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Non-destructive Approach to Testing of Concrete Damaged by Fire with the Usage of Fast Fourier Transformation and Wavelet Transformation of Signal Recorded by Impact-Echo Method

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Abstract. This publication presents results of testing of specimens taken from highway bridge, which was damaged by fire originated from car accident. Test specimens were cut from core bores removed from fire damaged areas and areas not affected by fire.

Specimens were tested by non-destructive acoustic impact-echo method and ultrasonic pulse velocity method. The measured values were supplemented by destructive tests.

The intention of this assessment is to compare different interpretation approaches to these acoustic methods. Impact-echo (IE) is method based on exciting the test specimen by mechanical impact [1]. As the mechanical wave spread through the material it is absorbed, reflected or refracted on each interface of materials of different acoustic impedance and by external boundaries. Each interface works as new source of vibrations, which are recorded by attached piezoelectric sensor. The recorded signal is then transformed by Fourier Fast transformation (FFT) [2] to frequency spectrum.

In this publication two different approaches of interpretation of impact-echo measurements are compared. Locating the dominant resonance frequency in frequency spectrum obtained by FFT and by continuous wavelet transformation (CWT) of signal.

Continuous wavelet transformation of signal helps understand which certain frequency occurred at specific point in time of recorded signal [3]. Presented paper focus on comparison of these signal imaging techniques.

Introduction

Concrete is the most used structural material in civil engineering, thus majority diagnostic approaches aim to study and evaluate the condition of concrete structures, wear state of structure, flaws, and defects. These approaches can be divided to destructive, semi-destructive and non-destructive methods of testing [4].

Diagnostics of concrete structure tends to reveal the condition of structure, analyze the measured data and designing a suitable economical retrofitting process, depending on the scale of damage. There is a demand to keep structure intact during the testing and without notable intervention with ongoing operation of construction. Therefore, the non-destructive methods of testing are most wanted for this assessment.

In this publication a diagnostics of highway bridge is being discussed and evaluated. The origin of bridge can’t be mentioned due to car accident investigation and ongoing research by Institute of Building Testing. The bridge was built in 2015 so it is a new structure. The damaged area consists of three concrete pier columns, cross beam, and bottom side of bridge superstructure. Fire emerged from car accident caused the damage to concrete elements.

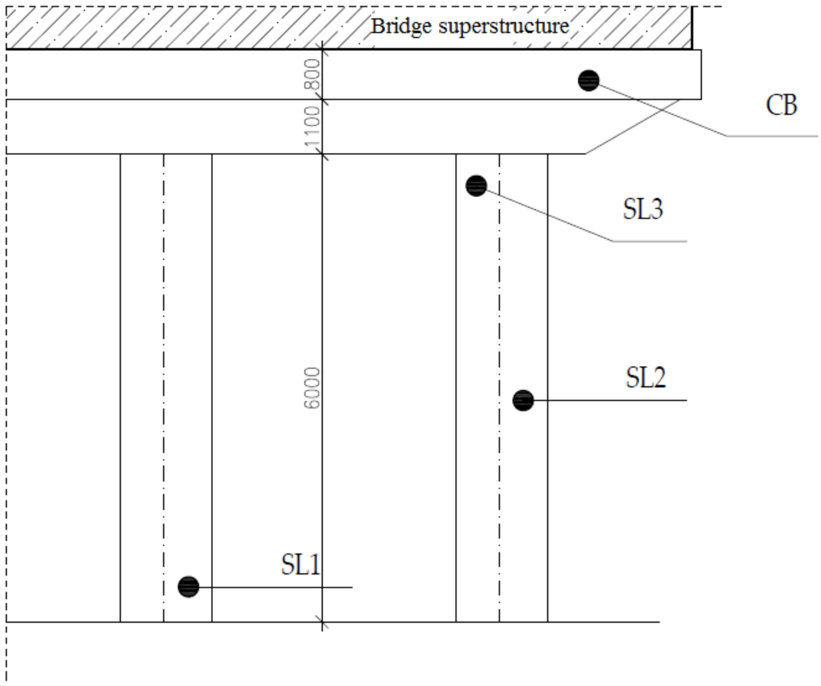

Fig.6 Scheme of damaged bridge and origin of each test specimen

In the presented publication four test specimens removed from bottom (SL1), middle (SL2) and top part of damaged columns (SL3) and from cross beam (CB) right above the fire are assessed. The scheme of bridge is at Fig.6. The four core bores were cut into test beams of parameters stated at Tab.4.

Tab.4 Basic parameters of test specimens

Parameter of test specimens	Name of test specimen			
	SL1[1]	SL2	SL3	CB
Weight [kg]	0.551	0.491	0.687	0.619
Length [mm]	160.1	121.0	167.4	159.2
Width [mm]	39.1	42.2	42.4	41.5
Height [mm]	40.4	42.2	42.4	41.5
Density [$kg \cdot m^{-3}$]	2177	2280	2033	2260
Origin	Footing of column	Middle of column	Head of column	Cross beam

[1] Test specimen SL1 was removed from second column to serve as a reference specimen.

Used methods

To determine physical-mechanical properties of affected areas, a destructive method on removed core bores was conducted to obtain compressive strength [5] of core bores from reference and thermally affected areas.

Non-destructive testing by Impact-Echo (IE) method was done on test specimens removed from bridge columns and cross beam. IE method is complex non-destructive acoustic method, which can provide information about inner structure of tested element and presence of internal flaws, air voids or cracks. This ability is based on skill of observer, who can process the measured data and interpret them. In Impact-Echo measurements are most often used piezoelectric sensors, which produce analog signal. The signal in time domain is recorded by different kinds of recording devices, such as digital oscilloscope. The typical setup for IE measurement is in the Fig.7.

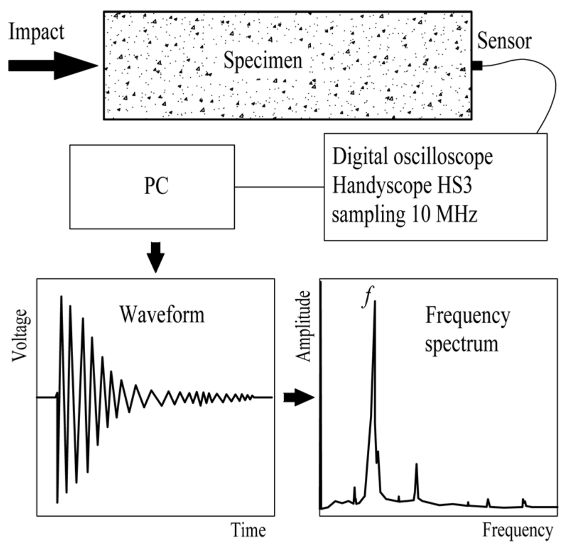

Fig.7 Typical setup for IE measurement [6]

Measurement by Impact echo was conducted on test specimens placed on rubber pads. As exciter of mechanical stress waves a spherical hammer of total mass 25.5 g was used. For recording of vibrations, a piezoelectric sensor MIDI 446s12 was used and for processing the signal was used a digital oscilloscope Handyscope HS3 with sampling speed of 10 MHz. For recording the longitudinal waves, receiver was placed in the front of test beam and exciter hit the test specimen at the opposite side [7].

The most common tool to interpret the measured signal recorded during Impact-Echo test is fast Fourier transformation (FFT) [2]. For example, the Fourier transform of the signal *f(t)* is:

$$F(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(t)\, e^{-i\omega t} dt \qquad (1)$$

This transform is a time-frequency representation as well as a function of time t_0 and frequency ω and provides an approximation to the frequency content of the signal over a small-time interval about time t_0. This approach is most widely used for signal processing in building vibro-acoustic diagnostics [1], [6], [8] as the dominant resonance frequency is most often assessed. The output of the FFT is frequency spectrum where dominant and harmonic frequencies are evaluated. We can describe a presence of defect or change in physical-mechanical properties by change of dominant frequency.

Continuous wavelet transformation (CWT) can be viewed as a filtering of the signal by a dilated version of mother wavelet $\psi(t)$. The wavelet can be viewed in time window with adjusted width and height, depending on scale – widening for long-scale (low-frequencies) information and narrowing for small-scale (high-frequency) content.

$$\Psi_{s,\tau}(t) = \frac{1}{\sqrt{|s|}} \Psi\left(\frac{t-\tau}{s}\right) \quad (2)$$

The CWT is a time-frequency, or more correctly a time-scale representation and produces a complex-valued surface. As the Gabriella Epasto and all mentioned [8], the CWT method of interpreting the signal can provide the dominant frequency as well as FFT, but in case of noised signal and heavily damaged material a CWT method can provide more parameters and a rapid detection of flaws and defects. In the presented paper a MATLAB R2017 software was used for calculating the spectrograms of IE signal.

Results of testing

Test specimens were tested in longitudinal way and obtained signal was processed by FFT and CWT. In the Fig.8 we can distinguish distribution of dominant frequency for each test specimen. Test specimen SL1 removed from footing of column have its resonance frequency at 8.77 kHz and test specimen shows visible marks of degradation by de-icing salts. The footings of other columns in the row have shown similar level of degradation distinguishable during in-situ inspection. The footings of other columns indicated also presence of salt degradation and freeze-thaw damage.

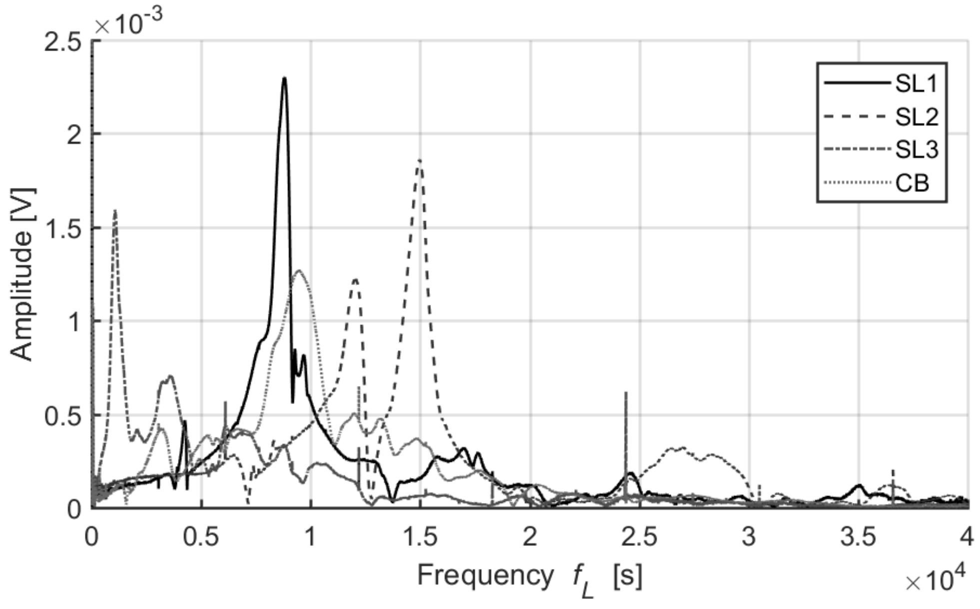

Fig.8 Change of longitudinal resonance frequency for each test specimen

Specimen SL2 removed from the middle of the column at height 2.5 m have resonance frequency 15.01 kHz and was the most preserved test specimen. Surface was black from smoke, but apart other test specimens SL2 remains its physical-mechanical properties at level, that we can describe as reference to other test specimens. This part of the column was spared from de-icing salts and direct flames emerged from car accident.

Both test specimens SL3 removed from head of the column and CB from cross beam were noticeably damaged by fire with presence of spalling [9] and rebars were exposed. Test specimen SL3 had lowest measured resonance frequency 1.02 kHz among all specimens and specimen CB had resonance frequency 9.48 kHz. At each affected surface a destructive compressive strength test was done on removed core bores. The comparison of measured resonance frequencies and compressive strength of concrete is at Fig.9.

In this graph noticeable correlation of cubic compressive strength and resonance frequencies for test specimen SL1, SL2 and SL3 can be seen. The footing of column from which test specimen SL1 was removed had compressive strength 62.1 MPa, the middle of column had 76.9 MPa and the head of column had 60.6 MPa. Cross beam had compressive strength 67.1 MPa and test specimen had resonance frequency 9.48 kHz. This frequency was determined by FFT interpretation of measured signal, and the correlation between strength and resonance frequency occurred for every test specimen SL1, SL2, SL3 and CB.

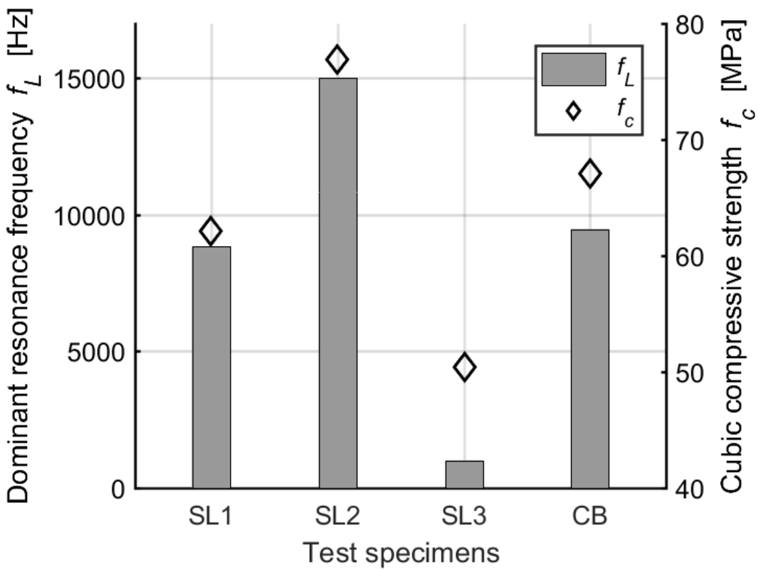

Fig.9 Comparison of cubic compressive strength of core bores and dominant longitudinal frequency from IE measurement of cut specimens

Spectrograms of signals obtained by CWT shows slightly different information about test specimens as can be seen in Fig.10 to Fig.13.

We can distinguish the occurrence of frequencies in time domain and with specific magnitude. At Fig.10 a quite recognizable frequency occurs at 8.67 kHz and keep its partial magnitude from beginning up to 6.7 ms. When we look at Fig.11 a bright resonance frequency and its harmonic frequencies can be recognized at 15 kHz. From this spectrogram can be harmonic frequencies distinguished apart from the spectrograms of other 3 specimens.

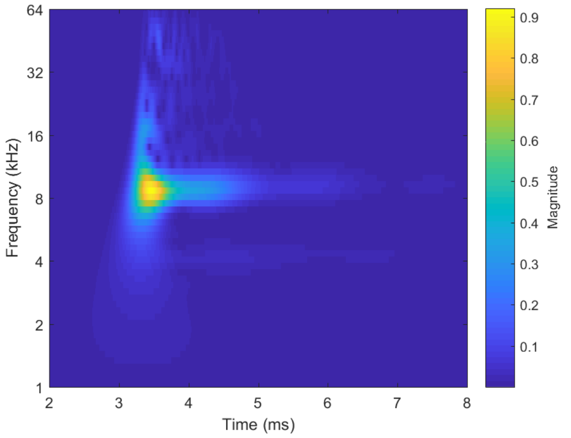

Fig.10 Wavelet transformation of signal from specimen taken from footing of column (SL1)

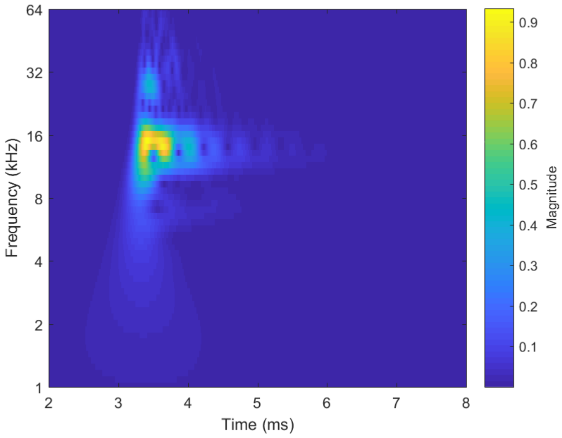

Fig.11 Wavelet transformation of signal from specimen taken from middle of column (SL2)

In Fig.12 a several dominant frequencies can be distinguished at 9.29, 7.55, 3.77 and 1.08 kHz. Specimen SL3 was removed from most damaged part of tested structure, and its resonance frequency obtained by FFT (1.02 kHz) match highlighted frequency 1.08 kHz at bottom of spectrogram. It seems that for the most degraded test specimen SL3 doesn't apply same rule as for the rest of the test specimens, where areas with highest magnitude match its resonance frequency obtained by FFT. At SL3 a center of rather wider area with 62% of maximum magnitude brightness seems to be the resonance frequency.

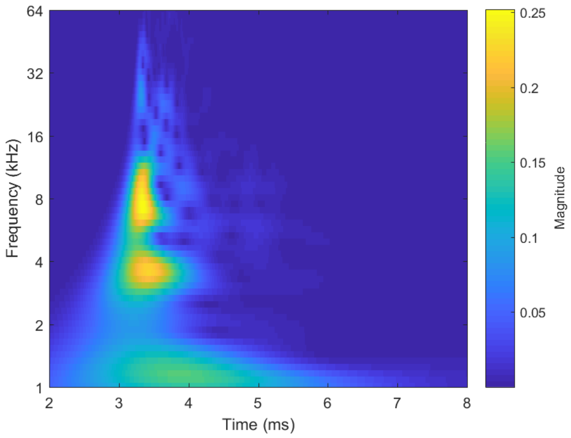

Fig.12 Wavelet transformation of signal from specimen taken from head of column (SL3)

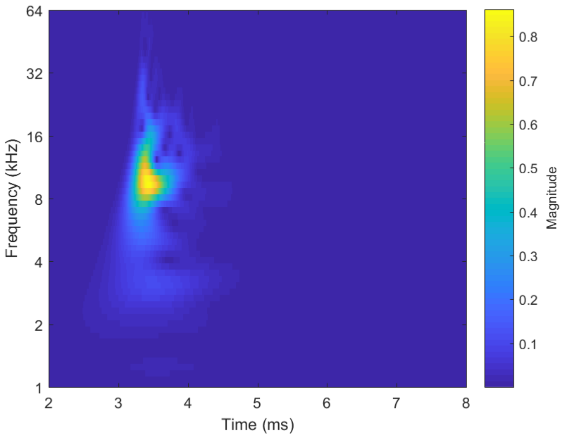

Fig.13 Wavelet transformation of signal from specimen taken from cross beam (CB)

Spectrogram of test specimen removed from cross beam at Fig.13 have brightness magnitude at resonance frequency 9.95 kHz, which is slightly higher than frequency from FFT (9.48 kHz). We can recognize deformed distribution of bright magnitude by similar way as in Fig.10 and Fig.12.

Conclusions

To design a suitable retrofitting process for construction damaged by fire a right diagnostic approach must be set. For this assessment numerous diagnostic procedures have been used over the years.

Presented publication compared two approaches to interpret measured signal from Impact-Echo measurement – a Fast Fourier transformation and Continuous Wavelet Transformation.

The measurement was conducted on test specimens removed from bridge damaged by fire emerged from car accident. Both methods were compared with cubic compressive strength of test specimens removed by core bore in-situ from bridge elements.

It seems that shape and dispersion of low magnitude areas of spectrograms could indicate presence of ongoing degradation by different factors. In such case, resonance frequency in CWT spectrogram can be represented by different magnitude than by the highest magnitude on spectrogram of signal.

Measured resonance frequencies corelated with compressive strength results both for FFT and CWT. Spectrograms provided additional information about dispersion of frequency over the duration of IE signal.

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