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Vibration-Impedance Approaches for Tendon Monitoring in Prestressed Concrete Structure

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ABSTRACT

In this paper, a hybrid health monitoring method combining vibration-impedance approaches is utilized to monitor strand breakage in a prestressed concrete (PSC) structure. The method includes frequency-based damage occurrence alarming and impedance-based damage identification. The frequency-based technique using changes in natural frequencies is produced for discerning the presence of damage in PSC structures. Variations in impedance responses are used to identify the location of damaged strands. The feasibility of the proposed method is experimentally evaluated on a lab-scale PSC structure for which vibration and impedance responses measured for several damage scenarios of the tendon damage.

1. INTRODUCTION

Since the introduction in the 1940s, prestressed concrete has been used widely in engineering structures, such as bridges and nuclear power plants due to several outstanding advantages over conventionally reinforced concrete (i.e., minimized member sizes and cracking control). In PSC structures, the prestressing force, an important parameter, is generated by the tensioning of high-strength tendons. During the construction period and service time, the loss of prestressing force can occur due to elastic shortening, creep, and shrinkage of concrete, steel strand relaxation, and frictional loss. When the loss of prestress forces reaches a particular threshold, the tensile stresses can increase in the concrete, contributing to cracking or excessive deflections. Therefore, the prestress force should be monitored properly to ensure structural integrity and to prevent catastrophic failures.

Over the past decades, vibration-based damage detection techniques have been applied for monitoring prestress force in PSC structures (Saiidi *et al.* 1994 and Kim *et al.* 2002). However, the vibration-based method uses low-frequency modal parameters, which are insensitive to local minor structural damages (Lu *et al.* 2006).

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Recently, an impedance-based SHM has emerged as a promising method due to its potential to detect minor and various damages in structures (Giurgiutiu *et al.* 2005). For PSC structures, the impedance-based method is employed to monitor the prestress-loss by mounting a PZT patch on a bearing plate of a mono-strand anchorage zone (Kim *et al.* 2010). Min *et al.* (2016) affixed multiple PZTs on a multistrand anchorage to monitor changes in tendon's tensile force.

In this study, a hybrid health monitoring method combining vibration-impedance-based techniques is employed to detect the tendon breakage in PSC structures.

2. TENDON MONITORING APPROACHES

Based on the hybrid health monitoring proposed by Kim *et al.* (2010), a hybrid method for strand breakage detection was designed, as shown in Fig. 1. The monitoring process includes two steps: alarming the occurrence of damage in a PSC structure by utilizing the change in natural frequencies and identifying the location of damage strands by using variations in EM impedance signatures.

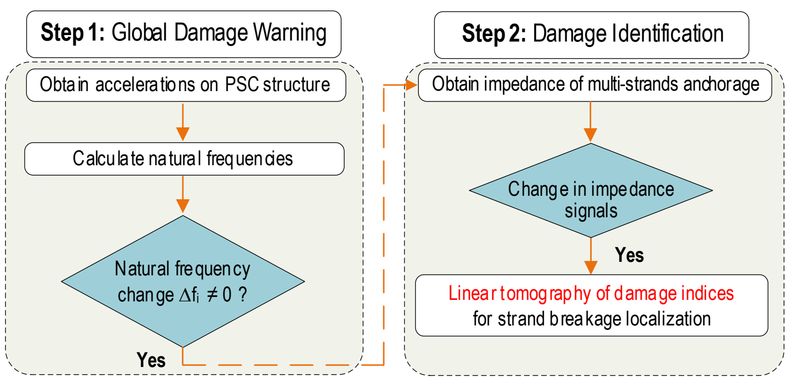


Fig. 1. Hybrid health monitoring scheme for PSC structure

<u>Global Damage Detection Method using Vibration Characteristics</u>

The occurrence of damage can be globally alarmed by using changes in dynamic responses of structures. The basic idea is that measured modal parameters are the functions of the physical characteristics of the structures. Thus, changes in the physical properties, such as reduction in the structural rigidity resulting from cracks, will cause detectable changes in modal parameters such as the natural frequency of the structure.

In this study, acceleration signals of PSC structrure were acquired. Then, these signatures were extracted by using the FDD (frequency domain decomposition) to get natural frequencies (Brincker *et al.* 2001). The variation of natural frequencies was as an indication of damage that occurred in PSC structure.

<u>Local Damage Detection Method using Impedance-based Method</u>

The impedance-based method is based on the coupling of mechanical and electrical characteristics. This method uses a piezoelectric patch embedded on the surface of a host structure as a sensor and an actuator. By actuating PZT with a voltage and measuring the electric current $I(\omega)$, the impedance can be obtained (Liang *et al.* 1994):

$$Z(\omega)=\frac{V}{I}=\left\{i\omega\frac{w_a l_a}{t_a}\left[\hat{\varepsilon}_{33}^{T}-\frac{1}{Z_a(\omega)/Z_s(\omega)+1}d_{3x}^{2}\hat{Y}_{xx}^{E}\right]\right\}^{-1} \tag{1}$$

where d_{3x} is the piezoelectric coupling constant in the x-direction at zero stress; and w_a, l_a, and t_a are the width, length, and thickness of the PZT patch, respectively. The equation (1) shows that the EM impedance, Z(ω), is a combining function of the EM impedance of the piezoelectric patch, $Z_a(\omega)$, and that of the host structure, $Z_s(\omega)$. Therefore, the change in structural parameters (*k, m, c*) can be presented by the change in EM impedance..

Variations in impedance signatures under structural damage can be quantified by the root mean square deviation (RMSD), as shown in Eq. (2).

$$RMSD\left(Z,Z^{*}\right)=\sqrt{\sum_{i=1}^{n}\left[\mathrm{Re}(Z^{*}(\omega_i))-\mathrm{Re}(Z(\omega_i))\right]^{2}/\sum_{i=1}^{n}\left[\mathrm{Re}(Z(\omega_i))\right]^{2}} \tag{2}$$

where $\mathrm{Re}\left(Z(\omega_i)\right)$ and $\mathrm{Re}\left(Z^*(\omega_i)\right)$ are the real components of the impedance signatures measured before and after the damage of the i^{th} frequency, respectively. A linear tomography of RMSD indices was plotted over the cross-sectional area to visualize the location of the damaged strands.

3. EXPERIMENTAL VERIFICATION

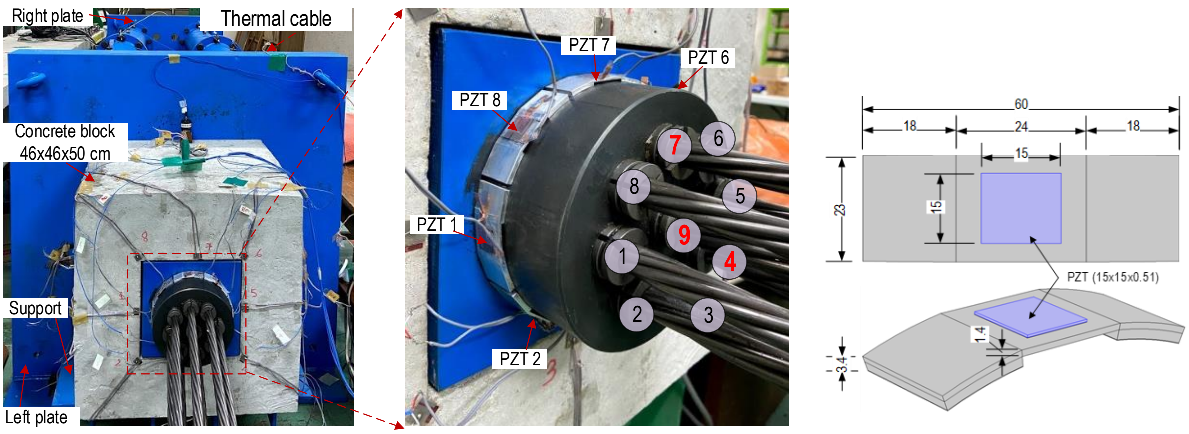
3.1. Experimental Setup and Test Scenarios

The tested prestressed structure consists of a steel frame and a PSC anchorage zone, as shown in Fig. 2a. The steel frame is a combination of four steel longitudinal tubes ($\phi_{outer}=0.216$m, thickness of 21 mm) with two steel plates located at both ends. The anchorage zone includes a reinforced concrete block with a size of 460x460x500 mm designed based on VSL International Ltd 2015 and nine prestressing strands with 15.2 mm in diameter. The left ends of strands were clamped to anchor by using wedges. The right ends were fastened by steel threads connecting to hydraulic jacks to control the prestress forces.

To obtain vibration responses, one accelerometer named Acc.1 was affixed on the concrete anchorage zone, as illustrated in Fig. 2a. The impact excitation was applied vertically on the top of the anchorage zone by using a rubber hammer. One ICP-type PCP 393B04 accelerometer was used to measure dynamic responses with the sampling frequency of 1 kHz. The data acquisition system comprises a 16-channel PXI-4472 DAQ, a PXI-8186 controller with LabVIEW (2009), and MATLAB (2004), as shown in Fig. 2a.

For impedance measurement, eight hoop-type PZT interfaces were placed on the anchor head at the near-bottom area, as shown in Fig. 2c. The interface consists of three parts, as demonstrated in Fig. 2d. Two bonded parts are 23x18x3.5 mm in size, and one flexible part is 23x24x1.4 mm. The arrangement of eight PZT interfaces was marked based on the order of outer strands (Strands 1-8), respectively. An adhesive (Loctite 401) was used to bond PZT patches to the interfaces as well as the interfaces to the anchor head. The data acquisition system included an impedance analyzer HIOKI 3532, and a PC with LabVIEW software.

a) A lab-scale PSC structure and installation of accelerometers



b) Test setup of concrete anchorage

c) PZT interfaces on anchor head

d) Geometric parameters of hoop-type PZT interface

Fig. 2. Experimental setup in lab-scale PSC structure on compressive steel frame

Three test cases (Cases 1-3) were performed, as listed in Table 1. In the experiment, firstly, one accelerometer, and the data acquisition system were used to attain dynamic responses of the structure under hammer impacts. Then, a wired impedance analyzer was used to record EM impedance signatures in the range 5-35 kHz (601 sweeping points). To minimize the temperature effect, the temperature on lab was controlled and kept nearly constant about 16.5°C by using the air conditioner system.

Table 1. Test cases for acceleration and impedance measurement in anchorage zone

Case	**Damaged Strand**	**Prestress force**
1	Intact	About 118.5kN for all strands
2	Strand 4	Strand 4: 0 kN; all others: 119.5 kN
3	Strands 4, 7, 9	Strands 4, 7 and 9: 0 kN; all others: 121.7 kN

3.2. Feasibility Evaluation of Frequency-based Strand Breakage Monitoring

As shown in Fig. 3, acceleration signatures were acquired from Acc.1 in the period of 30s under Case 1. As shown in Fig. 4, the singular value char of FDD method was conducted using the acceleration signals in intact case. The frequency of Peaks 1, 2 is 93.262 Hz and 300.293 Hz, respectively. Natural frequencies extracted from acceleration signals for one intact case and two damaged cases were listed in Table 2. From analyzed results presented in Table 2, it indicates that the strand breakage caused a reduction in structure's natural frequencies. Thus, change in vibration characteristics (i.e., natural frequency) can be used to alarm global damage in the PSC structure.

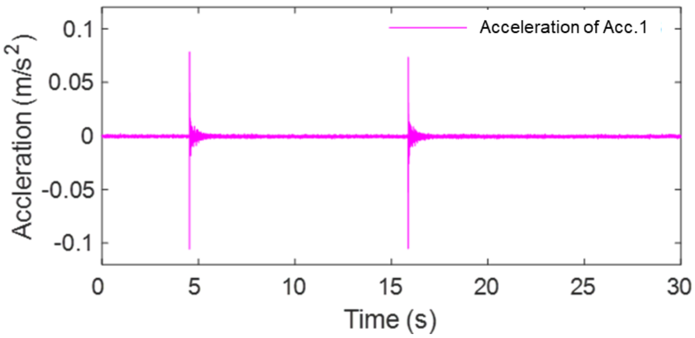


Fig. 3 Acceleration signal of lab-scale PSC structure

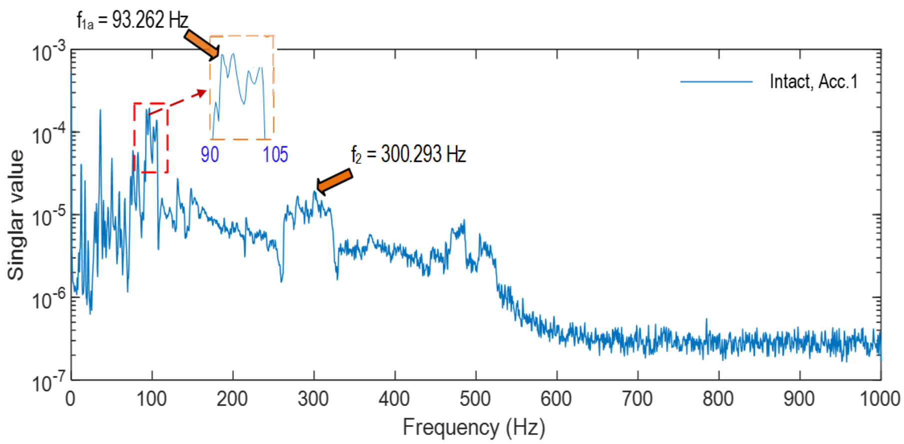


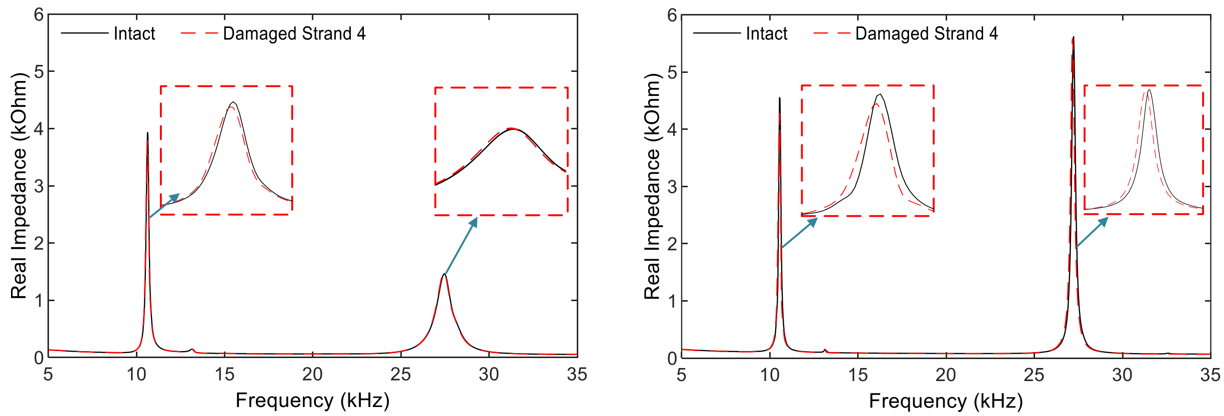
Fig. 4 Frequency response function using acceleration signals of Acc.1 in Case 1

Table 2. Experiment natural frequencies of lab-scale PSC structure

Case	**Natural frequency (Hz)**		**Variation (%)**	
	Mode 1	**Mode 2**	**Mode 1**	**Mode 2**
1	93.262	300.293	-	-
2	91.797	297.852	-1.57%	-0.81%
3	90.820	297.360	-2.62%	-0.98%

3.3. Experimental Verification of PZT Interface for Strand Breakage Localization

For the damaged outer strand 4, the impedance responses of hoop-type PZTs 2, 4 were shown in Fig. 5. PZT 4's impedance signals were shifted to the left, and two impedance peaks (Peaks 1-2) were sensitive to strand breakage. Meanwhile, the impedance responses of other PZTs (e.g., PZT 3 in Fig. 5a) were almost no changed.



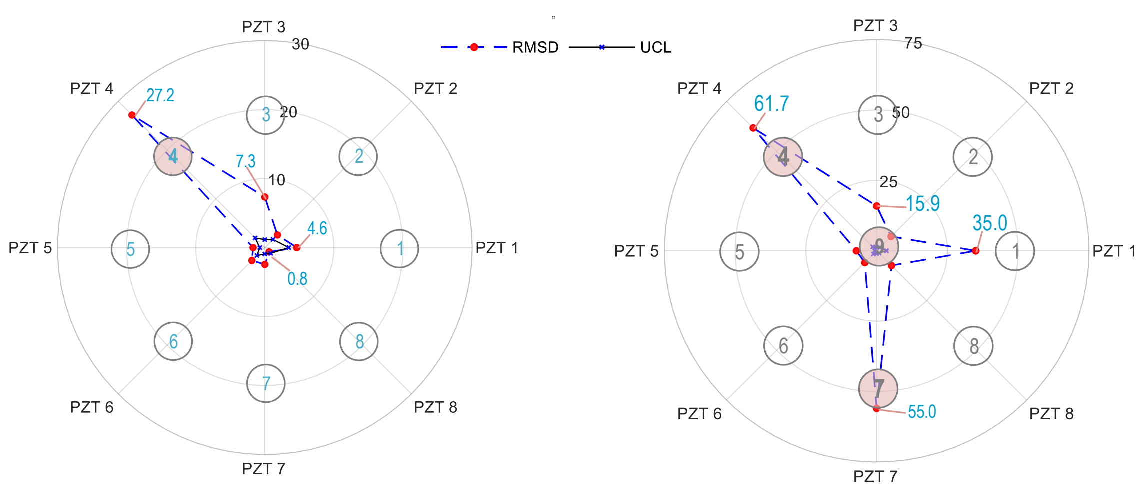
a) PZT 3 b) PZT 4

Fig. 5 Impedance responses of PZT sensor under breakage of Strand 4

Linear Tomography of Damage Index for Strand Localization

To visualize the location of damaged strands, the linear tomography of RMSD indices was built over the cross-sectional area of the multistrand anchor head. Since the sensitivity of RMSD indices depends on the distance from measured PZTs to damaged strands, the magnitudes of RMSD indices could be applied as a tomographic indicator for damaged domains. For two damage cases, the RMSD indices and UCL values of PZT 1-8 in the frequency range 5-35 kHz were plotted as the indicators over the cross-section of the anchor head, as shown in Fig. 6.

For the damage of Strand 4, the RMSD magnitude at Strand 4 (27.2%) was significant and above the UCL threshold, as shown in Fig. 6a. Notably, the RMSD index at Strand 4 was larger than Strand 3 (i.e., 7.3%) about 4 times, and Strand 8 (i.e., 0.8%) about 30 times. It indicated that the damage of Strand 4 was successfully localized. Similarly, Strands 4, 7, 9 were also detected, as presented in Fig. 6b.



a) Damaged Strand 4 b) Damaged Strands 4, 7, 9

Fig. 6 Linear tomography of RMSD indices (%) under damaged Strand 4 and damaged Strands 4, 7, 9 in frequency range 5-35 kHz

4. CONCLUSION

In this paper, the hybrid health monitoring method using vibration-impedance techniques was employed to monitor the strand breakage in the PSC structure. Firstly, the vibration-based damage occurrence alarming utilizing the changes in natural frequencies was used to monitor the damage occurrence on the PSC structure. Secondly, the impedance-based damage identification using the variations in impedance signals was applied to determine the location of damaged strands in the anchorage zone. The feasibility of the hybrid health monitoring method was experimentally evaluated on the real-scaled PSC anchorage zone installed on the prestressed structure.

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