한국전산구조공학회
2004년도 봄 학술발표회 논문집

토목 구조물의 PZT Impedance 기반 손상추정기법

PZT Impedance-based Damage Detection for Civil Infrastructures

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Abstract

This paper presents the feasibility of an impedance-based damage detection technique using piezoelectric (PZT) transducers for civil infrastructures such as steel bridges. The impedance-based damage detection method is based on monitoring the changes in the electrical impedance. Those changes in the electrical impedance are due to the electro-mechanical coupling property of the piezoelectric material and structure. An effective integrated structural health monitoring system must include a statistical process of damage detection that is automated and real time assessment of damage in the structure. Once measured, damage sensitive features from this impedance change can be statistically quantified for various damage cases. The results of the experimental study on three kinds of structural members show that cracks or loosened bolts/nuts near the PZT sensors may be effectively detected by monitoring the shifts of the resonant frequencies. The root mean square (RMS) deviations of impedance functions between before and after damages were also considered as a damage indicator. The subsequent statistical methods using the impedance signature of the PZT sensors were investigated.

1. Introduction

Recently, research and development activities on structural health monitoring led to the development of smart sensors and IT-based integrated sensing systems in the fields of mechanical, aeronautical and civil engineering. In the near future, structure health monitoring (SHM) will provide compelling value for preserving and extending the service lives of the civil infrastructure. Structural health monitoring technology is essentially aimed at the development of autonomous systems for continuous monitoring and integrity assessment in structures with minimum labor involvement. Therefore, a smart wireless monitoring system and low-cost but high-effect smart sensors such as piezoelectric sensor, optical fiber and MEMS are needed to be developed. In particular, the impedance-based technique, which uses smart piezoelectric ceramic (PZT) materials, has emerged as a powerful technique for SHM. In this technique, a PZT patch is bonded to the structure and a high-fidelity electro-mechanical admittance signature of the patch serves as a diagnostic signature of the structure. The basic principle of the impedance-based method is to track the electrical point impedance of the PZT patch bonded onto a structure. Physical changes in the structure cause changes in the structural mechanical impedance, which may induce changes in the electrical impedance of the PZT material. Those changes in the impedances of the PZT transducers are used to identify incipient damages in the structure. By operating at high frequencies (typically higher than 1 MHz), this technique is as sensitive as the traditional NDE techniques because the wavelength of the excitation is small enough to detect incipient and small damages. The PZT materials were originated from the fields of material/mechanical engineering. They have been widely used as a part of structural health monitoring systems for mechanical/aeronautical structures for a long time. The applications of PZT transducers to civil structures began relatively recently[1-3]. Ayres et al[4] reported on the use of PZT transducers for damage detection on a laboratory sized truss structure and a prototype truss joint. Tseng et al[5,6] and Bhalla[7] recently reported successful applications of this method on concrete and other civil-infrastructures.
In this study, experimental studies were performed on three kinds of structural members for identification of damages such as cracks or loosened bolts. For quantifying the deviation of the damaged cases impedance

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signatures with those of the intact case, a statistical technique is used. Based on the results of the experimental studies, applicability of the impedance-based damage detection technique using piezoelectric (PZT) transducers for civil infrastructures are discussed.

2. Basics of Impedance-based NDE Technique

The coupling effect of the electro-mechanical impedance of a system with an active material and a host structure can be conceptually investigated by using a simple 1-D electro-mechanical system[4, 7] as shown in Figures 1 and 2. The mechanical aspect of the active material (actuator) is described by its short-circuited mechanical impedance. The host structure is represented by its driving point mechanical impedance, which includes the effect of mass stiffness, damping, and boundary conditions. The actuator is powered by voltage, or current. The integrated electro-mechanical system may be electrically represented by an electrical admittance or impedance which is affected by the dynamics of the actuator and the host structure. In this study, the impedance-based modeling technique[8, 9] is used for non-destructive evaluation of steel structures.

The mechanical impedance Z of the host structure idealized as a SDOF system as in Figure 1 is defined as the ratio of a harmonic excitation force F_0 at an angular frequency ω to the velocity response $\dot{x}$ in frequency domain as

$$Z(\omega) = \frac{F_0}{\dot{x}} = |Z(\omega)| e^{i\theta} \quad (1)$$

where $Z(\omega) = \sqrt{c^2 + (\frac{m\omega^2 - k}{\omega})^2}$ and $\theta = \tan^{-1} \frac{m\omega^2 - k}{c\omega}$.

Although Equation (1) has been derived for a SDOF system in Figure 2, the mechanical impedance of a complex structural system can be obtained in terms of the real (dissipative) and imaginary (reactive) components. Those two terms can be considered to represent a purely resistive element (such as a damper) and a purely reactive element (such as a spring or mass, or both) of the 'equivalent SDOF' system.

In the 1-D interaction model shown in Figure 2, it is assumed that the PZT has only d_{31} effect, i.e., the induced strain is only in the 1-1, x-direction when an electrical voltage is applied in the 3-3, z-direction (lateral mode of the PZT). The length, width, and thickness of the PZT are l_A, w_A, and h_A, respectively. For the PZT, the relation between the mechanical and electrical variables is governed by the following constitutive equations[8, 9]:

$$S_{11} = s_{11}^E T_{11} + d_{31} E$$
$$D_3 = d_{31} T_{11} + \varepsilon_{33}^T E \quad (2)$$

where T_{11} is the stress in the 1-1 direction, S_{11} is the strain in the 1-1 direction, E is the electrical field in the 3-3 direction, D_3 is the electrical displacement in the 3-3 direction, s_{11}^E is the mechanical compliance of the PZT in the 1-1 direction under a constant electrical field, d_{31} is the piezoelectric constant, and ε_{33}^T is the dielectric constant of the PZT in the 3-3 direction under a constant stress.

The equation of motion for the in-plane vibration of the PZT actuator is

$$\frac{\partial^2 u(x,t)}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 u(x,t)}{\partial t^2} \quad (3)$$

where u is the displacement in 1 direction, c is the wave speed in the 1 direction given by $(Y_{11}^E / \rho)^{1/2}$, Y_{11}^E is the elastic modulus of PZT in the 1-1 direction under a constant electrical field, and ρ is the density of PZT.

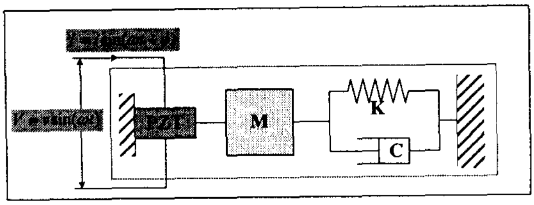


Figure 1 1-D Model of a PZT with its Host Structure[4]

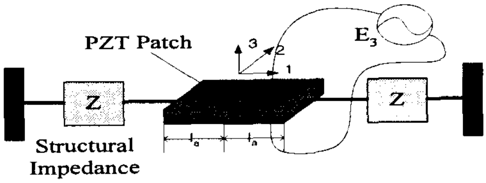


Figure 2 1-D Interaction Model[7]

The mechanical impedance of the PZT can be obtained from Equation (3) and (2) as[8, 9]

$$Z_A(\omega) = \frac{k\bar{Y}_{11}^E w_A h_A \cosh(kl_A)}{i\omega \sinh(kl_A)} \tag{4}$$

where k is the wave number given by ω / c.
Then, the output electric displacement field with the effect of the host structure can then be obtained as[8, 9]

$$I(\omega) = i\omega E w_A l_A [\frac{d_{31}^2 \bar{Y}_{11}^E Z_A}{Z_A + Z} \frac{\tan(kl_A)}{kl_A} + \bar{\varepsilon}_{33}^T - d_{31}^2 \bar{Y}_{11}^E] \tag{5}$$

Since the electric field is defined as $E = V / h_A$, the coupled electro-mechanical admittance (inverse of the EM impedance) can be obtained as

$$Y(\omega) = \frac{I(\omega)}{V(\omega)} = \frac{1}{Z_{total}} = i\omega \frac{w_A l_A}{h_A} [\frac{d_{31}^2 \bar{Y}_{11}^E Z_A}{Z_A + Z} \frac{\tan(kl_A)}{kl_A} + \bar{\varepsilon}_{33}^T - d_{31}^2 \bar{Y}_{11}^E] \tag{6}$$

Because $\tan(kl_A) / kl_A$ is close to one in the frequency range of interest in most applications of active materials, Equation (6) may be further simplified as

$$Y(\omega) = i\omega \frac{w_A l_A}{h_A} [\bar{\varepsilon}_{33}^T - \frac{Z}{Z_A + Z} d_{31}^2 \bar{Y}_{11}^E] \tag{7}$$

It is clear that the resonance of the electro-mechanical system occurs, when the PZT impedance, $Z_A(\omega)$, and the structural impedance, $Z(\omega)$, match (i.e., $Z_A(\omega) + Z(\omega) = 0$). Hence, changes of the mechanical properties of the host structure may be detected by monitoring the resonant frequencies of the electro-mechanical admittance functions shown in Equation (7).

3. Experimental Studies

3.1 Experimental Setup and Procedures

The experimental setup consists of a test specimen, PZT transducers, an impedance analyzer, and a personal computer (PC) equipped with data acquisition software as shown in Fig 3. PZT transducers are bonded to the specimen, and they are connected to the HP4194A impedance analyzer. Then, the impedance signatures (real parts) are extracted as functions of the exciting frequency. The PC is used to control the impedance analyzer. The size of the PZT patch is 1cmX1cm with the thickness of 0.02cm.

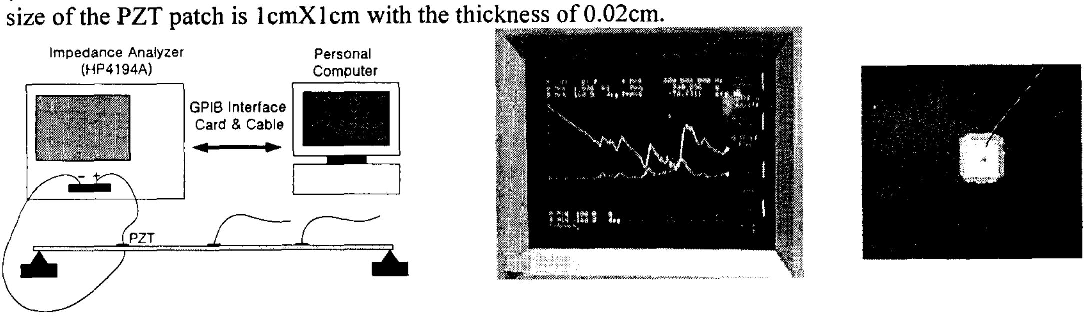


Figure 3 Experimental Setup and PZT Patch

3.2 Frequency Range

In order to select a suitable frequency range for acquiring the admittance signature, the PZT transducers on the test specimen are scanned over a wide frequency range of 100 kHz – 6MHz. The real signatures show many sharp peaks over a wide range of frequency. Two frequency ranges of 100-400 kHz, at an interval of 750 Hz and 3-6 MHz, at an interval of 7500 Hz, are chosen for a specimen in order to compute the effect of different frequency ranges on damage assessment. These signatures consist of a total of 400 data points, with many dominant peaks observed in these ranges. Actually, many other previous researchers have considered the resonant frequency in the frequency range of 100-400 kHz, which presents the lateral directional mode of the PZT patch. However, according to Saubery equation, $\Delta\omega \propto \omega_0^2$, the frequency shifts in the dominant peaks are proportional to the square of the original resonant frequencies. Therefore, in this study, only the range of 3-6 MHz which presents the thickness directional modes of the PZT patch was chosen, in order to get better shifted frequency resolution as a damage indicator.

3.3 Damage Index Approach

The prominent effects of damage (to the host structure) on the impedance signature are the appearance of new peaks in the signature and the lateral and vertical shifts of the existing peaks. For example, Figure 4 shows the effects damage (simulated by cutting 2.5cm and 3.0cm cracks) on the impedance signature of a PZT patch bonded to a steel plate. The signature was acquired through an HP4194A impedance analyzer in the frequency range of the thickness mode of the PZT patch, 2.2~2.9 MHz at an interval of 1750 Hz. Although the induced damage was small, the effect on the signature is very significantly visible (Figure 4(a)). This demonstrates the high order of sensitivity of the technique.

Traditionally, statistical pattern recognition techniques have been employed to quantify changes in the impedance signature due to damage; such as relative deviation (RD), root mean square (RMS) deviation, and mean absolute percentage (MPA) deviation. The RMS deviation index is used in this study as

$$RMSD(\%) = \sqrt{\frac{\sum_{i=1}^{i=N}(Z(\omega_i) - Z_0(\omega_i))^2}{\sum_{i=1}^{i=N}(Z_0(\omega_i))^2}} \times 100 \tag{8}$$

where $Z(\omega_i)$ is the post-damage impedance signature at the i-th measurement point and $Z_0(\omega_i)$ is the corresponding pre-damage value. Although the statistical methods are easy to implement and have the advantage of being non-parametric, their major shortcoming is that they are unable to correlate change in electrical impedance with any specific change in the structural properties.

In many structures, simply the damage detection might be more than sufficient, which can be done conveniently by means of conventional statistical indices. However, in the civil infrastructures, we often need to find out whether the damage is 'incipient' or 'severe'. We might even tolerate an incipient damage without endangering lives or properties. This fact has motivated us to extract the structural impedance from the measured impedance signatures for damage quantification. Studies for calibrating the changes in the impedance signatures with damage for typical civil infrastructures will be studied in the future.

3.4 Example I: Steel Plate with Cracks

A thin steel strip was used as a test specimen as in Figure 3. It is 100cm long, 10cm wide, and 0.6cm thick. Three PZT transducers of 1x1cm are bonded to the specimen with the same distance. Two cracks with length of 2.5cm and 3.0cm were introduced near PZTs 1 and 2 (2cm apart from each PZT sensor) sequentially as in Figure 3. Therefore, Damage Case I-1 has a crack near PZT 1, while Damage Case I-2 consists of two cracks near PZTs 1 and 2. Impedance signatures were assessed at the PZT transducers for the intact and two damage cases, and the results are shown in Figure 4. From the figures it can be observed that the impedance functions change in magnitudes and resonant frequencies, as cracks occur near the sensors. The decrease of the resonant frequencies is summarized for two damage cases at Table 1. The amounts of the frequency shifts are found to be very noticeable at the PZTs near the cracks. For instance, in Damage Case I-1, the resonant frequency at PZT 1 reduces by 29.75 kHz due to a crack near PZT 1, while the shifts at PZTs 2 and 3 are only 1.75 and 3.5 kHz, respectively. The frequency resolution of HP4194A impedance analyzer is 1750Hz. In Damage Case I-2, the frequency shifts at PZT 2 by 17.5 kHz due to an additional crack near PZT 2, while the corresponding shifts are very minimal at PZTs 1and 3. The RMS deviation was also considered as a damage indicator, and the results are shown in Figure 5. From the figures, it can be observed that the big RMS deviation values are shown at the PZT sensors located near the cracks. Therefore, we can conclude that cracks can be detected effectively by using both methods of the resonant frequency shifts and the RMS deviations in the impedance functions.

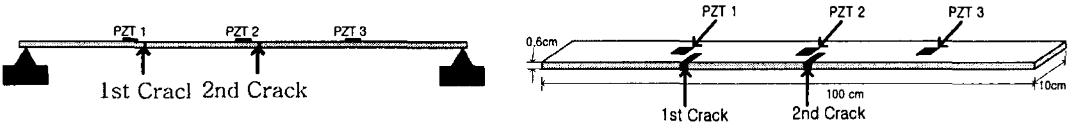
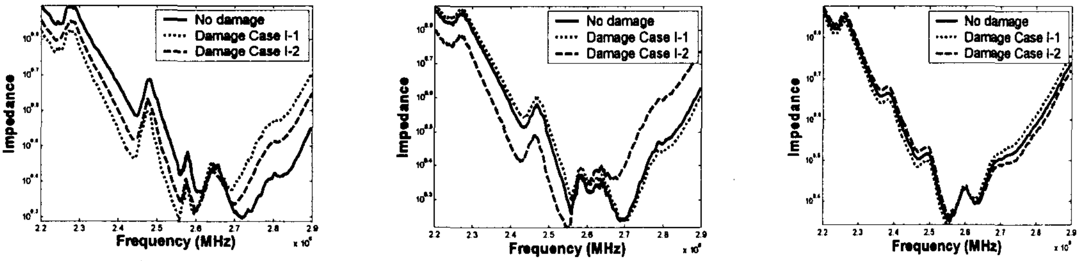


Figure 3 Test Specimen I



(a) PZT 1 (b) PZT 2 (c) PZT 3

Figure 4 Impedances at Three PZT Sensors of Exmple I

Table 1 Resonant Frequencies and Frequency Shifts of Example I (in Hz)

Cases	PZT 1 (Hz)	PZT 2 (Hz)	PZT 3 (Hz)
No damage	2719750	2697000	2557000
Damage Case I-1	2690000 (-29750)	2700500 (3500)	2555250 (-1750)
Damage Case I-2	2698750 (-21000)	2679500 (-17500)	2557000

(Note: The values in the parentheses are the shifts of resonant frequencies from the values without damages.)

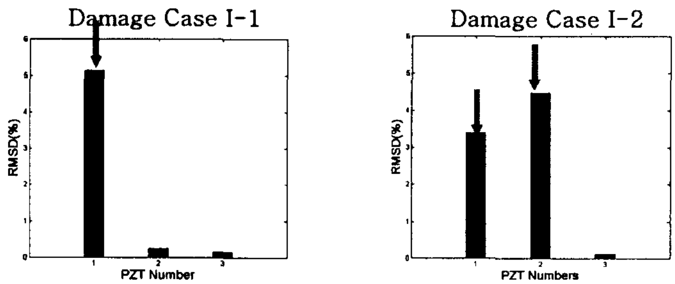


Figure 5 RMS Deviations for Each Damage Case of Example I
(Note: Arrows indicate the locations of cracks.)

3.5 Example II: Aluminum Plate with Loosened Bolts

A thin aluminum strip was used as a test specimen as in Figure 6. It is 80cm long, 8cm wide, and 0.6cm thick. A total of 15 holes of a diameter of 8mm were drilled at an equal spacing of 50mm within a span of 700mm. The holes were numbered from 1 to 15 beginning from the left. At first the intact case was simulated by fastening bolts and nuts at all of the holes. Then 15 Damage Cases were simulated by loosening a bolt/nut at a time. Sixteen PZT transducers of 8x8x0.2mm were bonded to the specimen with the same distance, and numbered from 1 to 16 beginning from the left.

Damage detection is carried out by checking the variations of the resonant frequencies of the impedances at the PZT sensors caused by each of the loosened bolts/nuts. Figure 7 presents the variations of the resonant frequencies measured at three PZT sensors. Big variations of the resonant frequencies can be noticed at the PZT Sensors 1, 4, and 13 in the vicinity of the loosened bolts/nuts. The RMS deviation was also considered as a damage indicator, and the results are shown in Figure 8. We expected big RMS deviation values at the corresponding PZT sensors near the loosened bolt/nuts. However, from the figures, it can be observed that the RMS deviation values are smaller than the other cases. Therefore, we can conclude that the shifts of the resonant frequency of the impedance give more reliable results than the RMS deviation of the impedance for detecting the locations of the loosened bolts.

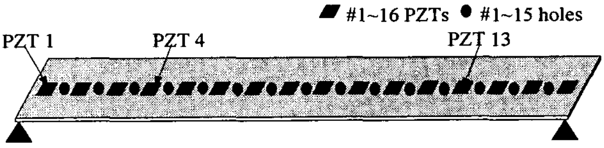
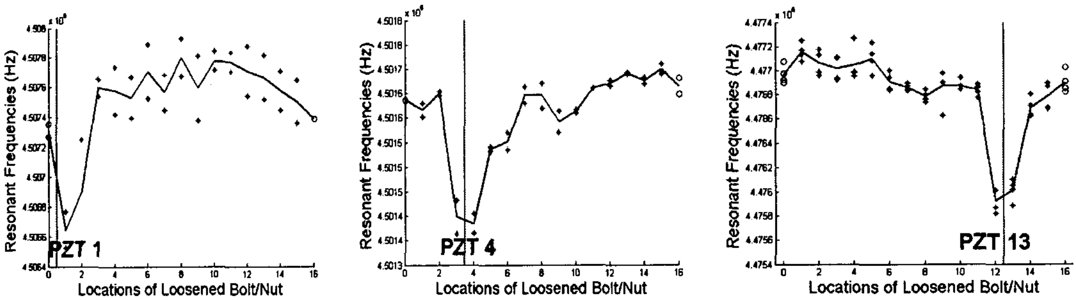
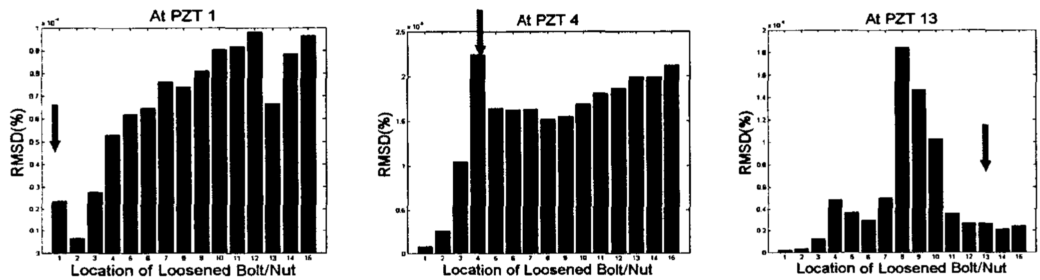


Figure 6 Test Specimen II



(a) at PZT 1 (b) at PZT 4 (c) at PZT 13

Figure 7 Variation of Resonant Frequencies of Impedance Functions at PZTs of Example II



(a) at PZT 1 (b) at PZT 4 (c) at PZT 13

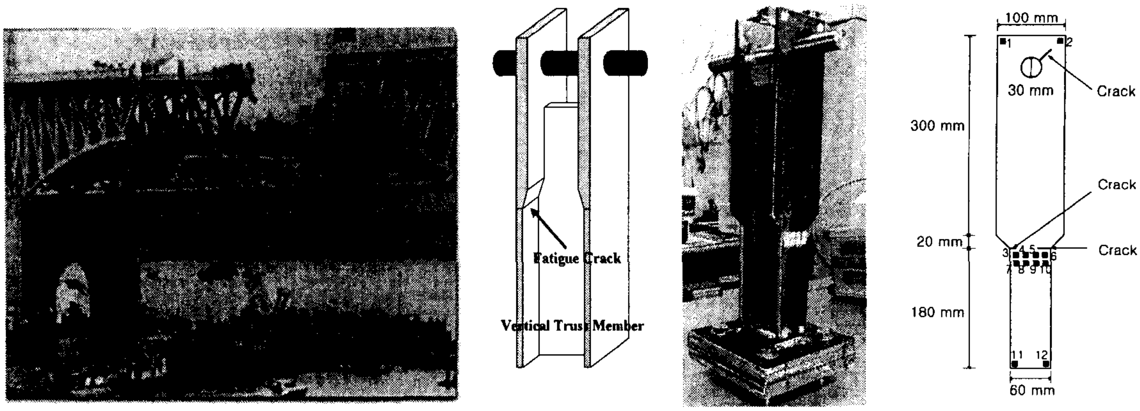
Figure 8 RMS Deviations of Impedance Functions at PZTs of Example II
(Note: Arrows indicate the locations of cracks.)

3.6 Example III: Steel Member with Wide Flanges

The third example is a vertical steel member. It is a rough schematic model for a vertical truss member of old Seongsoo Bridge in Seoul Korea, which caused the collapse of a gerber section in the middle of a span in 1994, as shown in Figure 9(a). The original member consists of two segments with wide flange sections of different flange thickness welded together as in Figure 9(b). Fatigues cracks developed at the tip of the transition zone of the flange thickness, and caused eventual sever of the member. The present specimen was drawn by introducing transition in flange width rather than in thickness as shown in Figure 9(c) for the simplicity in fabrication. The depth of the wide flange section is 500mm, the web thickness is 6mm and the flange thickness is 8mm.

Twelve PZT transducers of 8x8mm were attached to the outside surface of a flange as in Figure 9(d). Cracks were inflicted by cutting the flange at 3 locations sequentially, and 3 damage cases were constructed as described in Table 2. The impedance signatures were obtained for the PZT transducers in each damage case, and damage detection was carried out comparing the shifts of the resonant frequencies ant the RMS deviation caused by the damages. Figure 10 presents the resonant frequencies at the PZT sensors for the intact case and the frequency shifts after the damages. The results indicate that the locations and the sizes of the cracks may be effectively detected from the shifts of the resonant frequencies of the impedance functions obtained at the PZT sensors near the cracks. However, it shows that the crack detection becomes difficult as the crack occurs far from the PZT sensor.

For the purpose of comparison, the RMS deviations of the impedance signatures were also considered as a damage indicator. The results in Figure 11 show that the accuracy of the crack detection is fairly similar to the cases using the shifts of the resonant frequency.

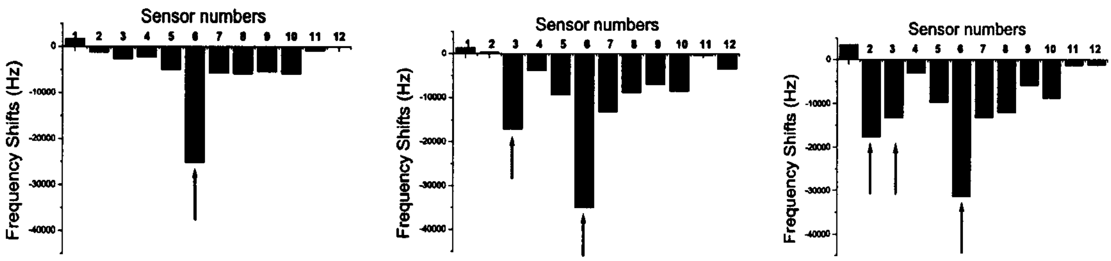


(a) Collapse of Seongsoo Bridge (b) Severed Member (c) Test Specimen (d) Cracks & PZT patches

Figure 9 Collapse of Seongsoo Bridge (1994) and the Test Specimen

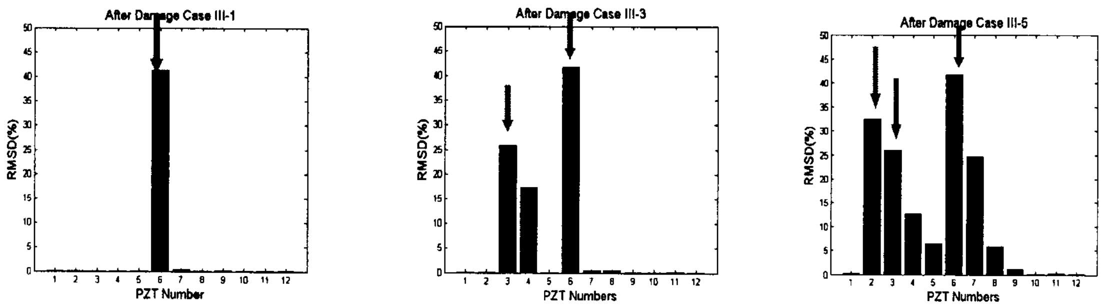
Table 2 Damage Cases of Example III

Damage Case III-1	A crack of 1 cm near PZT 6
Damage Case III-3	Two cracks of 2 & 1 cm near PZTs 6 & 3, respectively
Damage Case III-5	Three cracks of 2, 1, & 2.5 cm near PZTs 6, 3, & 2, respectively



(a) Damage Case III-1 (b) Damage Case III-2 (c) Damage Case III-3

Figure 10 Frequency Shifts after Damages of Example III
(Note: Arrows indicate the locations of cracks.)



(a) Damage Case III-1 (b) Damage Case III-2 (c) Damage Case III-3

Figure 11 RMS Deviations of Impedance Functions at PZTs of Example III
(Note: Arrows indicate the locations of cracks.)

4. Concluding Remarks

In this paper, the potential of employing smart piezoelectric (PZT) transducers for detection of damages in the civil infrastructures has been demonstrated through experimental results on three kinds of structural members of laboratory size. The electro-mechanical impedance technique has been adopted to detect various damages in the structure. This work is to enhance the capability of the conventional impedance-based structural health monitoring. The striking advantage of this non-parametric damage detection method over the conventional other modal analysis techniques is that of not requiring the knowledge of the modal parameters or the failure modes of the structure. And, while the global modes of structure at low frequencies are not affected by incipient-type damage, the impedance-based technique, which monitors the local modes at high frequencies, can detect incipient-type damage successfully. Therefore, the technique facilitates an avenue for minimum labor involvement without having to be highly skilled. The PZT transducer of even a small size (8mmX8mm square) has been ascertained to be very sensitive to an incipient damage.
From the results of this study, following conclusions are obtained.

1. The feasibility of the impedance-based damage detection method using PZT transducers for civil infrastructures was demonstrated.
2. Both methods using the resonant frequency shifts and the RMS deviation of impedance signatures at the PZT gave good results for crack detection.
3. However, the shifts of the resonant frequency of the impedance signatures at the PZT gave more reliable results for detecting a loosened bolt.
4. The PZT sensors need to be placed near the damages. To overcome this problem, the wave propagation method using the PZT actuator/sensor system will be studied.

Acknowledgements

The study is supported by Smart Infra-Structure Technology Center (SISTeC) sponsored by Ministry of Science and Technology (MOST) and the Korea Science and Engineering Foundation (KOSEF). Their financial supports are greatly acknowledged.

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