Application of PVDF Film to Stress Measurement of Structural Member

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Summary

In this paper a method to measure stress distribution using PVDF film and electrostatic voltmeter of non-contact type is developed. PVDF film is well suited to strain sensing applications for its excellent sensitivity and other good properties. The stress and strain distributions are determined from the measured potentials taking into account the piezoelectric constitutive law of film materials. First, in this paper the relationship between the electric potential and stresses is deduced in detail. Then, parameters used in the electric potential-stress relationship are estimated by an experiment applying the PVDF films to a smooth plate specimen. Next, a method to make isotropic piezoelectric material and a method to amplify the electric potential of the PVDF film by laminating two or more PVDF films together are also introduced and validated by experiment. Last, in order to check the accuracy of PVDF film as a stress measurement sensor, an experiment to measure the stress distribution of a plate specimen with an inclined crack is performed. The experimental results are in good agreement with those obtained from numerical calculation.

1. Introduction

Polyvinylidene fluoride (PVDF) is a synthetic semicrystalline polymer with piezoelectric properties. Since the discovery of piezoelectric effects in PVDF by Kawai [1], the properties of this material have been widely used in a variety of applications, particularly as sensors and transducers [2,3]. Some experimental studies have also been performed focusing on various electro-mechanical properties of PVDF [4,5,6].

The piezoelectric properties of PVDF are obtained by stretching and poling of extruded thin sheets of the polymer producing an alignment of molecular chain in the stretch direction. Polarization of PVDF is achieved by subjecting the polymer to an elevated, typically, 130℃ temperature and electric field of up to 100 kV/mm.

In this paper, thin PVDF films are utilized for the stress measurement of structures. PVDF film is a flexible, lightweight, tough engineering plastic available in a wide variety of thickness and large areas. It can be directly attached to a structure without disturbing its mechanical motion. So, PVDF film is well suited to strain sensing applications requiring very wide bandwidth and high sensitivity.

Two kinds of methods have been used for the stress measurement using PVDF film. One is to attach the electric terminal on the upper and lower surfaces of a PVDF film treated by aluminum electrode, and connect the terminals to an integration circuit by electrical wire. Electric current flows in the wire according to the change of the electric charge generated on the surface of the PVDF film. Then, the output voltage from the integration circuit becomes proportional to the applied strain of the member.

The other method is to measure the electric potential of the polarized surface of PVDF film by an electrostatic voltmeter of non-contact type. In this method, the measured electric potential is proportional to the applied strain of the member.

In this paper, stress measurement using the electrostatic voltmeter is discussed.

Firstly, the relationship between the electric potential on the surface of PVDF film and the applied strain is derived based on the piezoelectric

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Received 10th July 2002
Read at the Autumn meeting 14, 15th Nov. 2002

constitutive law. And the relationship between the electric potential and the stress is deduced.

Then, the parameters used in the electric potential-stress relationship are estimated by an experiment applying the PVDF films to a smooth plate specimen. Also, a method to make isotropic piezoelectric material and a method to amplify the electric potential of the PVDF film by laminating two or more PVDF films are discussed through the experiment.

Further, an experiment is carried out to measure the stress distribution of a plate specimen with an inclined crack. The experimental results are compared with the stress distribution obtained by numerical calculation.

2. Stress measurement using piezoelectric material

2. 1 Piezoelectric constitutive law

The piezoelectric constitutive law of the "d" type of dielectrics like the piezoelectric material is expressed by the following equations [7, 8]:

$$\varepsilon = s^E \sigma + d^T E \tag{1}$$

$$D = d\sigma + \eta^T E \tag{2}$$

where σ is the stress applied to the dielectrics; d is the piezoelectric strain constant; E is the intensity of the electric field; ε is the strain of the dielectrics; D is the electric flux density; s^E is the compliance of the piezoelectric material at fixed E and η^T is the permittivity of the dielectrics at fixed σ.

Fig.1 shows coordinate system of the piezoelectric material. Considering only normal strains of the dielectrics, Eq. (1) can be written as

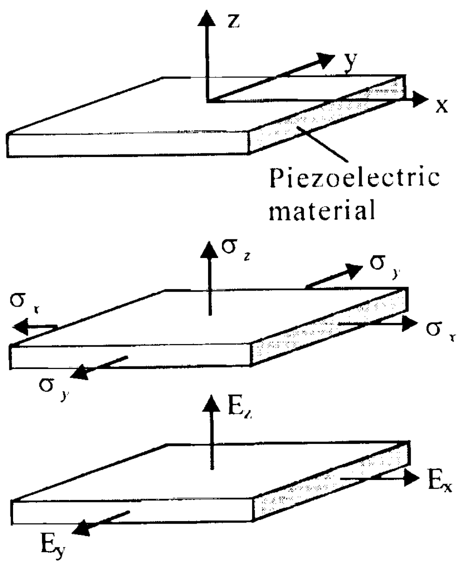

Fig.1 Coordinate system of the piezoelectric material

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{Bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E \\ s_{21}^E & s_{22}^E & s_{23}^E \\ s_{31}^E & s_{32}^E & s_{33}^E \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{Bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \end{bmatrix} \begin{Bmatrix} E_x \\ E_y \\ E_z \end{Bmatrix} \tag{3}$$

Solving Eq. (3), the normal stresses are

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{Bmatrix} = \begin{bmatrix} C_{11}^E & C_{12}^E & C_{13}^E \\ C_{21}^E & C_{22}^E & C_{23}^E \\ C_{31}^E & C_{32}^E & C_{33}^E \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{Bmatrix} - \begin{bmatrix} 0 & 0 & e_{31} \\ 0 & 0 & e_{32} \\ 0 & 0 & e_{33} \end{bmatrix} \begin{Bmatrix} E_x \\ E_y \\ E_z \end{Bmatrix} \tag{4}$$

where C^E is the symmetric stiffness matrix, i.e.

$$C^E = (s^E)^{-1} \tag{5}$$

and

$$\begin{aligned} e_{31} &= d_{31}C_{11}^E + d_{32}C_{12}^E + d_{33}C_{13}^E \\ e_{32} &= d_{31}C_{21}^E + d_{32}C_{22}^E + d_{33}C_{23}^E \\ e_{33} &= d_{31}C_{31}^E + d_{32}C_{32}^E + d_{33}C_{33}^E \end{aligned} \tag{6}$$

Eq. (4) is also simply expressed as

$$\sigma = C^E \varepsilon - C^E d^T E = C^E \varepsilon - e^T E \tag{7}$$

where

$$e = (C^E d^T)^T = dC^E \tag{8}$$

e, piezoelectric stress constant, is the ratio of stress change to the change of electric field when strains of the dielectric are constant.

Substituting Eq. (7) into Eq. (2), we have

$$\begin{aligned} D &= d\sigma + \eta^T E \\ &= d(C^E \varepsilon - e^T E) + \eta^T E \\ &= dC^E \varepsilon + (\eta^T - de^T)E \\ &= e\varepsilon + \eta^S E \end{aligned} \tag{9}$$

where

$$\eta^S = \eta^T - de^T \tag{10}$$

η^S is clamped permittivity. Usually, Eq. (7) and (9) are called as the piezoelectric equations of "e" type, i.e.

$$\sigma = C^E \varepsilon - e^T E \tag{11}$$

$$D = e\varepsilon + \eta^S E \tag{12}$$

Considering that the piezoelectric element is polarized in the thickness direction, it is assumed that all matrix elements of the permittivity η^T equal zero except η_{33}^T.

Using Eq. (10), Eq. (9) can be written as:

$$\begin{Bmatrix} D_x \\ D_y \\ D_z \end{Bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ e_{31} & e_{32} & e_{33} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{Bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \eta_{33}^S \end{bmatrix} \begin{Bmatrix} E_x \\ E_y \\ E_z \end{Bmatrix} \tag{13}$$

in which

$$\eta_{33}^{S} = \eta_{33}^{T} - (d_{31}e_{31} + d_{32}e_{32} + d_{33}e_{33}) \tag{14}$$

2.2 Stress measurement using electrostatic voltmeter of non-contact type

Fig. 2 shows the setup to measure the stress of structural member by using electrostatic voltmeter of non-contact type. The probe of voltmeter is fixed closely to the surface of piezoelectric material. The gap between the probe and the surface of the piezoelectric material is usually less than a few millimeters. As shown in the figure, the back surface of the piezoelectric material is earthed by wire and also one end of the wire is connected to the voltmeter. Stresses are determined from the measured voltages taking into account the piezoelectric constitutive law of the dielectrics.

In this measurement system, electric circuit is open at the surface of the piezoelectric element. Therefore the electric flux density D in Eq. (12) is zero at the surface of the piezoelectric element. Besides, the stress σ_z is zero at the surface of the piezoelectric element, so the following equations are obtained from the "e" type piezoelectric equations:

$$\sigma_z = C_{31}^{E}\varepsilon_x + C_{32}^{E}\varepsilon_y + C_{33}^{E}\varepsilon_z - e_{33}E_z = 0 \tag{15}$$

$$D_z = e_{31}\varepsilon_x + e_{32}\varepsilon_y + e_{33}\varepsilon_z + \eta_{33}^{S}E_z = 0 \tag{16}$$

Eliminating strain ε_z from the above two equations, the intensity of electric field E_z is solved as:

$$E_z = -\frac{(e_{31} - \frac{C_{31}^{E}}{C_{33}^{E}}e_{33})\varepsilon_x + (e_{32} - \frac{C_{32}^{E}}{C_{33}^{E}}e_{33})\varepsilon_y}{\eta_{33}^{S} + \frac{e_{33}^{2}}{C_{33}^{E}}} \tag{17}$$

The electric potential measured by the voltmeter is given by

$$V = hE_z \tag{18}$$

in which h is the thickness of the piezoelectric element. So the relation between the output voltage and the strain is

$$V = -h\frac{(e_{31} - \frac{C_{31}^{E}}{C_{33}^{E}}e_{33})\varepsilon_x + (e_{32} - \frac{C_{32}^{E}}{C_{33}^{E}}e_{33})\varepsilon_y}{\eta_{33}^{S} + \frac{e_{33}^{2}}{C_{33}^{E}}} \tag{19}$$

If the piezoelectric material is isotropic in x and y directions,

$$e_{31} = e_{32},\ C_{31}^{E} = C_{32}^{E} \tag{20}$$

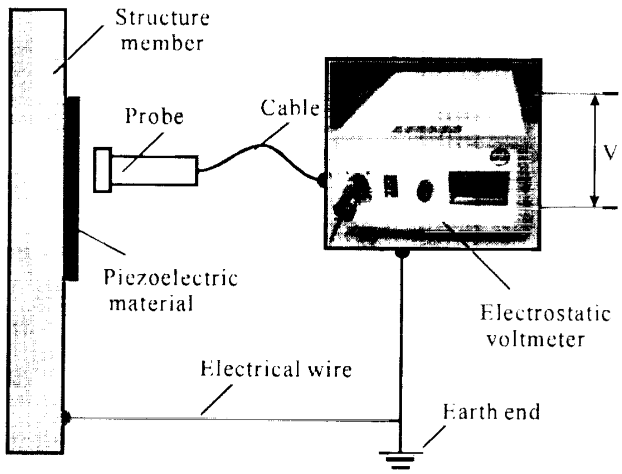

Fig.2 Stress measurement using electrostatic voltmeter of non-contact type

Then the following equation is obtained:

$$V = h\frac{(\frac{C_{31}^{E}}{C_{33}^{E}}e_{33} - e_{31})}{\eta_{33}^{S} + \frac{e_{33}^{2}}{C_{33}^{E}}}(\varepsilon_x + \varepsilon_y) \tag{21}$$

It means that the measured potential is proportional to the sum of ε_x and ε_y.

3. Relationship between stresses and electric potentials of PVDF film measured by electrostatic voltmeter

Permanent dipole polarization of PVDF is obtained through a technological process involving stretching and poling of extruded thin sheets of the polymer. Stretching provides the alignment of molecular chains in the stretch direction. So PVDF film has two in-plane material directions, i.e., parallel and perpendicular to aligned molecular chains. This means that PVDF film shows anisotropic feature and its electrical and mechanical responses differ depending upon the axis of applied electrical field or axis of mechanical stress or strain. Calculations involving piezoelectric activity must account for this directionality.

Fig. 3 shows three PVDF films are adhered to a structure component in three different directions. The lines drawn on the PVDF films denote the stretch direction of the films.

From the discussion in the last section, the output voltages from PVDF films can be expressed as:

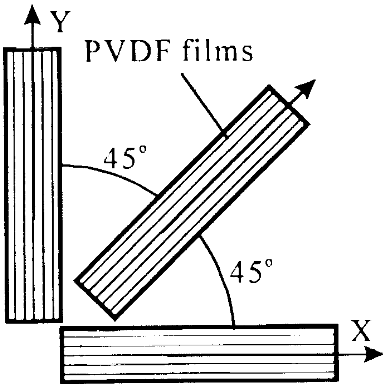

Fig. 3 PVDF films are adhered in three directions

$$\begin{aligned} V_x &= b_1\varepsilon_x + b_2\varepsilon_y \\ V_y &= b_2\varepsilon_x + b_1\varepsilon_y \\ V_{45} &= b_1\varepsilon_{45} + b_2\varepsilon_{-45} \end{aligned} \tag{22}$$

where ε_x, ε_y, ε_{45} and ε_{-45} are strains in four directions.

In plane stress state, if strains ε_x, ε_y and γ_{xy} at a point are known, normal strain in any direction at this point is given by

$$\varepsilon_N = l^2\varepsilon_x + m^2\varepsilon_y + lm\gamma_{xy} \tag{23}$$

where

$$l = \cos(N,x),\ m = \cos(N,y) \tag{24}$$

So ε_{45} and ε_{-45} can be expressed by the following equations:

$$\begin{aligned} \varepsilon_{45} &= \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\gamma_{xy}}{2} \\ \varepsilon_{-45} &= \frac{\varepsilon_x + \varepsilon_y}{2} - \frac{\gamma_{xy}}{2} \end{aligned} \tag{25}$$

Substituting Eq. (25) into Eq. (22), the following equation is obtained:

$$\begin{Bmatrix} V_x \\ V_y \\ V_{45} \end{Bmatrix} = \begin{bmatrix} b_1 & b_2 & 0 \\ b_2 & b_1 & 0 \\ \frac{b_1+b_2}{2} & \frac{b_1+b_2}{2} & \frac{b_1-b_2}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{26}$$

Substituting the stress-strain relationship of isotropic material in plane stress condition into Eq. (26), we have

$$\begin{Bmatrix} V_x \\ V_y \\ V_{45} \end{Bmatrix} = \begin{bmatrix} a_1 & a_2 & 0 \\ a_2 & a_1 & 0 \\ \frac{a_1+a_2}{2} & \frac{a_1+a_2}{2} & (a_1-a_2) \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} \tag{27}$$

$$\begin{aligned} a_1 &= (b_1 - \nu b_2)/E \\ a_2 &= (b_2 - \nu b_1)/E \end{aligned} \tag{28}$$

In the above, E is Yong's modulus and ν is Poisson's ratio.

By solving the inverse of the matrix in Eq. (27), σ_x, σ_y and τ_{xy} can be expressed as:

$$\begin{Bmatrix} \sigma_X \\ \sigma_Y \\ \tau_{xy} \end{Bmatrix} = \frac{1}{a_1^2 - a_2^2} \begin{bmatrix} a_1 & -a_2 & 0 \\ -a_2 & a_1 & 0 \\ \frac{-(a_1+a_2)}{2} & \frac{-(a_1+a_2)}{2} & (a_1+a_2) \end{bmatrix} \begin{Bmatrix} V_X \\ V_Y \\ V_{45} \end{Bmatrix} \tag{29}$$

When the electric potentials V_x, V_y and V_{45} are measured by the experiment, the stresses can be calculated by the above equation.

If the stretch direction of adhered PVDF film changes from that of principal stress σ_1 as shown in Fig. 4, the stress σ_L in the stretch direction of the film and σ_B perpendicular to σ_L can be expressed by the following equations from the Mohr's stress circle:

$$\begin{aligned} \sigma_L &= \frac{\sigma_1 + \sigma_2}{2} + \frac{\sigma_1 - \sigma_2}{2}\cos 2\theta \\ \sigma_B &= \frac{\sigma_1 + \sigma_2}{2} - \frac{\sigma_1 - \sigma_2}{2}\cos 2\theta \end{aligned} \tag{30}$$

Then the output voltage is given by

$$\begin{aligned} V_\theta &= a_1\sigma_L + a_2\sigma_B \\ &= (a_1\sigma_1 + a_2\sigma_2)\cos^2\theta + (a_1\sigma_2 + a_2\sigma_1)\sin^2\theta \end{aligned} \tag{31}$$

When the stress state is in uniaxial stress condition, i.e. $\sigma_1 = \sigma$ and $\sigma_2 = 0$, the above equation becomes

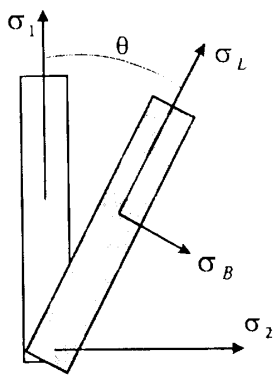

Fig. 4 Direction change of adhered PVDF film

$$V_\theta = \sigma(a_1 \cos^2\theta + a_2 \sin^2\theta) \qquad (32)$$

The values of a_1 and a_2 can be determined from the experiment discussed in the next chapter. The relation between θ and V_θ/σ can be shown in Fig. 5 in the case of $a_1 = 0.093$ V/MPa and $a_2 = 0.027$ V/MPa.

4. Experiments

4.1 Estimation of parameters a_1 and a_2

Experiments were carried out to estimate parameters a_1 and a_2 shown in Eq.(27). The specimen is a rectangular smooth plate made of SS400 mild steel, with Yong's modulus $E = 2.1 \times 10^5$ MPa and Poisson's ratio $\upsilon = 0.3$ as shown in Fig. 6.

Fully reversed axial sinusoidal wave loads, with load amplitude of 10, 15, 20, 25, 30 kN and frequency of 1Hz, were repeatedly applied to the specimen. The size of PVDF film is 12 mm × 12 mm, and totally 12 PVDF films were adhered at both sides of the specimen. In this experiment, the thin layer of aluminum deposited on both surfaces of the PVDF film is removed by putting the film into sodium hydroxide solution (5%).

In Fig.6, the lines drawn on the PVDF film show the stretch direction of the PVDF film. The PVDF film generates maximum electric charge when tensile strain is applied to this direction. The PVDF films are adhered at the three included angles 0°, 45° and 90° between the principal direction of the PVDF film and the applied load.

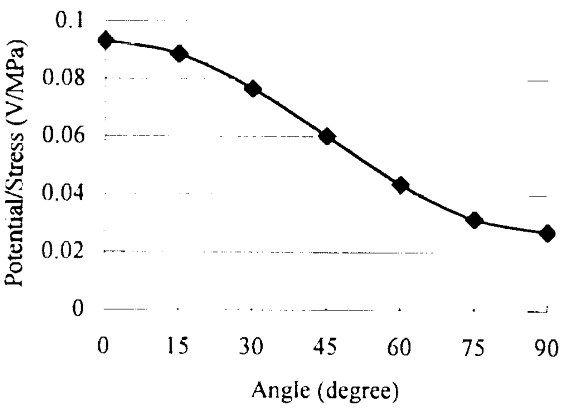

Fig. 5 Relation between θ and V_θ/σ

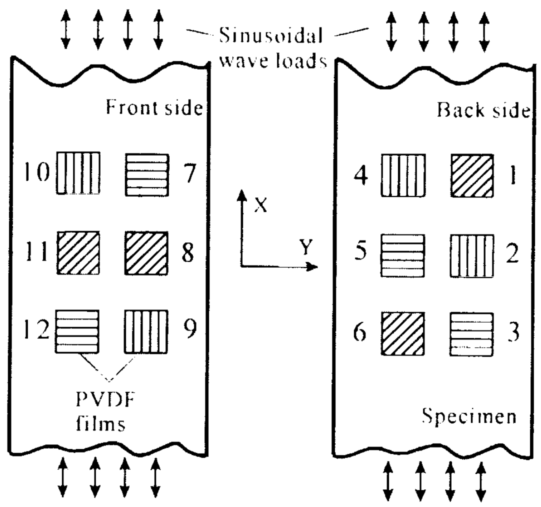

Fig. 6 PVDF films and specimen for experiment

Table 1 Measured output voltages in the experiment

Load amplitude (kN)			10	15	20	25	30
Stress range (MPa)			40	60	80	100	120
Output voltages (V)	0°	No. 2	3.2	4.8	6.4	7.8	9.6
		No. 4	4.0	5.6	7.4	9.4	10.8
		No. 9	3.8	5.6	7.4	9.4	11.2
		No. 10	3.8	5.4	7.4	9.0	11.0
		Average*	3.9	5.5	7.4	9.3	11.0
	45°	No. 1	2.2	3.2	4.2	5.2	6.0
		No. 6	2.0	3.2	4.2	5.4	6.2
		No. 8	2.4	3.2	4.8	5.8	7.0
		No. 11	2.4	3.2	4.4	5.4	6.4
		Average	2.3	3.2	4.4	5.4	6.4
	90°	No. 3	1.2	1.6	2.2	2.8	3.4
		No. 5	1.2	1.6	2.0	2.6	3.4
		No. 7	1.2	1.6	2.2	2.8	3.2
		No. 12	1.2	1.4	1.8	2.4	2.8
		Average	1.2	1.6	2.1	2.7	3.2

*Average output voltage of four films which are in the same direction.

The electric potential of the PVDF film is measured by the electrostatic voltmeter (TREK Model 347 and Probe Model 6000B-7C) and recorded by the voltmeter (NEC Omniace II RA1200). The values of a_1 and a_2 are calculated by Eq. (27) based on the output voltages from the voltmeter.

Table 1 summarizes the results of the experiment. The relations between the average output voltages and the stress ranges are shown in Fig. 7. By using linear regression, a_1 and a_2 can be obtained, i.e.

$$a_1 = 0.093\ \text{(V/MPa)},\quad a_2 = 0.027\ \text{(V/MPa)} \tag{33}$$

Substituting Eq. (33) into Eq. (28), b_1 and b_2 can also be calculated as:

$$\begin{aligned} b_1 &= \frac{E(a_1 + \nu a_2)}{1-\nu^2} = 2.33\times 10^4 (\text{V}) \\ b_2 &= \frac{E(a_2 + \nu a_1)}{1-\nu^2} = 1.27\times 10^4 (\text{V}) \end{aligned} \tag{34}$$

4.2 Electric potential of laminated PVDF film

From Eq. (27), the sum of stresses σ_x and σ_y has the following relationship with the output voltage:

$$V = V_x + V_y = (a_1 + a_2)(\sigma_x + \sigma_y) \tag{35}$$

The above equation gives an idea to make an isotropic PVDF film. If the polarities of two PVDF films, cemented together on the structural member, are in series in the thickness direction and the in-plane stretch direction of one film is perpendicular to that of the other (see Fig. 8(a)), the electric potential on the surface of the two layers of the PVDF films may be equal to $(V_x + V_y)$.

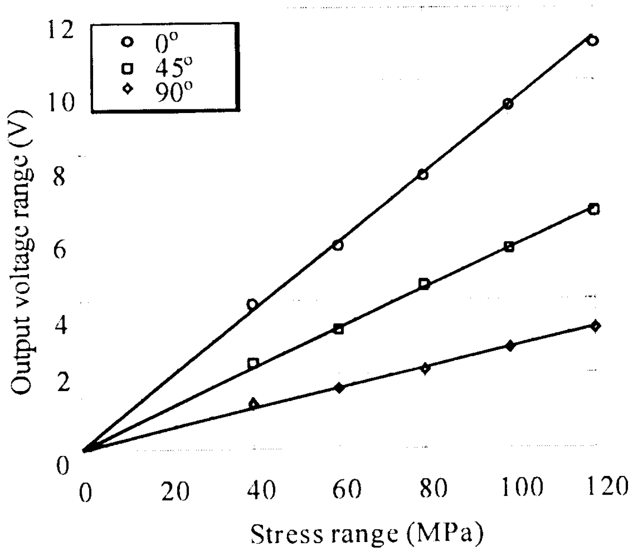

Fig. 7 Relations between the average output voltages and the stress ranges

From the above described method, if the in-plane stretch direction of one film is changed to be parallel to that of the other (see Fig. 8(b)), the electric potential on the surface of the two layers of the PVDF films may be twice of that of a single PVDF film.

In order to validate the above phenomena, the following experiment was carried out.

Fig. 9 shows the PVDF films adhered in eight patterns on a smooth specimen made of mild steel SS400. The lines drawn on the PVDF films show their stretch directions. From the figure we can see that No. 6, 7 and 8 films are cemented on the specimen by the way illustrated in Fig. 8(a). The differences between them are the angles between the stretch directions of the top films and loading direction, which are 0°, 45° and 90°, respectively.

No. 2, 3 and 5 films are cemented on the specimen by the way illustrated in Fig. 8(b), and No. 3 film is laminated by three layers of PVDF films. For comparison, single layer PVDF films No.1 and 4 are also cemented. The only difference is that their stretch directions are parallel or perpendicular to the applied loads.

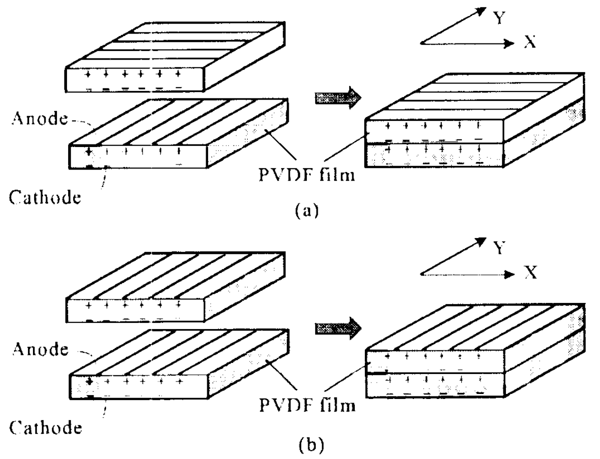

Fig. 8 Two PVDF films are cemented together in two ways

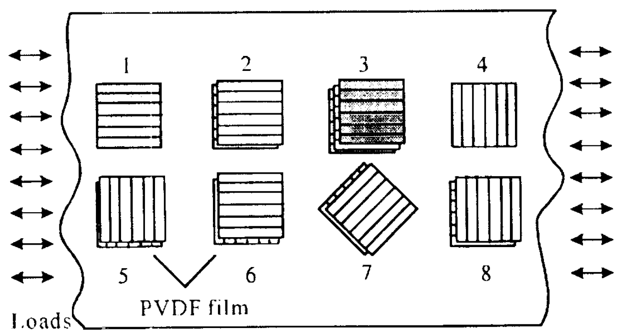

Fig. 9 Direction and number of PVDF films adhered

on the specimen

Fully reversed axial sinusoidal wave loads, with stress ranges of 30 kN and frequency of 1 Hz, were repeatedly applied to the specimen. The results of the output voltage from the electrostatic voltmeter are shown in Table 2 and Fig. 10.

From the comparison of the electric potentials of No.1, 2 and 3 films, we can see that the electric potentials of the PVDF are proportional to the number of PVDF films cemented together in the same direction. We can also confirm this thing from the comparison of the potentials between No.4 and 5 films, of which the stretch directions are perpendicular to the direction of loading.

Besides, if two layers of PVDF films are cemented together and their stretch direction are perpendicular to each other such as No.6, 7 or 8 films, the electric potentials become to be equal to the sum of the potentials of No.1 film and No.4 film. No difference can be seen among the potentials of No.6, 7 and 8 films. This proves that the two PVDF films laminated in the way illustrated in Fig. 8(a) become isotropic piezoelectric material.

Table 2 Output voltages of PVDF films from No.1 to No.8

No. of films	Number of layers of the films	Angle*	Output voltages (V)
No.1	1	0°	9.5
No.2	2	0°, 0°	19.5
No.3	3	0°, 0°, 0°	29.5
No.4	1	90°	3.0
No.5	2	90°, 90°	5.5
No.6	2	90°, 0°	12.5
No.7	2	-45°, 45°	12.0
No.8	2	0°, 90°	12.5

* Angle between the stretch direction of films and loading.

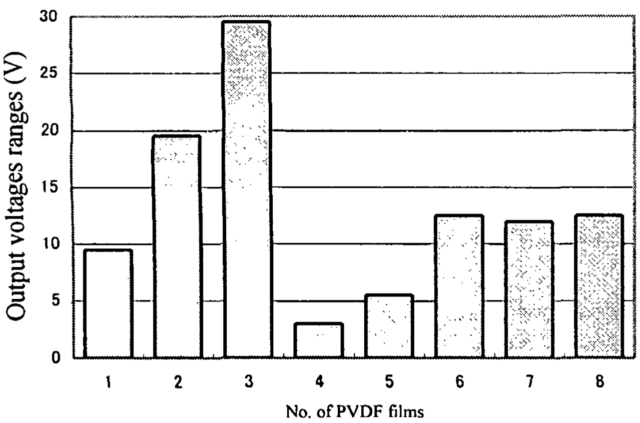

Fig. 10 Output voltages of PVDF films

4.3 Stress measurement of cracked specimen by the use of PVDF film

To validate the accuracy of PVDF film as a stress measurement sensor, an experiment was carried out by using a cracked plate specimen as shown in Fig.11. The specimen is rectangular plate (400mm length, 100mm width and 10mm thickness) and made of SS400 mild steel, with Yong's modulus $E = 2.1 \times 10^5$ MPa, Poisson's ratio $\upsilon = 0.3$.

Fig. 12 shows the shape of an artificial inclined crack machined in the plate specimen, the location of the PVDF film cemented near the crack tip and the measurement points of the electric potential on the PVDF film. Two PVDF films were cemented on the front and back surfaces of the specimen, respectively. The stretch direction of one PVDF film is parallel to the direction of x-axis to measure output voltage V_x, and the other PVDF film is to the direction of y-axis to measure V_y . The measurement points are the cross points of 5 mm square meshes drawn in Fig.12. Fully reversed axial sinusoidal wave loads, with stress range of 35 kN and frequency of 1 Hz, were repeatedly applied to the specimen. After getting the output voltages at designated points of PVDF films, stresses can be calculated from Eq. (29). The distance between the probe tip of the electrostatic voltmeter and the surface of PVDF film was maintained about 1.0 mm during the measurement.

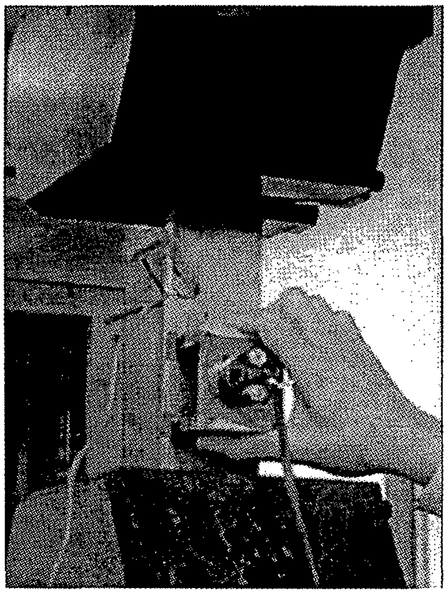

Fig. 11 Stress measurement near crack tip using

PVDF film

Stress distribution of the specimen was also calculated using ANSYS for checking the experimental result. Fig. 13 shows the mesh division of the FE model and the calculated distribution of stresses σ_x and σ_y. The comparison of the stress distributions between experiment and analysis are shown in Fig. 14. From the figures, we can see the results are in good agreement. It proves that PVDF film can measure the stress distribution very well. However, near the crack tip, the difference between the experimental and calculated results is obvious. In experiments, it is not easy to measure the stress at the crack tip, because stress gradient near the crack tip is very big. Besides, it is also hard to get real stress value at the crack tip by linear FEM calculation.

5. Conclusions

In this paper, a method to measure stress distribution of structures using PVDF film and electrostatic voltmeter of non-contact type is presented. The approach is based on the piezoelectric constitutive law, which links the stress distribution of structures to the measured electric potential of PVDF film cemented on the surface of the structures.

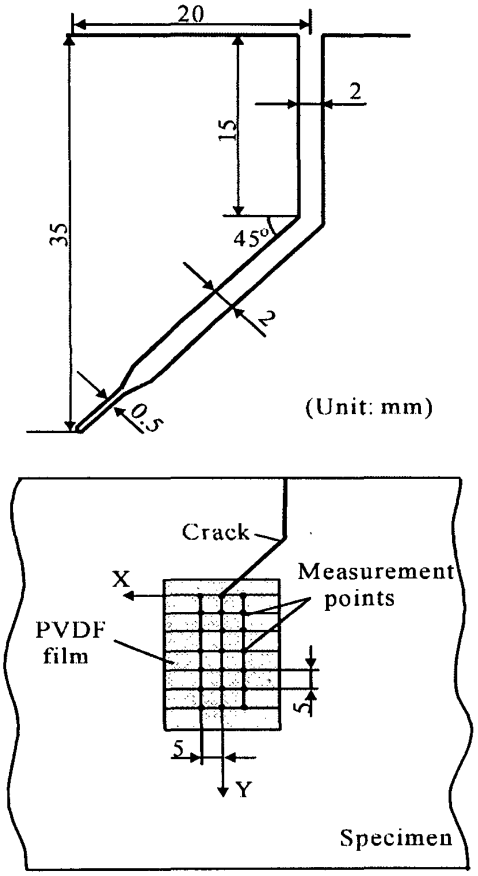

Fig. 12 Shape of the inclined crack and positions of

stress measurement

The relationship between the electric potentials and the stresses σ_x, σ_y and τ_{xy} is deduced, and the parameters a_1 and a_2 used in the relationship are obtained through an experiment applying PVDF films adhered on a smooth specimen under uniaxial stress condition.

A method to make isotropic PVDF film is also introduced, in which two layers of PVDF films are cemented together on the structure component, and the in-plane stretch direction of one film is perpendicular to that of the other. The electric potential on the surface of the two layers of the PVDF films will be equal to $(V_x + V_y)$, and also be the same when the two layers of PVDF films are changed together into different direction, which shows isotropic property. In addition, if the stretch directions of PVDF films cemented together are parallel, the electric potential on the surface of the PVDF films will be proportional to the layers of the films.

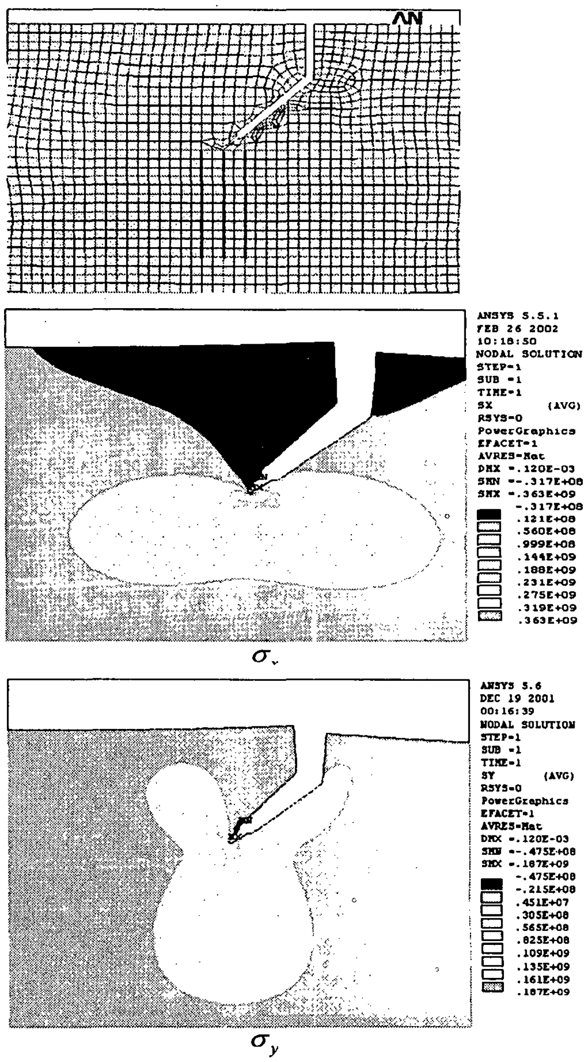

Fig. 13 Stress calculation using ANSYS

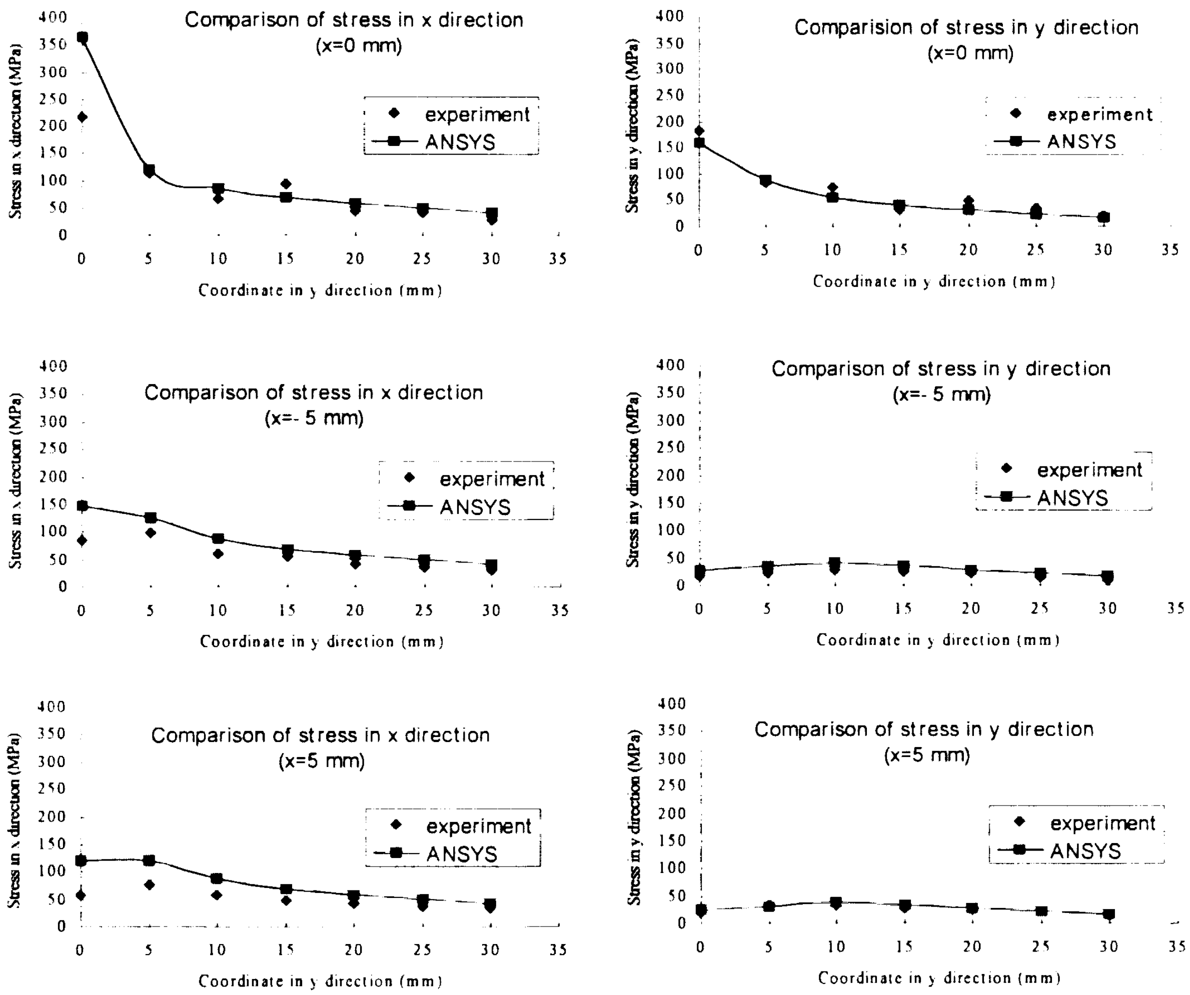

Fig. 14 Comparison of the stress distributions from two methods

An experiment to measure in-plane stress distribution near the crack tip of a plate specimen is also performed in order to validate the accuracy of PVDF film in stress measurement. Compared with the results of numerical calculation using ANSYS, the experimental results have demonstrated good precision of the present technique in measuring stress distribution of structures.

Acknowledgement

This research work was supported by Electric Technology Research Foundation of Chugoku.

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