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Author(s)	Sakino, Yoshihiro; Sakagami, Takahide; Kim, You-Chu
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Application of Self-Reference Lock-in Thermography to the Measurement of Fatigue Damage Parameter†

SAKINO Yoshihiro*, SAKAGAMI Takahide** and KIM You-Chul***

Abstract

A sacrificial test piece is used as a specimen attached to the member of a main structure to evaluate the damage before the appearance of a crack in a member of a bridge. If the crack length of the sacrificial test piece can be measured from a long distance, the damage in a member of the bridge can be evaluated more easily and cheaply.

In this paper, thin steel plates, which have initial cracks at the center, are used as sacrificial test pieces and a measuring method by self-reference lock-in thermography is proposed. Fatigue tests of the sacrificial test pieces were performed and crack lengths were measured by the proposed method from a long distance. As the result, it is ascertained that the crack length of the sacrificial test piece can be measured from a long distance by the proposed method in the case that the stress range is 30MPa or more, even if the frequency is as small as 3Hz.

KEY WORDS: (Fatigue), (Thermography), (Sacrificial test piece), (Bridge maintenance), (Crack growth)

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 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

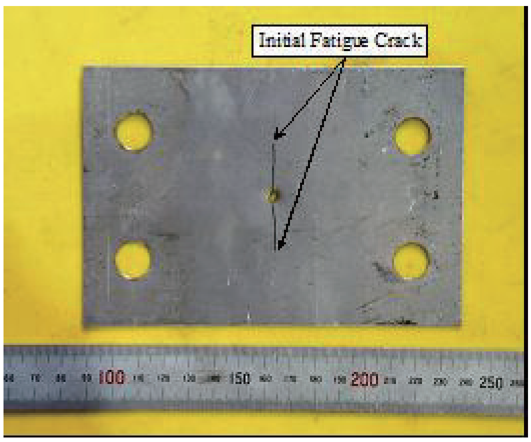

Fig. 1 Sacrificial test pieces

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* Assistant Professor
** Associate Professor, Department of Mechanical Engineering
*** Professor

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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[5), 6)].

In this paper, the estimating method for the fatigue damage parameter by crack growth of the thin steel plate as the sacrificial test pieces is summarized, and the applicability of this method under constant amplitude loading is demonstrated. In addition a measuring method for the crack length of the sacrificial test piece from a long distance by self-reference lock-in thermography is proposed. Applicable stress ranges and frequency of measurement by the proposed method are clarified.

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 loading can be written as follows;

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

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

Equation (1) is termed "the fatigue damage parameter"[7), 8)]. 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, A and m are constants.

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

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

where 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 "σ", 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 is assumed that m is approximately 3 for steel. It follows from Eq. (4), that;

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

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;

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

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 of 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 and depends on the size of the thin plate[5), 6)]. For the constant m, m=3 is widely used[9), 10)].

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

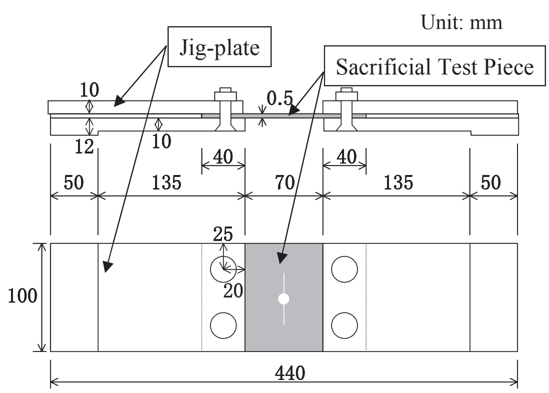

Fig. 2 Sacrificial test pieces with jig-plate

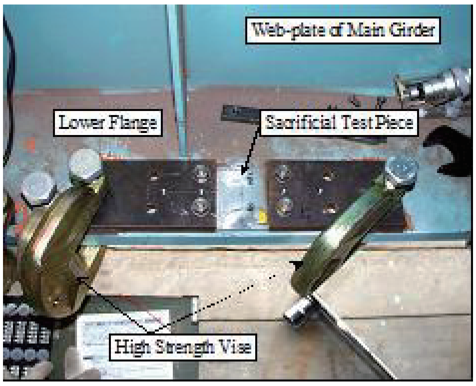

Fig. 3 Example of attachment to lower flanges of a highway bridge.

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 flange 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.

To avoid compression loading on the sacrificial test piece by uplift of the bridge member, 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 loading

Figure 4 shows the comparison between the fatigue damage parameters measured by the crack length of the sacrificial test pieces under the constant amplitude loading 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.

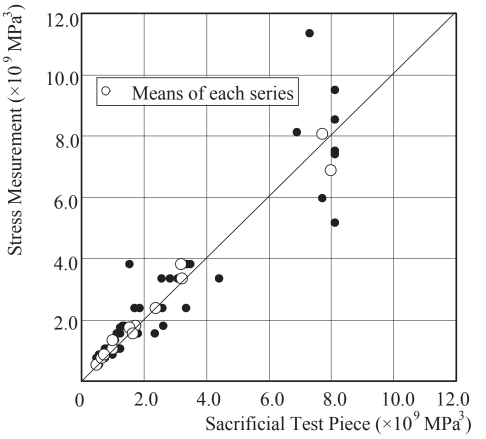

Fig. 4 Comparisons of fatigue damage parameter

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 loading. This demonstrates that the thin steel plate as a sacrificial test piece can estimate the fatigue damage parameter with practical accuracy under constant amplitude loading.

3. Remote Measurement of Crack Length by Self-Reference Lock-in Thermography

3.1 Outline of self-reference lock-in thermography

If the crack length of the sacrificial test piece can be measured from a long distance, the damage in a member of a bridge can be evaluated more easily and cheaply. We propose a measuring method of the crack length from a long distance by thermoelastic stress analysis.

Thermoelastic stress analysis has been attracting attention as a non-destructive surface evaluation technique for crack detection in steel structures. Thermoelastic stress analysis is a full field, non destructive technique for a surface stress mapping of structures based on the thermoelastic effect. This phenomenon arises from the fact that when a structural component is cyclically loaded, the structure expresses small and reversible temperature changes. If adiabatic and elastic conditions are achieved, these temperature changes are proportional to the sum of principle stresses. For example, the temperature change in a steel component under stress amplitude of 10MPa is about 10mK. Nowadays, the very small temperature change can be measured using a high precision infrared thermography.

When measurement is performed for a cracked structure, it is possible to obtain information about stress distribution, from which a singular stress field due to the crack, can be detected. In the vicinity of a crack tip, significant stress concentration is observed. Thus, visualization of a singular stress field enables crack detection[11)].

Since thermoelastic temperature change is quite small, lock-in infrared thermography using reference signal synchronized with stress, is commonly employed to improve the precision of stress measurements. A loading signal from an external source, such as a load-cell, strain gauge or displacement gauge, is usually employed as a reference signal in the conventional technique. However, it is usually difficult to obtain a reference-loading signal from actual large-scale steel

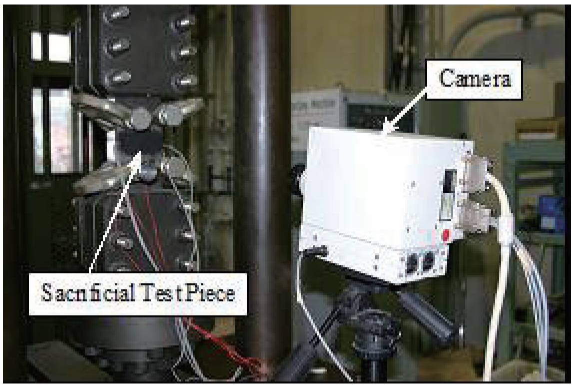

Fig. 5 Measurement of crack length in sacrificial test piece by self-reference lock-in thermography.

structures in service. Further, the observed loading signal is not a clear sinusoidal wave because it is a superposition of the characteristic oscillation components in service. These facts show that the conventional lock-in thermography is not applicable.

A self-reference lock-in infrared thermography technique is newly proposed, in which a reference signal is constructed by using the same sequential data on thermoelastic temperature change. Temperature change in a region of interest, such as crack tip, is correlated with that in a remote area, where uniform stress is applied, for reference signal construction. The temperature changes obtained from the region of interest and remote area are in-phase and have similar waveforms but big differences are found in their amplitudes. Consequently if a reference signal could be constructed from the signal obtained from a remote area, it is possible to perform correlation processing without an external reference signal. The lock-in algorithm based on the least squares method is employed for signal processing under random loading. It enables us to measure the distribution of relative intensity of applied stress under random loading without using any external loading signal[12].

3.2 Application to measurement of crack length in the sacrificial test piece

To examine the applicability of self-reference lock-in thermography to the measurement of the crack length of the sacrificial test piece from long distances, fatigue tests of the sacrificial test pieces were performed and crack length was measured by the proposed method. As shown in **Fig. 5**, 0.5 mm thick steel plate as the sacrificial test piece without jig-plates was fixed to the 9 mm thickness of a main member. 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. In order to propagate the fatigue crack, cyclic load was applied to the main member using a servo-hydraulic testing machine. Loading stress range was 120 MPa and frequency was 10 Hz.

Crack gauges (pitch = 0.5 mm), fixed in the back side of the thin steel plate, were used to measure the length of crack. Measurement of the crack length by self-reference lock-in thermography was performed every 0.5 mm of crack growth measured by crack gauge. Distance from the lens to thin steel plate was 2 m. Loading stress range and frequency during measurement were 120MPa-10Hz and 60MPa-3Hz. In the measurement of 26 mm crack length, 30MPa-3Hz and 15MPa-3Hz were also performed. Assuming the stress increase ratio is 3, the stress ranges of 120, 60, 30 and 15MPa of the sacrificial test piece correspond to those of 40, 20, 10 and 5MPa of the bridge member by using the jig-plate.

Figure 6 and **Fig. 7** show contours drawings of the relative thermoelastic temperature change distribution obtain by the self-reference lock-in thermography in the measurement of 20.5 mm and 38.0 mm. The applicable crack length of the sacrificial test piece is from 20 mm to 40 mm[12]. So Fig. 6 and Fig. 7 show the results of just about the lower and upper limits of applicable range. In spite of the crack length, the location of the crack tip can be estimated as the largest point of the thermoelastic temperature change.

Figure 8 shows the comparison between the crack lengths measured by crack gauge and those estimated by the self-reference lock-in thermography. Good agreement can be found between the crack length measured by crack gauge and those estimated by the self-reference lock-in thermography in all ranges, not only in the case of 120MPa-10Hz, but also in the case of 60MPa-3Hz. So it can be said that the proposed method of self-reference lock-in thermography can measure the crack length of the sacrificial test piece accurately.

Figure 9 (a) - (d) show contours drawing of the thermoelastic temperature change distribution obtained by the self-reference lock-in thermography for a crack length of 26 mm and in the loading conditions of 120MPa-10Hz, 60MPa-3Hz, 30MPa-3Hz and 15MPa-3Hz. As the stress range became smaller, the thermoelastic temperature change and the location of crack tip also became small and unclear. The crack length are estimated by the self-reference lock-in thermography as 25.9 mm in 120MPa-10Hz, 26.1 mm in 60MPa-3Hz, 25.8 mm in 30MPa-3Hz and 25.2 mm in 15MPa-3Hz. In the case of the stress range of 15MPa, the proposed method by the self-reference lock-in thermography underestimates the crack length. But in the case of 30MPa or more, the self-reference lock-in thermography can measure the crack length of the sacrificial test piece accurately.

From these results, the possibility of measurement of crack length from long distances by the self-reference lock-in thermography using a high sensitivity telescope lens is demonstrated.

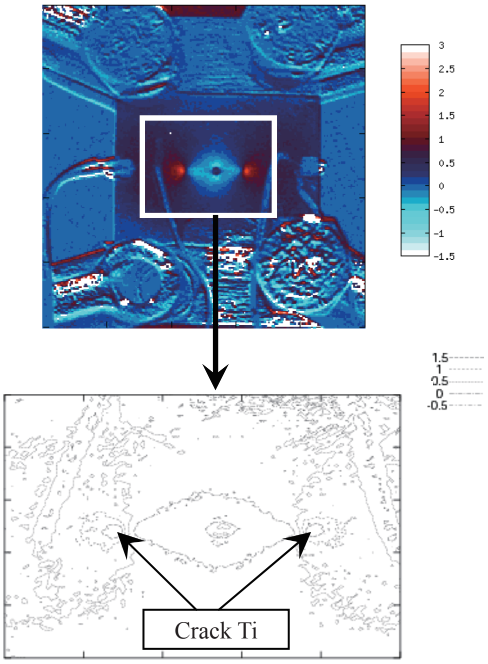

Fig. 6 Crack tip in sacrificial test piece searched by self-reference lock-in thermography (Δσ=120MPa, 10Hz, Crack length: 20.5mm)

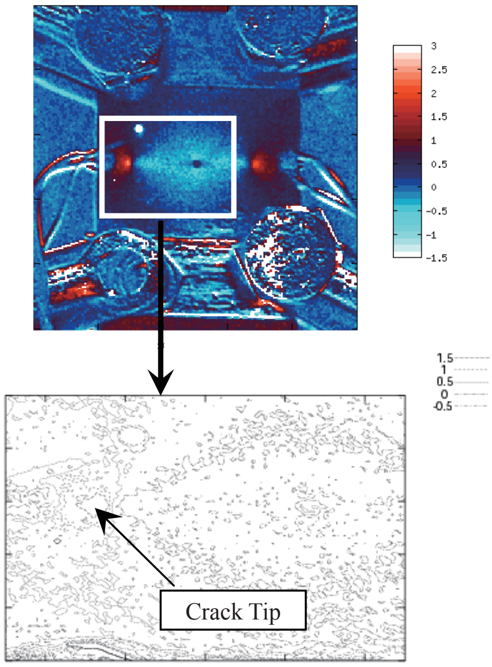

Fig. 7 Crack tip in sacrificial test piece searched by self-reference lock-in thermography (Δσ=120MPa, 10Hz, Crack length: 38.0mm)

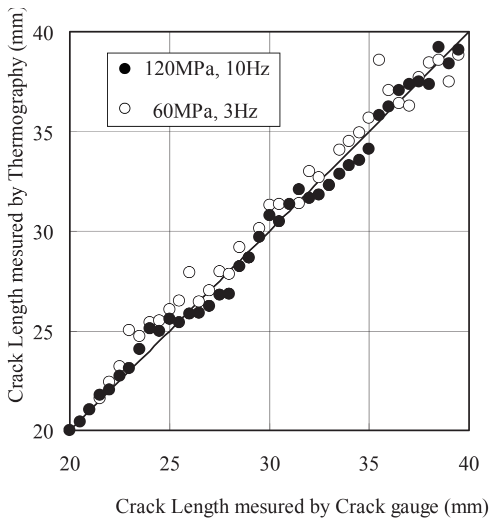

Fig. 8 Comparison between crack lengths measured by crack gauge and thermography

4. Conclusions

We propose a method to monitor the fatigue damage parameters on bridge members using thin steel plates with cracks as sacrificial test pieces. By using this method, the fatigue damage parameters can be estimated with lower cost than by conventional methods. In this study, the applicability of this method under constant amplitude loading is demonstrated. A measuring method of the crack length of the sacrificial test piece from a long distance by self-reference lock-in thermography was proposed and applicable stress range and frequency of measurement by proposed method were demonstrated.

Main results are summarized as follows.

(1) Even when the frequency is as small as 3Hz, the self-reference lock-in thermography can measure the crack length of the sacrificial test piece accurately in the case that the stress range is 30MPa or more.

(2) The possibility of measurement of crack length in the sacrificial test pieces in the bridge members from long distance by the self-reference lock-in thermography is demonstrated.

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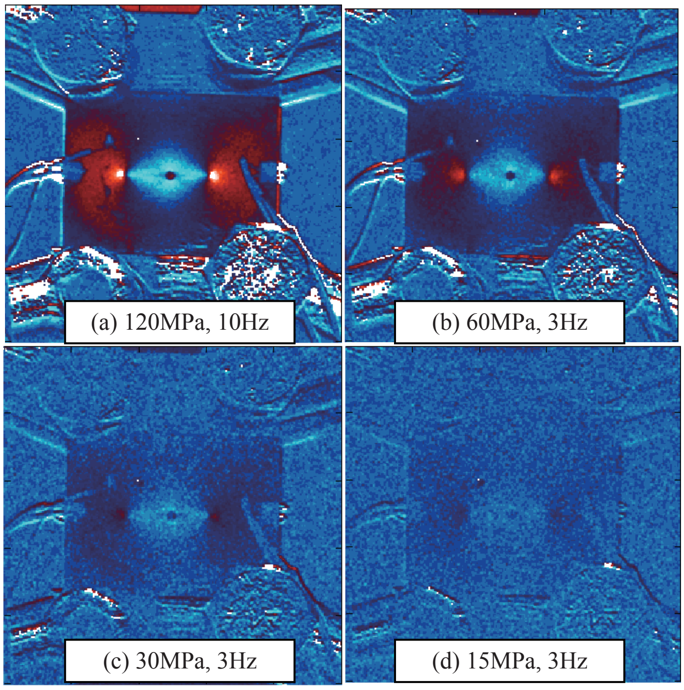

Fig. 9 Effects of stress range and frequency
(Crack Length: 27mm, Camera distance: 2m)

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