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| Author(s) | Sakino, Yoshihiro; Kim, You-Chul |
| Citation | Transactions of JWRI. 2009, 38(2), p. 95-101 |
| Version Type | VoR |
| URL | https://doi.org/10.18910/11974 |
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# Applicability of Thin Steel Plate with a Crack to Estimating of Fatigue Damage on Bridges† (Report II)
## –Effect of delayed retardation and applicability under fluctuating amplitude loads–

SAKINO Yoshihiro* and KIM You-Chul**

**Abstract**

*Thin steel plates, which have initial crack at the center, are used as "Sacrificial Test Pieces" in this study. The Sacrificial Test Piece is attached to a bridge member in order to evaluate the damage before appearance of a crack in the member. The purpose of this study is to clarify the effect of delayed retardation and to show the applicability of the thin steel plates as sacrificial test pieces under fluctuating amplitude loads. The fatigue damage parameters calculated by crack propagation length of thin steel plates under some fluctuating amplitude loads are compared with those calculated by the stress measurement.*

*From the results, the crack propagation lengths in the thin steel plates are affected by the delayed retardation of the crack propagation under fluctuating amplitude loads. However, it is shown that the relation between the fatigue damage parameter and the crack propagation length is almost linear through the hastening of the crack propagation after delayed retardation. And it is verified that the absolute value of the fatigue damage parameter can be monitored by the crack propagation length of the thin steel plates even under fluctuating amplitude loads.*

**KEY WORDS:** (Fatigue) (Bridge Maintenance) (Fatigue Damage Parameter) (Crack Growth) (Sacrificial Test Piece) (Fluctuating Amplitude Loads) (Delayed Retardation)

## 1. Introduction

"The sacrificial test piece" is used as a specimen attached to the member of a main structure in order to evaluate the damage before the appearance of a crack in a member of that structure. The sacrificial test piece is designed so that it is damaged earlier than the main members under the same loads because of crack and stress magnification. The damage to the bridge members can be estimated by the observation of the sacrificial test piece. If the fatigue damage parameter can be made clear by the behavior of the sacrificial test piece, the maintenance management of the structure can be determined. Some types of sacrificial test piece are proposed and investigations to apply these to the structures are going on[1)-4)].

As shown in **Fig. 1**, thin steel plates, which have initial cracks at the center, are used as the sacrificial test pieces in this study. When strains are applied to the

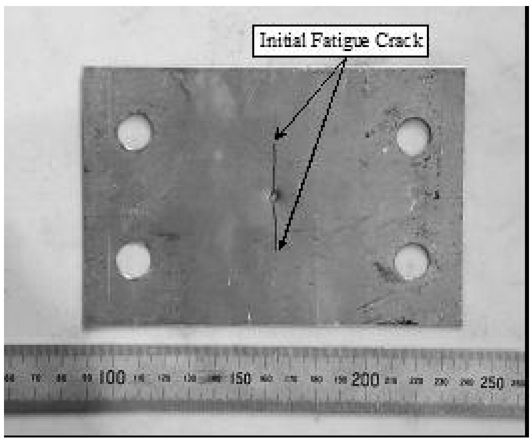


**Fig. 1** Sacrificial test pieces

† Received on December 18, 2009

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Transactions of JWRI is published by Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan

main member, these are transmitted from the main member to the thin steel plate and the crack in the thin steel plate will grow as a result. Therefore, the monitoring of fatigue damage parameters on the bridge can be carried out by the observation of the crack growth in the thin steel plate. If the thin steel plate can be used as the sacrificial test piece, it seems that fatigue damage on a bridge can be monitored widely. Because the thin steel plate is cheap, everyone can obtain it easily. In the previous research, the applicable range of crack length and the crack propagation properties of the thin steel plate to evaluate the fatigue damage parameter were obtained. And it was suggested that the fatigue damage parameter under constant amplitude loads can be estimated by the thin steel plate with practical accuracy[5)-7)].

The purpose of this study is to clarify effect of delayed retardation and to show the applicability of the thin steel plates as the sacrificial test pieces under the fluctuating amplitude loads. The fatigue damage parameters calculated by crack propagation length of thin steel plates under some fluctuating amplitude loads are compared with those calculated by the stress measurement[8), 9)].

## 2. Outline of Measurement of Fatigue Damage Parameter by Sacrificial Test Piece

### 2.1 Fatigue damage parameter

According to the Miner's law, damage of a bridge member by forced fluctuating amplitude loads can be written as follows;

$$\sum\left(\sigma_i^{\mathrm{m}} n_i\right) \tag{1}$$

where $\sigma$ is stress amplitude, $n$ is number of cycles and lower suffix $i$ is the operation number.

Equation (1) is termed "the fatigue damage parameter"[10), 11)]. We propose a method for measuring these fatigue damage parameters by crack growth of sacrificial test pieces. The basic theory and assumptions are as follows;

1) The crack at the center of the sacrificial test piece grows by the stress that is transmitted from the member to the sacrificial test piece.

2) The relationship between a stress intensity factor coefficient of the live load and the crack growth, which is generated by the stress intensity, is expressed by Paris' law as follows;

$$\mathrm{d}a_i/\mathrm{d}n_i = \mathrm{A}\left(\Delta K_i\right)^{\mathrm{m}} \tag{2}$$

where $a$ is the crack growth, $\mathrm{A}$ and $\mathrm{m}$ are constants.

3) The stress intensity factor coefficient under constant displacement amplitude can be expressed as follows[12)];

$$K_i = \mathrm{B}\sigma_i \tag{3}$$

where $\mathrm{B}$ is a constant.

Equation (3) shows that the stress intensity factor for the constant displacement amplitude testing can be expressed solely as the function of stress amplitude "$\sigma$", and can be expressed without considering the effect of crack length "$a_i$".

4) Substituting Eq. (3) in Eq. (2), produces Eq. (4);

$$\mathrm{d}a_i/\mathrm{d}n_i = \mathrm{A}\left(\mathrm{B}\Delta\sigma_i\right)^{\mathrm{m}} \tag{4}$$

It follows from Eq. (4), that;

$$a_i = \mathrm{A\,B^m}\left(\sigma_i^{\mathrm{m}} n_i\right) \tag{5}$$

5) The crack growths due to each stress component of live load do not affect each other and can be summed simply. Thus the total crack growth can be written as follows;

$$\sum\left(\sigma_i^{\mathrm{m}} n_i\right) = a/\mathrm{AB^m} \tag{6}$$

where $a$ is the total crack growth.

The constant A, B and m can obtain by examination or theoretical calculation in advance. So by these assumption, if $a$ is measured, the fatigue damage parameter (Eq. (1)) can be obtained via Eq. (6).

From some experiments and investigations, the constant A, that should be obtained by measuring the crack propagation velocity under the same stress amplitude, was determined as $\mathrm{A} = 7.94\mathrm{x}10^{-12}$. And the restraint coefficient B can be also decided by theoretical calculation, which depends on the size of the thin plate[5)-7)]. For the constant m, m=3 is widely used[13), 14)].

### 2.2 Application to bridge members

The sacrificial test piece was attached to four steel jig-plates by bolts. The shape and the dimensions of the jig-plates are shown in **Fig. 2**. The thickness of the sacrificial test piece is 0.5 mm, and the thickness of one side edge of the jig-plate is 12mm and other part of the jig-plate is 10mm. Using the jig-plates, the strain between the connected points is concentrated at the sacrificial test piece by the difference in stiffness between the thin plate and the jig-plate. Strain in the sacrificial test piece is concentrated more than about 3 times that of the bridge member by theoretical calculation. This strain concentration makes the crack growth faster, and the measurement in bridge members can be carried out in a short period.

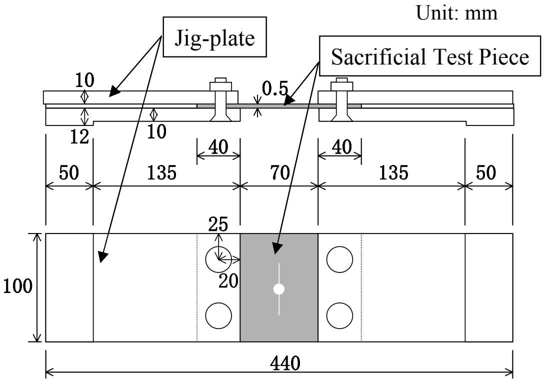


**Fig. 2** Sacrificial test pieces with jig-plates

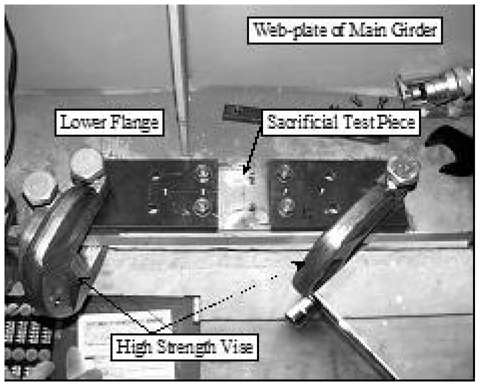


**Fig. 3** Example of attachment to lower flanges of a highway bridge.

To avoid compression loads on the sacrificial test piece by uplift of the bridge member, a pre-tensile stress is applied to the sacrificial test piece by heating the specimen before attaching to the member. After the specimen is attached, the temperature of the specimen falls to room temperature and pre-tensile stress will be forced into the sacrificial test piece because of thermal deformation.

The specimen is attached on the lower flange of bridge members with high strength vices at the edge of the jig-plates, as shown in **Fig. 3**. The high strength vices are often used on site for rigid fixing, and the vice is tightened up using a torque wrench.

### 2.3 Applicability under constant amplitude loads

To study the applicability of this method under constant amplitude loads, the thin steel plates were examined by three-point bending fatigue test, shown in **Fig.4**. The thin steel plates are fixed in the proposed way and jig-plates in the lower flange of H-section beam that are modeled from the highway bridge member. **Figure 5** shows the comparison between the fatigue damage parameters measured by the crack length of the sacrificial test pieces under the constant amplitude loads and those calculated by the stress amplitude and loading times (stress measurement). The horizontal axis represents the value of the fatigue damage parameter by sacrificial test piece and the vertical axis represents those of stress measurement.

Depending on the demanded accuracy, it seems that they approximately agree as estimates of the fatigue damage parameter. In particular, the means of each series agree well in all ranges of the fatigue damage parameter. So it can be said that the proposed method is valid under constant amplitude loads. This demonstrates that the thin steel plate as a sacrificial test piece can estimate the fatigue damage parameter with practical accuracy under constant amplitude loads.

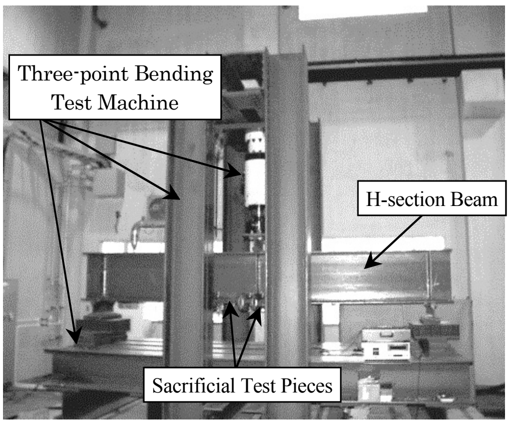


**Fig. 4** Constant amplitude loads test using by three-point bending fatigue test machine

## 3. Monitoring under fluctuating amplitude loads

### 3.1 Sudden decrease-increase loads

As a first step, the sudden decrease-increase loads pattern, shown in **Fig. 6**, is used in the three-point bending fatigue test. This experiment is planned to make clear that the delayed retardation of crack propagation occurs in the thin steel plate or not under the fluctuating amplitude loads.

Relations between the crack propagation velocity

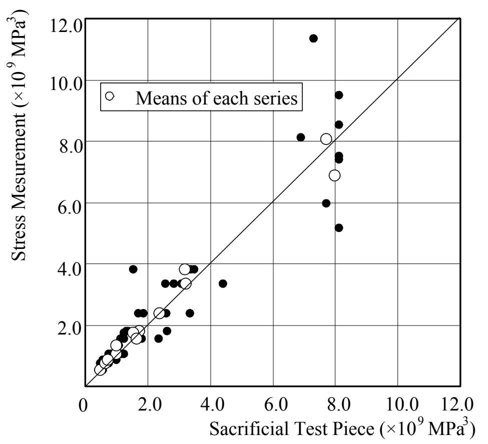


**Fig. 5** Comparisons of fatigue damage parameter

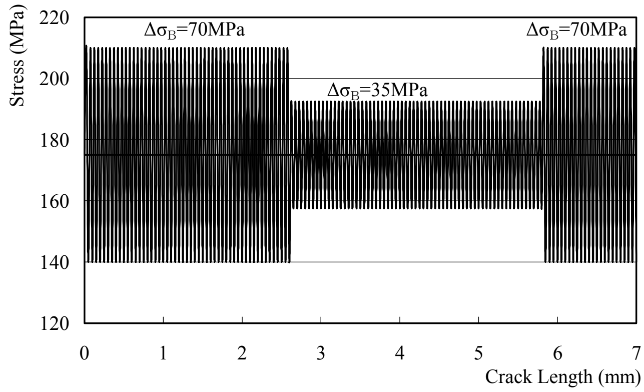


**Fig.6** Sudden decrease-increase loading pattern

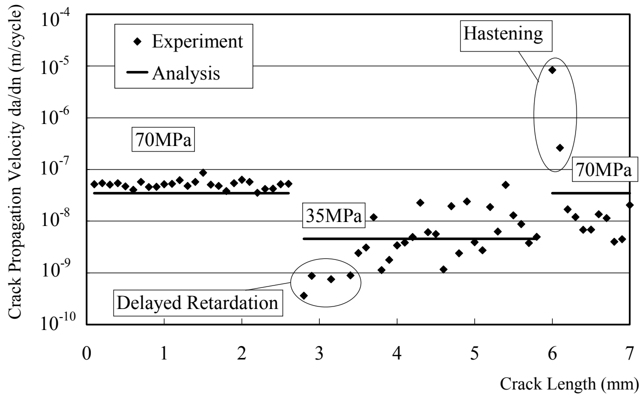


**Fig.7** Relation between crack lengths and crack propagation velocity under sudden decrease-increase loading pattern

and the crack length are shown in **Fig. 7**. Solid lines show theoretical crack propagation velocities. If the crack propagation property under the sudden decrease-increase loads is similar to that under constant amplitude loads, experimental crack propagation velocities under the sudden decrease-increase loads should be on the solid lines. But just after changing of stress amplitude from 70MPa to 35MPa, the delayed retardations are actually observed. And hastening of crack propagation is also observed just after changing of stress amplitude again from 35MPa to 70MPa. This phenomenon is observed in all specimens.

So it can be considered that the delayed retardation and the hastening affect the crack propagation velocity under the fluctuating amplitude loads.

### 3.2 Gradual increase-decrease loads

As a next step, the gradual increase-decrease loads, which has 166,465 times of frequency per a period, is used in this experiment. One period of this loading pattern is shown in **Fig.8**. As shown in **Fig.9**, this loading pattern is made up by reference to stress frequency distributions, were measured by a site experiment in actual highway bridges[15),16)]. However, the absolute values of stress amplitude are increased 1.5 times to shorten the experiment period. The Stress frequency distribution, which is used in the gradual increase-decrease loads, is shown in **Fig. 10**. 8 periods of loads are forced to the H-section beam, in which 4 set of the thin steel plates are fixed.

Relations between the crack length and the fatigue damage parameter calculated by stress measurements

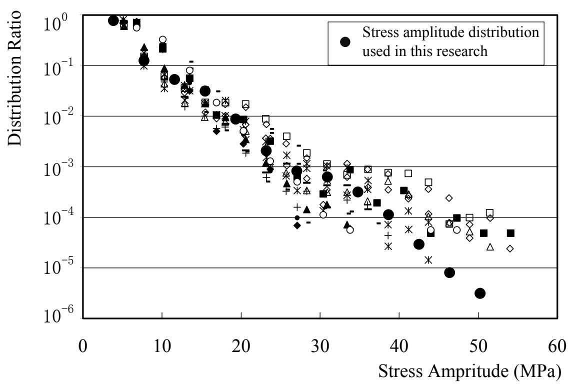


**Fig.9** Stress frequency distribution measured in highway bridge actually[15,16)]

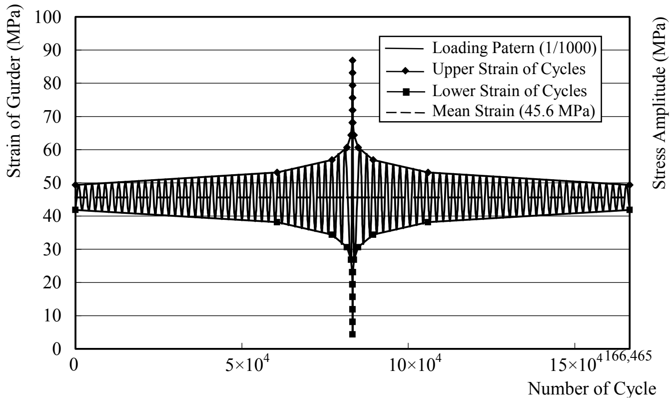


**Fig.8** Gradual increase-decrease loading pattern

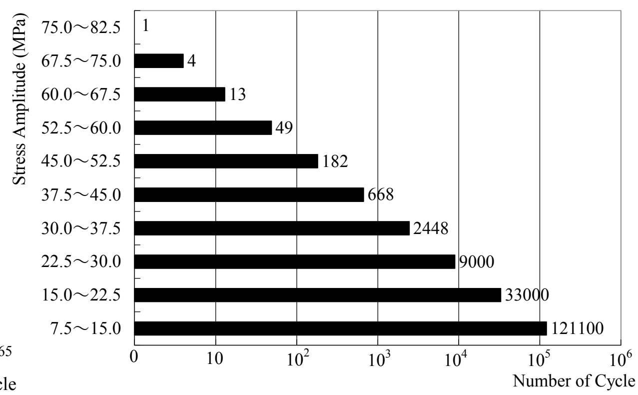


**Fig.10** Stress Frequency Distribution used in the Gradual increase-decrease loading pattern

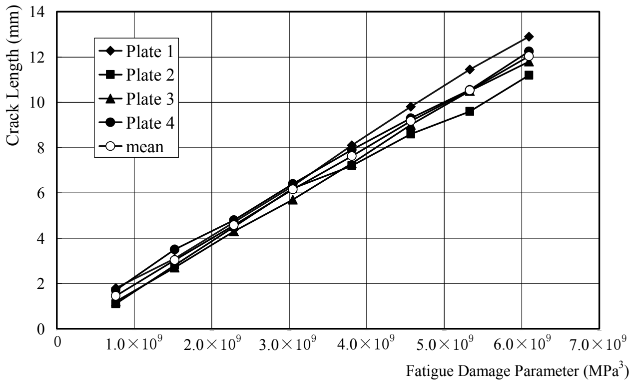


**Fig. 11** Relations betwee crack lengths and fatigue damage parameter calculated by stress measurement under gradual increase-decrease loadings

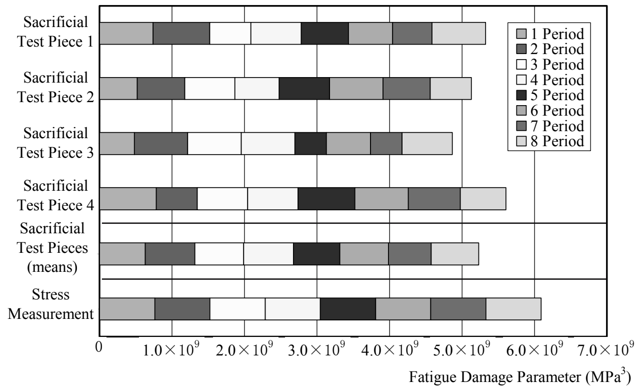


**Fig.12** Comparisons of fatigue damage parameter calculated by thin steel plates (Sacrificial Test Pieces) and stress measurement under gradual increase-decrease loads

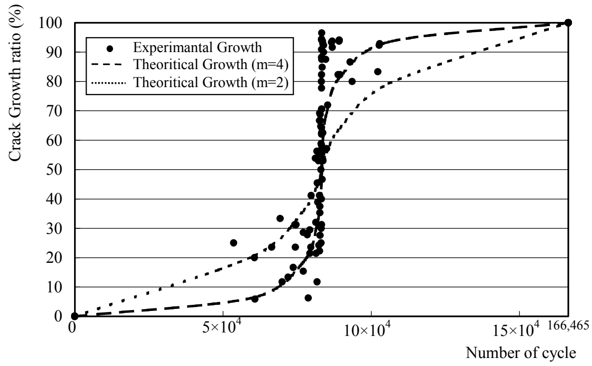


**Fig. 13** Crack growth ratio distribution in one loading period

under the gradual increase-decrease loads are shown in **Fig.11**. The relation between the fatigue damage parameter and the crack propagation lengths in the thin steel plates are almost linear even under the gradual increase-decrease loads. Also under this pattern of fluctuating amplitude loads, it is shown experimentally that Eq.(6) can be used.

**Figure 12** shows comparison of the fatigue damage parameter calculated by the thin steel plates (sacrificial test pieces) and those calculated by stress measurement. The absolute values of the fatigue damage parameter of the thin steel plates obtained by substituting for m =3 and A = $7.94 \times 10^{-12}$ are approximately in agreement with those of stress measurement. Also under this pattern of fluctuating amplitude loads, it is clear that the thin steel plates can estimate the fatigue damage accurately.

**Figure 13** shows crack growth ratio distributions per one loading period under the gradual increase-decrease loads. Dotted line and broken line show theoretical crack growth distributions in the case of m=2 and m=4. In the experiment under the constant amplitude loads, m is nearly 3 and never more than between 2 and 4 in any lot and series. If the crack propagation property under the gradual increase-decrease loads is similar to that under constant amplitude loads, experimental crack growth under the gradual increase-decrease loads should be in between dotted line and broken line. But some of black dots (experimental crack growth) are outside these lines. It seems that this is also the effect of the delayed retardation and the hastening of the crack propagation.

### 3.3 Pulse-type loads

To make clear the effect of the delayed retardation and the hastening of the crack propagation to the monitoring of the fatigue damage parameter under the fluctuating amplitude loads, the thin steel plates are examined under pulse type loads. The loading pattern is shown in **Fig.14**. It seems that this pulse-type loading pattern is one of the most sensitive loading patterns for the delayed retardation and hastening of the crack propagation. 4 periods of loads are forced to the H-section beam, on which 4 sets of the thin steel plates are fixed.

Relations between the crack lengths and the fatigue damage parameters calculated by the thin steel plates under the pulse-type loads are shown in **Fig.15**. The relation between the fatigue damage parameter and the crack propagation lengths in the thin steel plates are approximately linear and it is shown experimentally that Eq.(6) can be used even under the pulse-type loads.

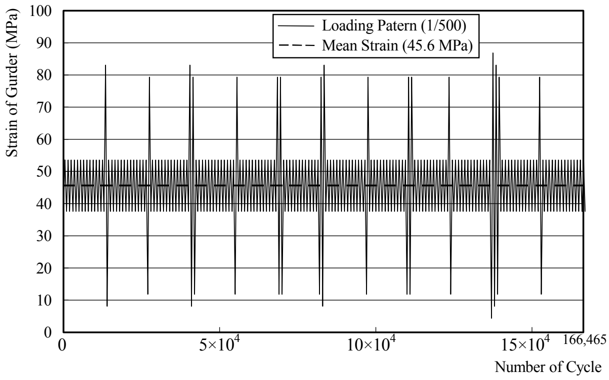


**Fig. 14** Pulse-type loading pattern

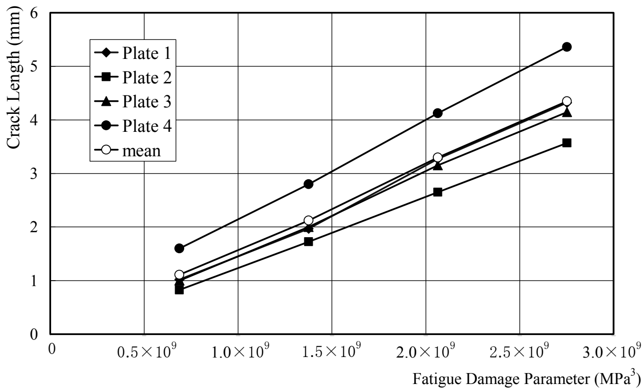


**Fig. 15** Relations between crack lengths and fatigue damage parameter calculated by stress measurement under pulse-type loads

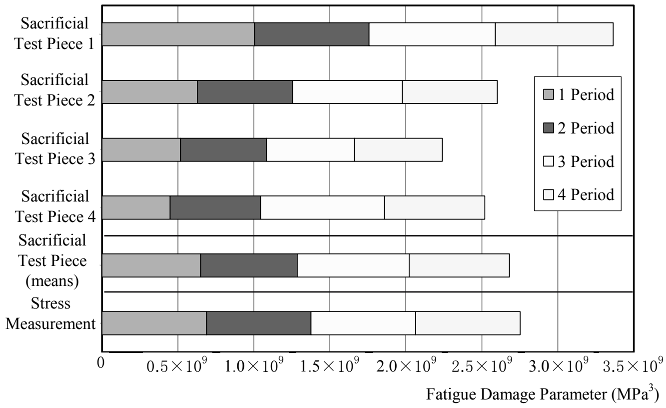


**Fig.16** Comparisons of fatigue damage parameter calculated by crack length of thin steel plates (Sacrificial Test Pieces) and stress measurement under pulse-type loads

The fatigue damage parameters measured and calculated by the thin steel plates (sacrificial test pieces) under the pulse-type loads are compared with those calculated by the stress measurement in **Fig.16**,. Under the pulse-type loads, the absolute values of the fatigue damage parameters approximately agree. In particular the means of 4 thin steel plates agree well.

So it can be considered that the relation between fatigue damage parameter and the crack propagation length in the thin steel plates are affected by the delayed retardation and the hastening of the crack under the fluctuating amplitude loads. But Eq.(6) can be used to monitor the fatigue damage parameter by the thin steel plate even under the fluctuating amplitude loads.

## 4. Conclusions

The method to monitor the fatigue damage parameter on bridge members by the thin steel plate as the sacrificial test pieces is proposed. By using this method, the fatigue damage parameter can be estimated with lower cost than by conventional methods. In this paper, the effect of delayed retardation is clarified and the applicability of the thin steel plates as the sacrificial test pieces under the fluctuating amplitude loads are investigated. The fatigue damage parameters calculated by crack propagation length of thin steel plates under some fluctuating amplitude loads are compared with those calculated by the stress measurement.

Main results are summarized as follows.

(1) The crack propagation lengths in the thin steel plates are affected by the delayed retardation of the crack propagation under the fluctuating amplitude loads. However, relation between the fatigue damage parameter and the crack propagation length in the thin steel plates is almost linear comparing in each period by the effect of hastening of the crack propagation after delayed retardation even under the fluctuating amplitude loads.

(2) The absolute value of the fatigue damage parameter can be monitored approximately by the crack length in the thin plates even under the fluctuating amplitude loads that were used in this research.

## Acknowledgments

The authors would like to thank Mr. Sakai K and Mr. Nakatsuji Y. for their help during the experiments. And this study was financially supported in part by the Grant-in-Aid for Young Scientists from JWRI.


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