Remote Characterization of Defects in FRP strengthened Concrete Using the Acoustic-Laser Vibrometry Method

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INTRODUCTION

Vibrations are commonly used to characterize objects because they interact with the material and can provide information on the mechanical properties of, or any defects in the object. Most objects can be characterized by some sort of natural frequency which is a function of the geometric, material, and boundary properties of the object. When the response of the object to an external force is measured over a range of frequencies, a response frequency spectrum can be generated that will be characteristic to the object's properties.

A material that is of interest to be characterized and inspected for defects is fiber reinforced polymer (FRP) strengthened concrete, which is seeing more use because of the protective and tensile capabilities of FRP and the ubiquity of concrete as a building material [1]. Typically measurement of vibrations or waves to characterize these materials for non-destructive testing (NDT) involves contact measurements with transducers such as ultrasound transmission, pulse-echo, and acoustic emission techniques [2]. Without using waves, other potential contact methods for NDT of concrete systems include x-ray and radar methods, among others. The issue is that these methods all share the necessity of close proximity to or physical contact with the material being measured. The capability of making measurements from a distance allows access to measurement of damage in locations that are physically difficult to access, and improves measurement speed for an area because equipment can simply be swept along a surface.

The standoff capability motivates the usage of the laser vibrometer as a measurement instrument, and an acoustic source to provide an airborne excitation to vibrate the material under test. Applications of laser vibrometers in NDT include detection of landmines [3,4] and inspection of composite materials [5,6,7]. The acoustic-laser vibrometry method has been shown to be able to detect defects in FRP-strengthened concrete [8,9]. In order to expand the capabilities of the methodology more in depth testing and analysis was conducted.

Objective

Simple NDT methods may only determine the existence of a defect in a material, while more sophisticated methods will provide some sort of information about the defect detected. The purpose of this paper is to explore the differences in vibration frequency response signatures of different defects as measured by the acoustic-laser vibrometry methodology, to determine more characteristics of the defect. An overview of the method and basic theory behind differences in the frequency response of defects are presented, followed by results from measured defects.

METHODOLOGY

The general concept behind the acoustic-laser vibrometry system is that air pressure from sound waves will induce vibrations in damaged areas of FRP-strengthened concrete, greater than that of surrounding intact areas. The methodology targets common defect modes in FRP-strengthened concrete that occur at or in the vicinity of the FRP-concrete interface, such as FRP debonding, delamination, or voids in the concrete [10]. 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. The amplitude of surface vibration is measured with a laser vibrometer that can be aimed to locate the defect with approximately millimeter accuracy. By using a frequency sweep or a broadband signal such as 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. Defects will have different frequency responses due to specific characteristics of the defect. The resonant frequencies of differently sized rectangular defects can be estimated by using plate vibration theory.

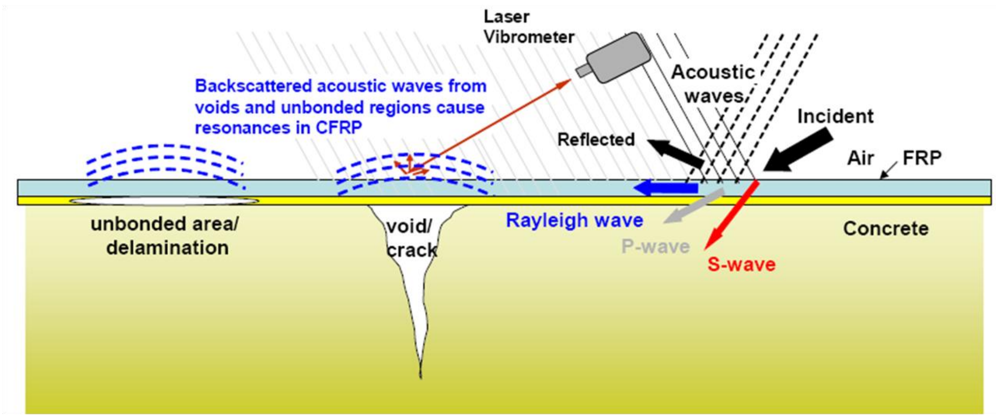


Figure 1: Illustration of the acoustic-laser vibrometry method [8]

Theory

To create a simple model for a delamination, void, or crack defect in FRP-retrofitted concrete, only the region of FRP detached from the concrete substrate by the epoxy is considered. The model for the defect is a rectangular clamped plate where the resonant frequencies can be determined numerically. Assumptions for this model are that the plate material is isotropic, whereas FRP is directional, any void under the plate has a negligible effect on the vibration of the plate, and the boundary where the FRP is bonded to the concrete is assumed to be a clamped condition. The numerical values for the defect's resonant frequencies are described by the following equations 1 and 2 [11]:

$$f = \frac{\lambda}{2\pi a^2}\sqrt{\frac{D}{\rho h}} \tag{1}$$

$$D = \frac{Eh^3}{12(1-\nu^2)} \tag{2}$$

where D = flexural rigidity of the plate, E = Young's modulus, h = thickness of the plate, ν = Poisson's ratio, ρ = density of the material, a = shorter side length of the plate, b = longer side length of the plate, λ = a frequency parameter that depends on the resonant mode, geometry, and boundary conditions of the plate, and f = resonant frequency. The key parameter here regarding defects of different shapes, despite having more or less the same dimensions is λ which is directly correlated to the frequency of the mode. For the case of a rectangular defect, the vibrational mode and the aspect ratio, a/b dictate the value of λ. As the aspect ratio becomes smaller, or as the defect becomes more crack-like and less square, the resonant frequencies corresponding to different vibrational modes shift, as shown in Figure 2. As the aspect ratio approaches 0, the first seven vibrational modes of a square plate converge to two modes. Therefore, when defects are shaped more like a crack with slender aspect ratios, we expect resonant frequencies to be grouped closer together when the frequencies are normalized to the frequency of the first resonant mode.

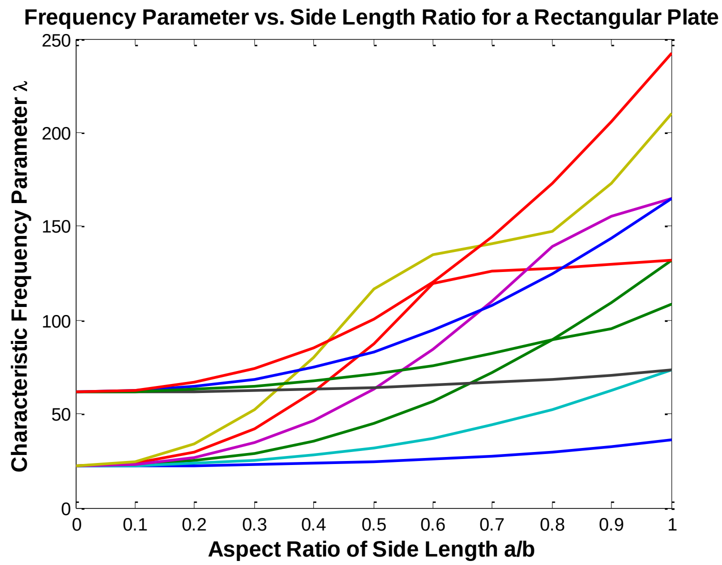


Figure 2: Plot showing frequency parameter λ as a function of defect aspect ratio [11,12]

Experimental Method

Testing was accomplished using a laboratory experimental setup consisting of a laser vibrometer, loudspeaker as an acoustic excitation, the test specimen, and data acquisition system as shown in Figure 3. The loudspeaker is used to excite the target specimen over a wide range of frequencies using a 0 – 20 kHz or 2 – 22 kHz frequency sweep. The laser vibrometer measures the surface vibration at the aimed spot on the defect, and the measured vibration time series is collected using the data acquisition system. The data is Fast Fourier Transformed (FFT) and normalized for the correct units to obtain the response vibration frequency spectrum of the defect.

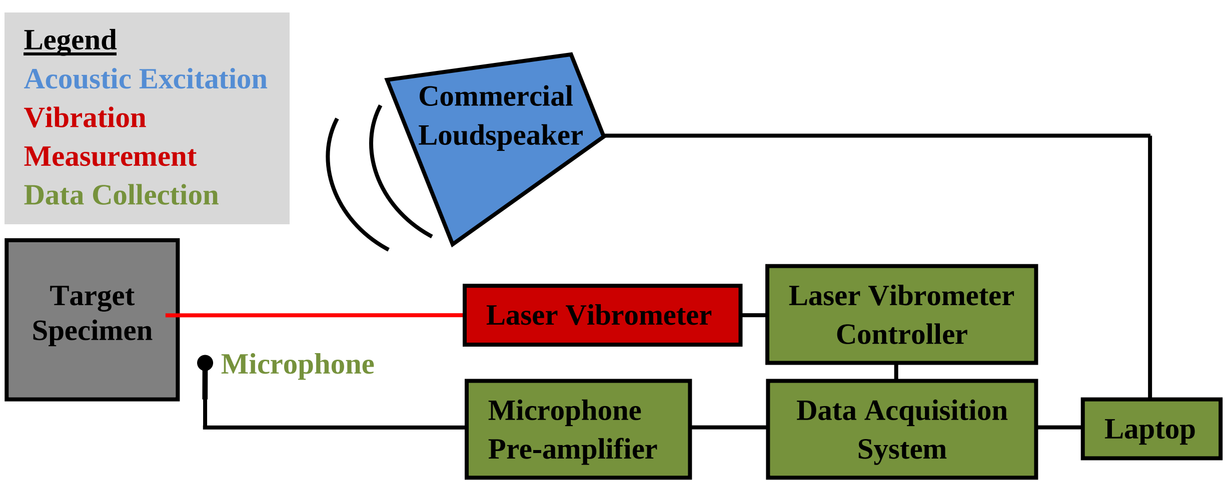


Figure 3: Diagram of experimental setup

Test Specimens

For the study of different defects ranging from square to more slender and crack-like, three specimens were measured with varying defect aspect ratios. FRPP2 is a FRP-bonded concrete panel with a 3" x 3" delamination defect, characterized in a previous paper, and shown in Figure 4 [9].

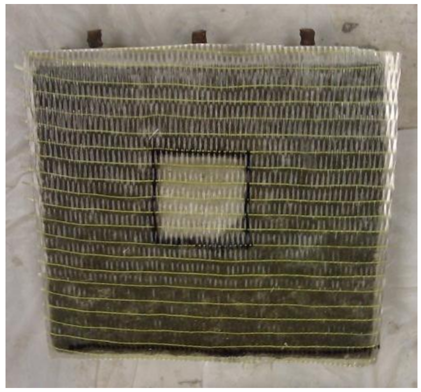


Figure 4: FRPP2, FRP-bonded reinforced concrete panel, 3" x 3" delamination defect [9]

FRPP5 is a FRP-bonded concrete panel with multiple defects of height 3" with widths of 0.125", 0.25", 0.5", 0.75", and 1" shown in Figure 5. These different crack widths represent aspect ratios of 0.04, 0.08, 0.167, 0.25, and 0.33.

Figure 5: FRPP5, FRP-bonded concrete panel with multiple defects

FRPP4 is a FRP-bonded concrete panel, shown in Figure 6 with a 0.25" x 3" defect at the surface where the FRP is debonded, and the void extends into the concrete at an angle approximating a shallow angled crack.

Figure 6: FRPP4, FRP-bonded concrete panel, angled 3" x 0.25" defect

RESULTS

Defect Aspect Ratio

The theory presented dictates that for a square defect, the resonant frequencies should be relatively evenly spaced, and as the defect gets more slender and crack-like, the resonant frequencies will tend to group together. In order to study this effect, measurements were made on defects with varying widths of 0.25", 0.5", 0.75", 1", and 3", with constant height of 3". Figure 7 shows measurements on the 3" wide defect FRPP2 at the center and corner. The first resonant frequency in Figure 7b is at 1.6 kHz, while the next two resonant frequencies are at 2.25 kHz and 2.8 kHz, for ratios of 1.4 and 1.75. The theoretical ratio for a square clamped plate made of isotropic material should be approximately 2, however FRP is a directional material, explaining the discrepancy.

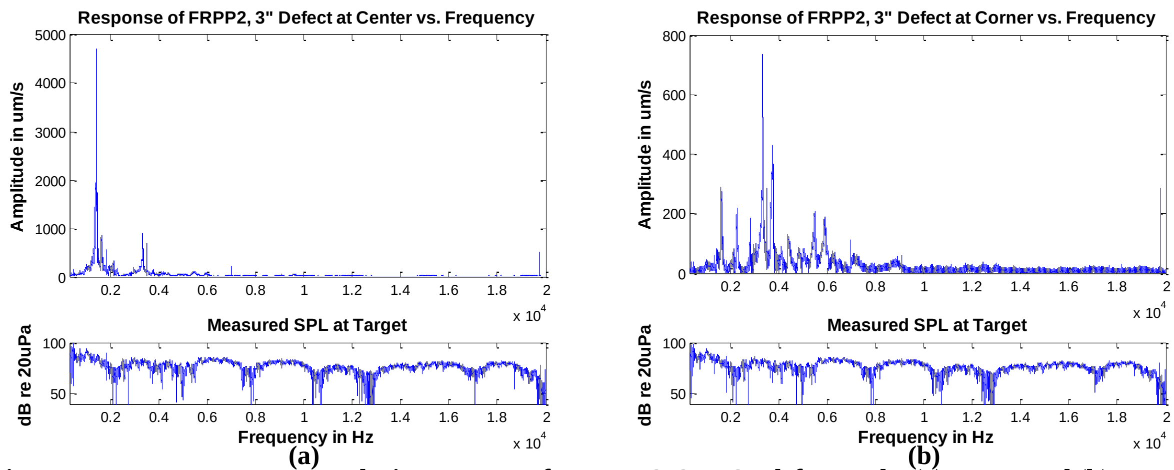
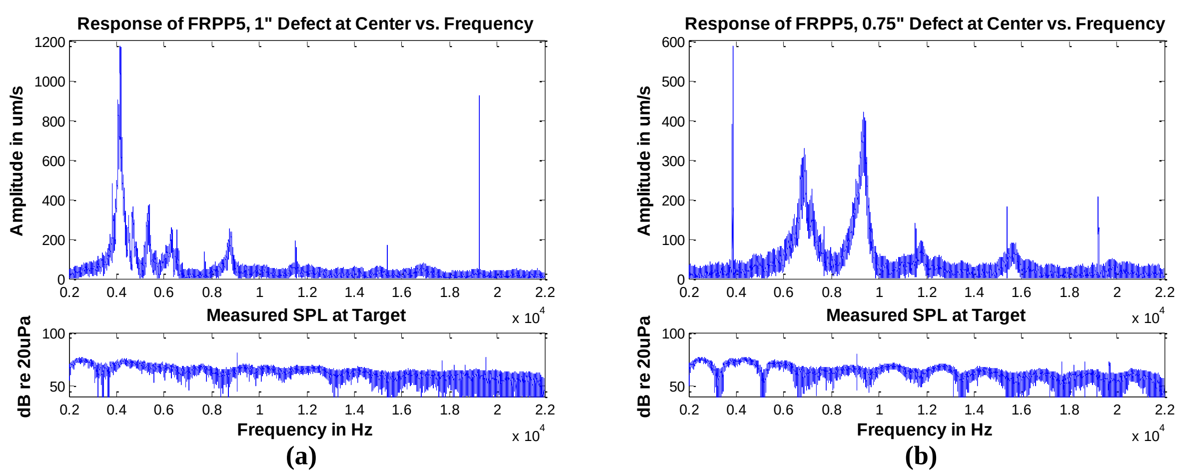
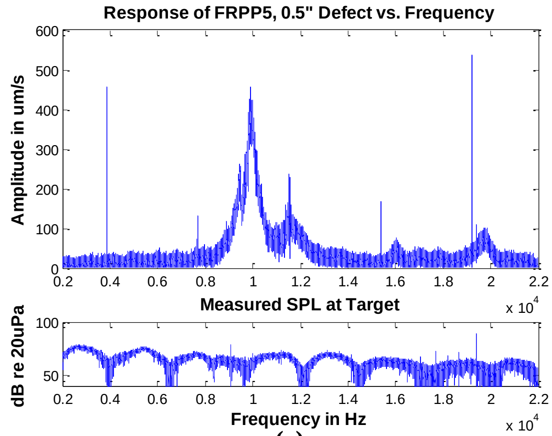


Figure 7: Frequency response velocity spectrum for FRPP2, 3" x 3" defect at the (a) center and (b) corner [9]

Three of the defects of width 0.5", 0.75", and 1" were measured on the FRPP5 specimen, and the response frequency spectrums are shown in Figure 8. The narrower crack defects of 0.125" and 0.25" when measured did not result in a visible vibrational response from the defect, and are not included. For the 1" defect shown in Figure 8a, the first resonant frequency is at 4.15 kHz, the second at 4.5 kHz, and the third at 4.68 kHz. These give ratios of 1.084 and 1.128, which are closer to each other than that of the 3" defect. For the 0.75" defect shown in Figure 8b, the first resonant frequency is at 6.85 kHz, the second at 7.18 kHz, and the third at 7.54 kHz. The ratios are 1.048 and 1.101. For the 0.5" defect shown in Figure 8c, the first resonant frequency is at 9.45 kHz, the second is at 9.9 kHz, and the third visible is at 11.5 kHz. The ratios are 1.048 and 1.217. One possible reason that the third resonant frequency is comparatively higher, might be that the broad peak of the first and second resonant frequencies hides another resonant frequency of lower amplitude.

Qualitatively, the resonant peaks become broader as the crack width is decreased, and this is seen for all three widths of defect. The reason for this broadening could be that the width of the peaks is relatively large compared to the spacing between peaks, and so they might tend to merge to form one peak instead. The width of the peak is related to the quality factor of the resonance which describes the damping, where the narrower the peak, the lower the damping of the resonance.





(c)

Figure 8: Frequency response velocity spectrum for FRPP5: (a) 1" defect, (b) 0.75" defect, (c) 0.5" defect

The response spectrum for the FRPP4 angled defect, shown in Figure 9, is quantitatively different than the ones on the FRPP5 specimen. The resonant frequencies are spaced closed together, with the first resonant frequency at 11.9 kHz, and the subsequent ratios for the next two resonant frequencies at 12.4 kHz and 12.9 kHz of 1.042 and 1.084. Qualitatively each frequency peak however is less broad, suggesting that the defect is less damped. This defect is slightly different than the FRPP5 specimen defects because the void is angled beneath the surface, instead of normal to the surface, which may account for the differences. The defect vibration may not be purely due to the vibration of the FRP defect, because the side of the defect with the angled crack may be less of a clamped boundary condition than the other three sides.

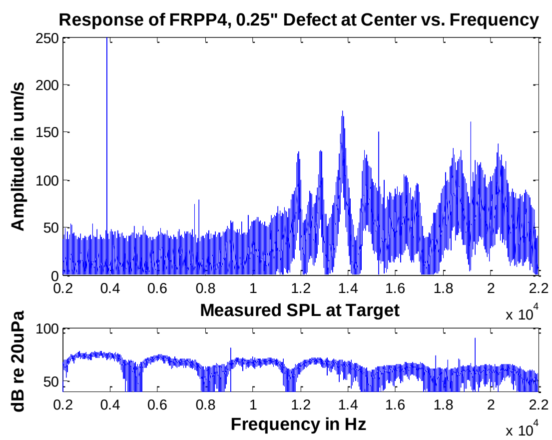


Figure 9: Frequency response velocity spectrum for FRPP4, 0.25" defect

Table 1 summarizes the ratios of resonant frequencies between the observed first resonant frequency and the second and third resonant frequencies. The ratio between the second and first resonant frequencies decreases as the defect width decreases, following the prediction from theory. The ratio between the third and first resonant frequencies also decreases for the most part, except for the 0.5" wide defect.

Table 1: Summary of resonant frequency ratios for different defect widths

Defect Width	Ratio of 2nd/1st Resonant Freq.	Ratio of 3rd/1st Resonant Freq
3"	1.4	1.75
1"	1.084	1.128
0.75"	1.048	1.101
0.5"	1.048	1.217
0.25"	1.042	1.084

Cracked FRP-strengthened Concrete

Another result from the measurement of the FRPP4 specimen is that a small vibration response was measured over a region where the FRP-concrete system is intact, however there is a crack that extends underneath the surface of the concrete by about 1cm. Figure 4a shows a couple of resonant frequencies around 12 kHz to 14 kHz with amplitudes of approximately 75 µm/s that are distinguishable by eye from the response spectrum over a region where there is intact material and no cracking in Figure 4b, which has several spurious peaks due to some source of noise. This suggests that shallow cracks in concrete may vibrate enough under acoustic excitation to be detected with a laser vibrometer, and the acoustic-laser vibrometry method may be useful for detecting cracking of a thin concrete cover.

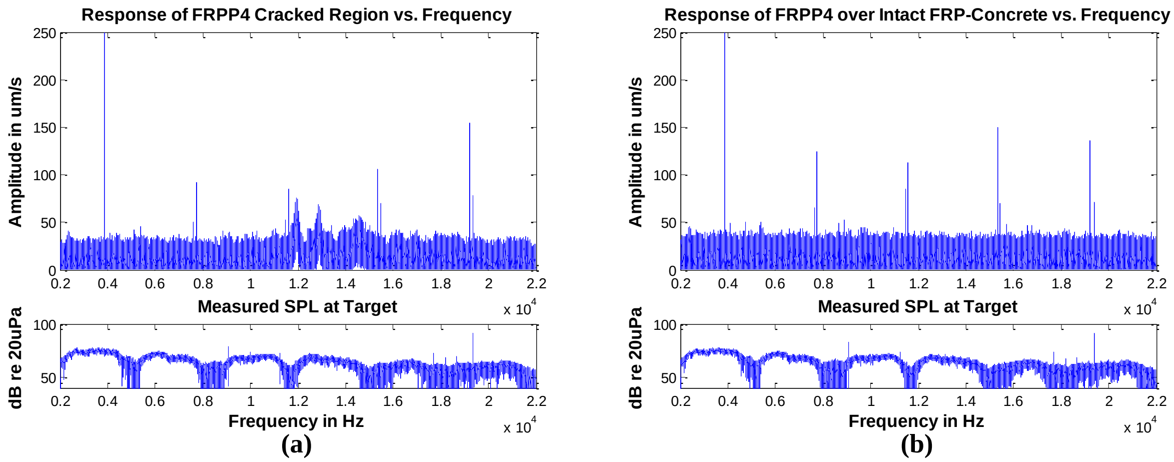


Figure 4: Frequency response velocity spectrums for FRPP4 over (a) cracked region and (b) intact material

CONCLUSIONS

There are differences in the response frequency spectrums between square shaped defects and slender rectangular crack-shaped defects both quantitatively and qualitatively. The spacing between resonant frequencies was shown by plate vibration theory to converge as the aspect ratio approaches zero. Measurements of defects of widths 0.25", 0.5", 0.75", 1", and 3" confirmed this as the ratio or spacing between the first and second resonant frequency decreased as the defect width decreased. Qualitatively, as the defect aspect ratio decreases, the resonant peaks also may tend to become broader suggesting higher damping of the resonance. The acoustic-laser vibrometry system was also capable of detecting a shallow crack defect under the surface of FRP-strengthened concrete, where there is no degradation of the FRP-epoxy-concrete interface, suggesting that the method may be applicable to NDT of reinforced concrete and other more challenging material systems.

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