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PREDICTION OF PRESTRESS FORCE ON GROUTED TENDON BY EXPERIMENTAL MODAL ANALYSIS

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ABSTRACT

The grouted tendon has been adopted to the containment building of some operating nuclear power plants in Korea and assessment of the prestress force on the grouted tendon is being issued as an important pending problem for the continuous operation beyond their design life. In order to assess the prestress force on the grouted tendon at present, indirect assessment techniques have being applied but they have limitations to accurately identify the real prestress force.

Therefore, the long-term research program was begun to assess the prestress force on the grouted tendon of the containment building using nondestructive techniques. As a first step of the research program, the experimental modal analysis was carried out using 6 post-tensioned concrete beams to obtain the variation of natural frequency according to the level of prestress force. The natural frequencies of post-tensioned concrete beams were calculated using numerical analysis with measured natural frequencies and the application possibility of natural frequency to predict the prestress forces of the post-tensioned concrete beams was confirmed.

1. EXPERIMENTAL MODAL ANALYSIS

1.1 Post-tensioned Concrete Beam

In order to investigate the variation of natural frequency according to the level of prestress force at the grouted tendon, post-tensioned concrete beams with the grouted tendon type were manufactured and they were representative of real wall and post-tensioning system of containment building at the nuclear power plant. The total number of post-tensioned concrete beams is 6 and their length is 8.0 m and area is 0.09(0.3×0.3 m) m^2. The 28-day compressive strength of concrete is 37.0 MPa, unit weight of concrete is 22.5 kN/m^3 and post-tensioning system is located at center of the post-tensioned concrete beam. Load cell was installed at the one end to measure accurately the prestress force which was applied to the post-tensioned concrete beam, as shown in Fig. 1. The anchorage type for prestressed strand is VSL Type P and the diameter of prestressed strand is 15.2 mm and 3 prestressed strands were used to apply the design prestress force. The final prestress forces which were applied to each post-tensioned concrete beam, are 0 kN, 146 kN, 264 kN, 356 kN, 465 kN, and 523 kN.

1.2 Experimental Modal Analysis

In order to get the natural frequency of post-tensioned concrete beams according to the level of prestress force, experimental modal tests were carried out. Among the experimental modal tests, impact hammer test and MIMO(Multi Input Multi Output) sweep test were adopted to get the natural frequency of post-tensioned concrete beams. The acceleration occurring from both tests, was measured by piezo-electrical sensors. In order to get the various mode shapes, 9 sensors were used as shown in Fig. 2. They were placed on top of the post-tensioned concrete beam and a sampling rate of 512 Hz was used.

Fig. 1. Post-tensioned concrete beam and load cell

Also, the loading point of an impact hammer and an exciter is P7 in Fig. 2. Impact hammer test was carried out 5 times to each post-tensioned concrete beam and the measured data were averaged. The frequency range of the impact hammer is from 0 Hz to 256 Hz. The loading magnitude of the exciter is 20 N and the frequency range of the exciter is from 2 Hz to 150 Hz.

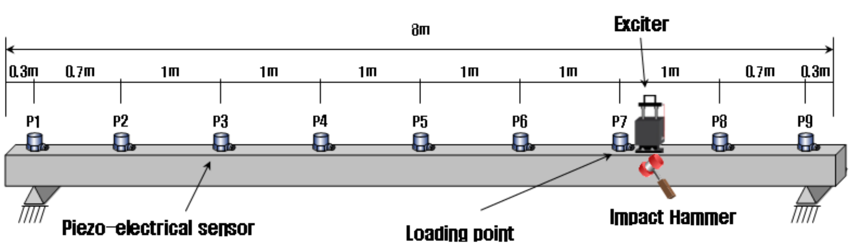
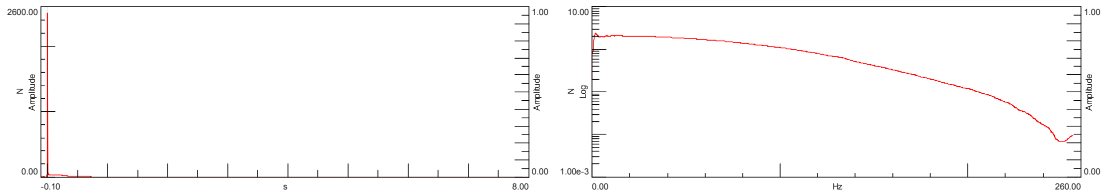


Fig. 2. Test setup

2. TEST RESULTS

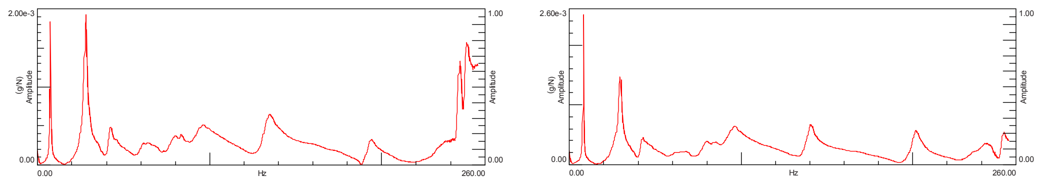
2.1 Impact Hammer Test

Fig. 3 shows the impact signal of the impact hammer and Fig. 4 shows the Frequency Response Function(FRF) according to the level of prestress force. Table 1 indicates the natural frequencies corresponding to the each modal number and prestress force. The natural frequencies of post-tensioned concrete beams were generally proportional to the level of prestress force as shown in Table 1.

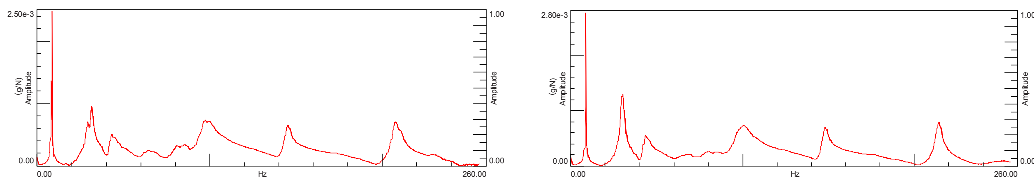


(a) Time domain (b) Frequency domain

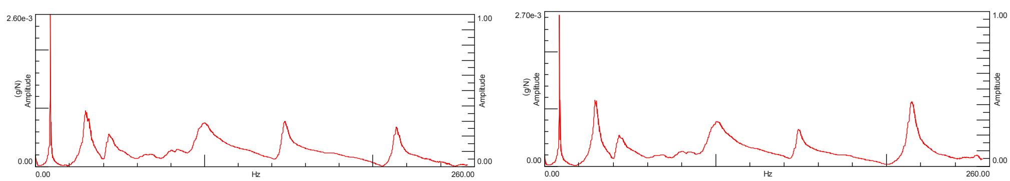
Fig. 3. Impact signal



(a) 0 kN (b) 146 kN



(c) 264 kN (d) 356 kN



(e) 465 kN (f) 523 kN

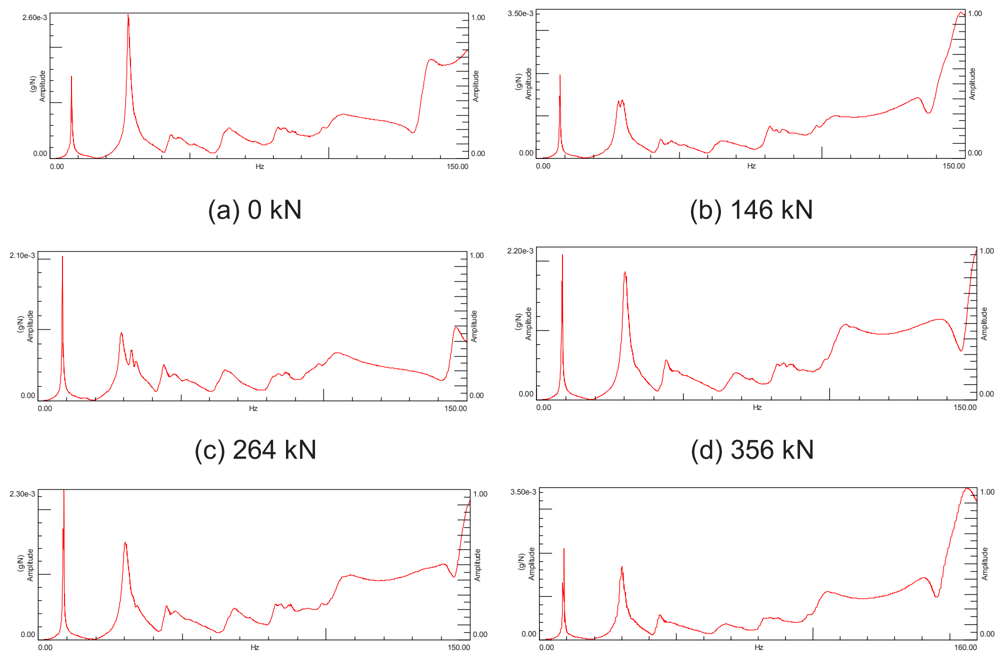
Fig. 4. Frequency response functions by impact hammer test

Table 1. Natural frequencies by impact hammer test

Prestress force (kN)	1^{st} mode (Hz)	2^{nd} mode (Hz)	3^{rd} mode (Hz)	4^{th} mode (Hz)
0	7.513	28.183	94.876	132.999
146	8.216	29.399	95.052	140.023
264	8.539	30.976	97.334	145.087
356	8.724	29.997	99.418	147.913
465	8.697	30.126	98.812	147.480
523	8.794	29.850	99.466	148.334

2.2 MIMO Sweep Test

Fig. 5 shows the FRF according to the level of prestress force and Table 2 indicates the natural frequencies corresponding to the each modal number and prestress force. Also, the trend of natural frequencies to the level of prestress force by MIMO sweep test was almost same as that of natural frequencies by impact hammer test.



(a) 0 kN (b) 146 kN

(c) 264 kN (d) 356 kN

(e) 465 kN (f) 523 kN

Fig. 5. Frequency response functions by MIMO sweep test

Table 2. Natural frequencies by MIMO sweep test

Prestress force (kN)	1st mode (Hz)	2nd mode (Hz)	3rd mode (Hz)	4th mode (Hz)
0	7.567	28.223	101.095	133.812
146	8.190	26.609	100.727	135.912
264	8.498	29.583	102.160	145.208
356	8.672	30.269	102.814	144.053
465	8.690	30.331	104.474	144.280
523	8.757	30.241	103.231	144.522

In order to examine the similarity of natural frequencies got by both impact hammer test and MIMO sweep test, difference ratio of natural frequency classified by modal number according to the level of the prestress force, was compared. 1st modal natural frequency shows the highest similarity with minimum difference ratio of 0.71 % and the 2nd modal natural frequency shows the lowest similarity with maximum difference ratio of 10.5 %. Therefore, both tests showed the good accordance to the natural frequency according to the level of prestress force and both test data are available for predicting the prestress force of grouted tendon. As shown in Table 1 and 2, MIMO sweep test showed more consistent relationship between natural frequency and prestress force than impact hammer test and 1st modal natural frequency is the best data to predict the prestress force of grouted tendon among 4 modal natural frequencies.

3. EFFECTIVE FLEXURAL RIGIDITY

3.1 Effective Flexural Rigidity

It is very difficult to calculate the natural frequency of post-tensioned concrete beam with prestress force using the modal analysis by general structural analysis programs because the prestress force can't be inputted to the modal analysis of general structural analysis programs. Therefore, prestress force should be converted to the effective flexural rigidity for modal analysis to calculate the natural frequency of post-tensioned concrete beam.

In order to derive the effective flexural rigidity, the following equation for natural frequency of vibration was used for a simply supported prismatic beam.

$$\omega_n^2 = -\left(\frac{n\pi}{L}\right)^2 \frac{N}{m} + \left(\frac{n\pi}{L}\right)^4 \frac{EI}{m} \qquad (1)$$

Where n = mode number, L = span length, N = axial compressive force, m = beam mass per unit length, E = modulus of elasticity, and I = moment of inertia for the beam section. The effective flexural rigidity EI can be expressed as a function of both natural frequency and prestress force from Eq. 1 and the resulting equation is as follows.

$$EI = \left(\frac{L}{n\pi}\right)^2 N + \left(\frac{L}{n\pi}\right)^4 m\omega_n^2 \qquad (2)$$

3.2 Numerical Analysis Model

Numerical analyses were carried out to calculate the natural frequencies of 6 post-tensioned concrete beams using SAP 2000. Beam element was selected to model the post-tensioned concrete beam and the hinge supported condition was adopted as the boundary condition as shown in Fig. 6. Also, the prestress force was considered as the effective flexural rigidity using Eq. 2.

In order to verify the reliability of the numerical analysis model, modal analysis was performed to the case without prestress force. Table 3 indicates the numerical analysis results and analytical case 1 was in case that concrete elastic modulus of the post-tensioned concrete beam determined by concrete material test, was inputted to the modal analysis and analytical case 2 was in case that the effective flexural rigidity determined by Eq. 2, was inputted to the modal analysis and measured data are 1st modal natural frequency by MIMO sweep test.

Comparing natural frequencies by both analytical case 1 and 2 with measured natural frequency by MIMO sweep test, the numerical analysis model well estimated the natural frequency of post-tensioned concrete beams without prestress force within the difference ratio range from 0.2 % to 1.2 %. Therefore, the reliability of the numerical analysis model and the effective flexural rigidity were confirmed.

Fig. 6. Numerical analysis model

Table 3. Numerical analysis results without prestress force

	Analytical case 1	Analytical case 2	Measured data
Natural frequency (Hz)	7.477	7.552	7.567
Difference ratio (%)	-1.2	-0.2	

Using the numerical analysis model and the effective flexural rigidity, modal analyses were performed to calculate the natural frequencies of 5 post-tensioned concrete beams with prestress force. Table 4 indicates the numerical analysis results and difference ratios between numerical analysis and MIMO sweep test were very small. Also, difference ratio becomes larger in proportion to the level of prestress force but maximum difference ratio may be less than 5 % because the range of prestress force which has been applied to the real structure, is less than 465 kN. Therefore, natural frequency measured by experimental modal analysis is available for the prediction of prestress force on grouted tendon.

Table 4. Numerical analysis results with prestress force

Prestress force (kN)	Natural frequency (Hz)		Difference ratio (%)
	Numerical analysis	MIMO sweep test	
146	8.34	8.19	1.8
264	8.77	8.50	3.2
356	9.03	8.67	4.2
465	9.16	8.69	5.4
523	9.28	8.76	6.0

4. CONCLUSION

As a first step to develop the nondestructive techniques to identify the prestress force of the grouted tendon, the experimental modal analysis was carried out using 6 post-tensioned concrete beams with the grouted tendon type.

Also, in order to consider the prestress force in the modal analysis, the effective flexural rigidity was deduced from the equation for natural frequency of vibration and numerical analyses were performed to calculate the natural frequency of 6 post-tensioned concrete beams.

As a result of tests, both impact hammer test and MIMO sweep test showed the good accordance to the natural frequencies according to the level of prestress force and the natural frequencies of post-tensioned concrete beams by two tests were generally proportional to the level of prestress force. Also, it were confirmed that the reliability of both numerical analysis model and the effective flexural rigidity, and relatively good accordance between analytical and measured natural frequencies. Therefore, natural frequency measured by experimental modal analysis is available for the prediction of prestress force on grouted tendon.

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REFERENCES

[1] Law, S.S., Lu, Z.R., “Time domain responses of a prestressed beam and prestress identification”, Journal of sound and vibration, 2005, 1011-1025.

[2] Hamed, E., Frostig, Y., “Natural frequencies of bonded and unbonded prestressed beams-prestress force effects”, Journal of sound and vibration, 2006, 28-39.

[3] Chen, H.L., Wissawapaisal, K., “Measurement of tensile forces in a seven-wire prestressing strand using stress waves”, Journal of engineering mechanics, 2001, 599-606.

[4] Saiidi, M., Douglas, B., Feng, S., “Prestress force effect on vibration frequency of concrete bridges”, Journal of structural engineering, 1994, 2233-2241