The Acoustic-laser Vibrometry Technique for the Noncontact Detection of Discontinuities in Fiber Reinforced Polymer-retrofitted Concrete

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ABSTRACT

Fiber reinforced polymer (FRP) retrofitted concrete is a composite material system that is more commonly used in construction for its improved strength properties or for rehabilitation of concrete structures. This material system is composed of a concrete substrate on which FRP is adhered with an epoxy matrix. When the system is subject to adverse mechanical or environmental effects, delamination of the FRP or damage at the FRP-concrete interface may occur, yet remain externally undetected because the damage is obscured by the FRP. In this paper, a robust standoff technique for finding discontinuities in FRP-retrofitted concrete at the FRP-concrete interface using a combined acoustic-laser vibrometry technique is presented. Experiments were conducted on a test specimen with a cubic discontinuity at the FRP-concrete interface. The frequency signature of the discontinuity, which provides a technique for determining the approximate size of the discontinuity, was found to be in agreement with theory. An image was constructed with a series of measurements that show the boundary and spatial vibrational behavior of the discontinuity. From that series of measurements a probability of detection and receiver operating characteristic curve was determined for the methodology. Estimates of the area rate of coverage of measurement for an operational system and suggestions for future studies are given.

KEYWORDS: Acoustic-laser vibrometry, noncontact, NDT, FRP, concrete.

Introduction

Nondestructive evaluation of concrete is important to the maintenance and monitoring of highways, bridges and many other civil infrastructure systems. However, it is difficult to evaluate some types of concrete structures, in particular, fiber reinforced polymer (FRP) retrofitted concrete structures. FRP strengthening and retrofitting of concrete structural elements in civil infrastructure systems has become increasingly popular since the 1990s, especially in areas where earthquakes are prevalent (Meier, 1995; Saadatmanesh and Ehsani, 1991). When discontinuities such as voids or delamination occur at the FRP-concrete interface of FRP-retrofitted concrete elements the FRP obscures the discontinuity such that visual detection may not be possible. Hence, nondestructive testing (NDT) is necessary. Detection of such discontinuities is especially important in cases where FRP has been retrofitted to previously damaged structures where detecting further damage becomes a critical monitoring issue. For these purposes, an NDT methodology is necessary.

Most currently available NDT techniques rely on physical contact. However, a robust standoff technique for measuring such damage does not exist; an NDT technique that is capable of remotely assessing damage is urgently needed. Currently available and recently studied NDT technologies for FRP-retrofitted concrete include elastic wave, ultrasound, X-ray and radar techniques (Buyukozturk, 1998; Yu and Buyukozturk, 2008). These techniques all share the disadvantage of requiring either contact or close proximity of equipment with the specimen under test. Standoff techniques of damage detection have numerous advantages over contact measurement techniques since they allow for measurement of damage in locations that are physically difficult to access, such as high above the ground or over water. With a standoff technique, measurements covering a large area are simpler since

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the equipment can simply be swept along a surface or re-aimed to measure a different location.

Laser vibrometry has the ability to measure the surface velocity of objects from relatively large distances. To first order, measurements of velocity are only limited by the laser power available and line of sight (Kachelmyer and Schultz, 1995). Commercial laser vibrometers are currently available and have been used in NDT research applications such as the testing of brake rotors and engine manifolds in the automotive industry, ripeness of fruit, land mine detection, bubbles in paint coatings, and damage in composite materials (Aranchuk et al., 2006; Beyer et al., 2004; Chen and McKillip, 2007; Emge and Buyukozturk, 2012; Ghoshal et al., 2003; Haupt and Rolt, 2004; Santulli and Jeronimidis, 2006; Staszewski et al., 2003). The laser vibrometer has untapped potential as a measurement instrument for the NDT of civil infrastructure.

Concept

The general concept behind the acoustic-laser vibrometry system is that air pressure from sound waves will induce vibrations in damaged areas of FRP-retrofitted concrete greater than those induced in surrounding intact areas. The debonding or delamination of FRP allows it to freely vibrate on the surface like a drum head, while in the case of intact material, epoxy firmly bonds the FRP to the concrete, as illustrated in Figure 1 (Buyukozturk et al., 2013). The amplitude of surface vibration is measured with a laser vibrometer that can be aimed to locate the discontinuity with approximately millimeter accuracy. By using a broadband signal such as a frequency sweep or white noise as the waveform for an acoustic excitation, the specimen is excited over a wide band of frequencies. The laser vibrometer measures the surface vibration of the target, obtaining the vibration frequency response to locate and characterize any anomalies. Different discontinuities will have different frequency responses, which can be used to estimate the size and shape of a detected discontinuity.

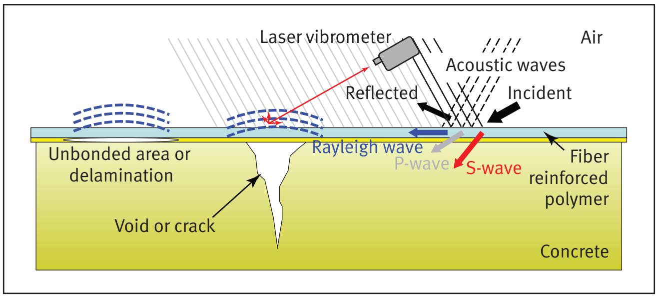

Figure 1. Illustration of the acoustic-laser vibrometry technique. Backscattered acoustic waves from voids and unbonded regions cause resonances in carbon-fiber reinforced plastic.

Preliminary results have been presented, but this paper gives a more complete treatment of the acoustic-laser vibrometry technique as applied to detecting discontinuities in FRP-retrofitted concrete (Buyukozturk et al., 2013; Chen et al., 2012). The theory behind the vibration of discontinuous areas is discussed as motivation for the detection methodology. The methodology and experimental techniques are explained, and measurements of a specimen characterizing the discontinuity are shown. These results are then used to estimate the area rate of coverage of an operational system, and conclusions and suggestions for future development are given.

Theory

The theory behind the acoustic-laser vibrometry technique involves a discussion of the reasons that discontinuities in FRP-retrofitted concrete vibrate under acoustic excitation and a simplified model to represent them to determine their resonant behavior.

Phenomenology

In FRP-retrofitted concrete there are a number of failure modes and discontinuities that can occur, shown in Figure 2

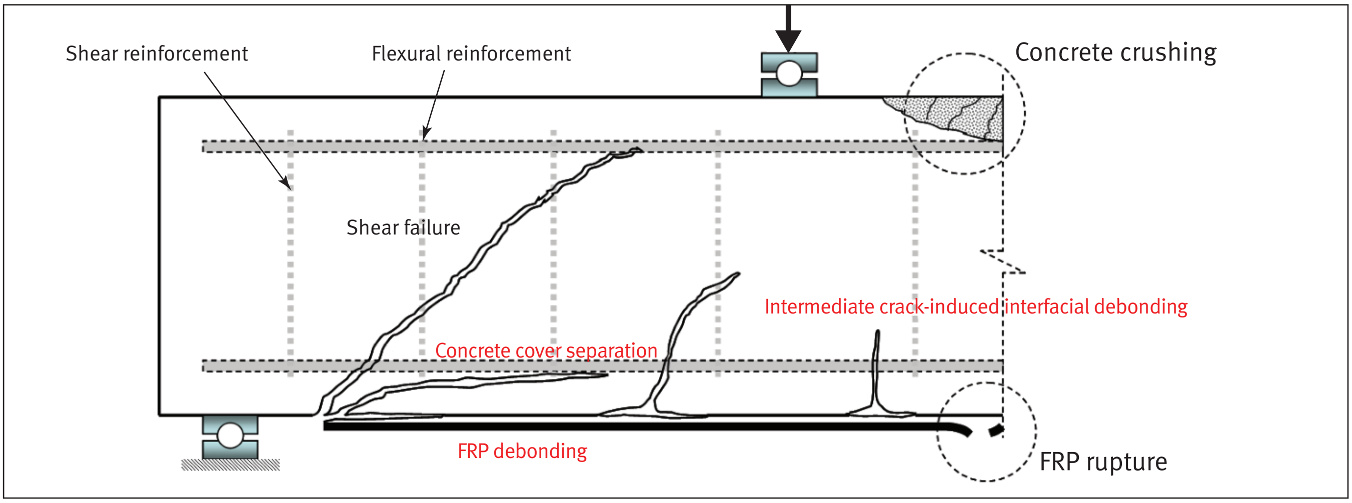

Figure 2. Different failure modes of a fiber reinforced polymer (FRP) concrete beam.

(Buyukozturk et al., 2004). The two types of damage that the system is designed to detect is FRP debonding or delamination in the form of voids at or in the vicinity of the FRP-concrete interface. The measurement methodology exploits this variation in surface compliance due to these anomalies. The debonding or delamination of the FRP, or existence of a void behind it, allows it to freely vibrate on the surface, while in the case of intact material epoxy firmly bonds the FRP to the concrete. If discontinuities are further below the surface, such as deeper cracks, there may not be enough vibration induced in the discontinuity by the acoustic source to be detectable by the acoustic-laser vibrometry technique. The next section discusses a simplified model for the vibration of a debonded area of FRP and shows how to estimate the resonant frequency of a discontinuity of a given size and geometry.

Simplified Model

To model a discontinuity where the FRP has debonded from the concrete in a certain area, consider a simplified mathematical model: a square plate with a clamped boundary, as shown in Figure 3. The plate represents the area of the FRP that has debonded, and a clamped boundary condition at the edge of the discontinuity represents where it is properly bonded to the concrete. The clamped boundary assumption is a reasonable simplification of the complex interaction between the FRP, epoxy and concrete. Even though FRP is a directional material because of the fibers, for simplicity it is assumed to be isotropic. The air in the discontinuity, which is much less dense and less stiff than the FRP, is assumed to have a negligible effect on the resonant frequencies of the plate.

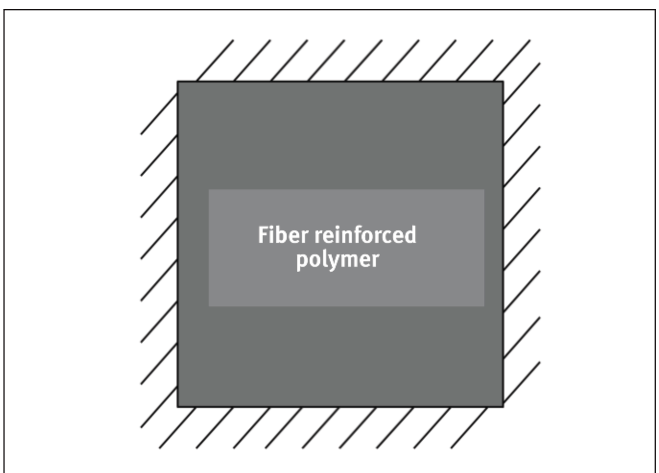

Figure 3. Mathematical model of fiber reinforced polymer plate.

The plate equation that governs this discontinuity is given in Equation 1:

$$D\nabla^4 w + \rho h \frac{\partial^2 w}{\partial t^2} = 0 \quad (1)$$

where
$D = (Eh^3) / (12[1 - \nu^2])$, the flexural rigidity of the plate,
E is Young's modulus,
h is the thickness of the plate,
ν is Poisson's ratio,
ρ is the density of the material,
$w = w(x, y, t)$, the transverse displacement of the plate as a function of spatial variables, x and y, and time, t (Leissa, 1969; Soedel, 2004).

The resonant frequencies of the plate are determined by Equation 2:

$$f = \frac{\lambda}{2\pi a^2}\sqrt{\frac{D}{\rho h}} \quad (2)$$

where
λ is a frequency parameter that depends on the resonant mode, geometry and boundary conditions of the plate,
a is the side length of the square plate,
f is the resonant frequency.

The expected resonant frequencies of the different vibrational modes of the plate can be calculated. A caveat is that, since an isotropic material was assumed and fiberglass is not an isotropic material, this technique is only reasonable for giving an estimate of the fundamental resonant frequency. Using the following material property values from the FRP system datasheet, resonant frequencies were calculated, shown in Table 1. These material properties are not measured numbers from our specific specimen, and can only be treated as approximate. When measuring discontinuities, if the properties of the FRP are known, an estimation of the discontinuity size can be back calculated from measured resonance frequencies if a geometry and boundary condition is assumed.

TABLE 1
Material properties of fiber reinforced polymer

Discontinuity side length	Young's modulus	Poisson's ratio	Density	Thickness	Calculated resonant frequencies Mode	Frequency (Hz)
0.0381 m	20.9 GPa	0.2	1800 kg/m^3	1.3 mm	1, 1	5151
					2, 1	10 503
					2, 2	15 488
					3, 1	18 875

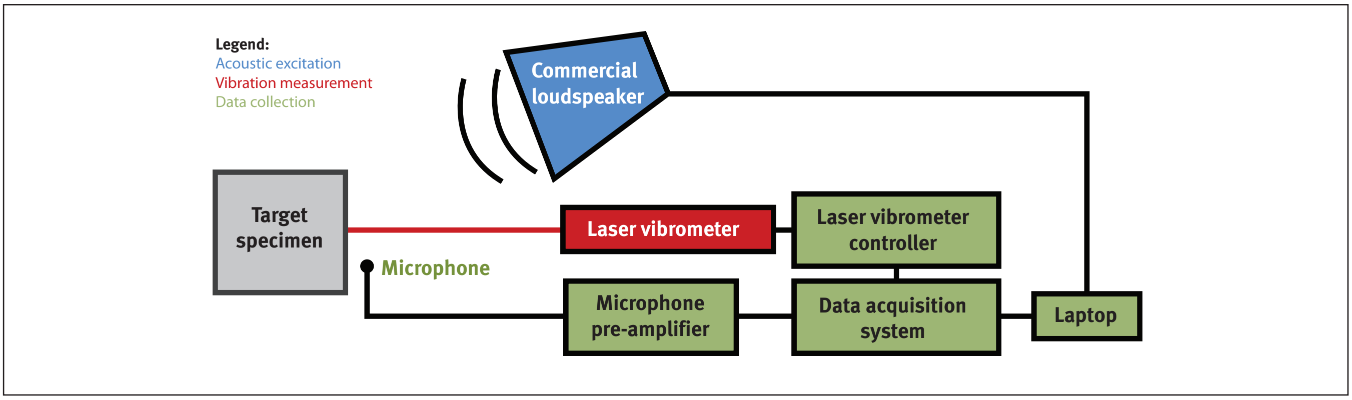

Figure 4. Diagram of experimental setup.

Experimental Approach

The implementation of the acoustic-laser vibrometry concept as a laboratory experimental setup is explained in this section. Data processing of the raw measured signal is explained and the test specimen is shown, along with a description of the measurement procedure.

Experimental Setup

Discontinuities are identified by their vibrational frequency response, which is excessive in amplitude compared to the surrounding intact material, so the key components of the system are the acoustic source that excites the target and the laser vibrometer that measures the surface velocity of the location of the aimed laser spot in the direction collinear to the beam as a function of time. To implement the methodology in a laboratory, a system composed of commercially available equipment was compiled for testing. The experimental setup involved a laser vibrometer, a loudspeaker, the target specimen and data collection equipment. The arrangement of the equipment was such that the laser vibrometer measured the sample perpendicular to its surface to avoid any errors in the velocity measured. The theory predicts a flexural wave in the discontinuity, so maximum amplitude is normal to the surface. The speaker was placed approximately 1 m away from the target specimen and slightly off the line of sight of the laser vibrometer to avoid obstruction of the laser. The laser vibrometer was placed approximately 3 m away from the specimen, a distance close enough to maintain good signal strength, while avoiding acoustic coupling from the speaker into the vibrometer. Data from a microphone near the target specimen were collected to ensure a relatively flat frequency response of the acoustic excitation to avoid spurious frequency peaks in the specimen response. Retroreflective tape bonded well to the target was used to ensure a good return signal from the target to the laser vibrometer; however, with a higher power laser vibrometer, retroreflective tape would not be necessary. A diagram of the experimental setup is shown in Figure 4.

Data Processing

The data collected from the laser vibrometer using the data acquisition system are in the form of voltage versus time. The correct scaling factors were used to obtain the velocity as a function of time for the laser vibrometer or decibels for the microphone. Furthermore, the amplitudes were also scaled so that the resultant amplitude would be similar to that of a pure sine wave excitation of a single frequency. This amplitude scaling factor was the square root of the frequency sweep duration multiplied by the frequency bandwidth. The data were processed using a fast fourier transform (FFT) to transform the data from the time-domain to the frequency-domain to obtain the vibration response frequency spectrum.

Test Specimen

To test the system, an FRP-retrofitted concrete panel was fabricated with a created discontinuity, as shown in Figure 5, designated FRPP1. The test specimen consisted of a concrete panel that was 30.48 × 30.48 × 10.16 cm and had three reinforcing bars inside. During the casting process of the panel, a 3.81 × 3.81 × 2.54 cm foam piece was placed in the mold to create an air void. Then, a wet layup procedure was used to bond the FRP to the panel with epoxy, with the air void resulting in a discontinuity under the FRP. The specimen is shown in Figure 5.

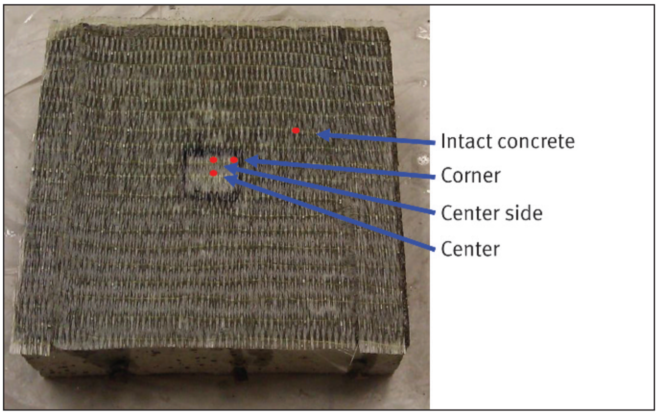

Figure 5. Fiber reinforced polymer-bonded concrete panel, cubic discontinuity, FRPP1, with measurement locations.

Measurement Procedures

The initial measurements conducted were intended to determine the resonant frequencies and vibration amplitudes of the discontinuity. A 60 s measurement was done, where the laser vibrometer measured the surface vibration at a point on the discontinuity, and a 0 to 20 kHz frequency sweep excitation was played over the speaker. The purpose of the frequency sweep was to cover a large range of frequencies with the acoustic excitation; however, at any single moment in time, the acoustic energy in a narrow band of frequencies should be concentrated to better excite any resonances. The discontinuity was measured in four locations: center of discontinuity, side of discontinuity, corner of discontinuity, and off of the discontinuity over intact material. The measurement locations over the discontinuity were chosen to obtain both the maximal response amplitude and the most varied frequency responses from the discontinuity. The measurement made over intact material, where the FRP-concrete system was undamaged, gave a control vibration signature that ruled out sources of noise as potential resonant frequencies and gave a reference for comparison to determine the detectability of the discontinuity. The measurement locations are shown overlaid on a picture of the specimen in Figure 5.

To determine the detectability and modal structure of the discontinuity, a separate grid of 13×10 individual measurements was made over an area including the discontinuity and the surrounding intact FRP. The center 7×6 measurements covered the discontinuity. A 10 s, 0 to 20 kHz frequency sweep was used to excite the target at a sound pressure level of approximately 90 dB. A measurement was made at each point and the resonance peak frequencies and amplitudes were determined to make surface plots of the vibration velocities at a given frequency in relation to their location.

Results

The measurements made of the FRPP1 specimen include the response frequency spectra of the discontinuity, the grid measurement to determine the modal structure of the discontinuity, and a comparison of different frequency sweep durations. From these measurements, a receiver operating

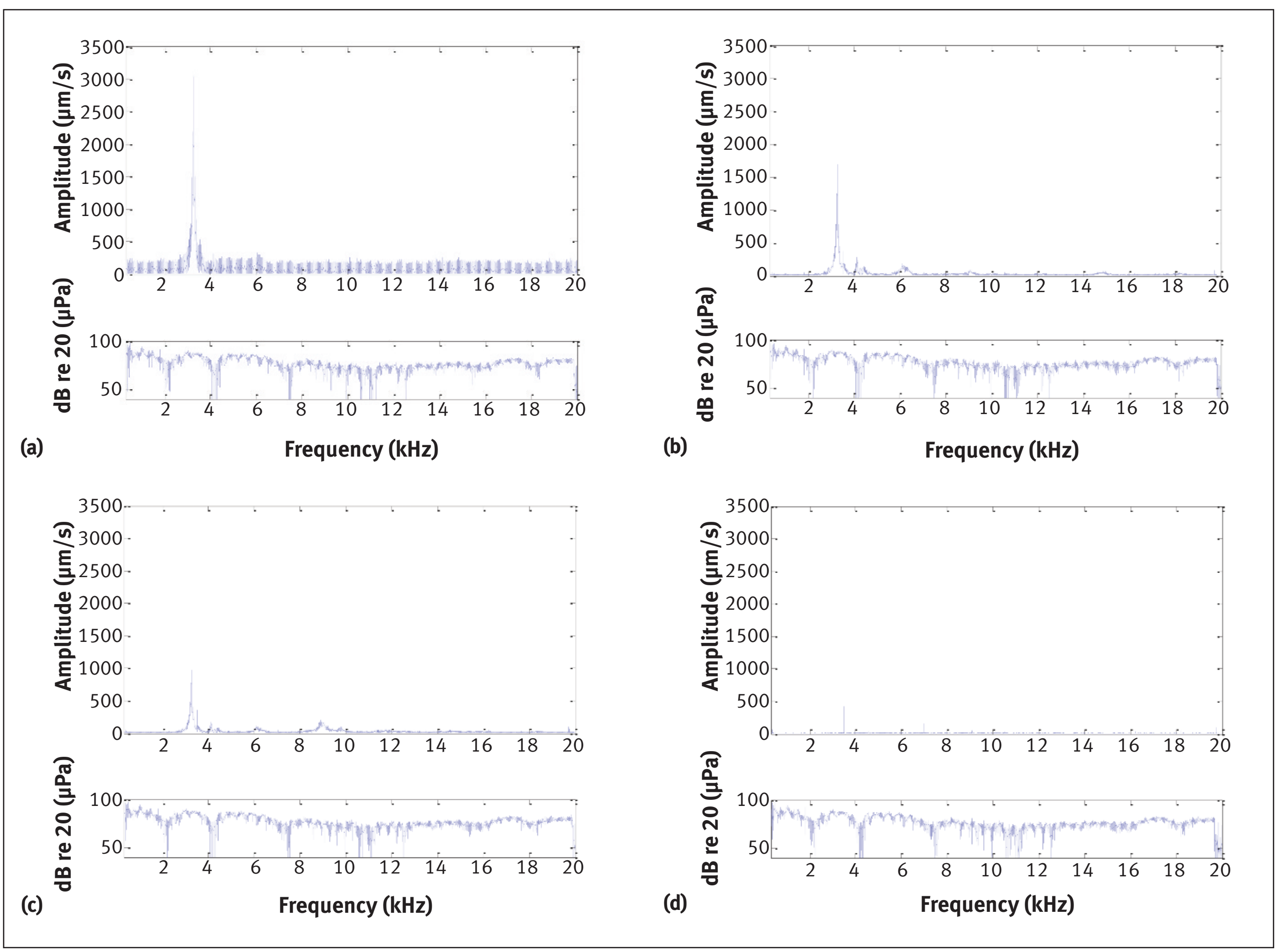

Figure 6. Response spectrums of the discontinuity versus frequency from a 0 to 20 kHz, 60 s sweep at the: (a) center; (b) side; (c) corner; and (d) intact material.

characteristic curve is calculated and the potential area rate of coverage of the methodology is discussed.

Discontinuity Response Frequency Spectrums

Figure 6 shows the response velocity spectrums of the test specimen as a result from the measurements made. The base resonant frequency observed of 3.2 kHz is comparable to the predicted resonant frequency of 5151 Hz from plate theory, especially when taking into consideration the possible variances in the material properties of the FRP. Also, the theory considered an isotropic material, while in practice, FRP is less stiff in the direction perpendicular to the fibers, resulting in a lower actual resonance frequencies. Table 2 gives a summary of the visually determined resonant frequencies from the measurements. These plots also show that there is a significant difference in the observed response when the measurement is made on the discontinuity versus off. The center of the discontinuity exhibits a scaled response upwards of 3000 μm/s, while the intact FRP-concrete system shows no distinct resonances and a noise floor of under 20 μm/s. The response amplitude is much greater over the discontinuity, and Figures 6a–c show distinct resonant peaks whereas the measurement over intact concrete in Figure 6d shows only a noise floor with some extraneous peaks due to noise. These extraneous peaks do not represent actual resonances because real resonant peaks should have a width corresponding to some quality factor of the resonance, and since these are very narrow they are due to some form of noise.

TABLE 2
Visually determined resonant frequencies for specimen FRPP1

Location	Frequency (kHz)				
	3.2	4.1	6.1	8.9	14.8
Center	X	X	X	–	–
Top center	X	X	X	–	X
Corner	X	X	X	X	–

Grid Measurements – Image Construction

The grid measurements are intended to show how the vibration amplitude varies with location on the discontinuity, and the frequency that the vibration is taking place. The intact material surrounding the discontinuities is deep blue, indicating low vibration amplitude, while colors indicating higher vibration amplitudes are over the discontinuity. The first three resonant frequencies at 3200, 4050 and 6050 Hz produced coherent vibration modes, and plots of them are shown in Figure 7.

Figure 7a shows the surface plot of vibration amplitudes at the first resonant mode of the FRPP1 specimen discontinuity, at 3200 Hz. The image shows the mode shape expected for the first resonant frequency of a clamped plate. There are no nodes and the velocity trends towards zero at the edges of the discontinuity. The boundary of the discontinuity and areas of intact FRP-concrete material are shown by the lack of vibration amplitude around the border.

The image constructed for the second resonant mode in Figure 7b of the discontinuity at 4050 Hz shows the mode shape expected for the second resonant mode of the discontinuity, as there is one vertical nodal line and presumably on either side, two portions of the plate that vibrate opposite to

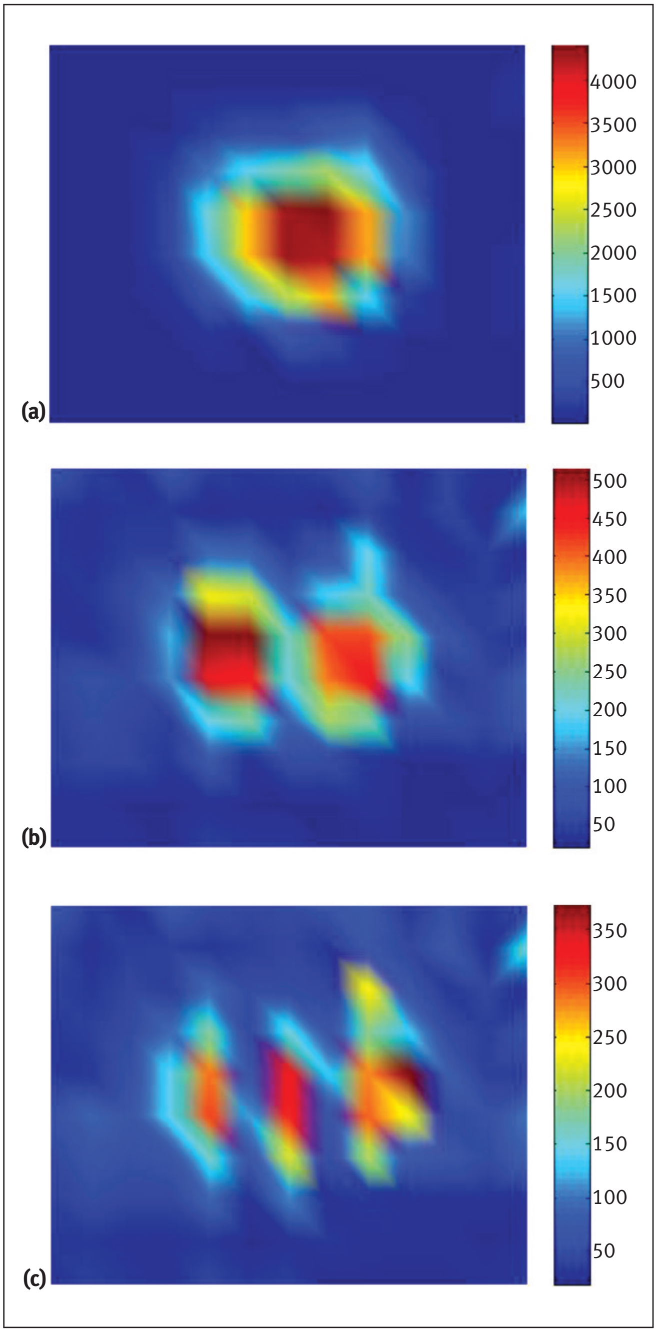

Figure 7. Images constructed of the specimen at: (a) 3200 Hz; (b) 4050 Hz; and (c) and 6050 Hz.

each other. The frequency of this mode, however, is not approximately double that of the first, which was expected from plate theory for a square clamped plate. Recall that the theory was only accurate for isotropic materials; however, FRP is not an isotropic material. FRP is a directional material with greater tensile strength in the direction of the glass fibers; therefore, the vibrational modes beyond the first have modal lines in the same direction of the fibers, because perpendicular to that direction, the material is less stiff. Therefore, the resonant frequency of the second mode does not match up with the predictions of plate theory.

Figure 7c shows the third resonant mode of the discontinuity at a frequency of 6050 Hz. The image shows two vertical nodal lines running in the same direction of the fibers of the FRP, and the boundaries of the discontinuity are relatively distinct. The image construction measurement of the test specimen is a technique for which the sizes of discontinuities can be determined, in addition to estimation from resonant frequencies. The grid of measurements shows the outline of the discontinuity because of the distinct boundary between higher vibration amplitudes over the discontinuity and lack of distinct vibration resonances over the surrounding intact material.

Receiver Operating Characteristic Curve Analysis

To analyze the performance of the acoustic-laser vibrometry technique and obtain a probability of detection, data from the image construction measurements, which represent a set of measurements both on and off the discontinuity, were used to generate a receiver operating characteristic (ROC) curve. The ROC curve is a simple way to visualize the measures of detector performance, true positive rate as a function of false positive rate, which changes as a detection level parameter is altered (Fawcett, 2006). A cutoff detection vibration level is specified, above which the measurement is classified as a positive detection of a discontinuity, and below which the measurement is classified as a negative detection. Since it is known which measurements were actually made on the discontinuity or competent material, true positives and false positives can be distinguished to determine the true positive and false positive rates. A true positive rate of one means that all measurements on a discontinuity were correctly classified as detections of a discontinuity, while a false positive rate of zero means that no measurements over intact material were incorrectly classified as detections of a discontinuity. A perfect binary detector has a true positive rate of one and a false positive rate of zero. Since the first resonant frequency provides the greatest vibration amplitude, it is used for the detection of the discontinuity. The ROC curve produced is shown in Figure 8.

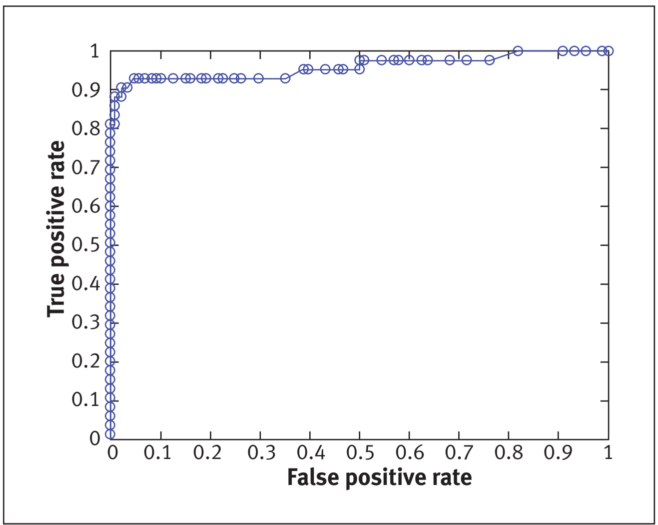

Figure 8. Receiver operating characteristic curve for FRPP1 discontinuity at 3200 Hz.

Figure 8 shows that a 90% positive detection rate with a false positive rate of only 2.3% is achieved at a detection level of 89 μm/s. Since the maximum vibration velocity of the discontinuity at the center is 4300 μm/s, this gives a very good signal-to-noise (SNR) ratio of 16.8 dB. A higher positive detection rate of 95% can be achieved; however, the false positive rate increases to 38.6%, which may be prohibitively high. It is assumed that there will be a relatively low area of discontinuities relative to intact material; therefore, a low false positive rate is more important than a marginal improvement in positive detection rate. The more useful detection criterion is the one that results in a low false positive rate of 2.3%, where positive detection rate is maximized without any significant increases in false positive rate. The sensitivity of the system is therefore 90% with a specificity of 97.7%.

Estimated System Performance

The key statistic that will govern the functionality of the system after the true the false positive rates is the area rate of coverage of the system. This is, effectively, the speed of measurement, and discussions here will focus on the time necessary to characterize a square meter using the acoustic-laser vibrometry technique. The two main measurement parameters that govern this are the spacing between measurements and the time necessary for a single point measurement. The measurement spacing can be adjusted finer or coarser to determine the minimum size discontinuity that will be detected. The time necessary for a measurement needs to be minimized without any loss of system performance.

Frequency Sweep Duration

A quick study of varying durations of the frequency sweep and measurement was performed to determine the change in the SNR. The measurements were made with a 0 to 20 kHz frequency sweep with lengths of 0.1, 1, 10 and 60 s, and other procedures were the same as previous measurements. Table 3 shows the results of the study.

TABLE 3
Results from frequency sweep duration study

Sweep length (s)	Frequency (Hz)	Average sound pressure level (dB)	Amplitude (µm/s)	Noise floor (µm/s)	Signal-to-noise ratio
0.1	3247.8	80.3481	5068.0	74.0646	68.4268
1	3245.7	80.4217	4909.4	74.6392	65.7751
10	3246.6	80.4584	4972.1	73.1881	67.9359
60	3247.0	80.2238	5097.8	73.5018	69.3561

The amplitude and noise floor, and as a result the SNR, stayed constant despite varying the frequency sweep duration. This suggests that the measurement time can be reduced from 10 to 0.1 s with no loss in system performance. Also, this suggests that a more complicated processing technique for frequency sweep measurements is optimal for extracting the best SNR out of the measurement, with multiple FFTs taken over smaller windows over the length of the measurement.

Area Rate of Coverage

From the measurements and parametric studies, a preliminary area rate of coverage for the system under specified conditions can be determined. With a scanning laser vibrometry system, which uses a movable or scanning mirror to reposition the laser spot, up to 30 spots per second can be scanned (Polytec, 2011). A generous assumption would be that each frequency sweep measurement would take only 0.2 s with a scanning laser vibrometer to allow for settling and measurement time, without decrease of the SNR.

The other factor besides measurement duration that determines the area rate of coverage is the measurement spacing, which determines the size of the discontinuity that can be detected. If a measurement is not made directly over a discontinuity, the discontinuity escapes detection. The equation that determines the time required to measure 1 m^2 dependent on the measurement spacing in a simple grid is given in Equation 3:

$$t = t_m \frac{1}{s^2} \tag{3}$$

where

t is the time required to measure 1 m^2 with a square grid of measurements,
t_m is the time required for one measurement,
s is the spacing between measurements, in meters.

Using Equation 3, the relationship between the time to measure 1 m^2 versus the measurement spacing, for an individual measurement time of 0.2 s, can be plotted, as shown in Figure 9.

For a square grid of measurements, a spacing of 0.44 cm is necessary to ensure the maximum circular discontinuity diameter that can be missed is 0.63 cm. The resulting measurement time is 10 331 s, or approximately 172 min. For a maximum circular discontinuity diameter of 1.27 cm, the spacing is 0.90 cm, and the measurement time is 2480 s, or approximately 41 min. For a maximum circular discontinuity diameter of 2.54 cm, the spacing is 1.80 cm, and the measurement time is only 620 s, or just over 10 min. Further improvement in the speed of measurement may come from using fewer frequencies of interest for a shorter duration frequency sweep, or the use of a chord of frequencies in a constant tone instead of a sweep, to reduce the dwell time and increase the area rate of coverage.

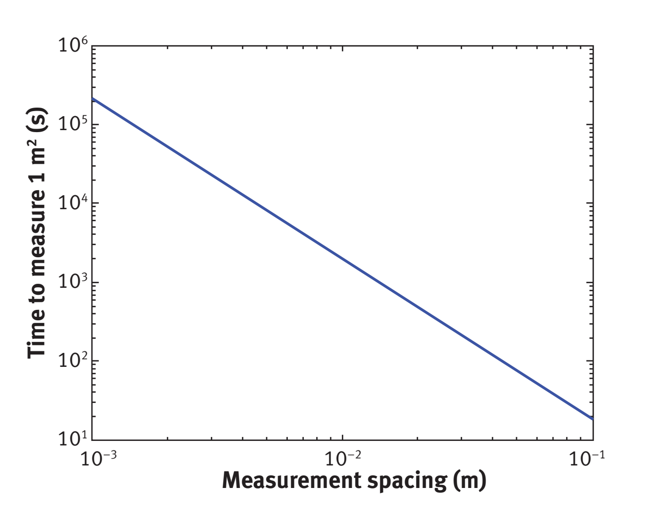

Figure 9. Time required to measure 1 m^2 versus measurement spacing.

Conclusion

The acoustic-laser vibrometry system has been shown to identify areas of FRP-retrofitted concrete where there is damage at the FRP-concrete interface in a standoff manner. A 3.81 × 3.81 cm discontinuity in a test specimen had a vibration amplitude more than 100× greater than the vibration amplitude in an area of intact material, which is a large SNR and demonstrates the robustness of the methodology. A measurement was made, covering the complete area of the discontinuity, and images of the vibration amplitude at the different resonant frequencies showing the resonant modes and boundary of the discontinuity were generated.

The system was able to detect discontinuities with a sensitivity of 90% and specificity of 97.7% under laboratory conditions. Estimations of the system performance suggest that a scanning laser vibrometer system could characterize 1 m^2 of material in just over 10 min with a minimum discontinuity size of 2.54 cm.

Future Work

Future analysis involves investigation of different sizes and configurations of discontinuities as well as parametric studies of varying conditions during measurement. A goal is to determine the type of discontinuity from characteristics of the frequency response signature. Investigations into these discontinuity details may also involve the numerical modeling of anisotropic materials and consideration of the nonlinearities of the FRP-epoxy-concrete material interaction. Also, there is the possibility that discontinuities that are not at the FRP-concrete interface but under the surface of the concrete may be detectable by the acoustic-laser methodology, and this needs to be investigated. More sophisticated laser vibrometers with more power would have the ability to measure materials without retroreflective tape, and scanning or multipoint capability would allow for faster measurements to be made. Ideally, a field system would make use of such laser vibrometers for improvements in performance and measurement speed.

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