Material Properties Measurement

Evaluating Tensile Force on Grouted Tendon using Impact Responses
B-H Kim, Kyungam University, republic of Korea; Y-C Song, J-B Jang, H-P Lee, Korea Electric
Power Research Institute, Republic of Korea

ABSTRACT

The feasibility for nondestructively evaluating tensile force on a grouted seven-wire strand embedded in a nuclear containment has been investigated. The attempts examine the energy transfer rate between the impact pulse at one end and the longitudinal stress wave responses at the other end. While the existing stress wave propagation technique has been succeeded in identifying the tensile stress on an ungrouted strand, no investigation has been found for the grouted strand yet. The major challenge lies in the significant energy attenuation caused by circumferential grouting. This study firstly reports that the energy attenuation level in a specific low frequency range relies on the applied tensile stress on a grouted strand.

INTRODUCTION

The advance of the material technology increases the use of high strength multi-wire steel strand as the structural members such as the cable-supported bridge, the pre-stressed concrete beam, nuclear containment, etc. Since a prestressed concrete (PSC) structure maintains a high stress level on normal times, monitoring the tensile stress of tendons embedded on concrete is an important engineering task. However, no practical method evaluating the tensile stress level on individual strand is available. In practice, thus, the load carrying capacity tests for the entire structure is often considered to examine the structural safety of the structure. Since such test is dangerous and uneconomical, however, the development of an intrusive and nondestructive evaluation technique to evaluate the tension level of an individual strand is desired.

Law and Lu [1,2] proposed a method to estimate tensile force and flexural rigidity of an ungrouted PSC beam using the displacement, strain, and load time histories of the beam. Their research is based on the results of Saiidi et al. [3] reporting that the flexural natural frequencies increase as the applied compressive force on tendon increases. Without experimental verifications, however, Hamed and Frostig [4] insisted that the flexural natural frequencies of a PSC beam are irrelevant not only to the applied tension force but also to the grouting conditions. Thus, two previous research results conflicts each other. For this issue, many discussions [5] have been conducted but no conclusion has been made yet.

Based on the physical phenomenon that the velocity of stress wave on a rod relies on the applied stress level, Chen and Wissawapaisal [6] estimated the tensile stress on seven-wire strands by means of detecting the arrival group velocity of stress wave at one end after injecting longitudinal ultrasonic stress wave (150kHz~350kHz) at the other end of strand. Using magnetostrictive ultrasonic transducers, Kwun et al. [7] reported the existence of notch frequency (75kHz~110kHz) that is a disappeared frequency induced by the applied stress level in seven-wire strands. Using the same concept of the arrival velocity difference on a stress field, Scalea et al. [8] and Chaki and Bourse [9] also conducted a similar pulse-echo technique utilizing magnetostrictive guided ultrasonic waves. However, the application of such high frequency methods to the strands on a grouted PSC is not feasible, because the cement grouting surrounding the steel strands causes significant energy attenuation. For the grouted tendons, it is known that the maximum inspection range of ultrasonic waves is less than 1.5m [10] while the typical length of a target PSC bridge is 30~35m and the height of nuclear containment is over 40m. Up to date, no attempt has been made to evaluate tensile forces on the grouted tendons.

This study examines the feasibility of nondestructively evaluating tensile force on the grouted seven-wire strands that is often installed in a PSC beam bridge or the nuclear containments. Since the strict limitation of the previous high frequency pulse approach lies on energy attenuation in the case of

More info about this article: http://www.ndt.net/?id=8919
grouted tendons, this study mainly focuses on the utilization of low frequency pulse because the low frequency propagates much far away regardless the grouting conditions.

EXPERIMENTS

Test Setup

As shown in Table 1 and Fig. 1, three post-tensioned concrete beams have been made. The KSD 7002 seven-wire strand B-type is installed at the center of the concrete cross section. The nominal diameter, area and ultimate strength of the strand are 15.2mm, 138.7mm$^2$ and 260,680N, respectively. To measure true applied tension levels on the strand, the load cell (CASKOREA Model CCHE-40TCK) has been installed at each beam. After applying the three tension levels on the beam, the 5 mm diameter duct has been grouted with cement. The concrete strength estimated by Schmidt hammer test is shown in the last column of Table 1. The beams are simply supported by two rollers located at 0.05m from each end.

![Figure 1 - Grouted Post-Tensioned Concrete Beam](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Height (m)</th>
<th>Applied Tension (N)</th>
<th>Conc. Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSC1</td>
<td>3.000</td>
<td>0.202</td>
<td>0.302</td>
<td>76,440 (29% Pu)</td>
<td>22.65</td>
</tr>
<tr>
<td>PSC2</td>
<td>3.003</td>
<td>0.201</td>
<td>0.297</td>
<td>114,660 (44% Pu)</td>
<td>21.37</td>
</tr>
<tr>
<td>PSC3</td>
<td>2.983</td>
<td>0.203</td>
<td>0.303</td>
<td>147,980 (57% Pu)</td>
<td>18.87</td>
</tr>
</tbody>
</table>

Table 1 - Test Specimens

Impact Tests

To excite the longitudinal axial modes, the impact hammer (PCB Piezotronics Model 086C04) has been applied to the core wire of the strand. The acceleration responses caused by the impact have been collected at the each end of seven wires. The installation of the accelerometers (PCB Piezotronics Model 352B10) is perpendicular to the end cross section of each wire. Using a data acquisition system (National Instrument Model NI C91O-9073 and NI9233 four channels), the various acceleration time histories are collected with a sampling ratio of 50 kHz.

For two case studies as shown in Fig.2, the impact tests are considered. In the first test, the core wire No. 5 on the right side of strand in Fig 3b is impacted and the resulting acceleration time responses at the circumferential three wires No. 2,3,4 on the left side of strand in Fig. 3a are sampled. In the second test, the accelerometers are installed on the left side of a center wire No.1 and the left side of a circumferential wire No.6 for the impact on the right side of a center wire No 5. Total sixty vibration tests are repeated for each test case.
EXPERIMENTAL RESULTS

Case Study 1

For the PSC1, a typical longitudinal impact signal at the wire No. 5 and its spectrum are shown in Fig. 4. It seems that the impact hammer has excited up to 6 kHz. The peak of the impact signal occurs at 1.06 μsec. The resulting overall acceleration time history is shown in Fig. 5, whereas Fig. 5b shows the initial part of the acceleration response. Two dominant peaks are observed for all the PSCs. They are the stress wave due to the impact. The first and second peaks occur at 1.82 μsec and 2.06 μsec as shown in Fig. 5b. After such two dominant peaks, the global axial vibration responses are started. Since total length of the core wire is 3.368 m and the arrival time of the first peak is 0.76 μsec, the velocity of the stress wave on the core wire is about 4431.6 m/s. For other beams, there is no difference on the velocity of the stress wave. Since the period of the two peaks is 2.40 μsec, it is expected that the spectrum of the acceleration signal will be disturbed at near 4166.7 Hz.
For each beam, the transfer functions between the impact signals and the acceleration responses are shown in Fig. 6. The dominant peaks on the spectrums denote the global axial modes of the beam. Table 2 summarizes such global modes only. It is seen that many local modes caused by the wire interactions exist between the global modes. Since the length of the PSC3 is 2.983m and the extracted first axial mode is 640.9 Hz, the velocity of stress wave on the concrete beam is 3823.6 m/s.
Recall that the $n$th natural frequencies, $f_n$ (in Hz), of free-free bar is

$$f_n = \frac{n}{2L} c_v$$  \hspace{1cm} (1)

where $n$, $L$, and $c_v = \sqrt{E/\rho}$ denote mode number, length, and velocity, respectively. The last row of Table 2 is computed using such measured concrete velocity. Inspecting the global frequencies in Table 2, no frequency changes with respect to the applied tension levels are found. The frequencies of the PSC2 are much larger than those of other beams while the PSC3 has the highest tension level. It is suspected that the major reason may lie in the mass uncertainty because the frequency differences increases with a constant ratio as mode number increases.

A graphical inspection of the extracted global modes is shown in Fig. 7. The theoretical bar frequency with free-free ends agrees very well in the lower modes. However, it is observed that the difference between the theoretical frequency and measured frequency become larger in the higher modes starting from the sixth mode.
Assuming that the dispersive effects caused by lateral inertia and variable cross-section exist, the bar velocity for the measured frequencies can be estimated by
\[ c_n = \frac{2L f_n}{n} \]  
(2)

The resulting bar velocity is shown in Fig. 8. It is seen that the bar velocity of the PSC2 is higher than other beams with an approximately constant difference. This is because the mass of the PSC2 is smaller than others. In addition, the bar velocity drops from the fifth mode. Moreover, the change rate of the bar velocity between the sixth mode and seventh mode is different with respect to the applied tension levels. This is due to the aforementioned interruption of the wire stress wave to concrete stress wave. Thus, it may be possible to quantify the applied tension levels on the beam using this phenomenon.

Case Study 2

Due to impact at the center wire location No. 5, the typical time history and transfer functions of acceleration at the core wire are shown in Fig. 9a and 9b, respectively. Comparing to the responses of the circumferential wires shown in Fig. 5a and 6a, no big difference is found. Fig. 10 shows the responses at the wire location No. 6. Since the wire location No. 6 is very close to the impact location No. 5, the magnitude of responses is very large. In addition, the peaks of global modes are hard to identify from the transfer function. The applied impact signals are very similar to Fig. 4.
The energy $E$ of a signal $y(k)$ is defined as [11]

$$E = \sum_{i=0}^{\infty} |y(k)|^2$$  \hspace{1cm} (3)

From the results of Case Study 1, the velocity of wire stress wave is faster than that of concrete stress wave. Thus the first arrival wave is the wire stress wave and such wave is smeared in overall vibrating acceleration responses. To examine the effect of wire stress wave on the global vibration signal, a band pass filter is specially designed in order to filter the frequency range from 3000Hz to 5000Hz. Here, the reason to specify such filtering range is due to the fact that the first arrival wire stress wave has a frequency of 4166.7Hz as mentioned in the previous case study. For the filtered accelerations and impact time history, the energy of each signal has been computed by Eq. (3). Next, the energy transfer rate between impact and acceleration has been examined. For each repeated test, the resulting energy transfer rate is shown in Fig.11 and their statistical mean $\mu$, the standard deviation $\sigma$, and the coefficient of the variation($COV$) $\delta = \sigma / \mu$ are shown in Table 3.

<table>
<thead>
<tr>
<th>No.</th>
<th>Mean</th>
<th>Std.</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSC1</td>
<td>0.1470</td>
<td>0.0229</td>
<td>0.1556</td>
</tr>
<tr>
<td>PSC2</td>
<td>0.1850</td>
<td>0.0087</td>
<td>0.0469</td>
</tr>
<tr>
<td>PSC3</td>
<td>0.2109</td>
<td>0.0039</td>
<td>0.0186</td>
</tr>
</tbody>
</table>

Table 3 - Statistics of extracted energy transfer ratio
As shown in Fig. 12, the mean values of the energy transfer rate are proportional to the applied tension levels. Moreover, the COVs of the energy transfer rate are inversely proportional to the applied tension levels as shown in Fig. 13. It is deducible that the strand becomes sturdy and the energy attenuation among wires decreases as the tension level increases. Measuring such energy transfer rate, therefore, it may be possible to determine the applied tension levels on the existing post-tensioned concrete beam. However, it is suspected that the proposed energy transfer rate may be also related to the length of the beam. For the test beams on this study, the examination of the length effect is not available. Regarding the length effect on energy attenuation with respect to the applied tension level, the further research is expected.

![Figure 12 - Applied tension level and the mean of energy transfer ratio.](image1)

![Figure 13 - Applied tension level and COV of energy transfer rate](image2)

**SUMMARY AND CONCLUSIONS**

Using the longitudinal vibration of strands, the feasibility study for evaluating individual tension force levels on grouted tendons has been conducted. For the three PSC beams with different tension force levels, two impact cases are examined. It turns out that the energy transfer rate is proportional to the applied tension force level.

Based on the analysis of two experiments, the following four conclusions could be made. Firstly, the first arrival wave form on the acceleration response stems from the wire stress wave. The
wire stress wave affects the global acceleration spectrum at a specific frequency range. Secondly, the global axial modes has nonlinearity starting from such frequency, and the change rate of the bar velocity at global modes relies on the applied tension force level of strands. Thirdly, the energy transfer rate is proportional to the applied tension level on strand. The higher tension applied to strands induces sturdy strand and makes more efficient energy transformation at a specific wire stress wave propagation frequency range. Finally, the further investigation regarding the length effect on the energy transfer rate should be investigated.

REFERENCES