage 1 is the rapid increase up to about 10 percent of total life, stage 2 is the uniform increase from 10 to about 80 percent of total life, and stage 3 is the rapid increase until failure. This trend is found in the fatigue

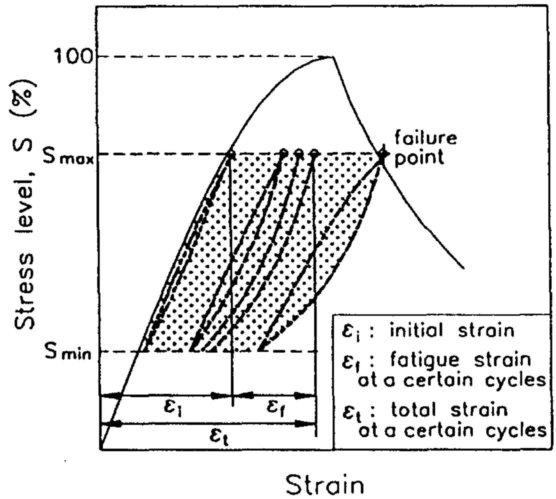


FIG. 4.
Fatigue behavior of concrete in compression.

deformation of all strength of concrete as shown in FIG. 5, however the second stage is longer for the higher-strength concrete.

FIG. 5 shows a series of total axial strains with cycle ratios, and the strains are the averages of measured values in two cylinders, as shown in TABLE 4. The higher the concrete strength is, the smaller the fatigue strain is at failure, that is to say, the internal damage is greatly localized for high strength concrete at fatigue failure.

FIG. 6 shows the relationships between the number of loading cycles and the fatigue strains of concrete LS and HS. Although the fatigue strain of concrete HS is smaller than that of concrete LS, the slope of strain increment curve of concrete HS is steeper than that of concrete LS, i.e., the rate of strain increment increases with the strength of concrete. Therefore high strength concrete is more brittle than normal strength concrete under fatigue loading.

FIG. 7 shows the measured total axial strain along with the monotonic stress-strain model for $S_{max}$ of 75 percent. The following model[12] was used to predict the monotonic stress-strain relationship.

Ascending part :

$$\sigma_c = f_c'\left[A\left(\frac{\varepsilon_c}{\varepsilon_0}\right)-(A-1)\left(\frac{\varepsilon_c}{\varepsilon_0}\right)^{A/(A-1)}\right] \tag{4}$$

Descending part :

$$\sigma_c = f_c' exp\left[-B(\varepsilon_c-\varepsilon_0)^c\right] \tag{5}$$

in which $$A=\frac{E_c\,\varepsilon_0}{f_c'}$$

$$B = \left(260 + \frac{100}{f_c'}\right)$$

$$C = 1.2 - 0.006 f_c'$$

$$\varepsilon_0 = 7 \times 10^{-4} \sqrt[3]{f_c'}$$

As can be seen in FIG. 7, the total strain at the fatigue failure point approximately coincides with the strain of descending part in monotonic stress-strain curve. As a result, the fatigue strain at failure of concrete LS should be greater than that of concrete HS as shown earlier in FIG. 6. Furthermore, FIG. 6 shows that the rate of fatigue strain increment increases with the strength of concrete, and then it can be concluded that fatigue life should decrease with increasing the concrete strength.

## Concluding Remarks

A fatigue study was conducted on cylindrical concrete specimens with various strength levels. From this investigation, the following conclusions can be drawn.

1) The fatigue life decreases with increasing the concrete strength. Based on test results, a model for $S_{max}$-$N_f$ relationship considering the effect of concrete strength was proposed.

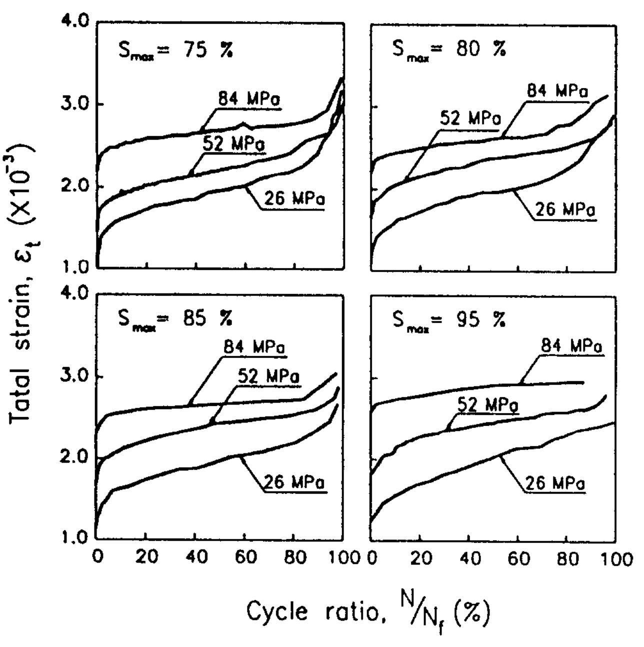


FIG. 5.
Measured variation of total strain with cycle ratio.

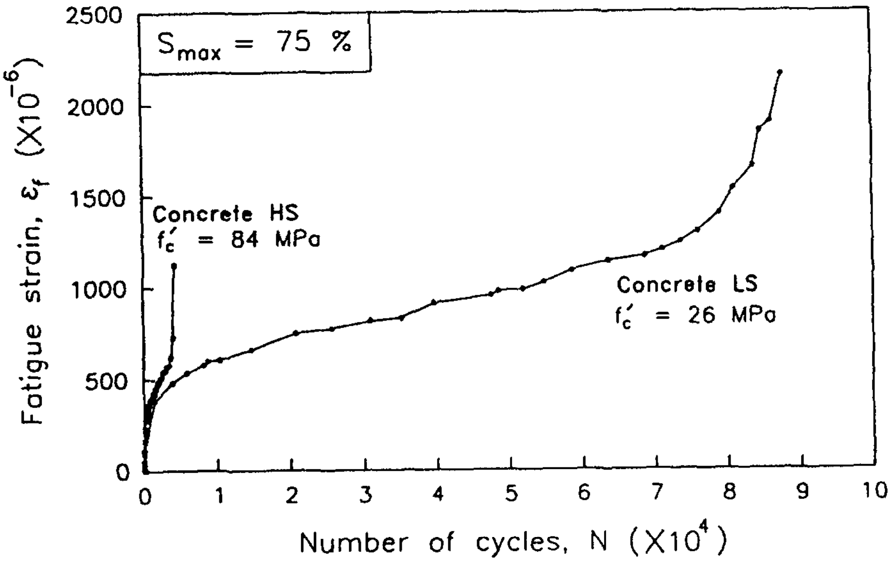


FIG. 6
Fatigue strain increment with number of cycles.

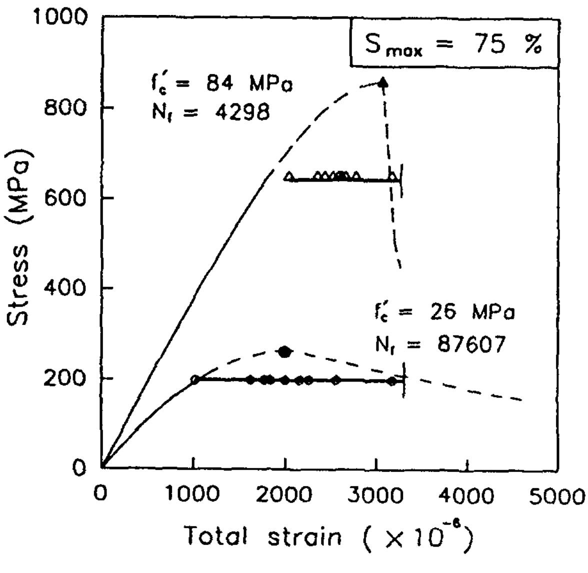


FIG. 7.
Fatigue strain increment along with monotonic stress-strain curve.

2) The values of strength ratio, $R_f$ ranged from 110 to 120, and decreased with increasing the concrete strength. The $S_{max}$ for the fatigue life of 1 cycle was successfully constructed using $R_f$ in modeling $S_{max}$-$N_f$ relationship.
3) The total strain at failure was found to be approximately the same as the strain of descending part in monotonic stress-strain curve. It is reasonable that the fatigue strain at failure decreased with increasing the concrete strength in the experiment. Furthermore, the rate of strain increment of concrete HS was greater than that of concrete LS.
4) The rate of strain increment, in contrast with the fatigue strain, increases with the strength of concrete. Therefore, the fatigue life should decrease with increasing the concrete strength. As a result, it can be concluded that high strength concrete is more brittle than low strength concrete under fatigue loading.

## Acknowledgment

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