Estimation of Existing Prestress Level on Bonded Strand Using Impact-Echo Test

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ABSTRACT

This work introduces a non-destructive way to evaluate existing prestress level on bonded seven-wire strands embedded in a post-tensioned concrete structure. The approach utilizes the experimental result that the longitudinal stress wave velocity varies with respect to applied stress level on the strands. A set of prestressed concrete beam specimens with different tensile stress levels have been prepared, and various impact-echo tests are conducted. It turns out that longitudinal elastic wave velocity of the strands is nonlinearly increased as the applied tensile stress level increases. To investigate field applicability and feasibility of the proposed approach, the longitudinal impact-echo tests are conducted for two prestressed bonded tendons embedded on a nuclear power plant. The estimation results clearly show that the existing prestress level of the tendon is close to the design value. It seems that the proposed impact-echo technique is feasible and applicable for the unique identification of existing prestress level on an individual strand embedded in a real post-tensioned concrete structure.

INTRODUCTION

Recently the use of pre-stressed concrete (PSC) system is rapidly increased in the construction industry. However, it is well-known fact that the prestress level of PSC is continuously reduced due to not only immediate elastic losses but also time dependent losses. Hence, the periodic monitoring for the prestress level of tendons is urgent demand. .

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Regarding the tendon force estimation technique, most of previous investigations [1,2] have focused on the unbounded PSC system using an ultrasonic pulse, For bonded strands, however, the ultrasonic wave technique cannot be applied because of severe energy dissipation between concrete and tendons[3]. The maximum inspection range of an ultrasonic wave is approximately 1.5m [4], while typical length of most PSC structure is over 30m.

For a bonded PSC system, Kim et al. [5] have reported that the longitudinal vibration characteristics of bonded PSC tendons could be used to identify existing prestress level of tendons. Their experimental result shows that the longitudinal frequencies of bonded tendons are nonlinearly proportional to the applied stresses. However, the applicability and feasibility of such longitudinal impact-echo technique have not been fully examined through full scale field test yet.

This study introduces a practical experimental formula to nondestructively estimate the existing prestress level of tendons by only measuring the longitudinal stress wave velocity. Then, the formula has been successfully applied to a full scale field test for two tendons embedded on a Wolsung nuclear power plant in Korea.

LONGITUDINAL IMPACT-ECHO TEST

Test Setup

As shown in Figure 1, a set of impact echo tests have been conducted for various PSC specimens. Dimension details and material properties of those specimens are summarized in Table 1. The symbols σ, σ_c, σ_s and N denote the applied tensile stress, the concrete strength, the ultimate strength of strand and the number of strands, respectively. The strands installed in the specimens are a B-type of KSD 7002 seven-wire strand. At the center of concrete cross section, a VSL wedge type anchor system with a duct is installed. The space between duct and strands is filled with cement paste grouting after tensile force is introduced. To measure the exact applied tensile stress, the load cells are installed at every PSC specimens except for PSC No. 1. The overview of the PSC specimens is shown in Figure 2.

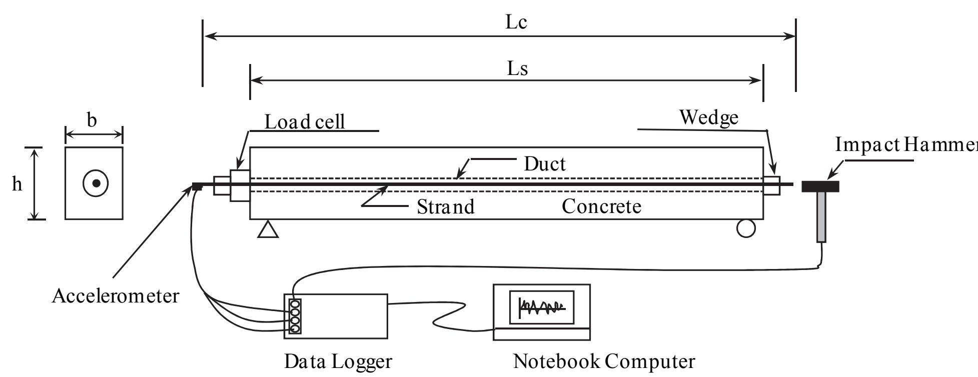

Figure 1. Test Setup.

Table 1. Dimension of PSC Specimens.

PSC No.	Concrete				Strands			
	b (m)	h (m)	Lc (m)	σ_c (MPa)	Ls (m)	σ (MPa)	σ_s (MPa)	N
1	0.302	0.302	7.999	37.08	8.278	10.0	1860	3
2	0.303	0.301	8.000		8.439	342.7		3
3	0.300	0.300	7.995		8.444	656.1		3
4	0.302	0.301	7.994		8.433	783.2		3
5	0.303	0.299	7.998		8.435	1071.9		3
6	0.303	0.302	7.993		8.433	1203.4		3
7	0.502	0.504	19.988	40.0	20.712	10.7		7
8	0.502	0.502	19.990		20.739	631.5		7
9	0.504	0.499	19.998		20.764	828.5		7
10	0.503	0.511	19.996		20.752	966.1		7
11	0.501	0.511	19.996		20.743	1218.1		7

(a) ***(b)***

Figure 2. Test Specimens: (a) 8m; (b) 20m.

Measuring Longitudinal Stress Wave Velocity

The longitudinal modes are excited by an impact at one end of strand, and the corresponding acceleration responses are captured by the accelerometer at the other. As shown in Figure 3, an impact hammer and accelerometer, PCB Piezoeletronics model 086C04 and 352B10, respectively have been employed. To simultaneously record both impact and acceleration signals, NI model CRIO 9073 with four channels NI 9033 is utilized. For the data collection, a sampling frequency of 25 kHz is used. For each specimen, more than 200 impact tests are repeatedly conducted.

Figure 4 shows an example of the impact and acceleration time histories for PSC No. 11. The arrival time (T) of a stress wave has been captured from Figure 4a. Dividing the physical length of strands (Ls), defined in Table 1, by the measured arrival time (T), the desired longitudinal stress wave velocity is extracted. After calibrating temperature effect at 25°C, the resulting velocities are summarized in Table 2.

(a) ***(b)***

Figure 3. Impact-Echo Test:(a)Impacting; (b) attaching accelerometers.

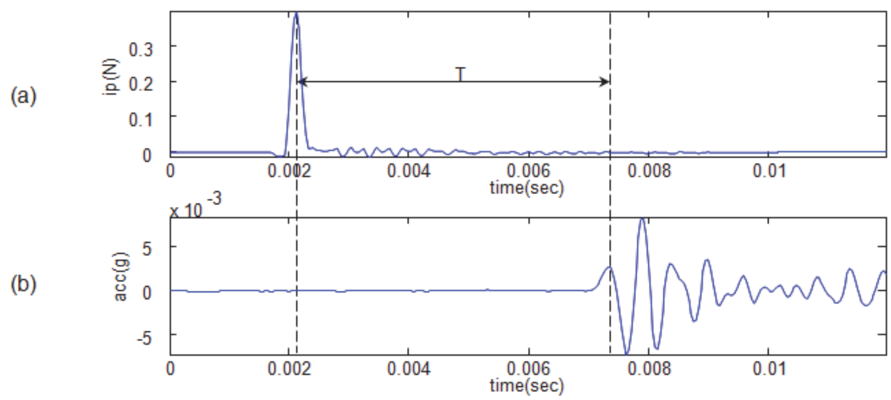

Figure 4. Measured Time History of PSC No. 11 :(a)Impact; (b)Acceleration.

Table 2. Measured Stress Wave Velocity.

PSC No.	σ (MPa)	V (m/s)
1	10.0	3147.0
2	342.7	3615.6
3	656.1	3834.2
4	783.2	3916.0
5	1071.9	3933.5
6	1203.4	3956.8
7	10.7	3501.7
8	631.5	3795.1
9	828.5	3919.8
10	966.1	3908.4
11	1218.1	3947.0

EXPERIMENTAL FORMULA

Applying the law of similarity to the experimental results, it is found that the relationship between the stress wave velocity and the applied stress has a following non-dimensional form.

$$V\sqrt{\frac{\rho_c}{\sigma_c}} = f\left(\frac{\sigma}{\sigma_s}\right) \tag{1}$$

It is seen that the measured data looks like the modified Ramberg-Osgood function [6]. As shown in Figure 5, thus, a curve fitting of the measured data to the function results in the following experimental formula.

$$V\sqrt{\frac{\rho_c}{\sigma_c}} = k_1\left(\frac{\sigma}{\sigma_s}\right)\left\{k_2 + \frac{1-k_2}{\left[1+\left(k_3\frac{\sigma}{\sigma_s}\right)^{k_4}\right]^{1/k_4}}\right\} + k_5 \tag{2}$$

Here, the symbol V(m/s) denotes the measured stress wave velocity of tendon while the symbol σ (MPa) denotes the desired applied tensile stress. The terms σ_c, σ_s and ρ_c denote the concrete strength, the ultimate strength of strand and the mass density of concrete, respectively. The five regression parameters k_1, k_2, k_3, k_4 and k_5 turn out 22.8571, 0.0104, 3.2916, 2.5125 and 25.4629, respectively.

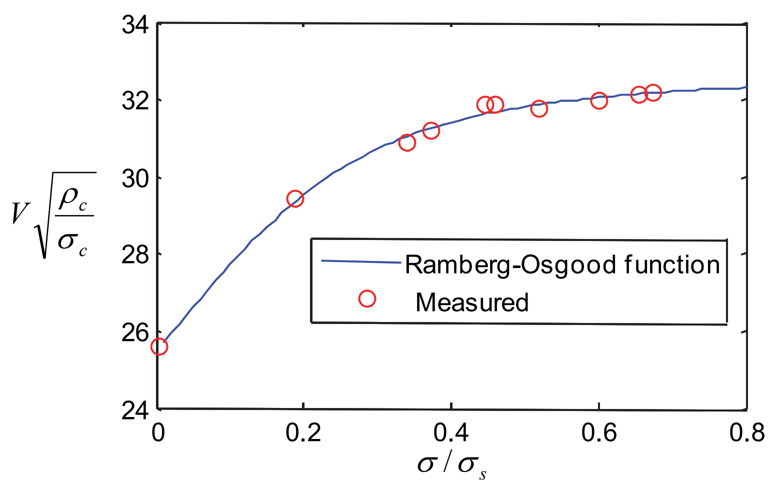

Figure 5.Experimental Formula.

It is observed that one could accurately estimate the existing tensile stress, σ , of a bonded PSC tendon by means of measuring the stress wave velocity, V, only if the applied stress level is lower than about 40% of the ultimate strength of tendon. However, the sensitivity of the curve becomes lower as the applied stress level higher. Therefore, one should pay special attention to the application of the curve when the applied stress level is over 40% than the ultimate strength of tendon.

FIELD TEST

Field Test Setup

As shown in Figure 6, the longitudinal impact-echo tests are conducted for two prestress bonded tendons embedded on a Wolsung nuclear power plant in Korea. For the data collection of total 110 test sets for each tendon, a sampling frequency of 25 kHz is employed. For each test set, more than 50 impact tests are repeated.

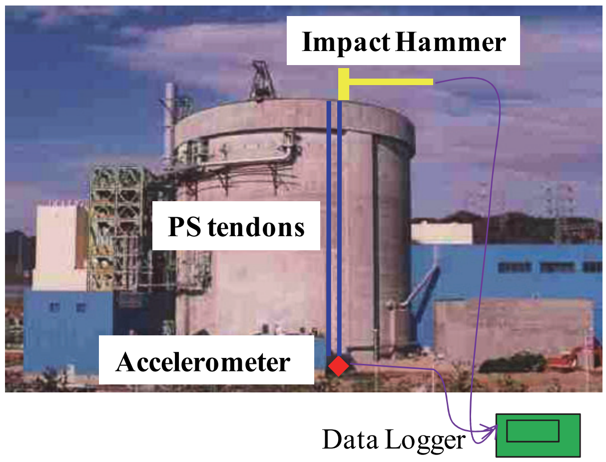

Figure 6.Field Experiments.

Field Test Results

In a design report, each vertical tendon consists of 105 prestress (PS) wires and the applied stress on the vertical wall tendons is 967 MPa. Nominal diameter, elastic modulus and ultimate tensile strength of wire are 7.01 mm, 200 GPa and 1760 MPa, respectively. The installed anchoring system is a BBRV wedge type with a duct. The space between duct and strands is filled with cement paste grouting after tensile force is introduced.

For tendon No.1, the measured impact signal and acceleration response time signal are shown in Figure 7. For the tendon No.1 and 2, the measured longitudinal stress wave velocities are 4115.1 m/s and 4129.3 m/s, respectively, at the temperature of 19.2°C.

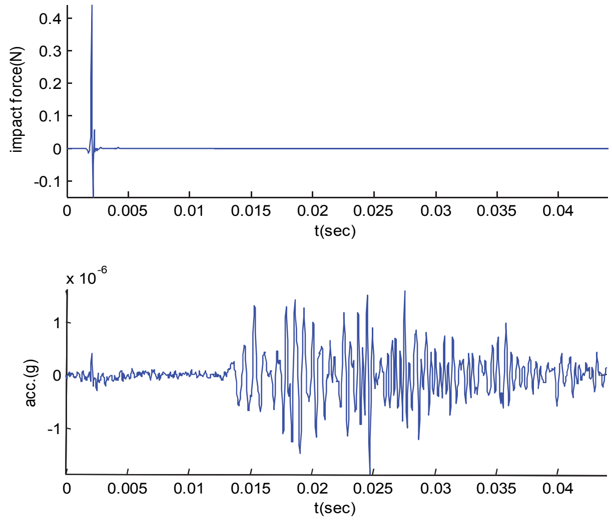

Figure 7. Measured impact and echo signals of tendon No.1.

To estimate the applied stress on a bonded tendon, Eq. (2) is used after temperature calibration. For the two measured wave velocities of tendons No.1 and 2, the curve fitting results are 992.9 MPa and 1089.9 MPa, respectively. Thus, one can say that the estimated prsstress levels of the two tendons are larger than the design value of 967 MPa.

CONCLUSION AND DISSCUSSION

To estimate existing tensile stress of a bonded tendon, an experimental formula has been proposed. The proposed formula requires measuring the longitudinal stress wave velocity. To examine feasibility and practicability of the proposed approach, the existing tensile stress levels on two prstress tendons embedded on a Wolsung nuclear power plant have been evaluated by measuring the wave velocities. Since the estimated prestress levels of two individual tendons are close to the design value, it seems that the proposed longitudinal pulse echo technique seems feasible and applicable for a real PSC structure.

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REFERENCES

1. Chen, H. L. and Wissawapaisal, K. Measurement of tensile forces in a seven-wire prestressing strand using stress waves, *J. Eng. Mech. ASCE*, 127, (2001) 599–606.
2. Scalea,F. L., P Rizzo, P. and Seible, F. Stress measurement and defect detection in steel strands by guided stress waves, *J. Mater. Civil Eng.*, 15 (2003) 219–227.

3. Chaki, S. and Bourse, G. Stress level measurement in prestressed steel strands using acoustoelastic effect, *Exp. Mech.*, 49(2009) 673–681.
4. Beard,M. D., Lowe, M. J. S. and Cawley, P. Ultrasonic guided waves for inspection of grouted tendons and bolts, *J.Mater.Civil Eng.*, 15(2003) 212–218.
5. Kim, B. H. Jang, J. B., Lee, H. P. and Lee, D. H. Effect of prestress on longitudinal vibration of bonded tendons embedded in a nuclear containment, *Nucl. Eng. Des.*, 240(2010) 1281–1289.
6. Kim, B. H. Jang, J. B. and Lee, H. P. Estimating tensile stress level of bonded strands embedded in nuclear containment using longitudinal elastic wave velocity, *The 8th int. conf. on condion monitoring and machinery failure prevention technologies*, 20-22 June 2011, Cadiff, UK.