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ANALYTICAL STUDY ON REAL-TIME DETECTION OF TENDON FAILURE IN PRESTRESSED CONCRETE BEAM

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ABSTRACT

This study discusses real-time detection of tendon failure in prestressed concrete (PC) beam based on FEA simulations of wave propagation. After the occurrence of elastic waves due to failure of the prestressing tendon, the waves propagate the PC beam as Lambs wave with multiple modes. S0 mode is targeted to extract by referring the dispersion curve of concrete plate. The elastic wave is captured by high-speed sampling measurement at multiple points. The space-time information is converted to wave number-frequency information by two-dimensional Fast Fourier transform(2D FFT), the wave number and frequency band corresponding to the S0 mode are extracted, and they are extracted by inverse 2D FFT. In the case of a practical PC beam as an example, it is found that there is a possibility that the velocity stable region of the S0 mode can be extracted by measurement at an interval of 0.48 m with 200 kHz sampling.

Keywords: Lamb wave, prestressing tendon

1. INTRODUCTION

PC tendon in civil structures is an important structural component in terms of load carrying capacity. Focusing on PC bridges, failure of PC tendons mainly due to corrosion has been reported, and in some cases, it has led to bridge fall. In order to secure in-service safety, it is necessary to develop a real-time monitoring method to detect tendon failure for PC bridges.

High tension stresses are introduced in PC tendons, and an elastic wave is generated at the time of failure. This study investigates the monitoring method to identify the failure point of the tendon by capturing the elastic waves.

FIGURE1 shows test data of out-of-plane response in the web of a PC beam when a PC tendon had a failure. The data were recorded by piezoelectric element. CH3 and CH5 are placed across the web as if they were facing each other. The CH3 and CH5 had similar responses in the beginning, and then show an antiphase each other. This might corroborate occurrence of Lamb wave. FIGURE2 is the response of CH3 in frequency domain. The major response was less than 10(kHz). Accordingly, this study starts with drawing dispersion curves; then, proceeds to identify and extract an appropriate wave mode to evaluate a point where the PC tendon had failure based on numerical simulation of FEA. As an example, a typical Japanese PC beam for bridge is modeled, and dynamic wave propagation from a tendon failure is simulated. The simulation result is processed by the wavenumber-frequency domain filter (*k-f* filter). Finally, appropriate data-acquisition interval (DAI) and window width in *k-f* filter are discussed in order to extract the targeted wave mode.

2. NUMARICAL SIMULATION

2.1 FEM model

FIGURE 3 is the model of the PC beam. The model is a full-scale size with the sectional dimensions shown in FIGURE 1, the beam length of which is 9980mm. The mesh size is 20mm to trace a wave of 400mm wavelength with 20 discrete plots. The frequency characteristics of the wave propagating on the surface is majorly less than 10 kHz; that is, the wavelength is mostly less than 400mm.

2.2 Analysis Process

The analysis takes two steps. The first step provides displacement of the node where the tendon breaks caused by tendon failure. The tendon behavior including the failure is modeled by connector element [ABAQUS]. The PC tendon is defined to release its axial restraint when the relative node distance reaches 22mm that is from the property of the used tendon steel strand.

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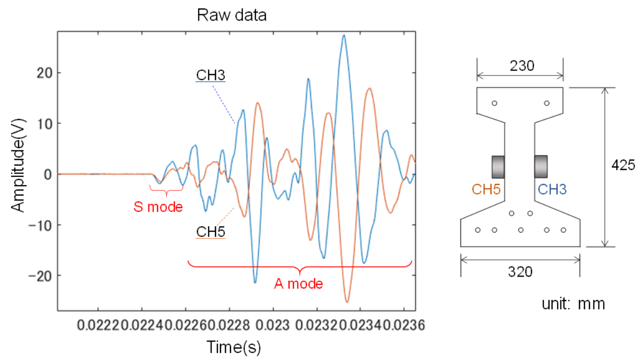


FIGURE 1: Out-of-plane response of PC beam

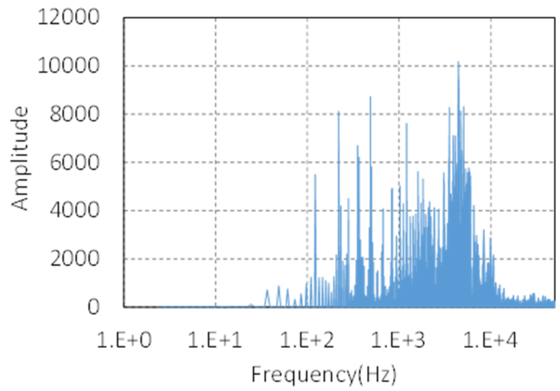
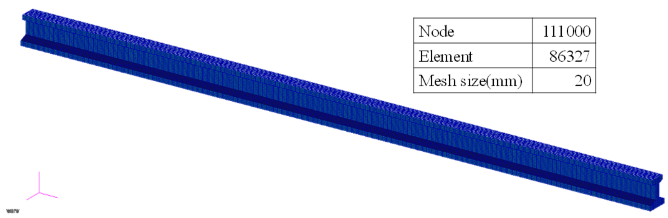


FIGURE 2: CH3 response in frequency domain



Node	111000
Element	86327
Mesh size(mm)	20

FIGURE 3: Simulation model

The second step simulates the wave propagation using the node behavior at which the tendon breaks.

3. WAVE EXTRACTION

FIGURE 4 shows dispersion curves for a concrete plate, the thickness of which is 80mm. For the purpose of identifying tendon failure location, velocity of the extracted wave mode should be stable. Since wave velocity of S0 mode is stable in the region less than 10kHz, wave extraction is targeted to S0 mode.

The mode extraction is processed by using *k-f* distribution [Hayashi et al.]. By measuring at multiple points along the web in longitudinal direction and arranging the data in a matrix, a matrix is created with positions (m) in rows, times (s) in columns, and signal intensities in elements. The matrix is processed by 2D FFT, then the data are converted to

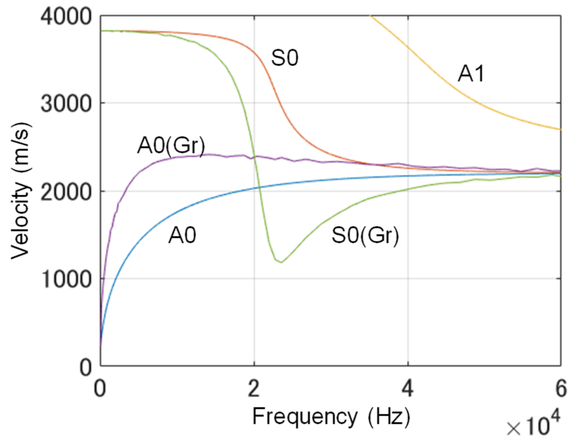


FIGURE 4: Dispersion curves of concrete plate (t=80mm)

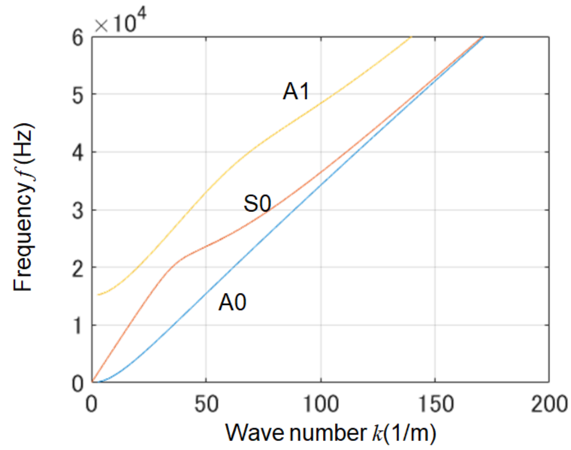


FIGURE 5: *k-f* distribution of concrete plate (t=80mm)

wavenumber (1/m) and frequency (Hz) as *k-f* distribution. S0 mode is extracted by applying inverse 2D FFT with the left signals along the S0 curve on $k-f$ distribution (FIGURE 5).

Window function processing is required to leave data only in the vicinity of the S0 mode on the *k-f* distribution chart. Hann window is centered on the S0 curve in each wavenumber. We assume that the sampling rate of data acquisition is at 200kHz, and consequently the number of data in frequency domain is larger than that of wavenumber. The window is accordingly directed to the frequency column. The window width might control the filtering characteristic because it may lose necessary signals if the width is small. The window width is set as a parameter to evaluate the wave extraction

The DAI is very important to consider the monitoring method. High-speed sampling at many points of data acquisition influence the in terms of cost, also DAI affects the wavenumber. Orange dots in FIGURE 6 indicates S0 curve in *k-f* distribution for the concrete plate of 80mm thickness. The blue circle in FIGURE 6 means the region of wavenumber and frequency in

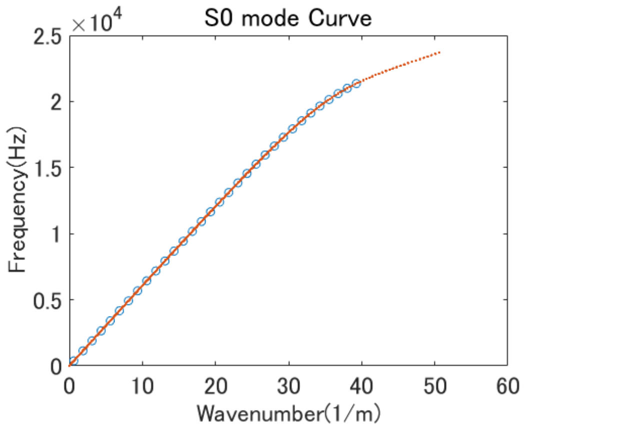


FIGURE 6: Region of wavenumber for S0 mode (80mm)

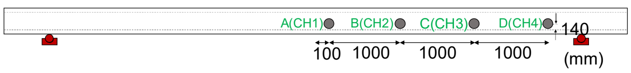
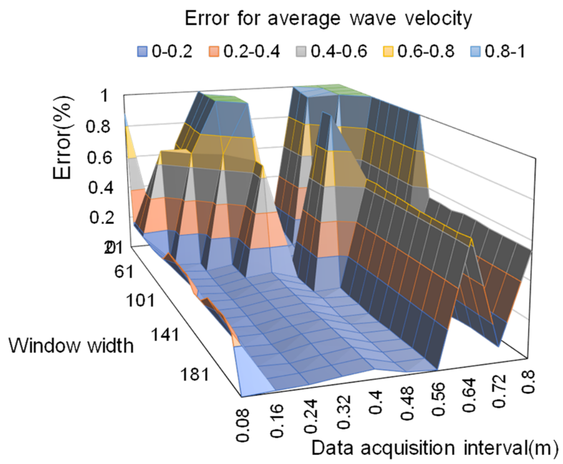
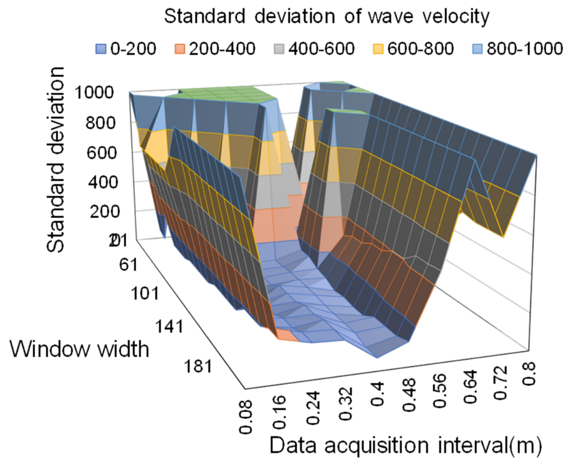


FIGURE 7: Evaluation points for wave velocity



(a) Average error



(b) Standard deviation

FIGURE 8: Error and standard deviation of extracted wave

the case of 80mm data-acquisition interval. It covers 0~38 wavenumber and 0~22kHz frequency. In case that the DAI is 480mm, the covered region will be 0~7 wavenumber and 0~4kHz frequency.

4. RESULTS

The wave velocity is evaluated by the time deference between two points using the cross-correlation function. The evaluation of velocity is compared with S0 velocity as 3813(m/s) for the average and standard deviation (STD) of 3 sections (A~B, B~C, C~D) shown in FIGURE 7. The evaluation parameters are the DAI which is from 0.08m to 0.8m at 0.08m pitch and the window width which is from 21 to 201 at 10 pitch.

FIGURE8 shows the error and STD of the wave velocity. As DAI becomes larger, both error and the variation of the wave velocity do larger. This is because discrete data from the large interval cannot express the waveform properly. On the other hand, if the DAI was small, the error and STD would be lessened but opposite results were shown in the region of 0.08~0.24m. This might be due to the mesh size, which was 20mm, of the FEM model.

Based on the above results, in this case study, the window width should be less than 181 and the measurement point spacing should be less than 480mm, then the tendon failure point can be identified by using time of flight of the extracted S0 wave.

5. CONCLUDING REMARKS

This study examined a method which detects tendon failure of PC beam in real time and identify the failure point. Following process is probably able to grasp the information of tendon failure and identify the failure location.

1) Draw dispersion curves of Lamb wave in a concrete plate
2) Determine to extract a wave mode, the velocity of which is stable in the region of frequency when tendon has a failure
3) The wave mode is extracted by *k-f* filter with 2D FFT
   - Note that appropriate window width in the *k-f* filter and DAI should be examined by numerical simulation
4) Time of flight of the extracted waves indicates the failure location

A case study targeted to a typical PC beam showed that DAI less than 480mm and window width less than 181 were necessary under 200kHz data sampling.

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