# 論文 Crack Growth Mechanism and Fatigue Strength of Concrete in Anchor System

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**ABSTRACT :** The fracture process of concrete structures is associated with cracks and crack growth. Unfortunately, until now the mechanism of crack growth under repeated or fatigue loading is not well understood yet. This paper discusses the crack growth mechanism and fatigue strength of concrete conducting the pull-out test of an anchor bolt under fatigue loading. An experimental work to observe crack growth was conducted using injection of ink through a number of narrow holes. A crack growth model is proposed and fatigue strength of concrete is discussed.

**KEYWORDS :** crack growth, fatigue strength, pull-out test, anchor bolt, ink-injection

## 1. INTRODUCTION

Cracking is an essential feature of concrete structures. It is well known that even under static or repeated loads the fracture process of concrete structures is associated with cracks and crack growth. Recently, with application of fracture mechanics to concrete structures the knowledge of crack mechanism and the role of fracture process zone are identified and clarified. Although analytical prediction of crack growth phenomena under static loading has been enabled, the mechanism of crack growth under repeated or fatigue loading is not well understood yet. It is straight forward to expect that the knowledge on static crack growth is extended to fatigue crack growth with proper modification.

This paper discusses the crack growth mechanism and fatigue strength of concrete conducting the pull-out test of an anchor bolt under fatigue loading. An experimental work to observe crack growth was conducted using injection of ink through a number of narrow holes provided in concrete. A simple crack growth model is proposed and fatigue strength of concrete is discussed in comparison with the experimental data calculated by the proposed model and by the equation proposed in the Japan Society of Civil Engineers (JSCE).

## 2. EXPERIMENTAL PROGRAM

### 2.1 SPECIMENS

To study crack growth and fatigue strength of concrete by an anchor bolt system, the anchor bolt was chosen so as to provide concrete cone failure. The anchor bolt was a headed anchor placed in formwork before casting concrete. The frictional resistance between a bolt and concrete was eliminated by wrapping the bolt shaft with vinyl tape. In this experiment two types of diameter of bolt, 16 mm and 20 mm were used with the embedment lengths of 30 mm and 45 mm, respectively. The properties of bolt and the concrete block are summarized in **Table-1**. The concrete block of dimension 400 mm x 400 mm x 250 mm is shown in **Fig. 1**. The concrete used is ready mix concrete with a high early strength cement and the maximum aggregate size was 25 mm.

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The target strength of concrete was 29.4 MPa and design slump value was 100 mm. The compressive and tensile strengths of concrete were obtained by a companion cylinders of 10 mm diameter and 200 mm heigth which were cast and cured in room temperature condition until one moth old.

**Table-1.** The properties of bolt and concrete block

| Bolt Type | JIS B 1180-1974 | |
|---|---|---|
| 1.Max Tensile Strength | 1059 MPa | |
| 2.Diameter of Bolt | 16 mm | 20 mm |
| 3.Embedment Length | 30 mm | 45 mm |
| Dimension of Block | 400x400x250mm | |
| 1.Compressive Strength | 31.9 MPa | |
| 2.Splitting Tensile Strength | 2.6 MPa | |

To observe crack growth in concrete, a number of narrow holes for injection of ink were made around a bolt by placing piano wires before casting concrete as shown in **Fig. 1**. Holes were completed by pulling out wires after hardening of concrete. The diameter of hole was 1.2 mm and the length was approximately the same as the embedment length of bolt.

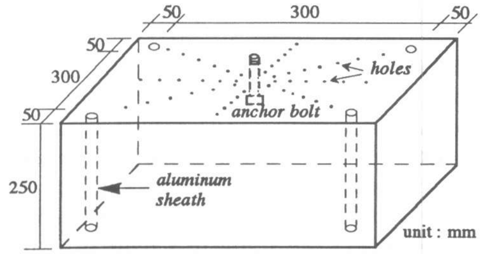



**Fig. 1** Concrete block specimen

Three load levels of fatigue test were performed. The load was given sinusoidally between a constant minimum load,$P_{min}$ = 10% of the ultimate capacity,$P_u$ and the maximum load,$P_{max}$ from start until failure or through 2 million load cycles. The values of $P_{max}$ were 60%, 70% and 80% of ultimate capacity. At the first cycle the specimen was loaded statically and then the loading was performed at a frequency of 5 cycles per second (5 Hz).

2.2 TEST PROCEDURE

Experiments were conducted using a servo actuator loading machine which was applied in both static and fatigue loadings. The loading machine has a load cell of 49 kN capacity with a reaction frame and a control panel. The applied load and displacement were monitored by a control panel and A/D converter. All measured data were recorded and stored through a personal computer. A schematic representation of the test specimen is shown in **Fig. 2**.

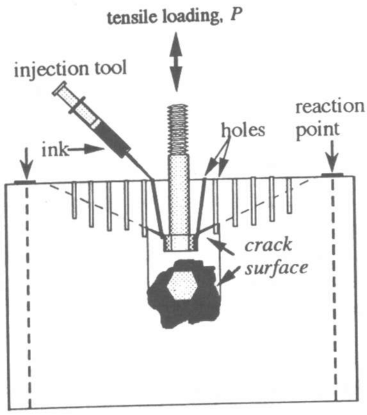



**Fig. 2** Test method

At a certain number of load cycles, ink-ethanol solution was injected into concrete through holes by a injection. The penetration time of ink was about 20 minutes and after that the remained ink in holes was vacuumed out by the same injection tool and dried using a hairdryer for about 5 minutes. After failure occured, the crack pattern dyed by ink was recorded in photograph for each specimen. With help of a scanner and computer calculation the area of cracked section was obtained.

## 3. TEST RESULTS AND DISCUSSIONS

3.1 MECHANISM OF CRACK GROWTH

Thirty six (36) specimens for the two cases of embedment lengths were prepared. Prior to the fatigue test, four specimens for each case were tested statically to estimate the ultimate static pull-out strength as the basis for determining the load levels in the fatigue test. Four specimens of 60% load level did not fail until 2 million cycles of load. These specimens then were loaded statically until failure. All specimens failed showed the cone failure.

A typical of a crack section dyed by ink at a certain number of load cycles are shown in **Fig. 3**. **Figs. 4** and **5** show the ratio between crack surface area and total cone surface area which are plotted as a function of the number of load cycles, *log N* and the ratio of load cycles to the cycles at failure, $N/N_f$ for the two cases of embedded length with three load levels. No significant difference in crack growth for both cases could be recognized. From these figures the mechanism of crack growth of cone failure in fatigue loading could be summarized as the following steps :

a) After the first load cycle there is an initial circumferential crack length at the edge of bolt depending on the level of maximum loads.
b) With the increase of the number of load cycles the circumferential crack propagates in stable manner. Until 90% of load cycles ratio the crack grows slowly.
c) Then the crack grows acceleratedly prior to the final failure. This was confirmed by rapid increase of displacement as shown in **Fig. 6**. The rate change of crack growth or displacement could be referred as an indication that a fatigue failure would follow.

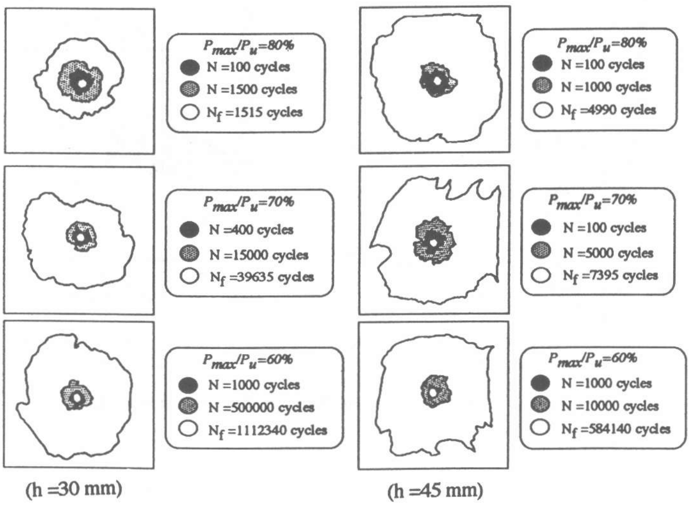



**Fig. 3** Typical crack area dyed by ink

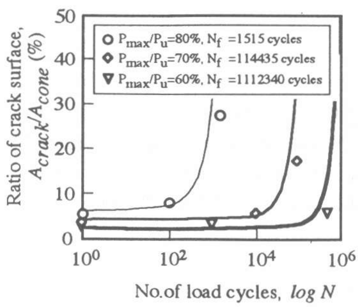



**Fig. 4** Crack growth with load cycles, *log N*

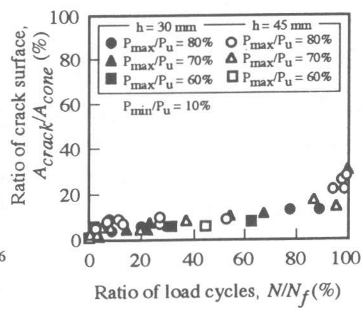



**Fig. 5** Crack growth with life ratio *N/Nf*

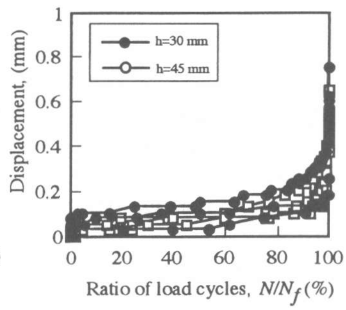



**Fig. 6** Displacement with life ratio *N/Nf*

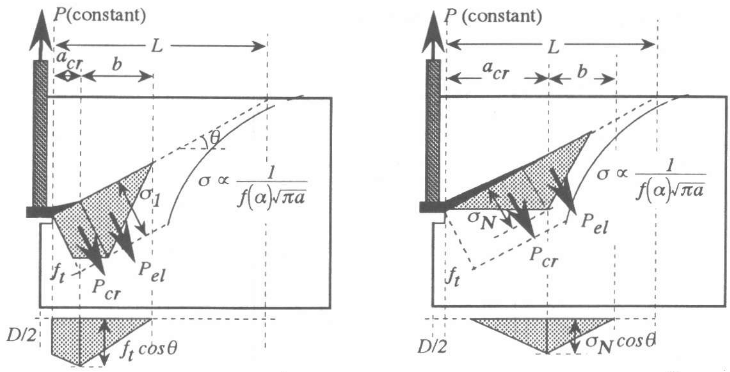
3.3 MODELING OF STRESS RESISTANT IN FATIGUE FRACTURE MECHANISM

In the fracture mechanics it is well known that the fracture process of concrere is governed by the existence of fracture process zone (FPZ). In the process zone stresses can still be transferred depending on the crack opening displacement [2]. Up to now, the length of this process zone obtained by test and computation are different from each other [3,4]. For the anchor system in static loading, Maruyama, et.al [5] and Eligehausen [6] reported that the ultimate capacity was reached when a relative crack length $a/L$ went up to 0.43~0.45. Taking these results into account, the stress resistant mechanism in fatigue fracture was modeled on the following assumptions :

a). Crack begins to propagate when a stress at tip of crack exceeds the maximum tensile stress, $f_t$ obtained from standard test.

b). After the first cycle of load there is an initial crack at the edge of a bolt with the length depending on the level of fatigue loading. The crack propagates with the increase of load cycles at an angle of $\theta$ ($\theta$ is an averaged value obtained from experimental results)

c). The applied load is resisted by both the elastic strength of the uncracked section of concrete and the bridging or interlocking action the cracked section or the fracture process zone (FPZ). The distribution of resistant stresses in uncracked and process zones is assumed to be a triangular shape and resultant forces were $P_{cr}$ and $P_{el}$, as shown in **Fig. 7**




(a) Stress diagram 1: After $1^{st}$ cycle
Stress at crack tip, $\sigma_1 = f_t$

(b) Stress diagram 2: After $N^{th}$ cycle
Stress at crack tip, $\sigma_N < f_t$

**Fig. 7 Stress resistant mechanism model in fatigue fracture**

Values of $P_{cr}$ and $P_{el}$ are given by

$$P_{cr} = 1/2\sigma_N.a_{fpz}.2\pi\left\{D/2 + 2/3a_{fpz} + \left(a - a_{fpz}\right)\right\} \tag{1}$$

$$P_{el} = 1/2\sigma_N.b.2\pi\left(D/2 + a + 1/3b\right) \tag{2}$$

where $a_{fpz}$ is a length of the fully fracture zone and $a$ is a crack length. The length of $a_{fpz}$ equal to $a$ when $a/L < 0.45$. $\sigma_N$ is the potential stress at crack tip at the $N^{th}$ cycle. Notations $b$, and $D$ are indicated in **Fig. 7**. The length of $b$ is assumed to be constant along propagation of crack. After first load cycle, $\sigma_N = f_t$. The potential stress $\sigma_N$ at the tip of crack for any crack length can be determined by,

$$P_{max} = \left(P_{cr} + P_{el}\right)\cos\theta \tag{3}$$

where $P_{max}$ denotes the constant applied load level.

**Fig.-8** shows the calculated potential stress at the tip of crack as a function of crack length for three load levels. In the beginning the potential stress decreases with increasing of crack length, but after the crack length exceeds the length of fracture zone (FPZ), the applied nominal stress decreases with increases of crack length and causes the potential stress at the crack tip turn to large and increases until failure occurs.

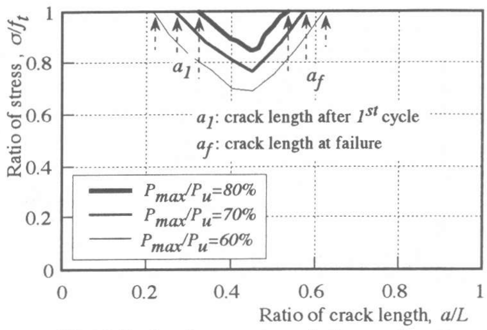



**Fig. 8** Ratio of stress at crack tip as a function of crack length

3.2 FATIGUE STRENGTH OF CONCRETE

Japan Society of Civil Engineers (JSCE) [7] has proposed an equatiom to predict a fatigue strength of concrete in compression, flexural compression, tension and flexural tension, as follow ;

$$log N = 17\left(1 - \frac{\sigma_{max} - \sigma_{min}}{f_u - \sigma_{min}}\right) \tag{4}$$

where $\sigma_{max}$, and $\sigma_{min}$ denote the maximum and the minimum applied stresses, and $f_u$ denotes the static strength.

**Fig. 9** shows the experimental results and a calculated relation by **Eq.(4)** in comparison with other results. Taking account of scattering of fatigue test data, it can be seen that the fatigue strength of concrete under pure tension, compression or flexure could be predicted reasonably by **Eq.(4)**, but for the case of concrete cone failure the equation looks somewhat unsafe. It might be attributed to the fact that **Eq.(4)** was originally based on the test results on the fatigue strength of concrete under uniaxial compression.

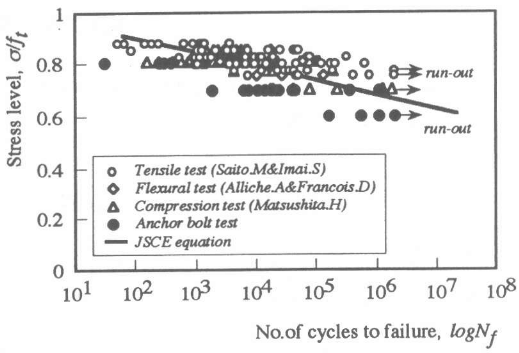



**Fig. 9 Fatigue strength of concrete in comparison to JSCE equation and other test results**

Using a variation of stress model as shown in **Fig. 8**, the **Eq.(4)** is again applied to calculate the fatigue strength of concrete in anchor system. After the firts cycle there is an initial crack length, $a_i$ with stress level $\sigma/f_t$ equal to unity. Due to a number of load cycles, crack propagates with a certain length and stress decreases to a certain level. A number of load cycles that is required to create a certain crack length is calculated by an **Eq.(4)**. This procedure is again applied for the new stress level and crack length until failure occurs. The fatigue strength is cumulative number of load cycles which is required to create total crack length, $a_f$ at failure.

**Fig. 10** shows calculated crack growth in comparison to the experiment results. In general the proposed model could represent a tendency of crack growth. The calculated fatigue strength of proposed model and the test results as well as that by an equation of JSCE is shown in **Fig. 11**. From this figure it could be seen that calculated results by the proposed model show a good agreement with experiment results.

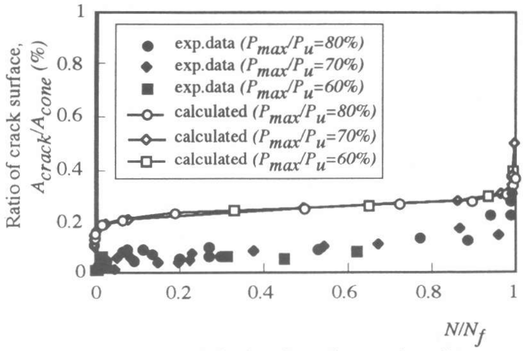



**Fig. 10** Calculated crack growth and exp. results with life ratio, $N/N_f$

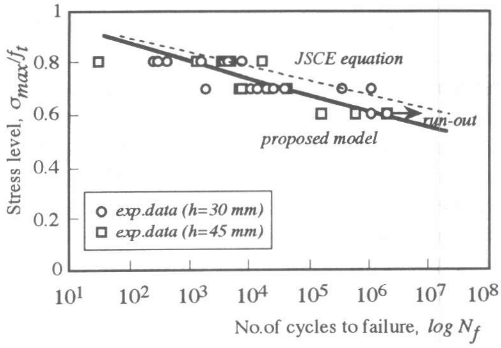



**Fig. 11** Fatigue strength by proposed model, exp. results and JSCE equation

## 4. CONCLUSIONS

From this study the folowings could be concluded :

1. With the increase of load cycles the circumferential crack of cone failure propagates in stable manner and until 90% of load cycles ratio the crack grows slowly. Prior to the final failure, the crack growth and displacement increase significantly.
2. A simple model of crack growth mechanism for concrete cone failure in anchor system was introduced. The proposed model could represent a tendency of crack growth and predict the fatigue strength of concrete practically.

## ACKNOWLEDGEMENT

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