Remote Detection of Debonding in FRP-strengthened Concrete Structures Using Acoustic-Laser Technique

O. Büyüköztürk, R. Haupt, C. Tuakta and J. Chen

Abstract Fiber-reinforced polymer (FRP) strengthening and retrofitting of concrete elements, such as beams, columns, slabs, and bridge decks, have become increasingly popular. Nonetheless, rapid and reliable nondestructive testing techniques (NDT) that are capable of remotely assessing *in-situ*integrity of retrofitted systems are needed. Development of a robust NDT method that provides an accurate and remote assessment of damage and flaws underneath the FRP plates/sheets is required. In this study, a NDT based on an acoustic-laser system is proposed for remote detection of debonding in FRP-strengthened concrete structures. This technique utilizes the difference in dynamic response of the intact and the debonded regions in a FRP-strengthened concrete structure to an acoustic excitation, which is then measured using laser vibrometry. Feasibility and accuracy of the technique were investigated through a series of measurements on laboratory-sized plain, reinforced, and FRP-strengthened concrete specimens. It was shown that the difference in dynamic response could be captured by the acoustic-laser system and is in good agreement with simple calculations.

Keywords Concrete • Debonding • FRP • Laser vibrometry • NDT • Remote

Introduction

FRP-concrete interface conditions cannot be fully revealed until the FRP composite layer is removed unless the member has already been subjected to apparent damage. Partial or complete removal of the FRP composite layer for damage observation may

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pose a danger of structural collapse. An FRP-retrofitted beam or concrete column may appear safe without showing signs of substantial damage underneath FRP composites and yet may contain severely deteriorated concrete and debonded FRP composites. A modest seismic event can cause such a scenario that significantly damages the FRP-concrete system without failure.

In order to effectively detect and characterize damages in FRP-retrofitted reinforced concrete (RC) structures, a NDT technique has to be capable of detecting the extent of concrete cracking, delamination in the interface regions, decohesion in epoxy or FRP, and sizeable voids trapped in the vicinity of interface regions. Several NDT techniques of FRP-concrete systems have been investigated, including stress wave (acoustic), infrared thermography, x-ray, and microwave (radar) techniques [1]. Acoustic emission and radar techniques have been of particular interest to researchers for possible damage detection of RC and FRP-retrofitted concrete structures tested in laboratory settings [2-7]. Limitations of many current techniques for the NDT of FRP-concrete systems include insufficient detection capability, testing equipment contact with the target, environmental conditions, and spatial resolution problems. To overcome these deficiencies, we propose to develop a non-contact and standoff acoustic-laser method for detecting such damages in FRP-concrete systems. It is anticipated that the method will be applicable to a wide variety of FRP-concrete retrofitted systems, and will represent a robust complementary capability to other rapid scanning techniques such as the microwave-based NDT.

Acoustic-Laser Technique for Damage Detection

The acoustic-laser detection technique is based on the concept that local damages, such as debonding and voids in the FRP-concrete interface region vibrate differently than intact regions. These vibration anomalies are direct functions of the damage dimensions and mechanical properties (Fig. 1). Vibration anomalies can be

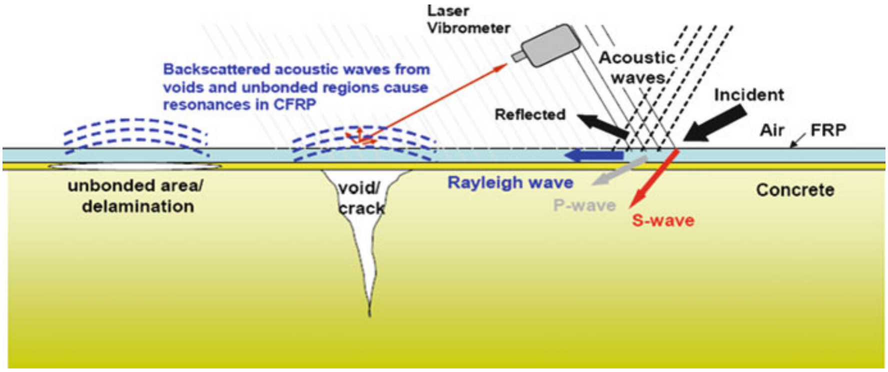

Fig. 1 Acoustic coupling to concrete structures

measured at the target surface using a laser vibrometer, and thus, target's near surface damages can be remotely detected, mapped, and quantified. The method represents a robust NDT technique well suited for thin-layered systems since debonding and voids in such systems occurring just below or within the FRP layering will interfere with acoustically induced surface waves traveling along the FRP-air interface. These discontinuities will produce vibration resonant frequencies as functions of the dimensions of the debonded region.

Acoustic source—parametric acoustic array

Parametric acoustic arrays (PAA) have been used in underwater sonar and commercial loudspeaker systems to transmit highly directional acoustic beams to targets. The PAA has two sources of sound; one source is typically ultrasound generated directly from high-frequency transducers; the other is lower frequency audible sound that is a product of the ultrasonic wave and nonlinear effects in the volume of air in front of the transducer (self-demodulation) [8]. A PAA can deliver the necessary level of acoustic power from considerable distances to localized regions of the FRP structure. To be able to detect voids of small size between FRP and concrete, the use of PAA source exhibits potential advantages of ultrasonic and high audible frequency acoustic excitation.

Vibration detection with laser doppler vibrometry

Laser vibrometry is based on the frequency modulation imparted on the laser carrier wave caused by a vibrating surface in contact with the laser beam [8]. LDV sensing of the acoustic vibration response of the FRP system offers significant advantages over contact sensors. The laser beam does not alter the target's mechanical properties, can provide location accuracies within millimeters, and can sample many points on the target rapidly, and can measure multiple target locations simultaneously with a multi-pixel vibrometer. Some commercial LDV systems are capable of sensing vibrations on targets 100-m from the laser, while custom designs can well exceed 100-m and remain eye-safe.

Experimental set-up and measurement procedure—acoustic-laser detection system

The acoustic-laser detection system was constructed from commercially available components including a 24-inch diameter Audio Spotlight Transducer (a PAA source) from Holosonics Research Labs, Inc., and a laser vibrometer from Polytec,

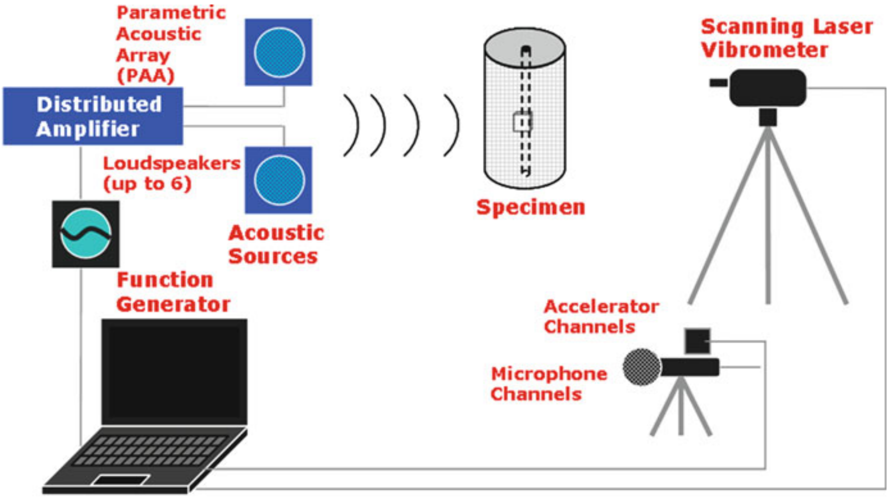

Fig. 2 Experimental setup for the acoustic-laser system

Inc., consisting of an OFV-505 optic sensor head and an OFV-5000 controller. An Earthworks 30M microphone was used to measure the acoustic wave characteristics delivered to the specimens. The PAA source was controlled by a laptop computer and generated FM linear chirps between 500-3000 Hz. Vibration response data were collected at a rate of 100 kHz using an IOtech 516E WaveBook. The measurement set-up is shown in Fig. 2.

Preliminary Study

To examine the feasibility of the acoustic-laser method, a preliminary experimental study was conducted to validate the reliability of the measurement. Two concrete cylinder specimens (30 cm height and 15 cm diameter) wrapped by GFRP sheet with artificial voids were used. Artificial voids of 1.9x1.9x1.9 cm^3(0.75x0.75x0.75 in^3) and 3.8x3.8x3.8 cm^3(1.5x1.5x1.5 in^3) cubes were introduced by inserting styrofoam pieces at the interface between concrete and the GFRP layer. Thickness of the GFRP layer was in the mm range and its Young's modulus was 148 GPa (21.465x10^6psi). The density was 1.5x10^3kg/m^3(5.4191x10^{-2}lb/in^3). Dynamic measurements were collected at MIT Lincoln Laboratory and vibration signatures were obtained as shown in Figs. 3 and 4.

Figure 3b shows the vibration velocities measured at single locations, one directly over the void (red and blue curves) and over an intact solid concrete region (black curve), as a function of acoustic excitation frequency. In Fig. 4a, b, results are shown for the loudspeaker source (a linear chirp from 50-2000 Hz) and for the PAA (a linear chirp from 2000-7000 Hz), respectively. The signature over the void exhibits larger velocity amplitudes than those of the intact region and may be useful for detecting an anomalous region in the sample. In the case of high

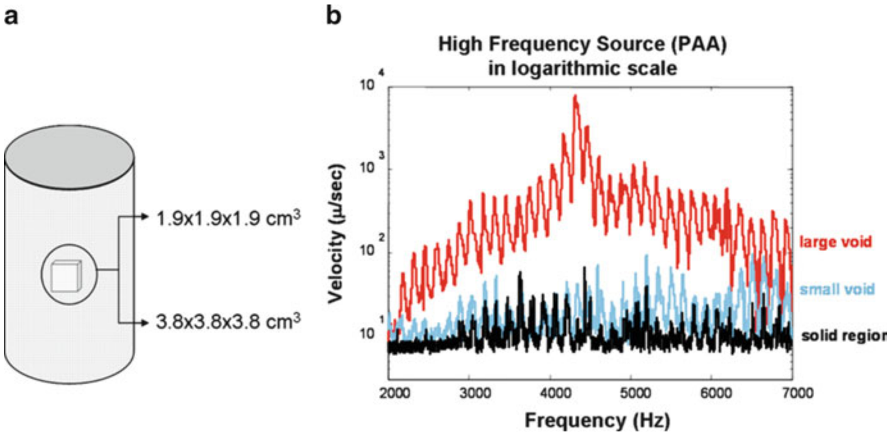

Fig. 3 GFRP-confined concrete specimen with a void (**a**) and vibration signatures of small void, large void, and solid region (**b**)

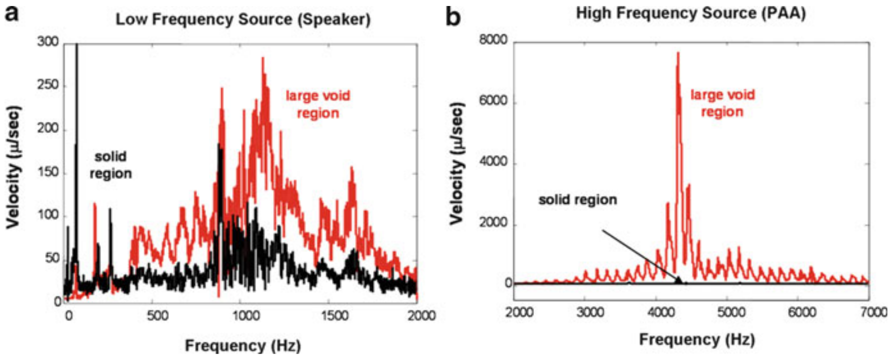

Fig. 4 Vibration signatures of a GFRP-confined concrete specimen containing a 3.8 cubic centimeter void in its surface under low (**a**) and high (**b**) frequency sources

frequency source, the larger void exhibits a distinct resonance at 4300 Hz. This is the resonance frequency of the first mode. The size of void can be inferred from the peak resonance frequency.

Assuming the GFRP layer over the defect behaved like a vibrating membrane, the resonance frequencies can be given as:

$$f = \frac{\nu}{2}\sqrt{\left(\frac{l}{L_x}\right)^2 + \left(\frac{m}{L_y}\right)^2} \tag{1}$$

where l and m are integers, v the speed of sound, and L_x and L_y the dimensions of the vibrating membrane. From Eqn. (1), with a speed of sound of about 340 m/s at sea level and room temperature, this gives us a fundamental frequency of 4474 Hz ($l=1$, $m=0$). This is very close to the resonance frequency of 4300 Hz measured over the void by the acoustic-laser system. The difference between these values were expected to be due to the following reasons; 1) different geometries result in different natural frequencies; 2) actual boundary condition at the edge supports will be different from the perfectly assumed boundary condition used in analytical solution; 3) the artificial void is made of soft polymer such that the void is not air only, hence the boundary condition underneath the GFRP is different from the one used in the analytical solution. Although better theoretical prediction can be made by finite element analysis (FEA), this preliminary study exhibited the reliability of the proposed acoustic-laser method.

In addition, the distinct and large vibration resonance signatures over the area covering the voids exhibit a high signal-to-noise ratio (SNR). In our measurement example shown in Fig. 3, the SNR approached 40 dB compared to an intact region. Furthermore, the size of the damaged area can be determined from the peak resonance frequency. In these types of measurements, it is anticipated that environmental interference or "clutter" will have minimal effects. It is anticipated that delamination and flaws in the FRP materials will have the largest vibration velocity response to sound waves compared to any other structures and environment in the measurement system.

Summary and Future Work

Our preliminary work has shown that the proposed acoustic-laser technique has a potential for detection of defect in FRP-concrete structural member. The vibration signatures measured by the laser vibrometer can be used to distinguish and characterize the defect in the GFRP-confined concrete specimens. It also offers good signal-to-noise ratio, and the effect of ambient vibration on detectability is expected to be minimal. Further experimental investigations will be focused on the effect of distance between detected surface and the acoustic source, the effect of sound pressure level and frequency on detectability.

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