Crack Detection in Concrete Elements Utilizing Piezoelectric Cables

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ABSTRACT:

Piezoelectric material is one of the typical examples of smart materials. The piezoelectrics offer the capabilities of both sensing and actuating. This paper presents a fundamental methodology of the crack detection for concrete structural elements utilizing piezoelectric cable sensors. The piezoelectric cable sensor is one of the most recently developed devices in the field of piezoelectric technology. In piezoelectric cables, piezoelectric film, which generally possesses a function of sensor, lies between the inner conductor and copper braid outer. The electrical output from the piezoelectric cable is proportional to the stress imparted to the cable. The piezoelectric cable mounted near the surface of concrete can detect concrete cracks. Such piezoelectric cables could provide concrete structures with the self-sensing capability for the damage assessment. In this paper, first of all, the characteristics of the piezoelectric cable are experimentally investigated. Then, three-point bending tests are conducted utilizing a fabricated concrete beam embedded with the piezoelectric cable for the purpose of demonstrating the effectiveness of this self-sensing concrete or self-detection of cracks.

INTRODUCTION

For the last couple of decades, civil engineers have been attempting to integrate a variety of advanced technologies into civil structures for the purpose of enhancing structural safety and functionality [1-12]. The integration of such innovative technologies has been changing the conventional images of not only civil structures but also the civil engineering field itself. In this regard, civil engineering has been stepping into a new stage of technological development. A typical example of this paradigm shift has been brought mainly by the integration of the “smart” concept into civil structures. Although the widely-accepted definition of “smart” structures has not yet become concrete, a combination of sensing and control technologies are expected to produce the next-generation of “smart” structures and to establish the field of “modern” structural engineering. The effective usage of the smart material-based sensing system expectedly

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lead to the development of "smart" damage assessment of structures or "smart" health monitoring [5-12].

Piezoelectric material is a typical example of these smart materials. The piezoelectrics offer the capabilities of both sensing and actuating. This paper presents a fundamental methodology of the crack detection for concrete structural elements utilizing piezoelectric cables. The piezoelectric cable sensor is one of the most recent developments in the field of piezoelectric technology [13]. In piezoelectric cables, piezoelectric film, which generally possesses a function of sensors, is inserted between the inner conductor and copper braid outer. The electrical output from the piezoelectric cable is proportional to the stress imparted to the cable. The piezoelectric cable mounted near the surface of concrete can detect concrete cracks. Such piezoelectric cables could provide concrete structures with the self-sensing capability for the damage assessment. First of all, the characteristics of the piezoelectric cable are experimentally investigated. Then, three-point bending tests are conducted utilizing a fabricated concrete beam embedded with the piezoelectric cable to demonstrate the effectiveness of this self-sensing concrete or self-detecting of cracks.

PIEZOELECTRIC CABLE SENSOR

Basic Characteristic of the Piezoelectric Cable Sensor

The piezoelectric material can be used as both sensors and actuators in structural systems. The piezoelectric cable sensor consists of the piezoelectric polymer insulator between the copper braid outer shield and inner conductor [13]. By the piezoelectricity, the output voltage of the piezoelectric cable sensor is proportional to the impact stress, tension stress and compression stress imparted to the cable. The capacitance of the piezoelectric cable sensor is 600 pF/m. The piezoelectric sensor has the resistance-capacitance (RC) high pass filter characteristics. The cut-off frequency, f_c, of the piezoelectric sensor is:

$$f_c = \frac{1}{2\pi\, R\, C} \tag{1}$$

where R is the resistance of the circuit, and C is the capacitance of piezoelectric cable sensor. For the purpose of minimizing the signal loss and noise, the unity-gain-buffer circuit shown in Figure 1 [13] is connected to the piezoelectric cable sensor in this paper.

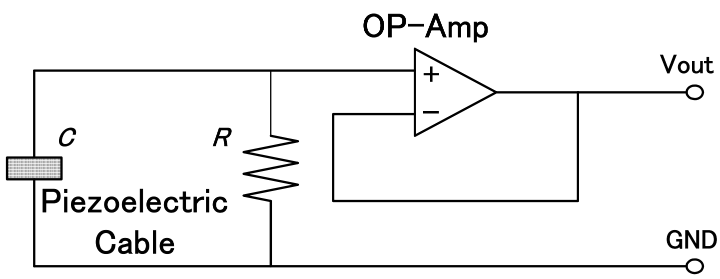


Figure 1 Unity-gain-buffer circuit

Frequency Response of the Piezoelectric Cable Sensor

For the purpose of investigating the frequency characteristics of the piezoelectric cable sensor, an acrylate board inserted piezoelectric cable sensor is subjected to the sweep sinusoidal wave given by the shaking table. The specimen consists of the three 1mm acrylate board and one 2mm acrylate board by pasting these boards together, and is equipped with the piezoelectric cable sensor. The cutoff frequency of the specimen is about 8.43 Hz in this experiment. Figure 2 shows the specimen for the shaking table test. To assess the accuracy, the responses of the piezoelectric cable were compared with those of a strain gage as the reference signal. Figures 3 and 4 show a comparison in the time and frequency domains between the piezoelectric cable sensor and strain gage when subject to the sweep sinusoidal waves from 5.0 Hz to 15 Hz. In Figure 4, the frequency responses of the piezoelectric cable sensor and the strain gage are normalized so that the maximum values are equal to one. These figures indicate the output of the piezoelectric cable sensor is in good agreement with strain gage over the cutoff frequency.

CRACK DETECTION IN CONCRETE ELEMENT

To investigate the capability of detecting the crack in concrete structure by utilizing the piezoelectric sensor, three-point bending test for the concrete beam specimen is conducted. The dimension of the concrete beam specimen is $40\times40\times160$ mm^3 shown in Figure 5. The length of the piezoelectric cable sensor is 175 mm and the cutoff frequency of the sensor is 1.52 Hz. The detail of the three-point bending test is shown in Figure 6. In the experiment, the lowpass filers with a cutoff frequency of 10.0 Hz are utilized to remove noise signal.

For the purpose of testing the monitoring capability of the piezoelectric cable sensor, the voltage shifts of this sensor are measured when the loads are rapidly released. This experiment employs the maximum values of the loads applied to the specimen as 0.4 kN, 0.6 kN, 0.8 kN, 1.0 kN, 1.2 kN, 1.5 kN and 2.0kN. To assess the accuracy, the responses

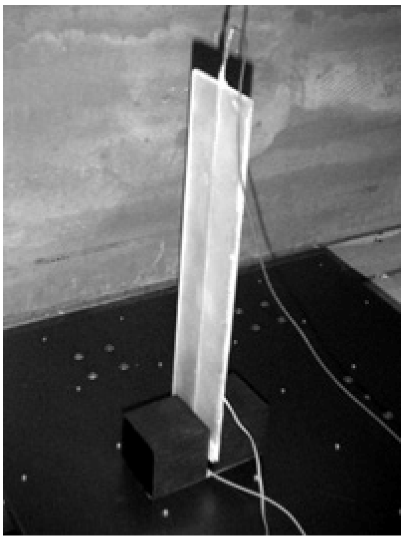
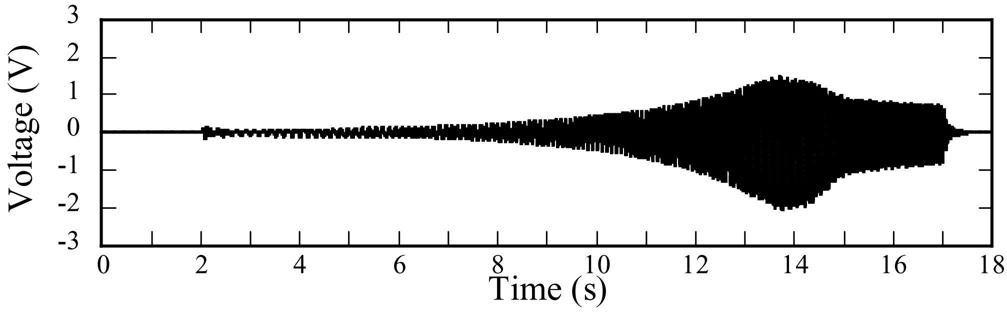
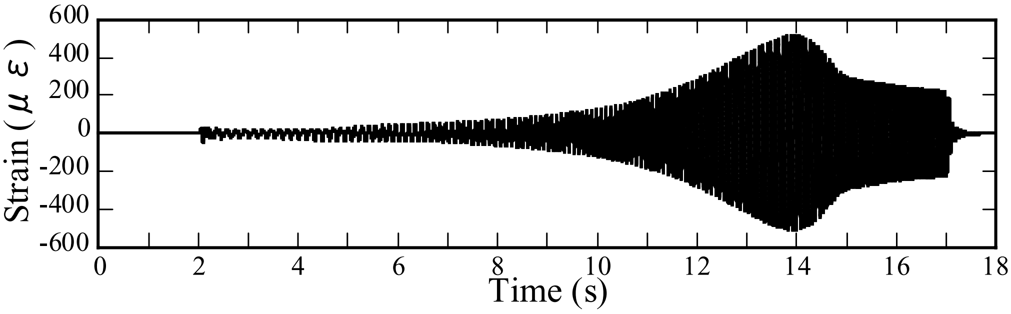


Figure 2: Acrylate board inserted piezoelectric cable sensor



(a) Output voltage of the piezoelectric cable sensor



(b) Response of the strain gage

Figure 3: Response time histories of sensors to sweep sinusoidal wave in time domain

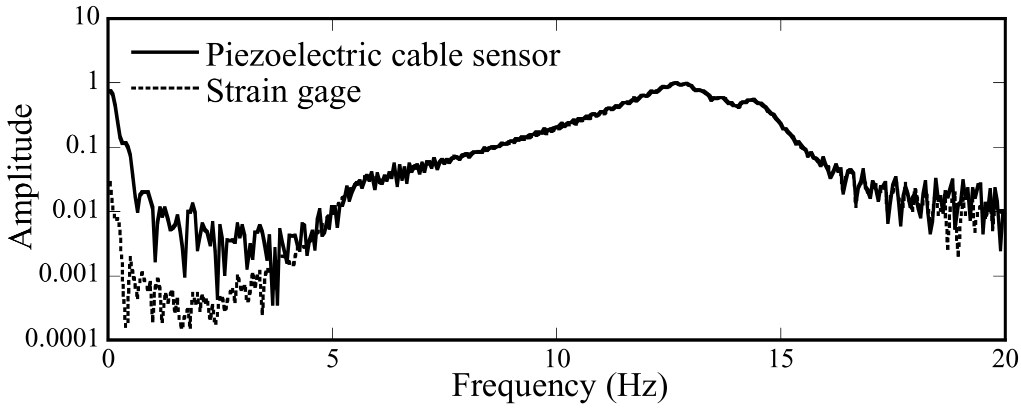


Figure 4: Frequency responses of sensors to sweep sinusoidal wave

of the piezoelectric cable were compared with those of the strain gage as the reference signals. The output voltages of the piezoelectric cable sensor and the strain gage are shown in Figure 7, when the loads were released. Table 1 indicates the output voltage shift when releasing the load, which inputs to the cement beam specimen. Figure 8 shows the relation between the voltage shift of the piezoelectric cable sensor and the load. In Figure 8, a linear relationship between the output voltage of the piezoelectric cable and amplitude of input load can be easily recognized. The relation between the

Figure 5: Cement beam specimen

Figure 6: Three-point bending test

Table 1: The output voltage of three-point bending test

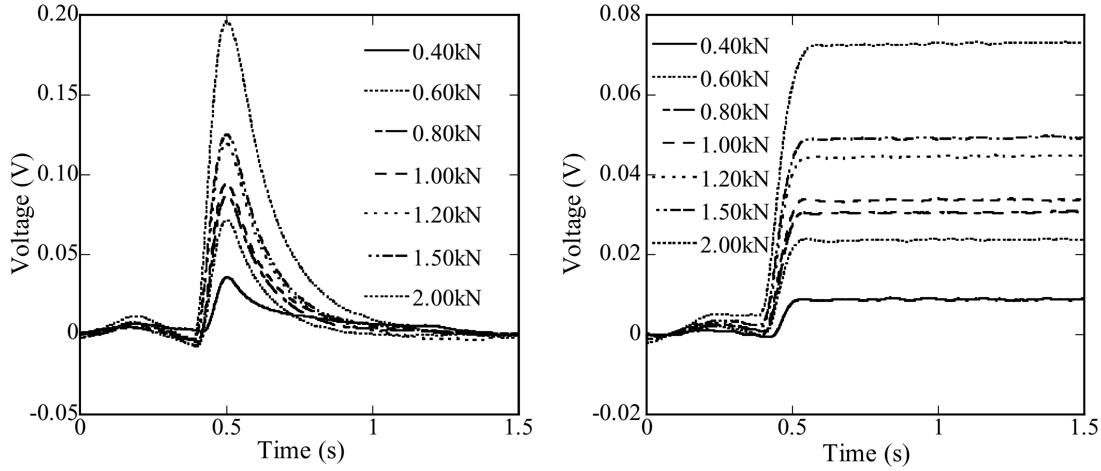
Load (kN)	0.40	0.60	0.80	1.00	1.20	1.50	2.00
Piezoelectric Cable sensor (V)	0.0341	0.0789	0.0918	0.1018	0.1230	0.1289	0.1995
Strain Gage (V)	0.0093	0.0239	0.0300	0.0332	0.0425	0.0467	0.0680

piezoelectric cable sensor and the maximum value of the load applied to the specimen can be expressed by the following linear function:

$$V_p = 0.0904 \times F + 0.0114 \quad (2)$$

where V_p is the output voltage of the piezoelectric cable sensor, F is the maximum value of the load applied to the specimen. Figure 9 shows the relation between the voltage shifts of the piezoelectric cable sensor and of the strain gage. The piezoelectric cable sensor can monitor the stress shift of the structural element, because Figure 7 indicates the relation between the piezoelectric cable sensor and the strain gage can expressed by using the linear function.

Next, to investigate the ability of detecting the crack occurrence, the three-point bending test is conducted till the specimen has the crack. In this experiment, the crack in the specimen occurred when the load became to 3.26 kN. Figure 10 shows the output voltages of the piezoelectric cable sensor and of the strain gage. Figure 10 indicates that the piezoelectric cable sensor can detect the crack in the concrete structure. And also, the piezoelectric cable sensor can monitor the releasing of the load applied to the specimen after crack occurrence. Compared with the strain gage, the piezoelectric cable sensor can detect the crack occurrence more clearly.



(a) Output of the piezoelectric cable sensor (b) Output of the strain gage

Figure7: Maximum voltage shift of releasing the load

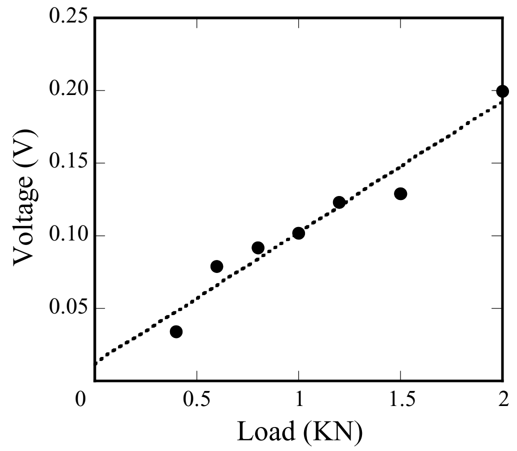


Figure 8: The relationship between output of piezoelectric cable sensor and the load

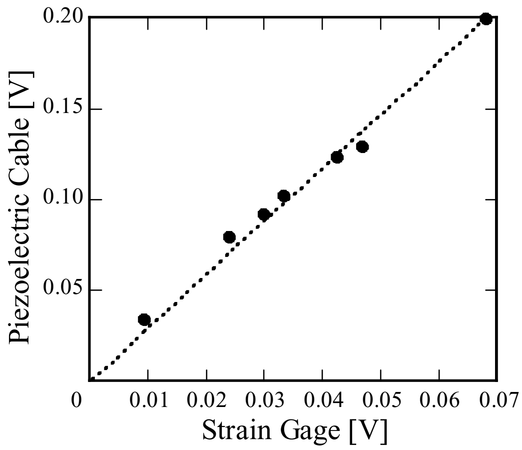
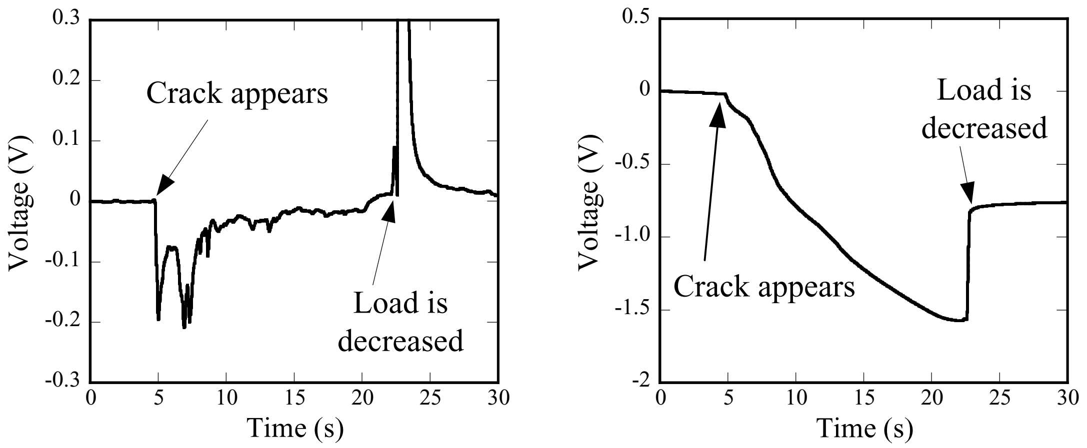


Figure 9: The relationship between Piezoelectric cable sensor and strain gage



(a) Piezoelectric cable sensor (b) Strain gage

Figure 10: Time history of the output voltage when the crack occurs

CONCLUSIONS

This paper presents a fundamental methodology of the crack detection for concrete structural elements utilizing piezoelectric cables. The effectiveness of the piezoelectric cable sensor is confirmed by conducting the fundamental experiments and comparing the strain gage. From the results of the fundamental experiments, the following points could be concluded:

1. The output voltage of the piezoelectric cable sensor is proportional to the impact stress, tension stress and compression stress imparted to the cable. The piezoelectric cable sensor can monitor the change of the strain in the structure.
2. The crack in the concrete structure can be easily detected by utilizing piezoelectric cable sensor. Because the piezoelectric cable sensor can measure the impact response of the concrete structure.

The effectiveness of the proposed methodology has been demonstrated by conducting the three-point bending test. The proposed monitoring methodology will provide the useful information for damage location.

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