STRUCTURAL MONITORING USING PIEZOELECTRIC FILM

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Abstract

Structural monitoring is a key component in maintaining a sound infrastructure. Various sensor systems for structural health monitoring have been developed and are available to quantify the deterioration of aged structures. In this paper, strain measurement using piezoelectricity of PVDF(polarized polyvinylidene fluoride) film is studied. Sensing performance of PVDF film was confirmed by the experimental comparison with traditional strain gage sensor. To use this PVDF film as a crack detection sensor, first the crack progress on aluminum specimen were monitored. Then the PVDF film sensors were used to monitor the initiation and propagation of cracks due to progressive application of loads on RC beams in the laboratory. These film sensors are able to monitor post-yielding behavior of material and identify the initiation and propagation of cracks of RC beam and applicable as damage detection sensor of monitoring system.

Key Words: structural health monitoring, PVDF film sensor, crack propagation, strain

1.Introduction

The expansion and development of urban areas have brought a large scale of stock of infrastructure. Now, the deterioration of existing infrastructure components has increased the demand for sound maintenance and routine structural integrity assessments. Structural health inspection is a key component in maintaining a sound infrastructure. Routine inspection is traditionally visual inspection that is convenient and effective. But, limited human resources and difficulties in securing maintenance budget decrease the thoroughness of these inspections. The application of intelligent and sound structural health monitoring may provide a successful means of improving the efficiency and accuracy of structural integrity of civil infrastructures.

The infrastructure may suffer several kinds of damages due to aging, environmental effects and long-term loading. Damage due to an extreme event is also possible in a structure at some time during its design life. Therefore, nearly all in-service structures require some form of maintenance, in which inspection of their integrity and health condition is very important to prolong their life span and to prevent catastrophic failure of these structures. In order to make a reasonable maintenance decision, it is essential to have a reliable damage assessment. Monitoring system is able to provide useful information on damages immediately after a severe loading event. There are many kinds

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of sensors available for monitoring civil structures. Optical fiber sensor can provide distributed damage information of structures. PVDF(polarized polyvinylidene fluoride) film is a candidate sensor for monitoring, because piezoelectricity of PVDF film can be utilized for strain measurement.

In this paper, the application of the PVDF film on static strain measurements is introduced along with the study on development of PVDF damage detection sensor in structural monitoring.

Photo-1 PVDF film
(Tokyo Sensor Co., Ltd./Model DT2-028K, DT4-028K)

2.Measurement of strain using PVDF film

PVDF film has different sensitivity of piezoelectricity in longitudinal direction and transverse direction. Therefore, a set of films attached in orthogonal direction was used for measurement of strain as shown in Fig.-1. The output voltage V(θ) from PVDF film relates to strain as shown in eq.-(1).

$$V(\theta)=\frac{A}{C\left(1+k_t^{\,2}\right)}\left\{f_1(\theta)\varepsilon_x+f_2(\theta)\varepsilon_y+f_6(\theta)\gamma_{xy}\right\} \tag{1}$$

here, ε_x:strain in x-direction, ε_y:strain in y-direction, γ_{xy}:shear strain, C:capacitance, A:area of the film, k_t: electro mechanical coupling coefficient.

In case of θ =0 or $\theta = \pi/2$, V(0) and V($\pi/2$) are obtained using eq.-(2) and (3) because of γ_{xy}=0.

$$V(0)=\frac{A}{C\left(1+k_t^{\,2}\right)}\left\{\alpha_{31}\cdot\varepsilon_x+\alpha_{32}\cdot\varepsilon_y\right\} \tag{2}$$

$$V(\pi/2)=\frac{A}{C\left(1+k_t^{\,2}\right)}\left\{\alpha_{32}\cdot\varepsilon_x+\alpha_{31}\cdot\varepsilon_y\right\} \tag{3}$$

F_1 and F_2 are introduced to represent property and area of film as shown in eq.-(4) and (5).

$$F_1 = \frac{A \cdot \alpha_{31}}{C\left(1 + k_t^{\,2}\right)} \tag{4}$$

$$F_2 = \frac{A \cdot \alpha_{32}}{C\left(1 + k_t^{\,2}\right)} \tag{5}$$

Strain ε_x, ε_y are obtained from eq.-(6)and (7), substituting . F_1 and F_2. to eq.-(2) and (3).

$$\varepsilon_x = \frac{F_1 \cdot V(0) - F_2 \cdot V(\pi/2)}{F_1^{\,2} - F_2^{\,2}} \tag{6}$$

$$\varepsilon_y = \frac{F_1 \cdot V(\pi/2) - F_2 \cdot V(0)}{F_1^{\,2} - F_2^{\,2}} \tag{7}$$

Namely, F_1 and F_2 are measured beforehand, and Strain ε_x, ε_y are calculated by substituting measured film voltage V(0) and V(π /2). to eq.-(6)and (7).

In this study, charge amplifier(integral circuit) was used to measure static response of structure, because the output voltage of PVDF film tends to decrease with time.

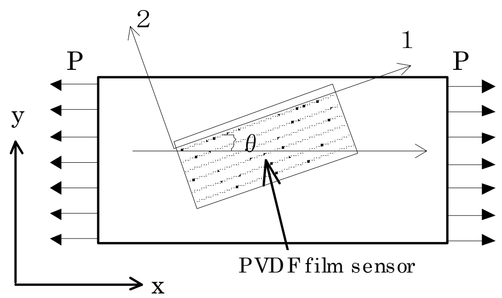


Fig.-1 Direction of PVDF film sensor measuring object

3.Measurements of post-yielding strain

In order to develop sensor system for structural monitoring, static loading tests were conducted using steel and aluminum specimens illustrated in Fig.-2. Fig.-3 shows the relationship between stress and strain measured by strain gage(SG1) in addition to PVDF film output voltage(PVDF1) in loading tests of steel specimen. The output voltage of PVDF film corresponds to strain gage measurements until the strain reaches 10,000 μ . Fig.-4 shows the comparison between strains measured by strain gage and PVDF film. Eq.-(6) and (7) cannot be applied after yielding, however, the error is not so large in measurement of the strain up to 10,000 μ .

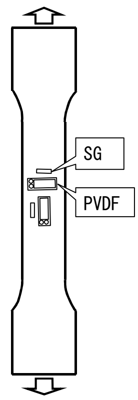
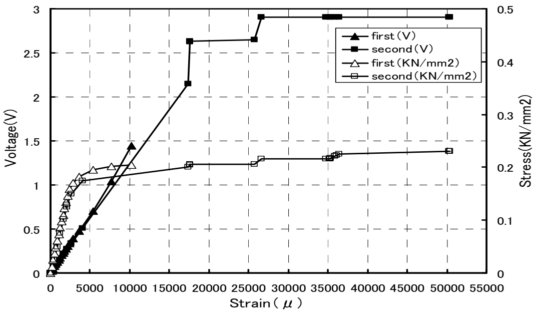


Fig.-2 Test specimen A



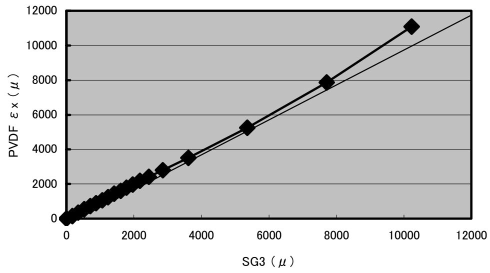
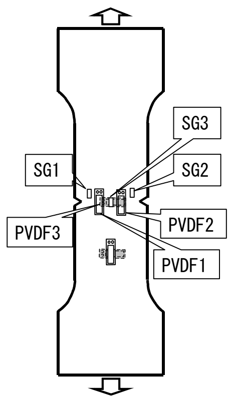


Fig.-3 Stress, Strain and PVDF film output voltage in loading test of steel specimen

Fig.-4 Comparison between strains measured by strain gage and by PVDF film

In order to monitor the yielding and crack propagation of an aluminum specimen with notch, static loading tests were conducted using specimen B as shown in Fig.-5. Fig.-6 shows the load and PVDF film output voltages. PVDF1 and PVDF2 show almost the same tracks until the peaks(the maximum load) and PVDF2 declined earlier than PVDF1. Photo-2 shows the specimen that almost ruptured and right crack propagated to the center of the specimen earlier than left crack. Fig.-7(a)~(c) show the relations between PVDF film output voltages and strain gage measurements.



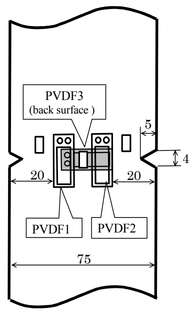


Fig.-5(a) Specimen B

Fig.-5 (b)Sensor arrangement

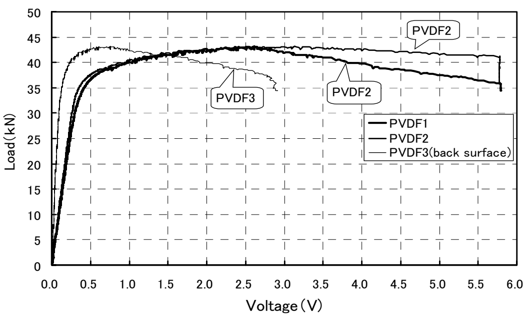


Fig.-6 Loads and PVDF film outputs(PVDF1,2,3)

Photo-2 Crack propagation into the center of the specimen

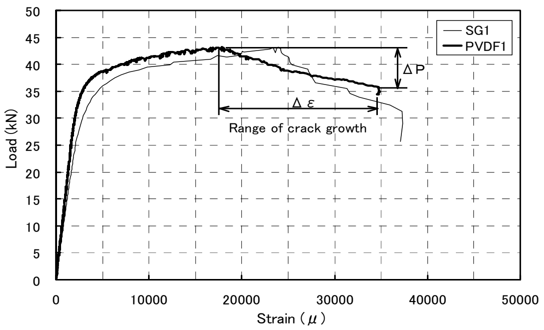


Fig.-7(a) Comparison between SG1 and PVDF1

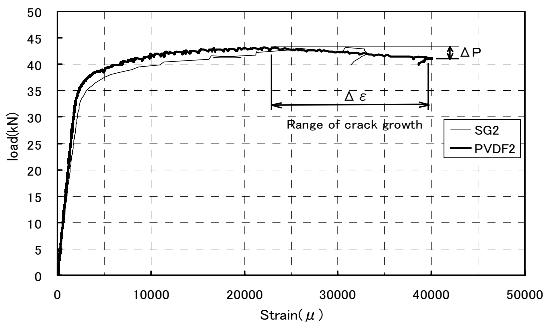


Fig.-7(b) Comparison between SG2 and PVDF2

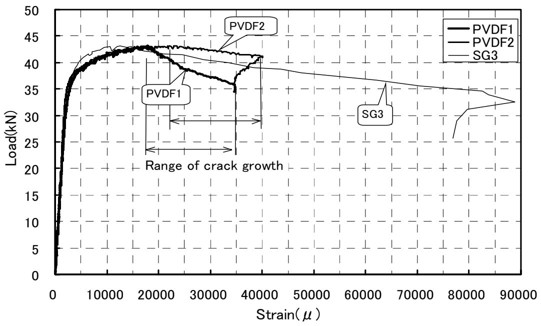


Fig.-7(c) Comparison between SG3 and PVDF1,2

4.Monitoring of cracks

The output voltage of the PVDF film reflects the strain in the whole film. When crack occurs, strains near the crack become large and strain distribution in the film is not uniform. In order to apply the PVDF film sensor for monitoring of damages in civil structure, the output voltage of the PVDF film was measured when crack occurs and propagates using artificial crack.

The PVDF film was attached on two steel plates placed with small gap between them(Fig.-8). This gap simulates the artificial crack. The relationship between the gap width and the output voltage of PVDF film were studied. The test results are shown in Table-1. The strain was calculated using initial gap width and gap increase.

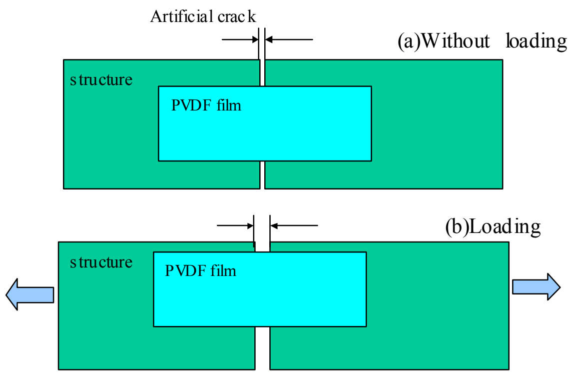


Fig.-8 Outline of crack initiation test

The output voltage of the PVDF film is almost proportional to the strain generated in the gap area. Namely, the output voltage with 5mm initial gap width and 3.0% strain is almost equal to the output voltage with 10mm initial gap width and 1.5% strain. This means that A in eq.-(1) corresponds to crack width and term { } in eq.-(1) corresponds to strain. At the same time, surface potential distribution was measured and the results are shown in Fig.-9(a) and (b). The surface potential was observed only near the gap. From the observations, it is concluded that PVDF film can detect crack generated in the structure and the output voltage is proportional to the gap width.

Table-1 The output voltage of PVDF film with gap width and strain

strain initial gap width	0.50%	1.0%	1.5%	3.0%	6.0%	10.0%
1mm			0.0131	0.0225	0.0425	0.0825
5mm	0.0381	0.085	0.14	0.316	0.7425	
10mm	0.06375	0.1925	0.33	0.75		

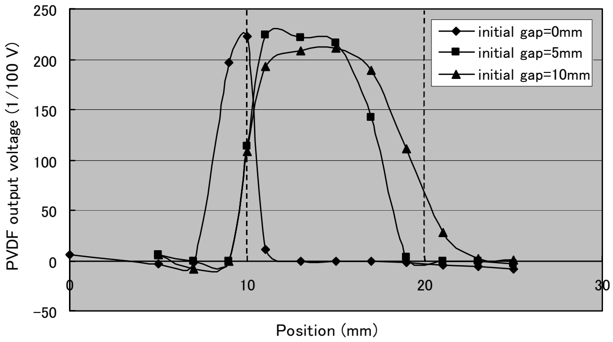


Fig.-9(a) Surface potential distribution(influence of initial gap width)

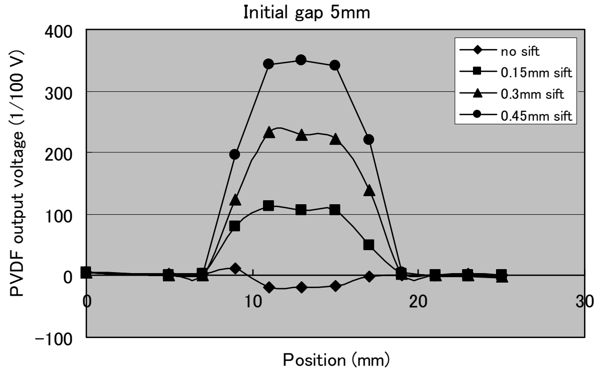


Fig.-9 (b) Surface potential distribution(influence of strain generated at gap)

Based on the results as mentioned above, loading test of a concrete beam was conducted to monitor the crack initiation and its propagation. The strain gages and PVDF films were attached on side-surface and bottom surface of a concrete beam(Fig.-10). The load vs deflection curve is illustrated in Fig.-11. The first crack was observed at about 20KN load.

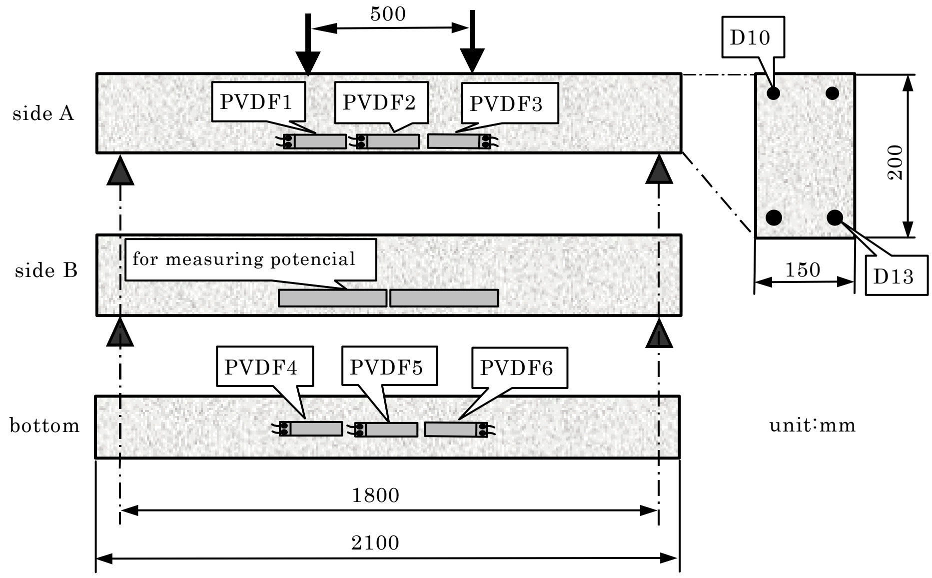


Fig.-10 Strain gages and PVDF films attached on the concrete beam

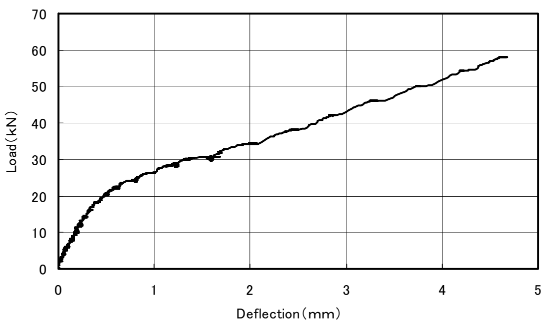


Fig.-11 Load and deflection curve

Photo-3 Cracks on the side surface of the beam

Fig.-12 provides the information on crack progress at the side surface of the beam. The output voltage of the film is small when the load is less than 20KN. The output voltage of the film (PVDF2,3) shows stepwise increase when the load exceeds 20KN. The output voltage of PVDF1 follows those of PVDF2 and 3. The crack progress at the bottom surface of the beam is estimated based on Fig.-13. The output voltages of PVDF4~6 correspond to those of PVDF1~3. Fig.-14 shows that the crack initiated at the bottom surface(measured by PVDF5) was also measured by PVDF2 in the side surface and the crack width in the side surface is always larger than that in the bottom.

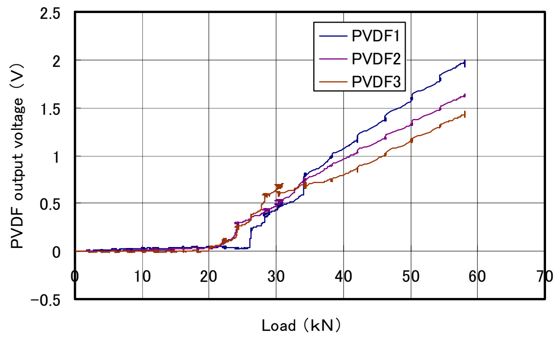


Fig.-12 Load and output voltage of PVDF film attached at the side-surface

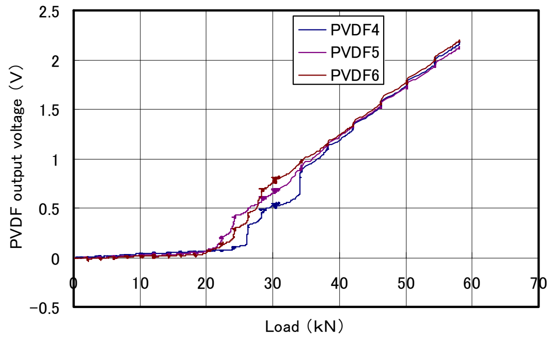


Fig.-13 Load and output voltage of PVDF film attached at the bottom-surface

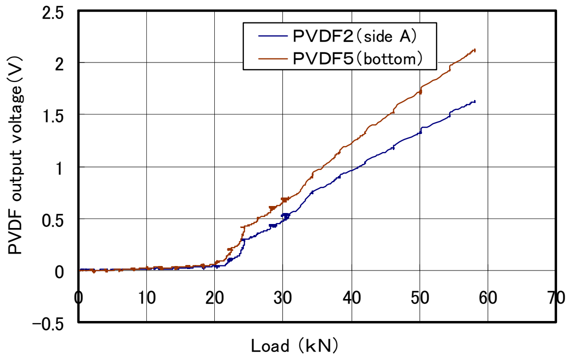


Fig.-14 Comparison of the output voltages of PVDF film attached at bottom-surface and at side-surface

5.Concluding remarks

The loading test was conducted in laboratory to confirm the performance of PVDF film as a sensor for structural monitoring. PVDF film can measure the strains after yielding of steel and aluminum. PVDF film can also detect crack development in concrete beam.

PVDF film is flexible and provides the easiness in attaching to civil structures. PVDF film does not require strain amplifier in case of dynamic strain measurement because of piezoelectricity. This feature may be utilized to save cost and power in field structural monitoring.

PVDF film has the potentials to be used as a sensor for monitoring of structures to detect damages such as yielding and cracks.

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