Evaluation of Fatigue Properties of Steel Bar by Smart Stress-memory Patch

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A fatigue sensor called “smart stress-memory patch” has been presented to evaluate the fatigue damage of infrastructures as bridges and ship. In this study, the smart stress-memory patch was applied to the steel bar to estimate the stress amplitude and the cyclic number. Firstly, the fatigue test of the steel bar with attached sensor was carried out and the fatigue crack growth behavior of the sensor was investigated. Secondly, the stress distribution of the sensor was calculated by using the finite element method to evaluate a complex strain transfer from the steel bar. Finally, the possibility of measurement for the stress amplitude and the cyclic number by using smart patch was evaluated. The fatigue crack growth rate of the attached sensor was decreasing with the crack growth. Especially when the stress amplitude was large, the crack growth rate decreased dramatically with the crack growth. The analysis of stress distribution shows that the size of plastic zone around crack tip decreases with the crack length and the load subjected to the sensor is similar to that of the uniform displacement testing. In addition, the modified stress intensity factor based on the uniform displacement testing is proposed to correct the shape effect of the attached sensor on crack growth behavior. Applying the modified stress intensity factor to the principle of smart patch, it was demonstrated that the stress amplitude and the cyclic number of the steel bar could be estimated from the crack lengths of two sensors.

KEY WORDS: health monitoring; fatigue sensor; copper; fatigue crack growth; finite element method.

1. Introduction

The structures such as bridges, ships, trains, aircraft, power plants, and buildings greatly contribute to the establishment of the present social infrastructure. In recent years, these structures are enlarged, lightened, and complicated to achieve the social demand, and the required mechanical property become severer than the past. The safety of the structures is supported by the development of new materials and the structural calculation technology. However, the failure accident of the structures is never ceasing. It is known well that many of failure accidents are caused by fatigue damage. The roller coaster accident in Japan in 2007 was caused by the fatigue fracture of the wheel axis. Moreover, accidents without the victim have occurred a lot and the economic loss is enormous. In the near future, it is expected that aging of the structures built at the high economic growth period becomes more advanced. Because of these factors, the inspection techniques to evaluate the fatigue damage of the structure are strongly required. The evaluation approaches of fatigue damage are divided roughly into two categories; the detection of existing defect by nondestructive testing, and monitoring of stress and strain. This paper focuses on stress monitoring techniques.

The strain gage is one of the most popular methods to measure the stress history of structures, which can assess the stress amplitude, the maximum stress, and the cyclic number. In recent years, the online monitoring system with a fiber Bragg grating sensor is also proposed. However, on the long-term monitoring there are several problems, such as huge volumes of data, the need of wiring and the electrical power supply. A sensor called “smart stress-memory patch” that can measure the maximum stress, the stress amplitude and the cyclic number simultaneously was proposed in the previous paper. Using this patch the maximum stress can be obtained by Kaiser effect of Acoustic Emission (AE) method, and the cyclic number and the stress amplitude can be estimated by crack length of the sensor. Since this patch needs neither the power supply nor wiring, it is possible to measure the fatigue loading for a long period. The patch is effective enough as non-destructive evaluation method because the maximum stress, the stress amplitude and the cyclic number can be evaluated.

The fatigue crack growth behavior of the sensor of smart patch under stress-controlled fatigue test has been investigated, and it is shown that the cyclic number and the stress amplitude can be estimated by smart patch in the previous paper. However, it is necessary to evaluate the fatigue crack growth behavior of the sensor which is attached to the structure, because the crack growth of the attached sensor would be different from the sensor itself which has been investigated in the past, according to the change in the restraint condition. In addition the evaluation of the effect of bonding is needed because the sensor is attached to the structure by using the adhesive. In the research on the tensile strength of overlapping bonding joint, the characteristic
of the adhesive is investigated.\textsuperscript{3–6} Meanwhile, the research on a complex bonding as a smart patch is hardly reported.

In this study, the fatigue test of the steel bar with attached patch was carried out and the fatigue crack growth behavior of the sensor was investigated. The stress distribution of the sensor was also calculated by using the finite element method to evaluate a complex strain transfer from the steel bar. Finally, the possibility of measurement for the stress amplitude and the cyclic number by using smart patch was evaluated.

2. Experimental Procedure

2.1. Materials

The sensor was made of electrodeposited (ED) copper of 99.96% purity because of its good corrosion resistance, stable crack propagation and easily observation of crack length. As-received and heat-treated (400°C, 30 min) ED Cu coupons with 0.1 mm thickness were prepared to change the fatigue crack growth behavior. Because this patch needs two sensors with different characteristics to measure stress history. The details of the principle of smart patch is described in the previous paper.\textsuperscript{2} The mean grain sizes were about 2 $\mu$m and 4 $\mu$m, respectively. Samples were cut to 40 mm length and 5 mm width. A single edge notch of 25 mm in length and 300 $\mu$m in width was introduced at the center from one side. The notch tip is a round shape with curvature radius of about 150 $\mu$m. The fatigue pre-crack was introduced under the maximum stress of 24 MPa until total crack length of about 2.7 mm. One surface of the sensor was polished to observe crack length clearly.

The steel bar (JIS G 3502 SWRS82B) with 7 mm in diameter, 400 mm long was chosen as a structure material. The static tensile stress of 780 MPa was applied to steel bar to simulate the real environment of usage. Afterward, the sensor was attached to the steel bar by using alpha-cyanoacrylate adhesive and attachment made of SS304 to correct the curvature. These materials and geometry are shown in Fig. 1.

2.2. Fatigue Test

The fatigue test was carried out in tensile loading under the constant maximum stress of 108, 156 and 208 MPa, with the stress ratio of 0.1 and frequency of 20 Hz. The fatigue crack growth behavior of Cu sensor was observed by CCD camera at 500-fold magnification during fatigue test. A crack growth rate was calculated by the incremental polynomial technique.

3. Analytical Procedure

3.1. Finite Element Model

Figure 2 shows the finite element mesh of the sensor and steel bar. Only the half of the entire samples was modeled. An element length of 0.1 mm is chosen around crack tip. The mechanical parameters of Cu sensor and steel bar are given in Table 1. The work-hardening properties, which were obtained from the experimental tensile tests, were applied to the copper specimen. The tensile stress of 10.4, 15.6, 20.8, 104, 156, and 208 MPa were applied to the steel bar to correspond to the maximum stress and the minimum stress in the fatigue test. The normalized crack length of the sensor was changed with 0.54, 0.64, 0.72, and 0.80 in each condition.

3.2. Stress Intensity Factor

It is expected that the small scale yielding state may not be satisfied because the plastic zone at crack tip is enough large compared with ligament of the specimen, and the discussion based on nonlinear fracture mechanics is needed. The $J$-integral is independent of the path around a crack and represents the strain energy release rate of nonlinear elastic materials. In this analysis, 20 integration paths were defined from the crack tip to the outside, and the $J$-integral was calculated from the stress distribution obtained by the finite element analysis. Because $J$-integral reached a constant value since the 5th path in each model, the mean value of $J$-integral obtained from 5 to 20th path was used for the calculation of stress intensity factor, $K_I$. Under small-scale yielding conditions and plane stress, the stress intensity factor, $K_I$, can be obtained from the following equation,

$$ J = G = \frac{K_I^2}{E} \quad (1) $$

where $E$ is Young’s modulus and this equation can be applied in the plane stress condition. $K_I$ calculated from Eq. (1) was converted into a dimensionless value ($F_I$) by using
the following equation in each loading condition,

\[ F_1 = \frac{K_1}{\sigma \sqrt{\pi a}} \] ............................(2)

where \( a \) is the crack length of the sensor. The crack growth behavior of the sensor was evaluated by using the shape factor obtained from Eq. (2).

4. Results

4.1. Fatigue Crack Growth

Figure 3 shows the fatigue crack path of the sensor attached to the steel bar during fatigue test with the maximum stress of 104 MPa. The scattering in fatigue crack growth was in the same range as the result of the previous paper,\(^1\) which allows us to measure the crack length of the sensor easily using by video microscope. Figure 4 shows the relationship between fatigue cycles applied to steel bar and crack growth rate of the sensor on each loading condition. The crack growth rate increased with the stress amplitude and the grain size. At all stress conditions the crack growth rate tended to decrease slightly with the crack growth. Especially when the stress amplitude was large, the crack growth rate decreased largely with the crack growth. Such a feature on the fatigue crack growth is quite different from that of the sensor itself investigated in the previous paper.

4.2. Numerical Results and Stress Intensity Factor

Figure 5 shows axial stress distributions of the sensor and steel bar when the applied stress is 104 MPa. It shows that the bending moment occurs around the crack tip in spite of fixing to the structure material, and the compressive stress is generated at the ligament of the sensor. On the other hand, the steel bar shows almost homogeneous stress distribution which is independent with the crack length of the sensor, presumably because the sensor is designed very thinly compared with the structure material. When the normalized crack length, \( \alpha \) is 0.54, the maximum compressive stress is 29.6 MPa. When \( \alpha \) is 0.80, the maximum compressive stress is 55.0 MPa and the plastic zone described in black is smaller than when \( \alpha \) is 0.54. Figure 6 shows the relationship between the plastic zone size and the normalized crack length. The size of plastic zone decreases slightly with the crack length. When the stress amplitude is large, the plastic zone size strongly decreases with the crack length. Such a feature corresponds well to the experimental results of the fatigue crack growth shown in the previous section.

\( J \)-integral around the crack tip was calculated, and the dimensionless stress intensity factor was obtained from Eqs. (1) and (2). The relationship between normalized crack length and calculated dimensionless stress intensity factor under each stress is shown in Fig. 7. The relationship, regardless of given stress, was able to be described in the following one equation,

\[ F_1 = A_0 + A_1 \alpha + A_2 \alpha^2 \]
\[ A_0 = 0.768, \quad A_1 = -0.052, \quad A_2 = -0.370 \] ........(3)

where \( A_0, A_1, \) and \( A_2 \) are constant values obtained from polynomial approximation of Fig. 7. Figure 8 shows the fatigue crack growth behavior predicted from this shape factor \( F_1 \). All data are fitted on one curve, the correlation coefficient of which was 0.836.

5. Discussion

5.1. Fatigue Crack Growth Behavior

Stress intensity factor of single edge-cracked tension specimen under uniform displacement is not dependent on the crack length, which is theoretically calculated.\(^7\) Meanwhile, the crack growth rate of this sensor tended to decrease with crack growth. Especially when the stress amplitude was large, the crack growth rate decreased strongly with the crack growth. Finite element analysis results showed plastic zone size decreases with ligament length (Fig. 6). Accordingly, such a specific crack growth characteristics of this sensor is attributed to the fact that ligament length is small and the size of plastic zone is limited by compression stress field on ligament.
5.2. Modified Stress Intensity Factor

The highly accurate expression of fatigue crack growth characteristics is required to improve the measurement precision of smart patch. Here, the crack growth characteristics of this sensor is assumed to comparable to that of single edge-cracked tension specimen under uniform displacement. Stress intensity factor of single edge-cracked tension specimen under uniform displacement is described as follows,

$$K = \frac{E_{Cu}}{\sqrt{L}} \left( \frac{\sigma u E L}{\sigma_{base}} \right)$$  \hspace{1cm} (4)

where $E_{Cu}$ is Young’s modulus of Cu sensor, $u$ is the displacement of the end of sensor and $L$ is the half-length of the sensor ($L$ is 10 mm in this study). If the strain of sensor is same as steel bar, the displacement of the end of sensor is described as follows,

$$u = \frac{\sigma_{base}}{E_{base}} L$$  \hspace{1cm} (5)

where $\sigma_{base}$ is maximum stress applied to steel bar and $E_{base}$ is Young’s modulus of structure material. Therefore, stress intensity factor of the sensor is obtain as follows,

$$K_u = \frac{E_{Cu}}{E_{base}} \sigma_{base} \sqrt{L}$$  \hspace{1cm} (6)

Since the small scale yielding state was not satisfied due to compression stress field on ligament of the specimen in the present study, the modified stress intensity factor, $\Delta K_{Mu}$, was proposed for this patch to correct the crack growth behavior like the previous paper,$^{1}$

$$\Delta K_{Mu} = U(R) (1 - R) \sigma_{base} \left( \frac{E_{Cu}}{E_{base}} \right) \sqrt{L} \cdot g(\alpha, \alpha_n, R)$$

$$g(\alpha, \alpha_n, R) = 1 + B_1(R)(\alpha - \alpha_n) + B_2(R)(\alpha - \alpha_n)^2 + \Lambda$$  \hspace{1cm} (7)

where $U(R)$ is the correction function considering crack closure effect, $g(\alpha, \alpha_n, R)$ is the correction function of shape factor, $R$ is stress ratio, $\sigma_{base}$ is the maximum stress applied to steel bar, $\alpha$ is normalized crack length of the sensor, $\alpha_n$ is initial normalized notch length of 0.5, $B_1$ and $B_2$ are constant values, respectively. The correction function of the sensor with grain size of 2 $\mu$m is obtain as,

$$g(\alpha, \alpha_n, R = 0.1)$$

$$= 1 + 1.967(\alpha - 0.5) - 17.14(\alpha - 0.5)^2 + 28.59(\alpha - 0.5)^3$$  \hspace{1cm} (8)

The correction function of the sensor with grain size of 4 $\mu$m is obtain as,

$$g(\alpha, \alpha_n, R = 0.1)$$

$$= 1 + 0.4586(\alpha - 0.5) - 7.806(\alpha - 0.5)^2 + 18.94(\alpha - 0.5)$$  \hspace{1cm} (9)

$\Lambda$ was decided to fit Paris law and the fourth order terms or
higher are ignored because they have little influence on results. As shown in Fig. 9, more accurate master curve of crack growth behavior were obtained. It is noted that Eqs. (8) and (9) can be applied only to a smart patch, because they are empirical relations using experimental results of this patch.

5.3. Estimation of the Stress Amplitude and the Cyclic Number

Smart patch can estimate the stress amplitude and the cyclic number by combining two sensors with a different characteristic. Applying the modified stress intensity factor to the principle of smart patch reported in the previous paper,2) the stress amplitude and the cyclic number of the steel bar can be shown by the following equations.

\[
N = \frac{C_2 W_2}{C_1 W_1} \left( \frac{E_{s2} L_2}{E_{s1} L_1} \right)^{m_{s1} - m_{s2}} \frac{F_1(\alpha_1)}{F_2(\alpha_2)}
\]

\[
\Delta \sigma = \frac{C_2 W_2}{C_1 W_1} \left( \frac{E_{s2} L_2}{E_{s1} L_1} \right)^{m_{s1} - m_{s2}} \frac{E_{b1}^m}{E_{b2}^m} \frac{F_1(\alpha_1)}{F_2(\alpha_2)}
\]

\[
F_i(\alpha) = \int_{\alpha_i}^{\alpha_f} \sqrt{\alpha} g_i(\alpha)^{-m_i} d\alpha, \quad i = 1, 2
\]

where \(\alpha_i\) is normalized crack length of sensor \(i\), \(C_i\) and \(m_i\) are constants of sensor, \(g_i(\alpha)\) is shape factor, \(W_i\) is width of sensor, \(L_i\) is length of sensor, \(E_b\) is Young’s modulus of base materials and is \(E_{si}\) Young’s modulus of sensor \(i\). As shown in Eqs. (10) and (11), the estimation of stress history depends on the sensor length, \(L_c\).

Substituting the normalized crack lengths \(\alpha_1\) and \(\alpha_2\) of two sensors to Eqs. (10) and (11), the cyclic number and the stress amplitude can be estimated. The estimated results with the maximum stress of 156 MPa are shown in Fig. 10. The dashed line represents the loading history actually given. In the beginning of crack growth, the estimated result was inaccurate because the difference between crack lengths \(\alpha_1\) and \(\alpha_2\) is small. After the normalized crack length of about 0.6, both the stress amplitude and the cyclic number can be estimated. It is considered that preparing sensors with different crack growth characteristics is effective to improve accuracy more. The crack growth characteristics could also be adjusted by using other materials to change \(m\) and \(C\) in Paris law. Moreover, Eqs. (10) and (11) indicates that a length and a width of sensors could change the crack growth characteristics.

The measuring range would be limited by time when the normalized crack length of sensors becomes about 0.8 to avoid an unstable fracture. In present study using the ED Cu of the grain size 2 \(\mu\)m and 4 \(\mu\)m, when the maximum stress is 104 MPa the measuring limit is 150 000 cycles, and when the maximum stress is 156 MPa that is 50 000 cycles, respectively. It is thought that the pure copper cannot be used under the maximum stress of 208 MPa or more because the sensor will be broken easily. Therefore, under a higher stress environment it is necessary to use other materials, such as nickel that shows higher crack-extension resistance, or to enlarge the length of ligament.
6. Conclusions

In the present paper, the smart stress-memory patch was applied to the steel bar to estimate the stress amplitude and the cyclic number. The following conclusions were obtained.

(1) The fatigue crack growth rate of the attached sensor was decreasing with the crack growth. Especially when the stress amplitude was large, the crack growth rate decreased largely with the crack growth. There was a correlation between the crack growth rate of the sensor and the stress amplitude applied to steel bar.

(2) The stress distribution of the sensor was calculated by finite element method. It was shown that the size of plastic zone around crack tip decreases with the crack length and the load subjected to the sensor is similar to that of the uniform displacement testing.

(3) The modified stress intensity factor is defined to correct the shape effect of the attached sensor on crack growth behavior. The empirical master curve of crack growth, which included the effect of the maximum stress and attaching the structure, was obtained by the modified stress intensity factor.

(4) The equation that estimates the stress history of the structure was obtained by applying the modified stress intensity factor to the principle of smart patch. It was demonstrated that the stress amplitude and the cyclic number of the steel bar could be estimated from the crack lengths of two sensors.

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