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Applicability of Thin Steel Plate with a Crack to Estimating of Fatigue Damage on Bridges† (Report I)
–Investigation of estimating method and applicability under constant amplitude loads–

SAKINO Yoshihiro*, KIM You-Chul** and HORIKAWA Kohsuke***

Abstract

Thin steel plates, which have initial cracks at the center, are used as the Sacrificial Test Pieces in this study. "The Sacrificial Test Piece" is attached to the member of a main structure in order to evaluate the damage before the appearance of a crack in the member of the main structure. The purpose is to show the practical applicability of "the thin steel plate with crack as the Sacrificial Test Piece" for monitoring the fatigue damage parameters on bridge members. In this research, it is decided that the applicable range of crack length and the crack propagation properties of the thin steel plate to evaluate the fatigue damage parameter are obtained. And it is suggested that the fatigue damage parameter under constant amplitude loading can be estimated by the thin steel plate with practical accuracy.

KEY WORDS: (Fatigue) (Bridge Maintenance) (Fatigue Damage Parameter)(Crack Growth) (The Sacrificial Test Piece)(Thin steel plate)

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 the main 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 the Sacrificial Test Piece are proposed[1)-4)] and investigations to apply these to the structures are going on.

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 [5)-7)]. When strains are applied to the 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

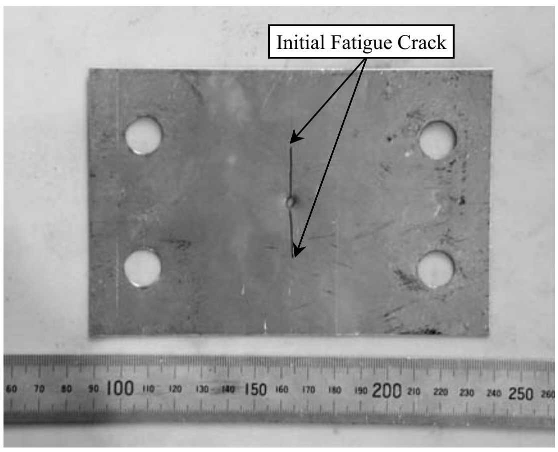

Fig.1 Sacrificial test pieces

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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 at a low price and widely. Because the thin steel plate is cheap, everyone can obtain it easily.

In this paper, the estimating method for the fatigue damage parameter by crack growth of the thin steel plate is investigated, and the crack propagation properties and applicable range of crack length of the thin steel plate as the Sacrificial Test Pieces to evaluate the fatigue damage parameter are obtained through a numbers of tests. The applicability of this method under constant amplitude loading is also investigated.

2. Monitoring of fatigue damage parameters

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

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

where

$\Delta\sigma_i$: stress amplitude (MPa)

n_i : Number of cycles by $\Delta\sigma_i$

Eq(1) is called "the fatigue damage parameter"[8),9)]. Generally the fatigue damage parameter can be calculated from $\Delta\sigma_i$ and n_i measured by strain gauges and a data recorder.

We propose a method for measuring these fatigue damage parameters by the crack growth of the thin steel plate. The basic theory and assumptions are shown as follows;

1) The crack at the center of the thin steel plate grows by the stress that is transmitted from the member to the thin steel plate.

2) The relationship between a stress component of the live load and the crack growth, which is generated by the stress component, 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_i : Crack growth by $\Delta\sigma_i$ (m)

A : Constants fixed by material

m : Constants fixed by material (=3)

ΔK : Amplitude of the stress intensity factor. (MPa・m$^{1/2}$)

3) The amplitude of the stress intensity factor under constant displacement amplitude can be expressed as follows[10)];

$$\begin{aligned}\Delta K_i &= \frac{\mathrm{E}}{\sqrt{1-\nu^2}}\frac{v_0}{\sqrt{\mathrm{H}}} = \sqrt{1-\nu^2}\sqrt{\mathrm{H}}\cdot\Delta\sigma_i \\ &= \mathrm{B}\Delta\sigma_i\end{aligned} \tag{3}$$

where

v_0 : Displacement of rigid body

$= \dfrac{\Delta\sigma_i}{\mathrm{E}}(1-\nu^2)\mathrm{H}$ (cm)

2H : Distance of rigid body (cm) (Effective length)

E : Young's modulus (MPa)

ν : Poisson's ratio

B: Constants fixed by " H " (Restraint coefficient) $= \sqrt{1-\nu^2}\sqrt{\mathrm{H}}$

Eq.(3) shows that the amplitude of the stress intensity factor for the constant displacement amplitude can be expressed only as the function of the stress amplitude " $\Delta\sigma_i$ ", and can be expressed without considering the effect of crack length " a_i ".

4) Substituting eq.(3) in eq.(2), eq.(4) is produced;

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

Assuming the crack growths due to each stress component of live load do not affect each other and can be summed simply, total crack length " a " is expressed from eq(4) as follows;

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

5) From eq(5), a relation between the fatigue damage parameter and the total crack length is obtained as follows;

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

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

3. Application to bridge members

In the proposal of the Sacrificial Test Piece, some ways to fixing to the main member were contrived[1)-4)]. In this research, fixing ways that satisfy the following three requirements are investigated to apply to the bridge members.

1) To control the sensitivity of the Sacrificial Test Piece and measuring period by amplification of stress amplitude.

The thin steel plate has been attached to four steel jig-plates by some bolts. The shape and the dimension of the jig-plates are shown in **Fig.2**. The thickness of the thin steel plate 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, a strain between the connected points is concentrated at the thin steel plate by the difference in stiffness between the thin plate and the jig-plate. In the case of the size shown in Fig.2, strain in the thin steel plate is concentrated more than about 3 times that of the flange by theoretical calculation. By this strain concentration, stress amplitude in the thin steel plate is also amplified about 3 times.

In this paper, a rate of stress increase is named "stress increase ratio α". Substituting eq.(7) in eq.(5), eq.(8) is produced;

$$\Delta\sigma_i = \alpha \cdot \Delta\sigma_{Bi} \tag{7}$$

$$a = \alpha^{\mathrm{m}} \cdot \mathrm{A\,B^m} \sum \left(\Delta\sigma_{Bi}{}^{\mathrm{m}} n_i \right) \tag{8}$$

where

$\Delta\sigma_{Bi}$: Stress amplitude of bridge member (MPa)

As shown in Eq.(8), The amplification of stress amplitude makes the crack growth α^{m} times faster, and the measurement in bridge members can be carried out in a short period. The measuring period is also controlled by changing the length of the jig-plate.

Substituting eq.(7) in eq.(6), a relation between the fatigue damage parameter of a bridge member and the total crack length is obtained as follows;

$$\sum \left(\Delta\sigma_{Bi}{}^{\mathrm{m}} n_i \right) = a / (\mathrm{A\,B^m}\,\alpha^{\mathrm{m}}) \tag{9}$$

2) To apply the pre-tension to the thin steel plate in order to use on the in-service bridge member.

To avoid compression loading on the thin steel plate by uplift of the bridge member, pre-tensile stress is applied to the thin steel plate by heating the specimen before attached 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 thin steel plate because of thermal deformation.

3) To fix the thin steel plate as the Sacrificial Test Piece rigidly to the bridge member without new stress concentration.

In this study, the specimen is attached on the lower flange of bridge members by 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. The high strength vice does not need a drilled hole and does not need to be welded to the main member. The high strength vice is more durable as compared to an adhesive.

To verify the applicability of the way of fixing, A

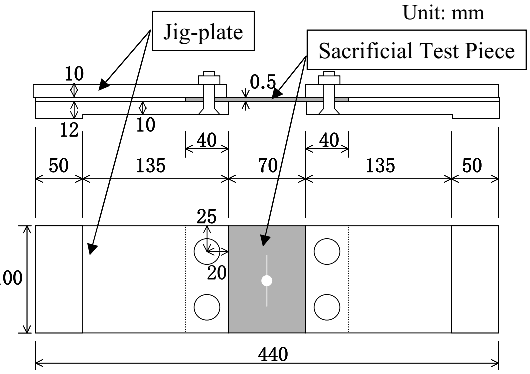

Fig.2 Sacrificial test pieces with jig-plate

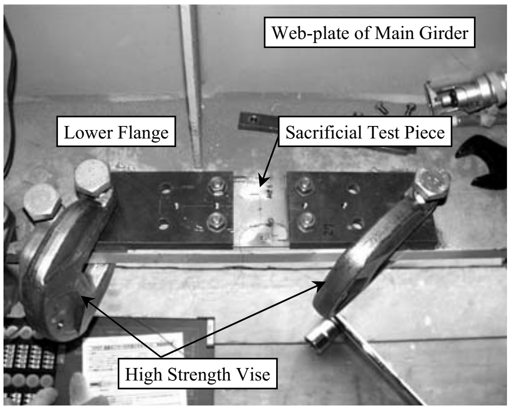

Fig.3 Example of attachment to lower flanges of a highway bridge

practical field test was done on a highway bridge, as shown in Fig.3. As a result, it was ascertained that the stress amplitude is amplified by using the jig-plate and the pre-tension can be applied in the proposed way.

4. Decision of restraint coefficient

Amplitude of the stress intensity factor ΔK used in this study is expressed as eq.(3) and ΔK is directly proportionate to the stress amplitude $\Delta\sigma_i$. Constant of proportionality B is expressed as follows;

$$\mathrm{B} = \sqrt{1-\nu^2}\sqrt{\mathrm{H}} \tag{10}$$

As shown in eq.(10), B is function of H and H is the

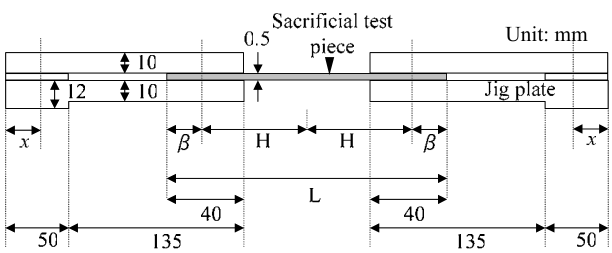

Fig.4 Definition of L, H, β, x

distance of the rigid body. In this study B is named "restraint coefficient" and H is named "effective length". The thin steel plate as the Sacrificial Test Piece and the jig-plates are fixed by countersunk bolt. The effective length is not clear because of joining by bolts.

Figure 4 shows definition of L, H, β and x. L is the full length of the thin steel plate and β is the distance from the edge of the thin steel plate to the point from where the jig-plate is regarded as the rigid body. Assuming that the value of β is constant in spite of the value of L, following equation is obtained.

$$H = L/2 - \beta \tag{11}$$

According to eq.(11), the relation between L and H should be linear with a slope of 0.5.

On the other hand, the stress increase ratio α by the jig-plate is expressed using L, H and x as follows;

$$\alpha = \frac{L + 29 - 2x}{1.95H + \dfrac{(L+19)\times 0.05/2 + 2x \times 0.05/2.2}{1.95}} \tag{12}$$

Eq.(12) can transform as follows;

$$H = \frac{L + 29 - 2x - \alpha\left\{(L+19)\times 0.05/2 + 2x \times 0.05/2.2\right\}}{1.95\alpha} \tag{13}$$

So an experiment to estimate stress increase ratio α using some length of the thin steel plate was performed and the relation between L and H was obtained by substituting α in eq.(13). The values of x, H and β were obtained and because the slope of the L - H relation should be 0.5, B can be decided.

Thin steel plates with four sizes of L (10cm, 20cm, 25cm and 30cm) were used in the experiment as shown in **Fig.5**. Initial fatigue cracks did not exist at the center.

The three-point bending fatigue test machine, shown in **Fig.6**, was used. The thin steel plates with jig-plates are fixed by the way proposed in chapter 3 on the lower flange of an H-section beam modeled from the highway bridge member. The section size and length of H-section beam were 600×300×12×19mm and 4,000mm. Strain gauges were pasted on the center of the thin steel plates and on the same place of the H-section beam. Then static load was forced to the center of the H-section beam by a 500kN actuator and strain of the thin steel plates and the H-section beam was measured. From these, the stress increase ratio α was calculated. Load step was every 50kN from 0kN to 400kN and this load series was repeated three times.

Figure 7 shows the relation between L and H that was converted from α. Plots are means of every load series and a solid line is regression line with the slope fixed as 0.5. The regression equation is express as follows;

$$H = 0.5L - 0.84 \tag{14}$$

A difference of the plots is small and the plots agree with the regression line well.

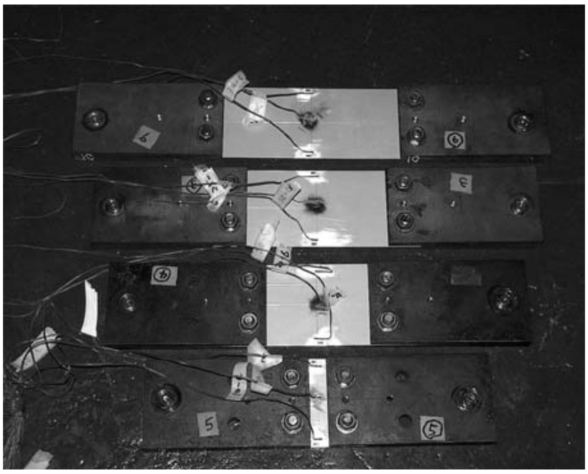

Fig.5 Specimens for decision of restraint coefficient

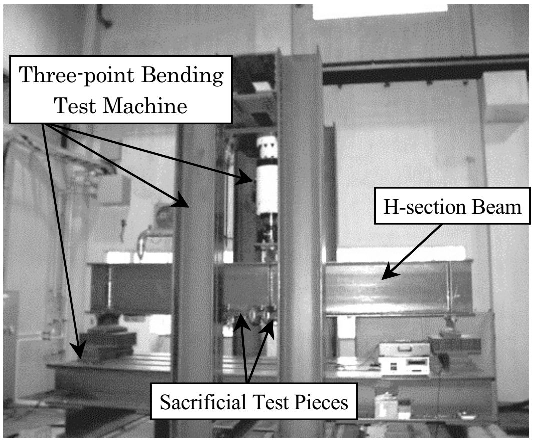

Fig.6 Monotonic amplitude loading fatigue test by three point bending test machine

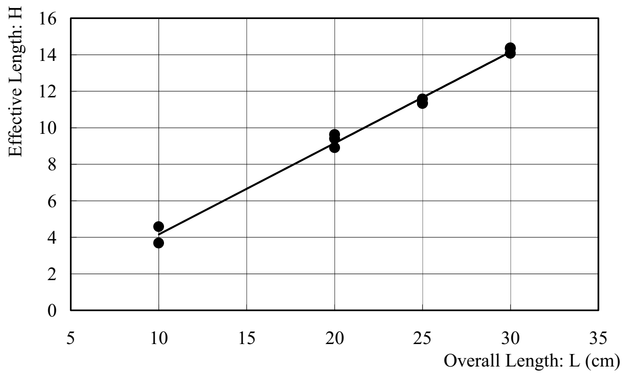

Fig.7 Effective lengths H — overall length L relationship

From these results, x =1.46cm is obtained by the requirement that slope of the L - H relation should be 0.5 and β =0.84cm is obtained from the intercept regression equation. In the case of the full length L of the thin steel plate that used in this research (L=15cm), H = 6.66cm is obtained from these values. Substituting H = 6.66cm in eq.(11), the restraint coefficient B =0.246 is decided.

Test results indicate the assumption that value of β is constant in spite of value of L is correct, because the plots agree with the regression line that the slope is 0.5. So in the case that the thickness and width of the thin steel plate are 0.5mm and 100mm, the restraint coefficient B can be calculated easily by the eq.(15), using the full length of the thin steel plate L and Poisson's ratio ν .

$$B = \sqrt{1-\nu^2}\sqrt{0.5L\text{-}0.84} \quad (15)$$

5. Applicable range of crack length

As one can see from eq.(4), the crack propagation velocity "da/dn" is not affected by crack length "a". So the crack propagation velocity should remain stable under the constant stress amplitude in all ranges. But eq.(3) is valid only in the case that both of the plate width and the crack length are infinite. The plate width and the crack length in the shin steel plate are not infinite, so we should make clear the applicable range of the crack length that eq.(3) and eq.(4) can be valid.

Figure and photo of applicable range test are shown in **Fig.8**. A couple of the thin steel plates are fixed to front and back of the main member whose thickness is 9mm without jig-plates. Backing plates are put between the main member and the thin steel plates and then the thin steel plates and backing plates are fixed by the high strength vices. Material of the main member and backing plates are mild steel.

The crack length of the thin steel plates was measured every 10,000 cycle of the constant amplitude loading by uniaxial fatigue machine. Scale-readout microscope was used to measure the length of crack. Three ranges of stress amplitude, 60MPa, 80 MPa and 120 MPa, were loaded and stress ratios were 0.33, 0.27 and 0.2, respectively. One series of test (two thin plates) in case of 60MPa and 80 MPa, and two series of test (four thin plates) in case of 120MPa were run.

Figure 9, **Fig. 10** and **Fig. 11** show the crack propagation velocity $\Delta a/\Delta N$ and the crack length a relationship under the constant stress amplitude. No.1 and No.2 show the data of right side crack and left side crack in the front thin steel plate. No.3 and No.4 show the data of right side crack and left side crack in the back thin steel plate. No.5 ~ No.8 are the same in the second series of tests.

As mentioned above, the crack propagation velocity should remain stable under the constant stress amplitude because the crack propagation velocity is not affected by crack length. So it can be said that the stable range of the crack propagation velocity is the applicable range of the thin steel plate as the sacrificial test piece.

According to the results, the crack propagation velocity from 2cm to 4cm of the crack length remains approximately stable regardless of the stress amplitude. A cause of unstability of the crack propagation in the area under 2cm seems that the crack length is too short to satisfy the qualification of semi-infinite crack length. A cause of unstablility of the crack propagation in the area over 4cm seems that the ligament length is too short to satisfy of qualification of semi-infinite ligament length.

So in the case of the steel plate of 10 cm in width that used as the Sacrificial Test Piece in this research, it can be said that the applicable range of the crack length in the thin steel plate is from 2cm to 4cm.

6. Crack propagation properties under constant amplitude loading

In case of calculating the fatigue damage parameter from the crack length a by eq.(9), the constant A and m should be decided besides the restraint coefficient B that was decided in the chapter 4. These constants are decided by measuring the crack propagation velocity

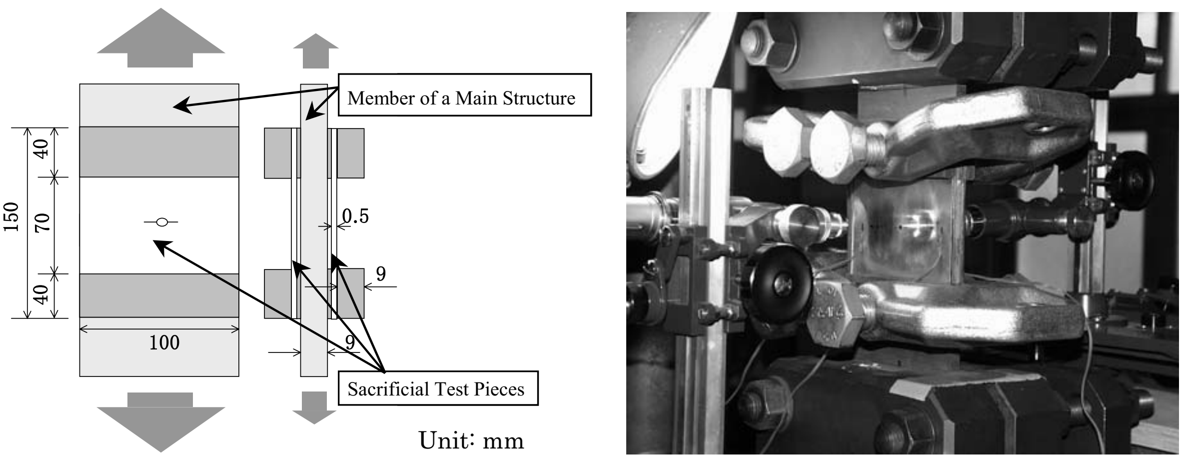

Fig.8 Figure and photo of applicable range test

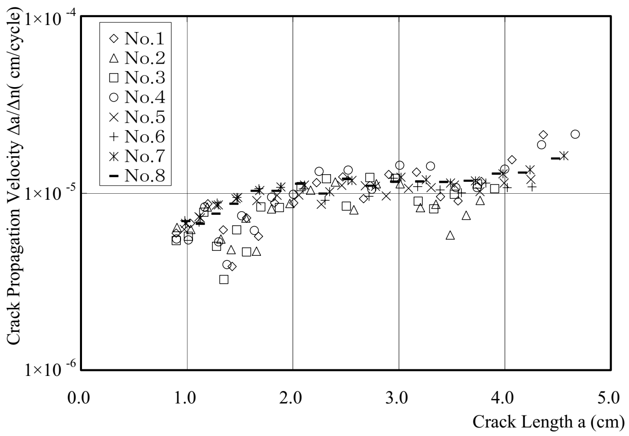

Fig.9 Δa/ΔN-a relationship (Δσ=120MPa)

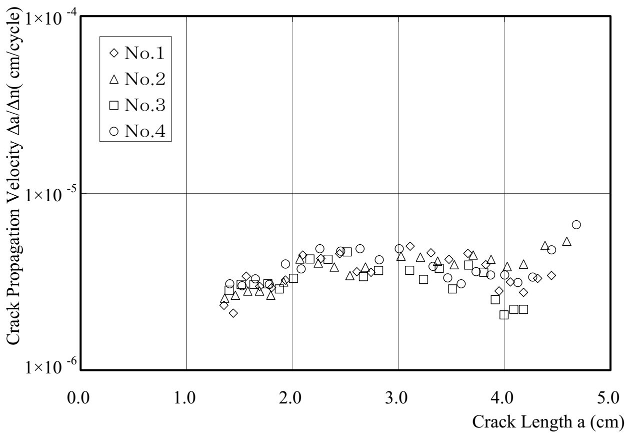

Fig.10 Δa/ΔN-a relationship (Δσ=80MPa)

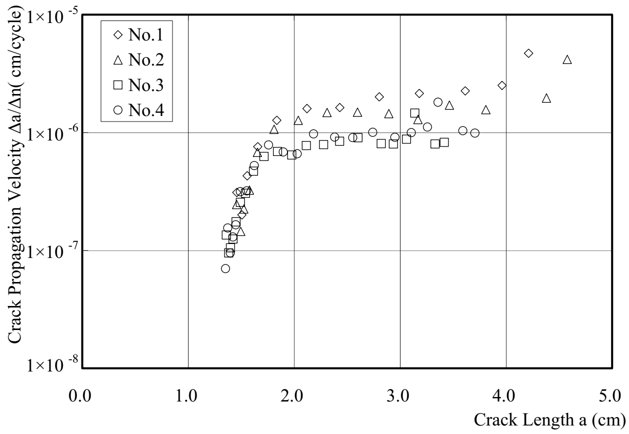

Fig.11 Δa/ΔN-a relationship (Δσ=60MPa)

under some stress amplitude. So the constant A and m were decided by experiments. The experimental method is the same as that of chapter 4 but the thin steel plates with fatigue cracks in the center were used in the experiment in this chapter. To investigate of the effect of the mechanical property, two sorts of the thin steel plates that were made in another lot were used. Four set of the thin steel plate with the jig-plate were examined in one series and a total of five series of experiment were run. Series 1, 3, 4 are same lot and series 2, 5 are another lot of the thin steel plate.

In the series 1 ~ 3, the crack lengths were measured by microscope after every 10,000 cycle of the constant amplitude loading for 10 ~ 15 times. And then same measurements were done 2 or 3 times after changing the stress amplitude of the bridge member $\Delta\sigma_B$. In the series 4 and 5, the crack lengths were measured by crack gauges under the constant amplitude loading of about 30MPa.

Figure 12 shows relationships between the crack propagation velocity and the stress intensity factor in the thin steel plate. Data of specimen No.2 in series 2 were disregarded because the thin steel plate was damaged when it was fixed to the H-section beam. Difference in the crack propagation between the two sorts of the thin steel plates was not observed. So plots are not distinguished in Fig.12 by each sort. It seems that the same value of constants can be used if steel type and size are same.

In most of "fatigue design recommendations for steel structures" including IIW[11] and JSSC[12], m=3 is widely used. Substituting m=3, following regression equation is obtained.

$$\log(\mathrm{d}a/\mathrm{d}n) = 3.0 \cdot \log(\Delta K) - 11.1 \qquad (16)$$

The solid line in Fig. 12 is a regression line with the value of m is fixed as 3. The plots and the solid line agree well. From these results, it can be said that the Paris' law, eq.(2), and m=3 can also apply to the thin steel plates. And we also obtain that the values of A is 7.94×10^{-12} by transforming eq.(16) to shape of eq.(2).

From these experiments and investigations, the constants m and A, those should be obtained by measuring of the crack propagation velocity under the same stress amplitude, can be decided as m =3 and A = 7.94×10^{-12}.

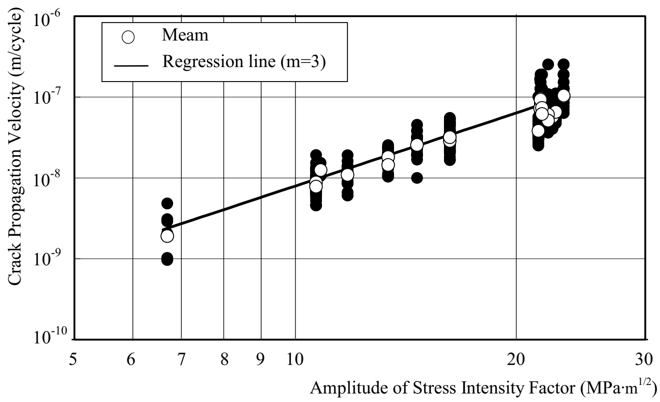

Fig.12 Crack propagation velocity – amplitude of stress intensity factor relationship

7. Applicability of the thin steel plate as the sacrificial test piece under constant amplitude loading

In chapter 4 ~ 6, the value of constants and applicable range of crack length were decided to estimate the fatigue damage parameter via eq.(9). By using these, the fatigue damage parameter can be estimated from only crack length a. Therefore from the measured crack length in the experiments in chapter 6, the fatigue damage parameters were estimated. The value of 2.55 for series 1 ~ 3 and 2.77 for series 4, 5 were used as the stress increase ratio α. These were means that were measured by strain gauges pasted in the thin steel plate and the H-section beam.

In **Fig. 13 ~ Fig. 17**, the fatigue damage parameters measured and calculated by the crack length of the thin steel plate (Sacrificial Test Pieces) under the constant amplitude loading are compared with those calculated by the stress amplitude and loading times (Stress Measurement). **Figure 18** shows a comparison of all series. 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 the estimation of the fatigue damage parameter. Especially the means of 4 set of the Sacrificial Test piece agree well in all ranges of the fatigue damage parameter as shown in Fig.18. So it can be said that the proposed method is valid under the constant amplitude loading. And it is demonstrated that the thin steel plate as the Sacrificial Test Piece can estimate the fatigue damage parameters with practical accuracy under the constant amplitude loading.

8. Conclusions

We propose a method to monitor the fatigue damage parameters on bridge members by the thin steel plate

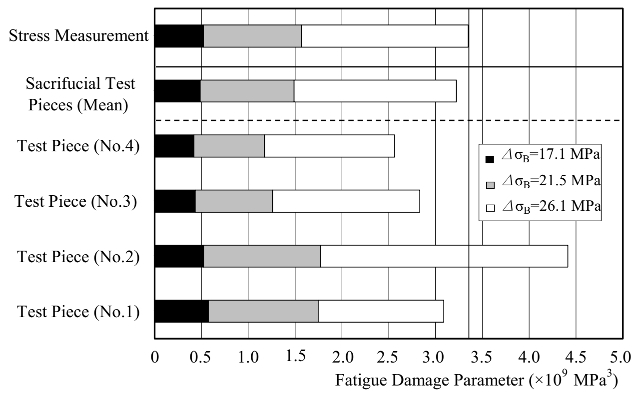

Fig.13 Comparisons of fatigue damage parameter (Series 1)

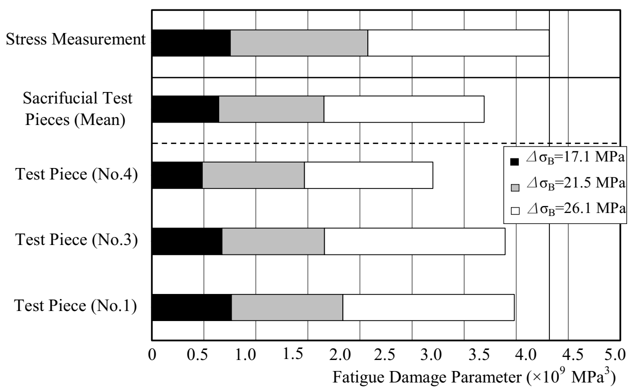

Fig.14 Comparisons of fatigue damage parameter (Series 2)

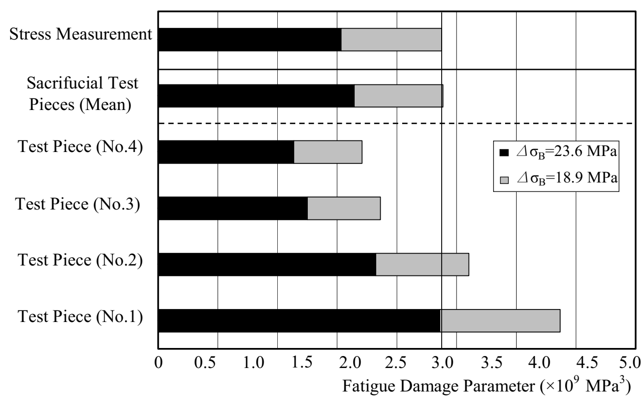

Fig.15 Comparisons of fatigue damage parameter (Series 3)

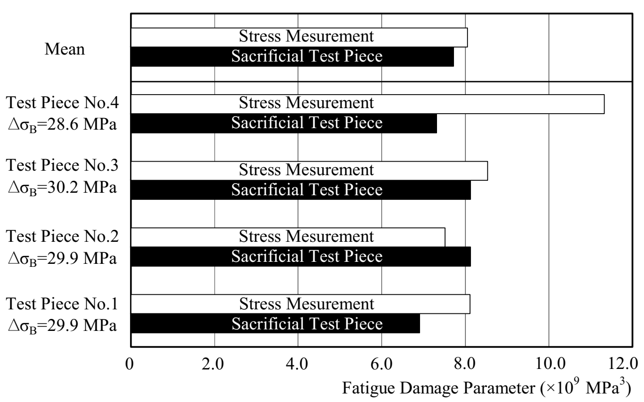

Fig.16 Comparisons of fatigue damage parameter (Series 4)

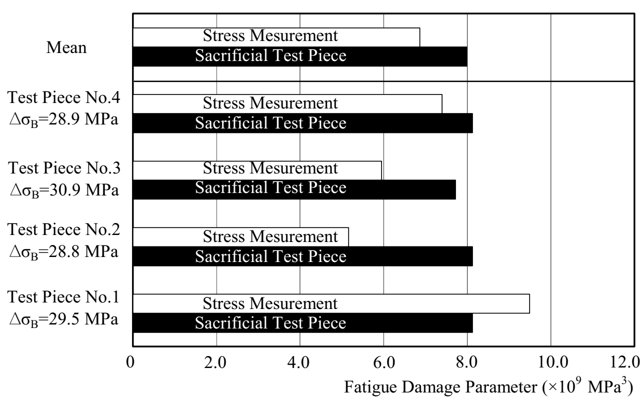

Fig.17 Comparisons of fatigue damage parameter (Series 5)

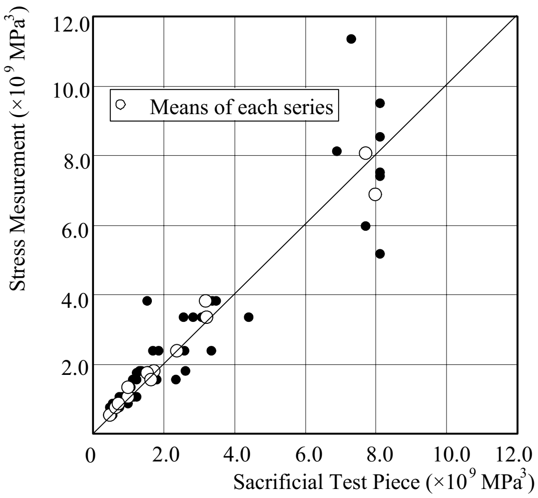

Fig.18 Comparisons of fatigue damage parameter (ALL)

with crack as the Sacrificial Test Piece. By using this method, the fatigue damage parameters can be estimated with lower cost than by conventional methods. In this study, the applicable range of the crack length and the constants that are needed to estimate by this method were obtained by experiment. And we have verified that the fatigue damage parameters under the constant amplitude loading can be carried out by monitoring the crack growth of the thin steel plates.

Main results are summarized as follows.

(1) Even on the in-service highway bridge, it is ascertained that the stress amplitude is amplified and the pre-tension can be applied in the proposed way using the jig-plate, the thermal deformation and the high strength vices.

(2) In the case of thickness and width of the thin steel plate are 0.5mm and 100mm, that used in this research, the restraint coefficient B can be calculated easily by the following equation, using the full length of the thin steel plate L and Poisson's ratio ν.

$$B = \sqrt{1-\nu^2}\sqrt{0.5L-0.84}$$

(3) In the case of the steel plate of 10 cm in width that used as the Sacrificial Test Piece in this research, it can be said that the applicable range of the crack length in the thin steel plate is from 2cm to 4cm.

(4) It can be said that the estimating method is valid under the constant amplitude loading. And it is demonstrated that the thin steel plate with a crack as the Sacrificial Test Piece can estimate the fatigue damage parameters with practical accuracy under constant amplitude loading.

It seems that more experiments under some patterns of fluctuating amplitude loading and more considerations will be needed to be used in the bridge member. These will be described in report II.

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