Chapter

NDT Methods for Evaluating FRP-Concrete Bond Performance

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Abstract

The long-term bond performance, 15+ years, of FRP-structural systems applied to reinforced-concrete structures is largely unknown and not widely tested. FRP-structural system performance is a function of FRP-concrete bond condition and is subject to deterioration over time. The purpose of this investigation is to test and validate the non-destructive testing impulse-excitation technique to evaluate bond condition of FRP systems applied to concrete structures, in particular concrete highway bridges. The objective is to identify changes in the FRP-concrete bond state by analyzing changes in impulse excitation (impact) frequencies and sinusoid waveforms. Hammer impact tests were performed on two FRP-retrofitted highway bridges in Missouri and a bonded FRP test plate in the laboratory. Signal analysis of recorded impact acoustic emissions was performed on frequencies and waveform damping ratios of bonded and de-bonded FRP material on two bridges and in the lab. The frequencies and sinusoidal waveforms of the bonded and de-bonded FRP material on the bridges had a high degree of correlation to those of the bonded/de-bonded laboratory FRP plate. This investigation confirms the impulse excitation technique to test FRP bond on concrete structures, which provides accurate data on the bonded versus de-bonded FRP-bond condition.

Keywords: bridges, FRP systems, non-destructive testing (NDT), impact-echo, signal analysis, frequencies, damping ratio

1. Introduction

The use of fiber reinforced polymer (FRP) structural systems to strengthen and rehabilitate concrete bridges over the past three decades has given engineers the capability to extend the life and serviceability of highway bridges. When used on reinforced concrete (RC) highway bridges these FRP systems provide unique structural qualities which significantly improve bridge load performance and service life. However, the question is for how long?

For transportation infrastructure owners who have used FRP systems to strengthen highway bridges there is an ongoing concern focused on the long-term durability of these structural systems and how well they will sustain bridge load capacity and performance over time. Bridge owners are faced with two primary questions: (1) how do FRP structural systems on RC highway bridges perform over extended time (15+ years) under the influence of frequent cyclic loading (heavy truck traffic), moisture, and freeze-thaw cycles, and (2) how can accurate field data be obtained on FRP-plate bond conditions to evaluate changes in load performance, to establish cost-effective maintenance procedures, and to determine long-term durability of the applied FRP systems? This concern increases when a highway system has a large number of strengthened bridges in which the load rating of the bridges is dependent on the FRP-concrete bond performance.

With a number of highway bridges having been strengthened with FRP systems over the past several decades in Missouri, Kentucky, Ohio, Canada, Europe, e.g., Slovenia and Macedonia, and the Far East, there has not been an effective field testing system to evaluate and verify the bond condition of large areas FRP material applied to these bridges. While a number of good NDT systems are available to test FRP bonding on concrete structures, these systems are limited in their capabilities to scan extensive areas of FRP material applied to bridge structural members and to produce reliable bond condition data.

The purpose of the investigation in this chapter is to verify field testing capabilities of a light-mobile impact machine for scanning and producing accurate FRP-concrete bond data on bridge structural members retrofitted and strengthened with FRP-structural systems.

The objective of this NDT system, based on the impact-echo principle, is to provide a testing procedure capable of rapidly scanning long lengths FRP plates bonded to bridge structural members, for producing reliable FRP-concrete bond data, and for locating and accurately identifying de-bonded areas, if present [1]. Based on current testing methods, there is a need for an improved cost-effective testing procedure to evaluate FRP-strengthened bridges.

2. Research significance

Quantifying long-term durability of FRP-structural systems applied to concrete structures, and RC bridges in particular, is an on-going issue for the industry and users of such systems. Being able to guarantee FRP systems applied to concrete structures will remain bonded for 20–30–50 years is a challenge. The process to obtain reliable field data proving FRP laminates remain bonded over long periods of time had not been accomplished on a wide scale.

While the impact-echo NDT method has been effective in testing concrete structures for many years its application for evaluating FRP-structural systems applied to RC bridges is not fully developed [2]. The development and testing of the mobile impact machine presented in this paper expands the application of NDT procedures in the field to evaluate bridge CFRP plate-concrete bond conditions. The NDT method presented potentially provides bridge owners a means to rapidly assess bond conditions and to identify associated changes (decreases) in bridge load performance.

2.1 Scope of CFRP applications on RC bridges requiring bond testing

The extent of CFRP material applied to RC highway bridges requiring bond testing is challenging. As an example, in 2001, in one CFRP-bridge strengthening project in the Republic of Northern Macedonia, to meet Eurocode 2-Part 2 (EN 1992-2:2005), 17 slab and girder bridges on the M2 (European Corridor 8, EC-8) were designed and strengthened to NATO MLC 100, having a total of 10,847 m of CFRP plate, including CFRP fiber wrap in bridge structural member shear areas. Two additional slab bridges on the M1 were strengthened in 2002 with 1894 m of CFRP plate.

An example of the length of CFRP material applied to one slab bridge on the M2 is illustrated by bridge B36 at km 67 + 409 in **Figure 1**, showing the distribution of

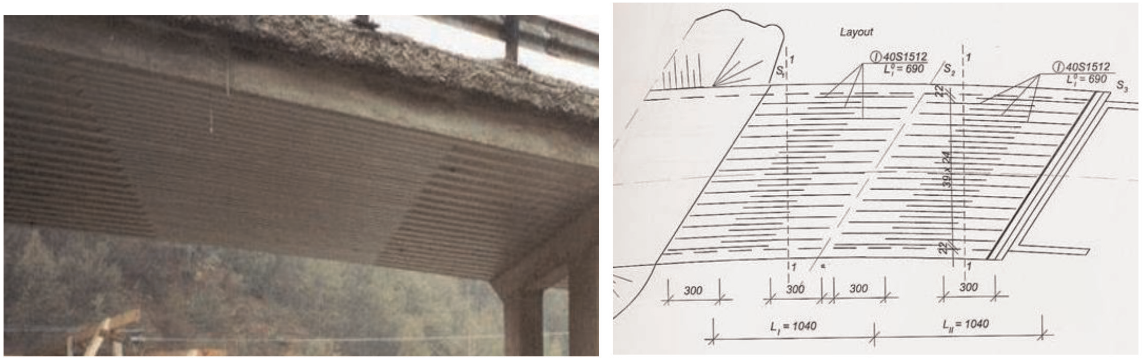


Figure 1.
Bridge B36 with 792 m in 80 CFRP plates.

the CFRP plates applied in each of two 10 m spans. The center 3.9 m of each 10 m span have 40 S1512 plates parallel to one another in the area of maximum bending moment of the span. The CFRP-concrete bonding in this area is critical for sustaining the designed load capacity for MLC 100 [3].

2.2 FRP-concrete de-bonding mechanisms

The focus of the research presented in this chapter is to develop an effective NDT method to identify FRP-concrete de-bonding on RC structures. The de-bonding of FRP material from concrete is caused by multiple factors. Failure of the adhesive bond of externally applied FRP systems is caused by a number of mechanisms and is referred to as “delamination” or “de-bonding.” In their paper, Degala et al., have identified the following parameters as affecting bond interface behavior: concrete tensile strength, adhesive mechanical properties, effective bond length of the FRP, member size and scale, concrete section geometry, structural member loading geometry, degree and rate of loading, FRP retrofit geometry, environmental and mechanical exposure, e.g., moisture and thermal effects, and the mixed mode relationship of de-bonding mechanisms. Any one, or any combination of these mechanisms, can cause de-bonding of FRP material from concrete [4].

The purpose of the NDT method presented in this chapter is to identify FRP-concrete de-bonding in the life cycle of the FRP-strengthened structure and to identify any of the above de-bonding mechanisms potentially affecting RC structure performance to allow early intervention and corrective measures.

3. Experimental program

The scope and purpose of this experimental investigation was to field test and validate a newly developed impulse excitation (impact) machine on CFRP (carbon fiber-reinforced polymer)- strengthened structural members on an RC highway bridge to obtain impact signal data reflecting the condition of the CFRP bond on concrete. The objective was two-fold: (1) to obtain impact data recordings on FRP-strengthened RC bridges and to compare those signal waveforms to the waveforms obtained from the concrete and bonded and de-bonded CFRP plate in the laboratory, and (2) to establish the operability and design limits of the impact machine on bridges. The goal was to verify the capabilities and practicality of such an impact machine in the field on RC bridges, to test FRP laminates on concrete, and to produce reliable FRP-concrete bond data.

3.1 NDT methods for testing FRP-concrete bond

To illustrate the practicality of this impact machine for field testing large areas of CFRP laminates on RC bridges, comparison is made to other NDT procedures used for testing FRP laminates. The use of non-destructive testing (NDT) to evaluate FRP-concrete bond offers a range of effective methods capable of providing data on the behavior and condition of FRP-structural system bonding on concrete structures. There are a number of NDT systems available to evaluate CFRP-structural system bonding on concrete structures, which include acoustic stress waves, infrared thermography, X-ray, microwave, high-frequency radiation, ultrasonics, and laser vibrometry, to detect de-laminations in the FRP-concrete interface regions. Each NDT method offers unique advantages for testing FRP bond under specific conditions [5].

Two systems are considered for comparison to the NDT system presented in this paper. The first system uses pulsed infrared thermography to detect defects in CFRP parts and plates by producing eddy currents generating heat in the part. Heat applied to the test specimen provides spatial temporal distribution of surface temperature whereby defects disturb the heat flow. This system provides high contrast images and is effective in identifying defects in aircraft and automotive parts. It is not economical for scanning large CFRP areas [6].

The second system uses an acoustic-laser technique which generates a sound vibration signature used to identify and characterize defects in CFRP-concrete structural members. Having a good signal-to-noise ratio the system can accurately identify the size of defective areas and has the capability to stand off from the test specimen. It does require set-up of a number of pieces of equipment to generate the acoustic vibrations. The rate in meters per hour at which this system is able to test long lengths of CFRP plates on concrete bridge member is not indicated. Both methods have the capability to identify in detail the precise location and degree of de-bonding of FRP material from concrete [7].

Using acoustic-stress waves from a light-hammer device the NDT method presented in this paper is designed to rapidly scan long lengths of bonded CFRP plates and record changes in impact frequencies. The objective of this system is to quickly provide bonding data over large areas of CFRP plates.

For this investigation the use of the impulse excitation technique with the impact-echo procedure provides an effective and rapid means of data generation to assess the bond condition of large areas of CFRP laminates applied to RC bridges. The advantage of this method over the other three NDT methods is its inherent speed of testing and the volume of bond data produced in the form of digital waveforms.

3.2 Impulse excitation technique

The impulse excitation technique (IET) is a non-destructive testing method for evaluation of elastic and damping properties of materials. This technique is based on the mechanical excitation of a solid body by means of a light impact. For isotropic homogeneous material of simple geometry, such as a prismatic bar, e.g., CFRP plate, the resonant frequency of the free vibration provides information about the elastic properties of the material and its bond to a substrate, i.e., concrete. The amplitude decay of the free vibration is related to the internal friction of the material, i.e., dissipation, or damping, of the vibration energy in the specimen.

Using impulse excitation (impact) on bonded FRP-laminates, the impact frequency, signal amplitude, and the rate of sinusoidal decay (damping ratio) of the harmonic waveform provide information on the condition of the FRP bond to the concrete structural member. Signal analysis of the waveform frequencies, damping ratios, amplitudes, and phase shift provide a detailed and accurate picture of the state of the FRP laminate-concrete bond. The type of harmonic signal produced by the impulse excitation method is a decaying sinusoidal waveform [8].

3.3 Harmonic oscillations

To analyze the waveform data generated by the impulse system, it is useful to consider the characteristics of a decaying harmonic oscillation, shown in **Figure 2**. The natural frequency of a simple continuous harmonic oscillation when the forcing function is zero is expressed by the second order differential in Eq. (1).

$$\mathbf{\frac{dx^2}{dt} + c\frac{dx}{dt} + kx = 0} \tag{1}$$

where c and k are constants related to the impulse system and material tested, and $\mathbf{c \geq 0, k \geq 0}$. When the harmonic oscillation is driven by forcing function $f(t)$ on mass m then $f(t)$ is expressed in Eq. (2).

$$\mathrm{m}\,\frac{\mathrm{dx}^2}{\mathrm{dt}} + \mathrm{c}\frac{\mathrm{dx}}{\mathrm{dt}} + \mathrm{kx} = \mathrm{f(t)} \tag{2}$$

The general solution of $f(t)$ for a dampened harmonic waveform is given by Eq. (3).

$$f(t) = \mathrm{A}\, e^{-\zeta\omega\mathrm{n}t}\,(\cos(\omega_\mathrm{d} - \phi)) \tag{3}$$

where A is initial amplitude, ω_n is the natural frequency in rad/s, ϕ is phase angle, ζ is the damping ratio on ω_n. The dampened frequency ω_d is the natural frequency ω_n modified by the dampening ratio.

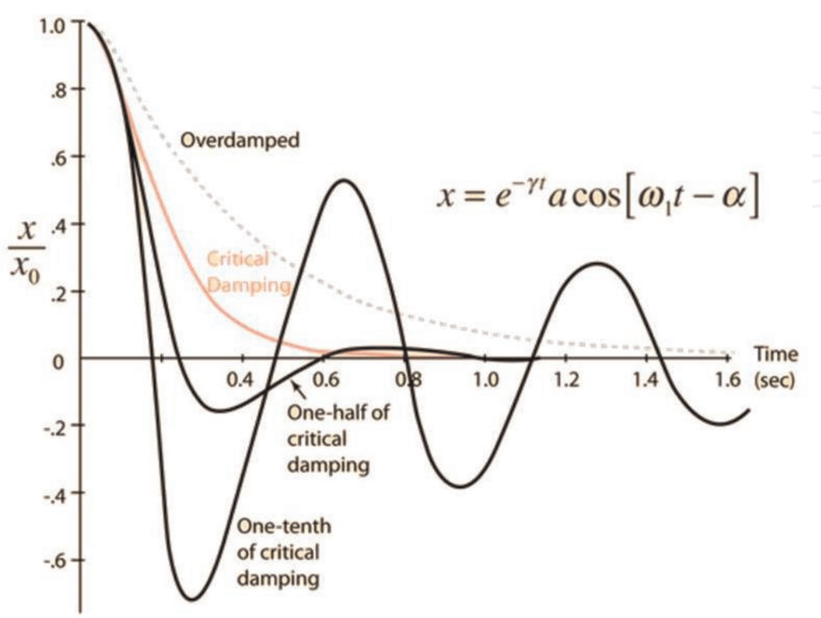


Figure 2.
Exponentially decaying harmonic oscillation @ varying rates.

3.4 Damping ratio

The rate of exponential decay in a harmonic oscillation is expressed by the damping ratio, a system parameter denoted by zeta (ζ) that characterizes the frequency response of the harmonic oscillation. The simplest example is a mass m suspended from a spring with a spring constant k, with a damping ratio c. When a single forcing function $f(t)$ is applied to the mass $x(t)$ the result is a harmonic oscillation with a unique rate of decay determined by the damping ratio, which is a function of the internal resistance of the system driven by the forcing function.

The damping ratio expressed by zeta (ζ) is the ratio of actual damping to critical damping cc, Eq. (4), such that ζ = actual damping/critical damping cc, where $cc = 1$. The damped circular frequency ω_d is the natural frequency ω_n reduced by the factor $\sqrt{\mathbf{1}-\zeta^2}$.

$$\omega_d = \sqrt{1-\zeta^2}\omega_n \tag{4}$$

3.5 Fourier transform of impact signal

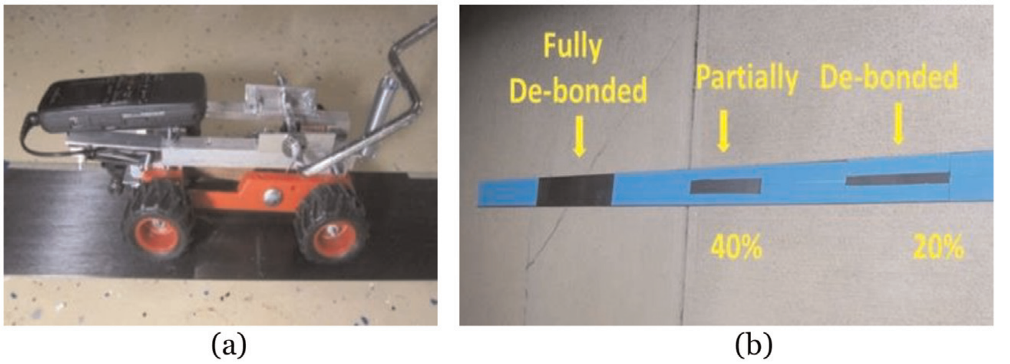
The impact oscillation frequency from the forcing function $f(t)$, where $f(t) = Ae^{-\zeta\omega nt}$ (cos ($\omega_d-\phi$)) is represented by the Fourier transform of the damped cosine in Eq. (5).

$$f\ (\omega) = (j\omega + a)/\left(-\omega^2 + 2j\omega a + {\omega_o}^2 + a^2\right) \tag{5}$$

where $a = \zeta\omega_n$ and $\omega_o = \omega_{n.}$ The Fourier transform provides the frequencies of the time domain signals $f(t)$. As the NDT device moves across the surface of the CFRP plate changes in impact signal frequencies can be identified. A change in the signal frequency indicates a change in the CFRP-concrete bond condition. If the impact frequencies across the plate remain relatively constant, the plate is fully bonded.

4. Impact machine

The latest impact machine, **Figure 3**, is a 5 × 17 cm single 3D-printed frame made with polylactic acid (PLA) plastic by fused filament fabrication, is used for its strength and workability. PLA, or polylactide, is a biodegradable and bioactive thermoplastic aliphatic polyester derived from renewable resources and provides a



(a) (b)

Figure 3.
(a) Mobile impact machine and (b) laboratory CFRP test plate.

strong structural frame which attenuates vibrations and sound, ideal for this impact machine application. The machine has a single 10 cm lever (cherry wood) with one 10-24 screw for the impact hammer, driven by a four-pin actuator wheel. The machine produces 25 impacts per meter, with a 0.4 pound impact force. The impact sound wave signals generated are recorded with a microphone and digital data recorder mounted on the machine.

5. Experimental procedure

The experimental investigation was conducted in two phases. Phase one involved testing in the laboratory with the impact machine, **Figure 3a**, on a bonded, de-bonded, and partially de-bonded CFRP plate, **Figure 3b**, and on the concrete to which the CFRP plate was bonded. The purpose of obtaining impact waveforms on the laboratory concrete was to compare them to the waveforms on the bridge concrete. Similarly the impact waveforms obtained from the laboratory bonded and de-bonded CFRP plate are used to compare to the bonded and de-bonded CFRP material on the bridges. A partially de-bonded CFRP plate was simulated in the laboratory with 40 and 20% de-bonding of the test plate, **Figure 2b**. Multiple passes of the impact machine in the laboratory on the concrete, bonded, de-bonded, and partially de-bonded CFRP plate were made with the data recorded on a Sony M2 digital recorder. The recordings were displayed in a Tektronix 475 oscilloscope and video recorded. The video recordings were broken down into still pictures of the waveforms, from which the impact signal frequencies and damping ratios were measured. The frequencies were obtained from the inverse of the time displayed on the oscilloscope screen. The damping ratios were measured with curve fitting of the decayed sinusoid waveforms.

Phase two used a similar impact test procedure in the field on the Creasy Springs Lane bridge and the Coats Lane bridge. Impact tests were run on the bridge concrete first, and then multiple impact runs were performed on various beams of the RC channels. While not all beams were tested, randomly selected beams were tested, generally those where the paint was gone exposing the CFRP material. Performing impact tests on painted CFRP material will require a modified (stiffer) impact machine to produce stronger signals to reflect the CFRP-concrete bond conditions.

The laboratory test consisted of running the impact machine, in a number of cycles, first on concrete and then on a bonded, de-bonded, and partially de-bonded CFRP plate to produce impact signal waveforms representing the three CFRP-concrete bond conditions. To obtain signal waveforms on RC bridges, field tests were performed on two CFRP-strengthened county highway bridges in Missouri. The test involved running the impact machine on the bottom side of beams on the bridge channel sections. The two bridges tested were the 39 foot (12 m) Coats Lane bridge and the 19 foot (6 m) Creasy Springs Road bridge, both on county roads in Boone County, near Columbia, Missouri. Both bridges were constructed in the early 1970s with precast reinforced concrete channel sections with a four in (10 cm) deck slab running the length of the bridge. The channel beams were strengthened with CFRP plate and fabric material to increase the bridge load rating from 15 to 20 tons. The bridge channel sections (**Figure 3**) have a 10 cm CFRP plate on the bottom of each beam and 60 cm fabric wrap with 12 wraps per beam. The bridges were strengthened in the early 2000s [9].

The Creasy Springs Road bridge, **Figure 4**, constructed with precast RC channels like Coats Lane, has the same CFRP plate and fabric configuration on the channel beams as the Coats Lane bridge.

On the Creasy Springs Road bridge impact testing, **Figure 5**, was done on the second beam in the first channel (west side) and then on the third, fourth and sixth beams as far as the extension pole could reach over the water. It is noted CFRP de-bonding was found on the second beam, **Figure 5c**.

The Coats Lane bridge, **Figures 6** and **7**, has eight RC channels, two beams per channel. Testing was performed on the first channel second beam (north west side), **Figure 6a**, and then on beams six, seven, and eight in areas were the paint had flaked off, **Figure 6c**.

5.1 Experimental results

Impact waveform data was compiled on results of testing the CFRP plate in the laboratory and on the Creasy Springs Road and Coats Lane bridges in Missouri. Selected samples of the hundreds of impact data points (signal waveforms) are shown in **Figures 8–13**. The waveforms obtained in the laboratory for concrete, bonded, and de-bonded CFRP material are compared to the waveforms obtained on the concrete and CFRP material on the two bridges. Comparisons are made of the frequencies and damping ratio in the three scenarios.

Figure 4.
Creasy Springs Road bridge.

(a) (b) (c)

Figure 5.
Creasy Springs Road bridge—impact testing on channel beams. (a) Second and third beams, (b) testing fourth beam, and (c) CFRP de-bonding second beam.

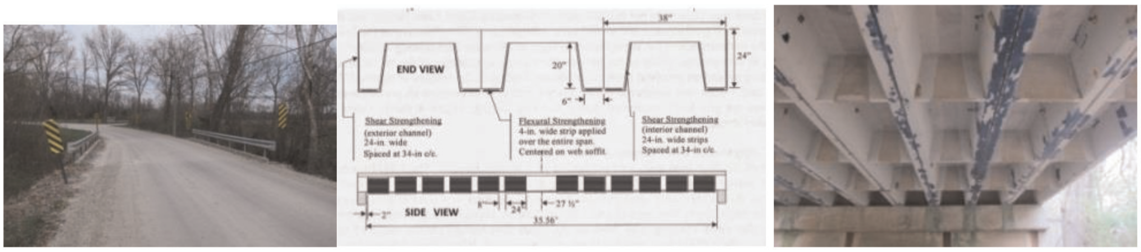


Figure 6.
Coats Lane bridge (Boone County, MO) with CFRP configuration on channel beams.

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(a) (b) (c)

Figure 7.
Coats Lane bridge—testing channel beams. (a) Second beam, first channel, (b) impact testing, (c) beams 6–8.

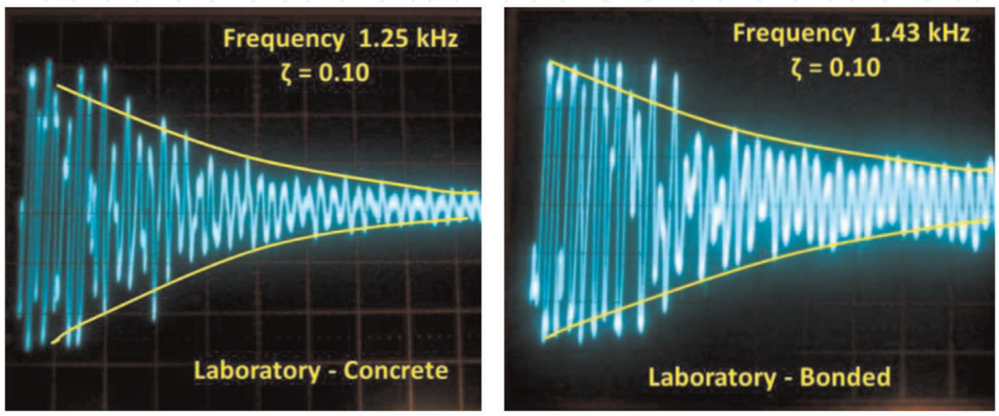

Figure 8.
Impact waveforms—laboratory—concrete and bonded CFRP plate.

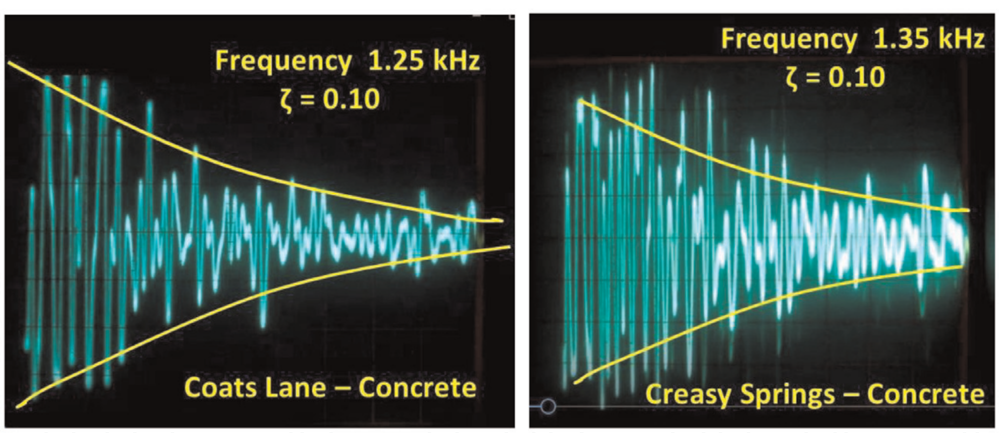

Figure 9.
Waveforms—concrete—Coats Lane and Creasy Springs bridges.

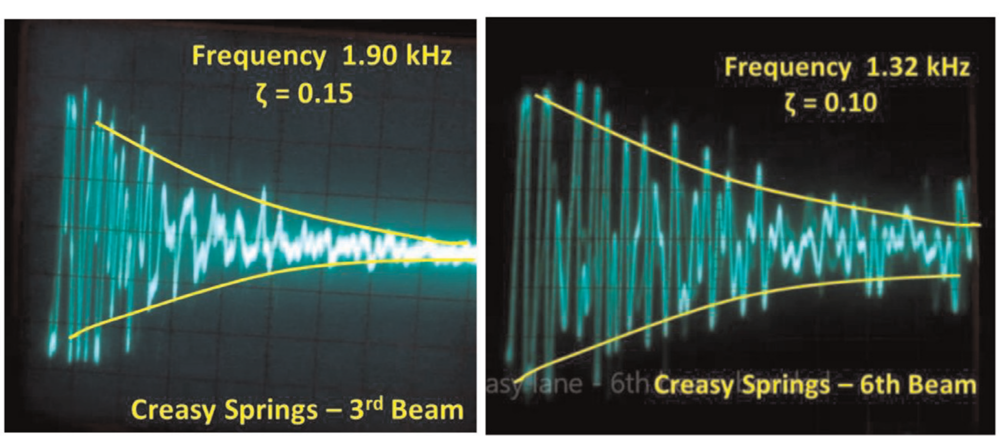

Figure 10.
Waveforms—Creasy Springs bridge—bonded CFRP plate.

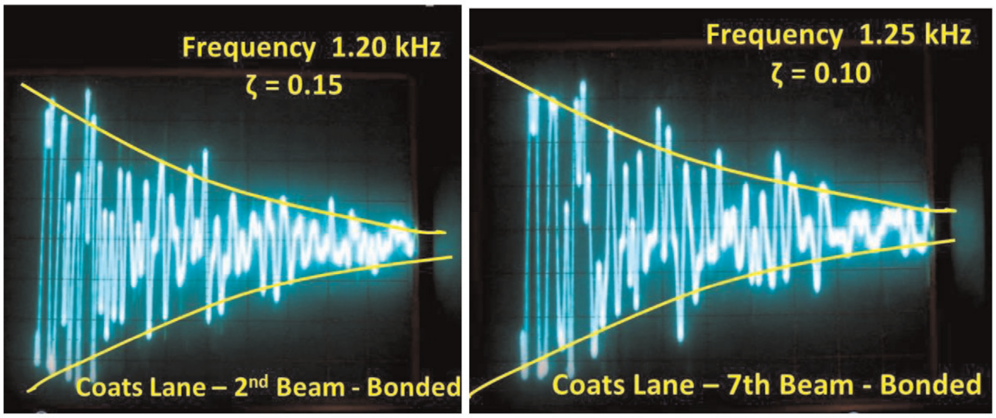

Figure 11.
Waveforms—bonded CFRP plates on Coats Lane channel beams.

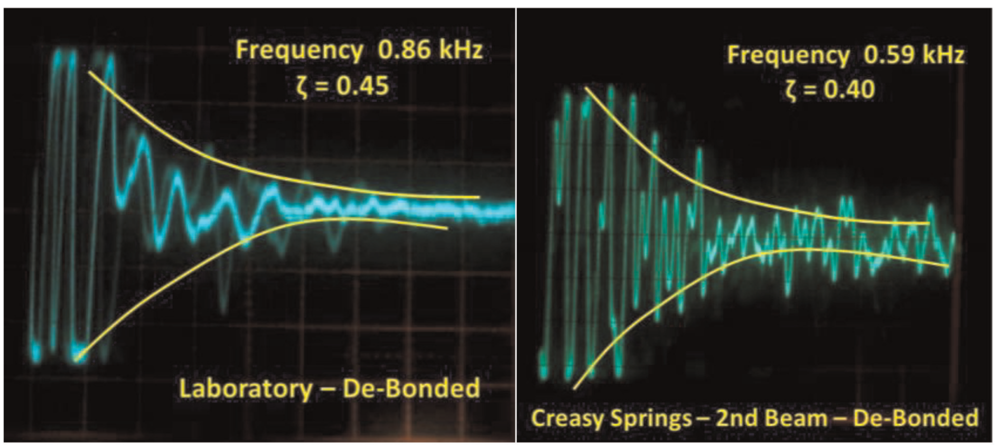

Figure 12.
Waveforms—de-bonded CFRP plate—lab and Creasy Springs bridge—second beam.

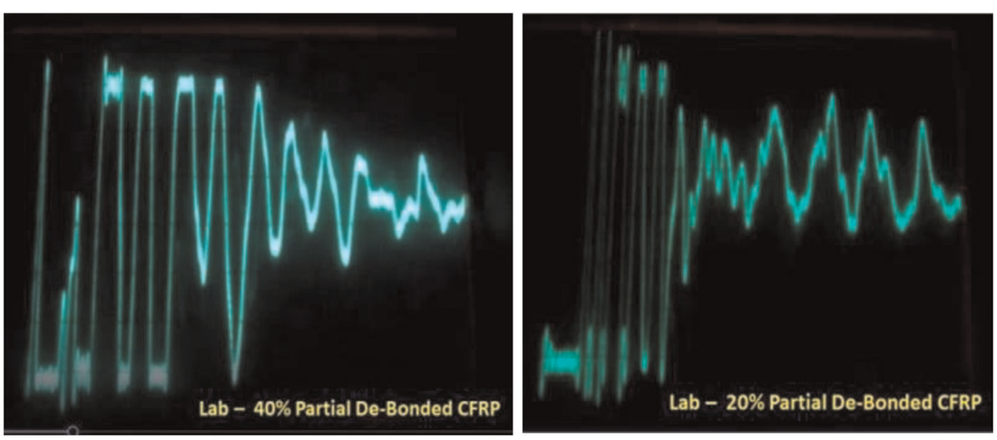

Figure 13.
Waveforms for partially de-bonded CFRP plate—40 and 20%.

The results of the impact tests on the two bridge and the laboratory are summarized in Appendix A, **Table 1**.

The laboratory concrete waveform produced a frequency of 1.25 kHz and a damping ration of 0.1. The concrete waveform on the two bridges also produced a frequency of 1.25 kHz, plus or minus 15 hz, and a damping ratio close to 0.1. The CFRP bonded frequency in the laboratory was 1.43 kHz, with a damping ration of 0.1. The CFRP bonding frequency obtained on the two bridges was 1.90 kHz on

Laboratory CFRP test plate					
Acoustic signal	Concrete	Plate bonded		Plate de-bonded	
Frequency (kHz)	1.25	1.43		0.86	
Damping ratio ζ	0.10	0.10		0.45	
Creasy Springs bridge					
Acoustic signal	Concrete	Second beam		Third beam bonded	Sixth beam bonded
		Bonded	De-bonded		
Frequency (kHz)	1.35	—	0.590	1.90	1.32
Damping ratio ζ	0.10	—	0.40	0.15	0.10
Coats Lane bridge					
Acoustic signal	Concrete	Second beam bonded	Sixth beam bonded	Seventh beam bonded	Eighth beam bonded
Frequency (kHz)	1.25	1.20	1.32	1.25	1.28
Damping ratio ζ	0.10	0.15	0.10	0.10	0.15

Table 1.
Acoustic impact data: laboratory test plate and RC highway bridges.

Creasy Springs and 1.32 kHz on Coats Lane, each with a damping ratio of 0.1. Impact test on Coats Lane channel beams two, six, and seven had frequencies of 1.20, 1,25, and 1,25 kHz, plus or minus 15 hz, with all damping ratios close to 0.1. The frequency and damping ratio of the CFRP de-bonding in the laboratory and the CFRP de-bonding found on beam two on the Creasy Springs bridge, **Figures 5c** and **9**, were closely related, with 0.895 and 0.590 kHz respectively, and damping ratios of 0.3 and 0.4. Partial de-bonding on the laboratory test plate was tested with the resulting waveforms shown in **Figure 13**, for 40 and 20% de-bonding. The impact machine can detect partial de-bonding. It is noted the relationship between the frequency and damping ratio changes as the de-bonded area of the CFRP plate become smaller, but still having a distinctive waveform produced which indicates de-bonding, **Figure 11**. The impact machine cannot indicate the degree of partial de-bonding. Other NDT methods, such as thermal imaging, are required to determine the degree and extent of partial CFRP de-bonding.

The application of the mobile impact machine, **Figure 3a**, with its data recorder proved successful in detecting bonded and de-bonded CFRP material in the laboratory and in the field on RC highway bridges. The waveforms for bonded and de-bonded CFRP material produced in the laboratory were consistent and similar to the bonded and de-bonded waveforms produced on the two RC bridges. This indicates the concept of using the impact-echo NDT method with the impact machine to test FRP-bonding on RC bridges and producing bond condition data is valid. It was noted the impact data obtained in the field on the two bridges had a relatively high degree of noise in the waveforms. Improvements in the impact system and data recording method, with noise filters, can improve the impact signal to noise ratio, producing a relatively cleaner and more distinguishable and measurable waveform, denoting CFRP-concrete bond condition.

6. Conclusion

The main purpose of this investigation was to test and validate the application of the NDT impulse-excitation technique to measure bond condition of

FRP-structural systems applied to concrete structures. This impact method produces acoustic emissions from bonded FRP material displaying a decaying sinusoidal waveform with unique frequencies and damping ratios. The frequencies and damping ratios identify two FRP bond state conditions: bonded and de-bonded. The de-bonded state has lower frequencies with higher (faster decay) damping ratios. The change in impact frequencies and the rate of decay in the damping ratio are the two primary parameters identifying changes in the FRP-concrete bond state.

Two FRP-retrofitted highway bridges in Missouri were tested in this investigation. Tests were made on a bonded/de-bonded FRP plate in the laboratory to provide control and a reference for the bonded and de-bonded states. Impact data results from the two bridges matched the laboratory test data for the bonded and de-bonded conditions. Impact tests on the bonded FRP material on the bridges had frequencies in the 1.25 kHz range with damping ratios of 0.10. These values matched the 1.20 kHz frequency and 0.10 damping ratio for the bonded FRP material in the lab. The de-bonded area on one bridge had a frequency of 0.85 kHz and damping ratio of 0.40 matching the de-bonded FRP values in the lab.

The NDT impulse excitation technique testing the bond of FRP-structural systems applied to concrete structures produces clear decaying sinusoidal waveforms. Signal analysis of the waveform frequencies and damping ratios confirmed a direct correlation to the FRP-concrete bond condition. Field and laboratory test results in this investigation validated the impulse excitation technique applied to bonded FRP material accurately measures the bond state between the FRP material and the concrete structure. The use of the impulse excitation technique in this investigation to evaluate FRP-bond condition has broader applications for the non-destructive testing of FRP-retrofitted concrete structures and related fields in civil engineering.

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Conflict of interest

The author declares no conflict of interest.

Appendix A

See Appendix A, Table 1.

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