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CAPTURING MINUTE STRESS CHANGES AND RESIDUAL STRESSES IN STRUCTURAL CONCRETE USING THE ULTRASONIC CODA WAVE COMPARISON TECHNIQUE

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ABSTRACT

Condition and health monitoring of concrete structures have experienced an increasing interest over the last decade. Many types of sensors are utilized for this purpose such as strain gages, accelerometers, displacement sensors, etc. The response of a structure to low, i.e. service-level loads can be particularly useful to capture changes over time, including accumulation of damage, changes in the load path, etc. Typically, strain gages attached to the concrete surface are utilized to measure strain and then infer stress from them. As such, these measurements represent a surface observation. In contrast, stress waves propagate through the thickness of a member and can thus interact and can detect internal changes. This study uses the ultrasonic coda wave comparison (CWC) technique to monitor minute stress changes in reinforced concrete structures due to external loads. Additionally, residual stresses can also be captured in the coda portion of the recorded ultrasonic waveforms and quantified by means of magnitude-squared coherence (MSC). Measurements from a laboratory experiment as well as an in-service bridge field test are presented and discussed in this paper. The results demonstrate that the CWC technique is able to capture minute stress changes due to low-level load cycles as well as provide additional information regarding residual stresses and associated potential damage.

Keywords: Stress wave; ultrasound; coda wave comparison; concrete; residual stress; magnitude-squared coherence; structural load testing; highway bridge.

1. INTRODUCTION

Utilizing ultrasonic stress waves to measure in-situ stress was originally studied by Hughes and Kelly [1], establishing the theory of acoustoelasticity after third-order elastic constants had been introduced by Murnaghan [2]. Acoustoelasticity explains the dependency of stress wave velocity with internal stresses. While this theory has found application for metals, it has proven difficult to reliably work with heterogeneous materials [3]. Concrete, consisting of rock aggregates, a cement matrix, and air pores, is considered such a material, causing multiple scattering of ultrasonic waves. In the last decade, researchers have investigated using the coda, also known as the diffuse portion of an ultrasonic signal, and correlated them with material changes inside the concrete. Typically, cross-correlation is employed to determine the time shift in the coda wave that occurs due to stress changes. While coda wave interferometry (CWI) appears to be sensitive to changes in internal stress, it might not be sensitive enough to capture very small stresses under service-level loads. As an alternative approach, the coda wave comparison (CWC) technique has been proposed by the authors [3]. In this technique, instead of using only a portion of the coda wave, the entire recorded ultrasonic waveform is considered. Magnitude-squared coherence (MSC) is employed to estimate the difference between two signals in the frequency domain. ΔMSC(λ) has been found extremely sensitive to minute changes in stress as well as have the ability to detect residual stresses under very small applied load cycles, which is discussed in this paper.

2. EXPERIMENTAL TESTS

2.1 Measurement setup

In this paper, data from both a laboratory as well as a field test are discussed. For both of them, a pitch-catch setup in through-transmission configuration was used employing two Panametrics V103 normal-wave transducers. One of them was used as a transmitter (T) and the other one as a receiver (R), as illustrated in Figure 1. The transmitted pulse was a Morlet-type pulse with a central frequency of 50 kHz and produced by a BK Precision 4053 arbitrary waveform generator. For the field test, a Trek 2100HF high-frequency amplifier was used in addition to intensify the transmitted pulse. A 4-channel high-speed data recorder (DAQ, Elsys TraNET FE) was used to record both the transmitted and recorded waveforms at a sampling rate of 10 MHz (with 500 kHz low-pass anti-aliasing filters). The DAQ was set to trigger on the transmitted pulse and record 32,768 samples in order to capture both the coherent, as well as the coda portions of the ultrasonic signals.

2.2 Laboratory Test

The objective of this test was to evaluate the CWC technique's ability to monitor minute stress changes and compare its data with strain measurements. For this purpose, a one-quarter-scale reinforced concrete beam was built and instrumented. The beam has a rectangular cross-section of b x h = 4 x 7 in (101 x 178 mm) and is 58 in (1,473 mm) long. It was loaded in four-point bending configuration using a span length of 52 in (1,320 mm); the distance between loading points was 12 in (305 mm), as shown in Figure 1.a. The beam was loaded by using a programmable hydraulic concrete cylinder compression-testing machine (Forney LP, 1112-kN-capacity). The ultrasonic transducers were attached in the tension zone of the beam located at mid-span and 1.5 in (38 mm) above the beam soffit, as shown in Figure 1.a. Ultrasonic measurements were initiated every 32 ms throughout the loading process. Additionally, strain was measured with a 2 in (51 mm) long strain gage installed on one side of the beam just below an ultrasonic transducer, as shown in Figure 1.a. The strain gage was connected to a strain conditioner (Vishay- Model 2110B) and the output signal recorded by the DAQ system described in Section 2.1. A photo of the entire laboratory test setup is provided in Figure 1.b.

The beam was loaded to a maximum load, P = 300 lb (1.33 kN) followed by unloading using two different rates. The applied load produced a tensile stress at the beam soffit equivalent to approximately 15% of the theoretical cracking load, P_{cr}.

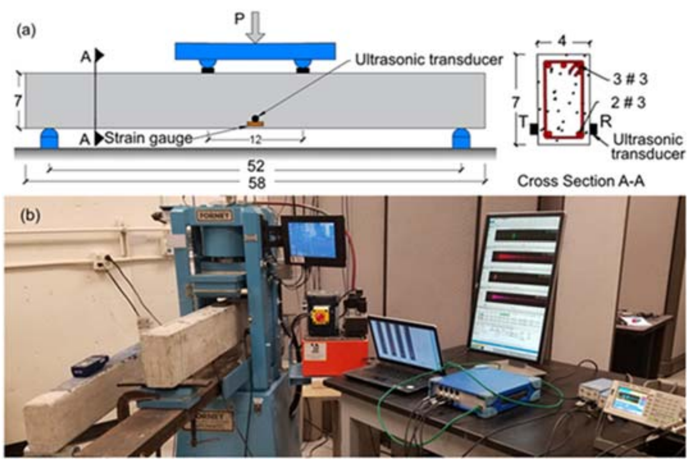

FIGURE 1: a) ELEVATION VIEW OF LABORATORY TEST SETUP WITH INSTRUMENTED BEAM AND b) PHOTO OF LABORATORY TEST SETUP. DIMENSIONS IN (in), WHERE 1 in = 25.4 mm.

3.3 Field Test

The objective of the field test was to evaluate the feasibility of the CWC technique to monitor small internal stress changes in a concrete girder under field conditions. A prestressed concrete highway bridge was selected for this purpose located on Highway I-84 near Echo, Oregon. It has a structural health monitoring (SHM) system as part of the FHWA Long-Term Bridge Performance (LTBP) program. The bridge consists of three non-continuous beams with lengths of 40, 80, and 40 ft (12.2, 24.4, and 12.2 m), as shown in Figure 2.a. The continuous bridge deck is made of reinforced concrete. The ultrasonic measurements were taken during an in-service load test performed to calibrate the SHM system in July 2017. A truck with a water tank was used in this test; its weight information is shown in Figure 2.b. The loading process consisted of the truck crossing the bridge in walking speed from east to west in the right lane with 13 stopping points. This process was repeated, allowing for a comparison between identical loadings back to back. Ultrasonic transducers were mounted to the left and right of the bottom flange of the first interior beam at mid-span (location highlighted with red circles in Figure 2).

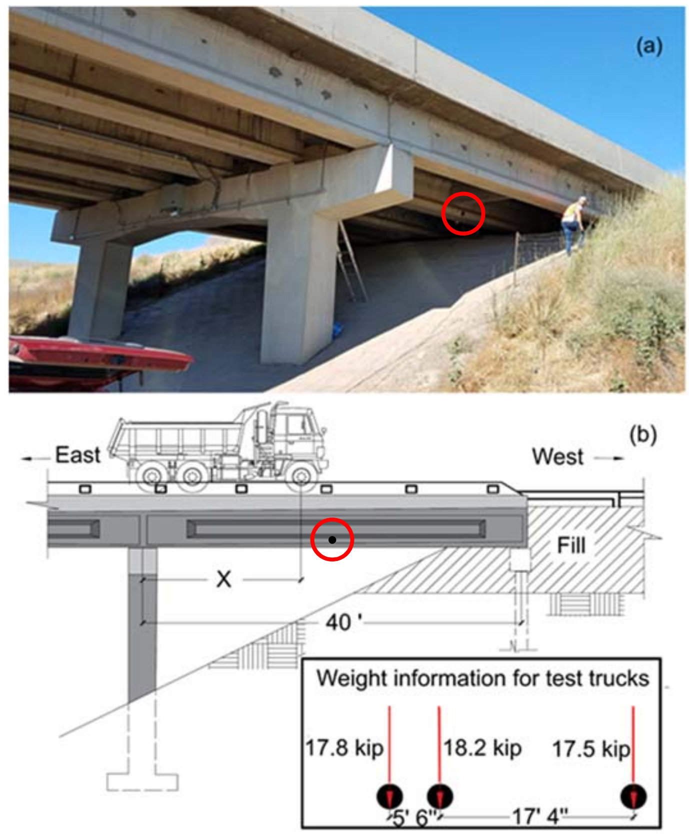

FIGURE 2: a) PHOTO OF INSTRUMENTED BRIDGE AND b) ELEVATION VIEW OF INSTRUMENTED END SPAN WITH INSERT SHOWING TEST TRUCK DETAILS. DIMENSIONS IN (ft), WHERE 1 ft = 0.305 m.

3. RESULTS AND DISCUSSION

3.1 Laboratory Test

In order to attain a better understanding about how the applied load affects ΔMSC, the results at f = 50 kHz were selected, which is equal to the center frequency of the transmitted pulse. Figure 3.a and 3.b show measured strain and computed ΔMSC(f), respectively, vs. applied load (stress). In Figure 3.a, it can be observed that the strain gauge is not sensitive enough to capture the small strain variations accurately as the measurement contains a high level of noise. The ΔMSC(f) value shown if

Figure 3.b on the other hand, has a negligible level of noise. For the loading portion "L", both ΔMSC(*f*) and applied load follow the same pattern and the same slope due to the linearity of their relationship, since the strain was within its elastic limit. The maximum measured strain is approximately 20 με, which is very close to the theoretically predicted value of 23 με. For the unloading portions "UL1 and UL2", although there is a linear relationship between the applied load and measured strain, the slopes of the measured strain and ΔMSC(*f*) are different from the slopes of the applied load, especially during the fast unloading portion "UL2". This behavior occurs because of the loading memory of the material. In other words, although the beam was loaded within the elastic range, the load still caused a temporary residual strain that had an influence on the unloading strain. This is particularly pronounced when a member is loaded for the first time, which is the case here. In fact, when the beam was unloaded, the strain went back to zero after approximately 2 s, as shown in Figure 3.a. The ΔMSC(*f*) response, however, is different, as it only slowly recovers, capturing a potential residual stress observed by the residual, ΔMSC_{res}.

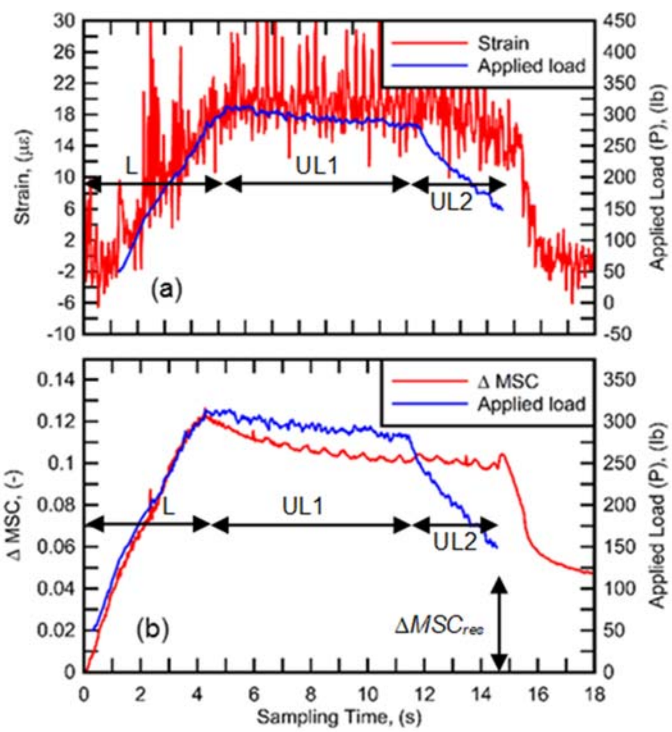

FIGURE 3: (a) STRAIN AND APPLIED LOAD VS. TEST TIME. (b) MSC(*f*) AND APPLIED LOAD VS. TEST TIME. LABELS "L" AND "UL1 AND UL2" REFER TO LOADING AND UNLOADING PORTIONS, RESPECTIVELY.

3.2 Field Test

Figure 4 shows the MSC(*f*) for the repeated truck loadings. Generally, both loadings gave the same results and the small-observed mismatch is likely due to differences in the truck speed and stopping time. Despite there being no traffic closure in the second lane of the bridge, the ΔMSC's results have an acceptable level of noise. The results show there are several sharp drops in the ΔMSC(*f*) curve (select samples are highlighted with black circles) when the truck arrived at a stop location. This phenomenon is likely related to the truck's sudden stopping, which resulted in an impact causing structural vibrations. For this test, unfortunately, strain (or deformation) measurements are not available. However, the engineers conducting the load test confirmed that during maximum loading, the maximum tensile strain at the location of the ultrasonic transducers can be expected to be approximately 10 με. Note that strains of this magnitude could not be captured and resolved by traditional strain gauges.

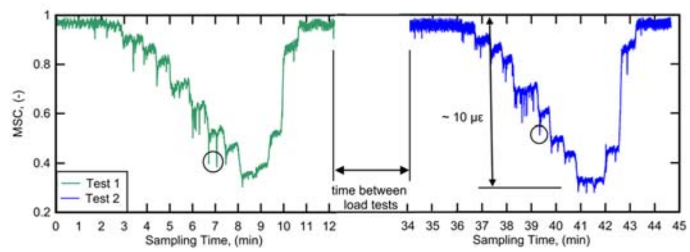

FIGURE 4: ΔMSC(*f*) VS. TEST TIME FOR REPEATED LOADINGS.

4. CONCLUSIONS

This paper discussed how the coda wave portion of an ultrasonic signal is sensitive to minute stress changes in concrete members. The resulting changes that occur in the coda wave can be captured by using magnitude-squared coherence, and are found to linearly correlate with changes in stress. Additionally, by studying the measurements taken after unloading, information regarding the loading history can be revealed.

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