# Effect of fiber fatigue rupture on bridging stress degradation in fiber reinforced cementitious composites

T. Matsumoto, P. Chun, & P. Suthiwarapirak

*The University of Tokyo, Tokyo, Japan.*

ABSTRACT: This paper investigates the bridging stress degradation of fiber reinforced cementitious composites under fatigue loading experimentally and theoretically. The fatigue tension experiments of Engineered Cementitious Composite (ECC) under constant displacement amplitude were conducted, and the degradation of bridging stress was measured. Three displacement amplitudes were examined in order to change the stress level of individual fibers. As a result, the larger the displacement amplitude, the earlier the bridging stress decreased. Also, the decrease of bridging stress was observed to cease around $10^5$ cycles. Next, the analytical modeling of bridging stress degradation was carried out. The model accounts for the loss of fatigue ruptured fibers, where fatigue rupture is based on the S-N relation of a fiber type, depending on the stress level and the number of cycles. Overall, the developed model shows a good agreement with the experimental results, showing the validity of the model developed in the study.

Keywords: fiber fatigue rupture, bridging stress degradation, ECC

## 1 INTRODUCTION

The mechanical degradation of cementitious materials due to fatigue loading is one of the main causes of the damage of fatigue intensive infrastructures, such as RC bridge slabs. The initiation and the propagation of cracks in cementitious materials under fatigue load result in the degradation of tensile and flexural performances. Those crack mechanisms govern the fatigue failure of structures.

The investigation of mechanical degradation of cementitious materials due to fatigue loading is necessary before introducing them for structural application for two reasons. First, it is to make sure whether if the fatigue degradation of the material is less enough for long-term application or not. Second, the mechanical degradation characteristics of materials are applicable to the prediction of structural performances. The study of crack bridging characteristics of cementitious materials relates to fatigue crack propagation process.

This paper studies the bridging stress degradation of ECC (Engineered Cementitious Composite) under fatigue loading. ECC exhibits different fatigue failure mechanisms from others. Namely ECC exhibits the distribution of multiple crack due to pseudo-strain hardening process before the failure due to a localized crack (Kanda et al. 2001, Kanda & Li 1999), while other cementitious materials exhibit fatigue failure due to a single localized crack. Therefore, the crack bridging degradation characteristics of typical concrete and FRC is not applicable to ECC. It is necessary to develop a new approach for investigating the bridging stress degradation characteristics and for determining the bridging stress degradation relation of ECC.

This paper proposes the method for determining the bridging stress degradation relations of ECC by two approaches; micromechanics based approach and experimental based approach. The ECC used here is the one reinforced with polyvinyl alcohol (PVA) fibers.

For micromechanics based approach, the bridging stress degradation is proposed based on micromechanical theory of fiber in cementitious matrix. The fiber bridging characteristics of a single fiber under fatigue loading are considered in the development of bridging stress degradation law.

In experimental based approach, the uniaxial tensile test method is proposed for investigating the fatigue stress degradation characteristics of ECC. The uniaxial tensile test is conducted both under static and fatigue loading. The bridging stress relation and bridging stress degradation relation can be obtained from those experiment results. The bridging stress degradation characteristics and the failure mechanisms of ECC are also investigated by the uniaxial test. The fatigue failure mechanism and multiple crack distribution fatigue characteristics of ECC can be observed, and they are used for the verification of theoretical degradation law.

The development of bridging stress degradation relation of ECC is essential because it is considered as one of material properties in the selection of ECC for fatigue intensive infrastructures. Moreover, it can be introduced as a basic input of analytical model for predicting structural fatigue performances when ECC is applied to infrastructure repairs.

## 2 MICROMECHANICS BASED FATIGUE BRIDGING STRESS DEGRADATION RELATION

### 2.1 *Fiber Bridging Characteristics*

Under static loading, after a crack initiates on the direct tensile specimen, the transferring of bridging stress across a crack occurs due to fiber bridging action. Multiple cracks initiate consecutively so that it can sustain tensile loading without sudden failure because of their Pseudo Strain Hardening (PSH) (Kanda et al. 2001). Under fatigue loading with constant strain amplitude, the mechanical degradation due to fiber bridging leads to the degradation of bridging stress of each crack with the increase in loading cycles. The degradation rate of crack bridging of multiple cracks in ECC is defined as the bridging stress degradation relation.

The consideration of fiber bridging characteristics on the crack plane is essential for developing fatigue bridging stress degradation relation. In the design of ECC, fiber properties such as tensile strength and interfacial bond strength are considered in order to exhibit a balance proportion between fiber rupture and fiber pull out so that the ECC can induce multiple cracking conditions (Kanda & Li 1999). Therefore, on the crack plane of ECC, two kinds of fiber bridging characteristics, fiber fatigue rupture and fiber pullout, can be expected. The bridging stress degradation is governed by two main fiber bridging characteristics: the fiber/matrix interfacial bond degradation and fiber fatigue rupture.

Interfacial bond degradation is one of bridging stress degradation source. In fiber cementitious composites, fibers exhibit stress degradation, which is mainly due to the fiber/matrix interfacial damage or the decay of bond strength between fiber and matrix (Zhang et al. 2001).

Fiber fatigue rupture is the other source. Under cyclic fatigue loading, the rupture of a fiber takes place even when the tensile stress of fiber has not reached the tensile strength. In fiber cementitious materials, the exposed fibers along a crack plane under cyclic fatigue loading that show higher tensile stress level fail earlier by fatigue rupture. The rupture failure leads to the decrease in bridging stress across crack. Fiber fatigue rupture is considered to be dependent on the number of cycles, N, and tensile stress level, $\sigma_t$.

### 2.2 *Development of Bridging Stress Degradation Model Considering Fiber Fatigue Rupture*

In this study, the micromechanics based fatigue bridging stress degradation model is developed based on the consideration of fiber fatigue rupture.

ECC is designed in order that fibers on a crack plane exhibit high tensile stress level.

In order to develop bridging stress degradation relation, the formulation of the bridging stress relation of fiber cementitious materials under static loading is introduced as a basic concept.

### 2.2.1 *Basic assumptions*

The basic assumptions for the development of bridging stress degradation relation of PVA-ECC are shown below

1. Fibers are 3-D randomly distributed in location and orientation
2. The interfacial bond between fiber and matrix is due to relative bond stress. The elastic shear bond stress is neglected.
3. The deformation of matrix is small enough compared with the slip of fiber so that it can be neglected.
4. The effect of Poisson's ratio of fiber is neglected and the Elastic modulus of fiber is considered to be constant.
5. The fiber rupture occurred when the fiber stress reach fiber fatigue strength.
6. Fibers behave rupture failure not pull out under fatigue loading.

The bridging stress degradation relation of the ECC is derived by considering the rupture failure of fibers due to fatigue in the bridging stress relation model. The fiber fatigue rupture is mentioned in the next section.

### 2.2.2 *Effect of fiber rupture due to fatigue loading*

Under fatigue loading, fibers break even when the tensile stress has not reached the tensile strength. The rupture of fibers causes the reduction of total crack bridging stress. The fiber fatigue rupture relation is illustrated in Figure 1 and it is simply defined as:

$$\frac{\sigma_N}{\sigma_{\max}} = 1 - k \cdot \log(N) \qquad (1)$$

where N is the number of cycles that fibers break at fatigue tensile stress, $\sigma_N$. $\sigma_{max}$ is the ultimate tensile strength of fiber. The above equation holds for $N < 10^5$, and the ratio becomes constant for $N \geq 10^5$.

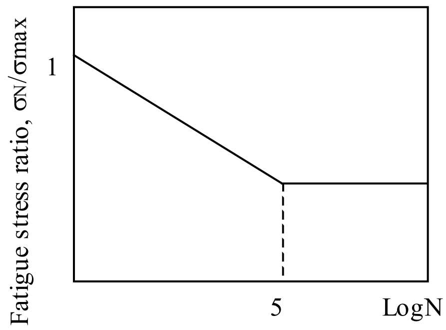



Figure 1 Consideration of fiber fatigue rupture

### 2.2.3 *Bridging stress degradation relation*

The bridging stress degradation relation of ECC is derived by the summation of bridging force of fibers distributed in cementitious matrix. The condition for fiber fatigue rupture is included so that the relation is also a function of number of loading cycle, N. The bridging stress degradation relation that is a function of crack width, δ and number of cycles, N can be expressed as

$$\begin{aligned}
&\sigma(\delta, N) \\
&= \frac{1}{A_c} \sum \left[ P(l_e, \delta, \phi, N) dN_f \right] \\
&= \frac{N_f}{A_c} \sum \left[ P(l_e, \delta, \phi, N) p(\phi, z) dp \right] \qquad (2) \\
&= \frac{v_f}{A_f} \int_{\phi=0}^{\frac{\pi}{2}} \int_{z=0}^{\frac{L_f}{2}\cos\phi} P(l_e, \delta, \phi, N) p(\phi) p(z) dp
\end{aligned}$$

where $N_f$ is the number of fibers. $A_f$ and $L_f$ are cross section area and length of fiber respectively. P refers to the bridging load of a single fiber that is a function of embedded length, $l_e$, crack width, δ, inclining angle, ϕ, and number of loading cycles, N. It is noted that the formulation of P is similar to the case of the bridging stress relation under static loading. The difference is only the consideration of condition for fiber fatigue rupture in the equation. p(ϕ) and p(z) are random distribution of fibers.

After substituting all parameters which is related to fiber and matrix properties of ECC, bridging stress degradation can be determined as a function of number of loading cycle, N and crack width, δ.

## 3 EXPERIMENTAL BASED FATIGUE BRIDGING STRESS DEGRADATION RELATION AND UNIAXIAL TENSILE FATIGUE TESTS OF PVA-ECC

The bridging stress degradation can be simplified as a function of some parameters, such as crack width and number of loading cycles with coefficients, and it can be determined by experimental approach. Uniaxial fatigue test of specimen with notch at the middle was proposed in order to determine the bridging stress degradation relations of a single crack cementitious material. However, for ECC which is a multiple cracking failure material, there is still no proposal of a uniaxial fatigue test setting for determining bridging stress degradation relation and for investigating bridging degradation characteristics. In this section, an experimental method for determining the bridging stress relation and bridging stress degradation relation of ECC is developed.

### 3.1 *Uniaxial Tensile Fatigue Test*

Although in theoretical consideration, the uniaxial test can represent well the bridging stress degradation characteristics of cementitious materials, the testing method poses several difficulties, such as how to control the initiation of cracks in a specific area, and how to eliminate total failure of the specimen at or near the grip where uniaxial stress condition does not exist (Saito & Imai 1984, Gopalaratnam & Shah 1985).

The special design of specimen shape and dimension is essential in order to control the initiation of crack in a specific area. The grip between a specimen and a loading device should be considered as one of the important issues; otherwise, failure may occur at or near the grip that is out of the investigation area.

#### 3.1.1 *Design of specimen*

The shape of ECC specimens was specially designed in order that multiple cracks distribute in a specific measuring length. In the case of single crack failure materials, a notch can be introduced to control cracking location. However, in order to control multiple cracks of ECC, a notch is not practical. The gradual reduction of width of specimen for a specific length is considered as a candidate in the design.

The important issues for the design of ECC tensile specimen shape are shown below:

- The ratio between the maximum stress and minimum stress in the control area should be less than the ratio between the ultimate strength and the first crack strength of ECC.
- The length of control area should be long enough in order to provide uniform stress distribution in the control area.
- The control area should have the length that is compatible to the measurement devices.
- The rapid change of specimen size leads to the stress concentration occurring at the change portion. In order to reduce the stress concentration effect, gradual change of width of specimen is necessary.

An FEM elastic analysis was conducted in order to confirm that the specimen shape and dimension satisfied all the above conditions. The final decision of the shape and the dimension of ECC specimen are shown in Figure 2.

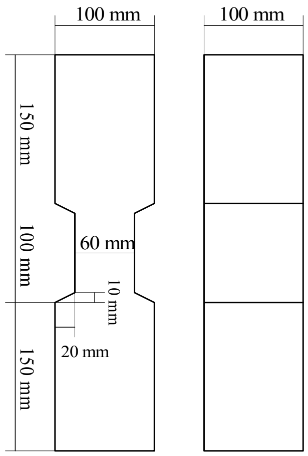



Figure 2 Shape and dimension of tensile specimen

#### 3.1.2 *Design of grip set*

The grip between specimen and loading machine is one of important part in the design of uniaxial test devices. It has to assure that failure of specimen occurs away from the grips and that there is no failure due to the separation of the interface between specimen and grip. For ECC that shows higher tensile strength than typical cementitious materials, the grip and its bond should be strong enough so that it will not fail by the separation of the interface.

The detailed diagram of epoxy grip used in this test is explained below. Four side plates with height of 50 mm are introduced in order to have enough stress-transferred area. Moreover it was designed by adding an extruded part on each side plate as shown in the figure. Epoxy is introduced between specimen faces and all four-side plates. An epoxy has enough shear strength and it should be easy to remove after testing.

### 3.1.3 *Materials and fabrication*

Static and fatigue tensile tests were conducted for ECC reinforced with polyvinyl alcohol (PVA) fibers that are hereinafter referred to as PVA-ECC. The mix proportion of the ECC and the properties of PVA fibers are shown in Table 1 and 2, respectively.

Table 1 Mix proportion (Kanda et al. 2001)

| | |
|---|---|
| Water | 1 |
| Cement | 0.32 |
| Fine aggregate | 0.42 |
| Super plasticizer | 0.03 |
| Methylcellulose | 0.00071 |

Table 2 Properties of PVA fibers (Kanda et al. 2001)

| | |
|---|---|
| Length (mm) | 12 |
| Diameter (μm) | 37.7 |
| Volume fraction (%) | 2.1 |
| Elastic modulus (GPa) | 36.7 |
| Fiber strength (MPa) | 1610 |
| Interfacial bond strength (MPa) | 2.01 |

A mixer with 50 liters in capacity is used in the fabrication of ECC specimens. Fifteen tensile specimens were cast into formworks where three specimens were used as redundancies. According to the capacity of the mixer, ECC was mixed in two batches with the same mix proportion. After the fabrication, all specimens were cured under constant temperature of 20 degrees Celsius and relative humidity of 60%. The age of specimens at testing is at least one month so as to alleviate the effect of initial hydration development.

### 3.1.4 *Data measurement*

Four π-shape displacement transducers (π gauges) with gauge length 100 mm were used for the purposes of control and measurement of the deformation or tensile strain. During the test, data measured at the maximum strain and at the minimum strain were recorded.

### 3.1.5 *Apparatus and test procedure*

The apparatus employed in this study was a 200 kN capacity feed back controlled loading machine. Both static and fatigue loading tests were carried out under π-gauge control condition. The average value of two π-gauges from opposite sides was used for controlling applied strain. The other two π-gauges were attached to specimen to measure crack opening displacement.

The uniaxial tensile tests were conducted under static loading condition before fatigue loading. The static tensile strength and the strain capacity before localization of the ECC were determined. Based on the tensile strain capacity from the static test, three levels of maximum tensile strain levels were assigned for fatigue specimens. The selected maximum tensile strain levels are 0.01, 0.015 and 0.02, and three specimens were conducted for each tensile strain level.

The uniaxial tensile fatigue tests were performed under π-gauge control condition or strain control condition. Specimens were subjected to a 4-Hz sinusoidal cyclic loading. The test was conducted with constant amplitude between maximum tensile strain, $\varepsilon_{max}$, and minimum tensile strain, $\varepsilon_{min}$.

For the first loading cycle, specimen was gradually loaded until it reached the assigned maximum strain level; then, the specimen was unloaded in order to determine the minimum strain level for each specimen. The minimum strain level is defined as the tensile strain when applied load turns to zero. Then, a 4-Hz cyclic fatigue loading with constant amplitude between the maximum tensile strain and the minimum tensile strain is applied for at least 200,000 cycles but not more than two millions cycles. The decrease in load was recorded both at the maximum tensile strain and minimum tensile strain.

3.1.6 *Test set-up and test preparation*

Before testing, specimen was painted white to facilitate visual and microscopic observations during test. Then, epoxy was introduced for attaching both ends of the specimen to the grips. In order for epoxy to gain enough strength, the process of putting epoxy should be prepared at least two hours before the test starts. Four π-gauges were attached to all faces of specimens. The experiment set-up is shown in Figure 3 and 4.

3.2 *Uniaxial Tensile Test Results*

The experimental results of three static and nine fatigue specimens are presented in this section. The failure of the PVA-ECC and the fiber bridging characteristics on the crack plane of both static and fatigue specimens are discussed.

3.2.1 *Static tensile test results*

In the static tensile test of the ECC, it is found that with gradual increase in π-gauge control displacement, distributed cracks occurred in the control area since sudden drop of stress due to new crack initiation is observed. When a number of cracks occurred for the specimen, one crack becomes localized, and at this moment rapid decrease of stress was observed.

The tensile stress-strain relationship of the ECC is utilized for the later determination of fatigue tensile stress levels.

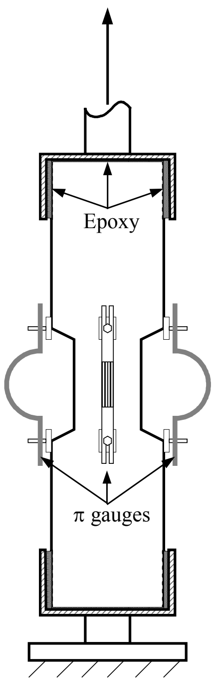


Figure 3 Experiment set-up

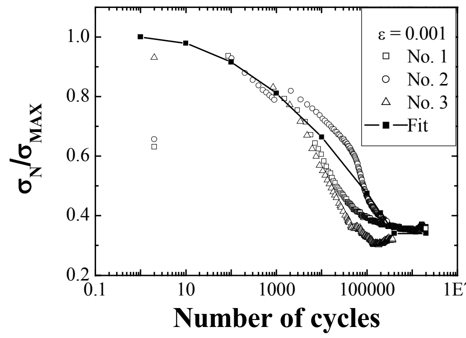

Figure 4 Uniaxial tensile test

3.2.2 *Fatigue tensile test results*

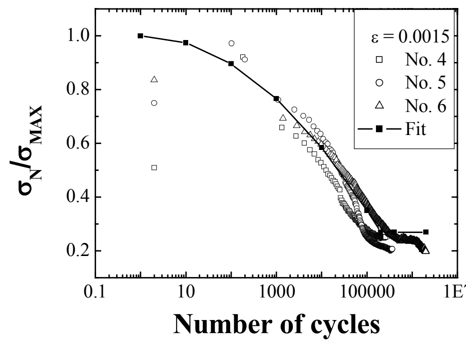
The results of uniaxial tensile fatigue test of ECC with three different maximum tensile strain levels are shown in Figure 5. It is noticed that fatigue stress gradually reduced at low fatigue loading cycles, the rate of stress reduction increased when the number of cycles increased. Furthermore, the fatigue stress of ECC tended to be constant or nearly constant when the number of loading cycles was in the range of between $1x10^5$ and $5x10^5$cycles, depending on the maximum tensile strain level.

3.2.3 *Bridging stress degradation relation from the experiment results*

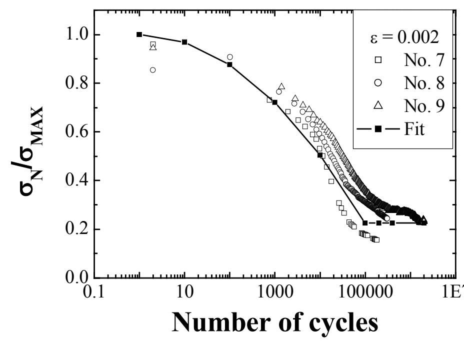
The bridging stress degradation relation is simply assumed as a function of number of cycles, N and tensile strain, $\varepsilon_t$. From the shape of degradation curve shown in the figure, parabolic relation on logarithmic term is assumed as given by




(a)




(b)




(c)

Figure 5 Fatigue test results when tensile strain is equal to (a) 0.0010 (b) 0.0015 (c) 0.0020

$$\frac{\sigma_N}{\sigma_1} = f(\varepsilon_t, N) = (k_1 + k_2\varepsilon_t) * (LOG_{10}N)^2 \quad (3)$$

The constants $k_1$ and $k_2$ are obtained by fitting the test results. For this ECC, it is shown that when $k_1$ and $k_2$ are equal to 0.11 and 10 respectively, the fatigue test results can be represented by the above relation (fitting lines in Figure 5).

## 4 COMPARISONS BETWEEN MICROMECHANICS BASED AND EXPERIMENTAL BASED BRIDGING STRESS DEGRADATION RELATIONS

The comparison between the bridging stress degradation relations of the PVA-ECC by micromechanics based and experimental based approaches are shown in this section.

It is shown that the micromechanics based bridging stress degradation relation exhibits the same shape as that from the uniaxial test (Figure 6). When the coefficient, k in the fiber fatigue rupture relation (Equation 1) is assumed to be 1/8.5, it is found that the micromechanics based bridging stress degradation relation agrees well with that from the uniaxial test. Therefore, it is deduced that the micromechanics based bridging stress degradation model is applicable for reproducing the stress degradation characteristics of this PVA-ECC.

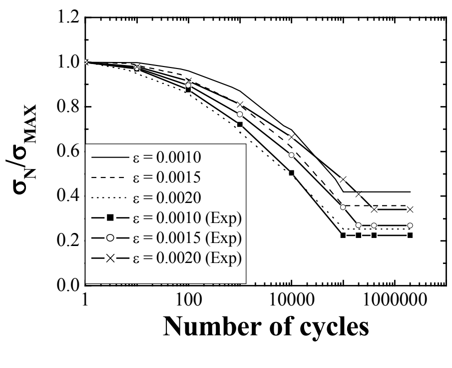



Figure 6 Comparison between bridging stress degradation relation obtained by experiment and micromechanics based model

## 5 CONCLUSIONS

In this paper, the determinations of bridging stress degradation relations by micromechanics based and experimental based approaches are proposed for ECC.

It is shown that the bridging stress degradation relation of ECC can be obtained by both micromechanical and experimental approaches. For micromechanics based approach, the fiber bridging characteristics on a crack plane is taken into account in material model development. Fibers are assumed to break under fatigue rupture. A simple fatigue rupture relation of fiber that is a function of number of loading cycles is introduced in the model.

The determination of bridging stress degradation relation by micromechanics based approach is an effective method since the relation reflects all general properties of fibers, such as, fiber strength, bond strength, length, and area. That means the bridging stress degradation relation can be predicted when general properties of fibers are known.

The uniaxial tensile fatigue test is proposed for determining the bridging stress degradation in experimental based approach. The fatigue test of PVA-ECC was conducted by strain-control condition, and three maximum tensile strain levels were selected for fatigue loading test. It is found that the bridging stress degradation relation of the ECC exhibited parabolic shape on semi-logarithmic scale. Fatigue stress gradually reduced at low fatigue loading cycles, and the rate of stress reduction increased when the number of cycles increased. The shape of these relations is similar from those obtained from micromechanics based model.

The determination of bridging stress degradation relation by uniaxial fatigue test is a practical method. The bridging stress degradation relation is assumed based on some basic parameters. In this study, the relation was assumed to be a function of tensile strain and number of loading cycles with some coefficients. The coefficients in bridging stress degradation relation could be obtained directly by fitting those experiment results.

It is also suggested that in order to propose a micromechanics based model that can be used for determining the bridging stress degradation relations of all kinds of ECC, all dominant fatigue failure mechanisms of ECCs should be taken into account in the model development. In this study, the simple assumption of fiber fatigue rupture of PVA-ECC is considered as a main mechanism for the first step in the development.

## REFERENCES:


Gopalaratnam, V. S. & Shah, S. P. 1985. Softening Response of Plain Concrete in Direct Tension. *ACI Journal* May-June: 310-322.

Kanda, T. & Li, V. C. 1998. Interface Property and Apparent Strength of High-Strength Hydrophilic Fibers in Cement Matrix. *Journal of Materials in Civil Engineering* 10(1): 5-13.

Kanda, T. & Li, V. C. 1999. New Micromechanics Design Theory for Pseudostrain Hardening Cementitious Composite. *Journal of Engineering Mechanics* 125(4): 373-381.

Kanda, T., Saito, T., Sakata, N., & Hiraishi, M. 2001. Fundamental Properties of Direct Sprayed Retrofit Material Utilizing Fiber Reinforced Pseudo Strain Hardening Cementitious Composites. *Proceedings of the Japan Concrete Institute* 23(1): 475-480 (in Japanese).

Kawasaki, H. 2002. Designing the form of the Steel Fiber for Fiber Reinforced Concrete based on a Micromechanical Pull-out Model. *Master thesis*: The University of Tokyo.

Matsumoto, T, Suthiwarapirak, P., & Asamoto, S. 2002. Model Development of ECC Fatigue Analysis. *Proceedings of the Japan Concrete Institute* 24(1): 237-242 (in Japanese).

Saito, M. & Imai, S. 1984. Direct Tensile Fatigue of Concrete by the Use of Friction Grip. *ACI Journal* July-August: 431-438.

Zhang, J., Stang, H., & Li, V.C. 2001. Crack Bridging Model for Fibre Reinforced Concrete under Fatigue Tension. *International Journal of Fatigue* 23: 655-670.