Damage inspection of fiber reinforced polymer-concrete systems using a distant acoustic-laser NDE technique

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ABSTRACT

In this paper, a distant acoustic-laser NDE technique is proposed, utilizing a high powered standoff parametric acoustic array (PAA) and laser Doppler vibrometry (LDV), for the detection of debonding and delamination in multi-layer composite systems. Fiber-reinforced polymer wrapped concrete cylinder specimens with artificial defect were manufactured and used in the validation of the technique. Low-frequency (50 Hz 2 kHz) and high-frequency (2 kHz 7 kHz) focused sound waves were generated by PAA, and surface dynamic signatures of the specimens were remotely measured by LDV. From the results it is found that the proposed technique successfully captures the presence of near-surface debonding/delamination.

Keywords: : Debonding detection, acoustic-laser NDE, parametric acoustic array (PAA), laser Doppler vibrometry (LDV), dynamic signature

1. INTRODUCTION

Fiber reinforced polymer (FRP) materials have become increasingly important in civil infrastructure applications since the 1990s. Existing applications include concrete internal reinforcements, pre- and post-stressing tendons, external strengthening and repair, as well as all-composite structural systems. In particular, externally strengthening and retrofitting of reinforced concrete (RC) elements such as beams, columns, slabs, and bridge decks using FRP have been predominant owing to the increasing number of substandard structures as a result of design code revision, physical aging, effect of loads, environmental deterioration, and inadequate maintenance. The use of FRP composites for the externally strengthening of RC structures has also been adopted in design codes and standards by various professional societies around the world, including American Concrete Institute (ACI), American Society of Civil Engineers (ASCE), American Society of Testing and Materials (ASTM), Canadian Society of Civil Engineers (CSCE), and Japanese Society of Civil Engineers (JSCE).

For flexural strengthening of RC elements, light-weight FRP laminates in the form of plates and sheets are often bonded to the soffits of the RC elements. Previous investigations on large scale retrofitted RC beams have shown that premature failures usually take place through various possible mechanisms including concrete crushing and steel yielding, FRP rupture, shear failure, concrete cover delamination, and debonding in the vicinity of FRP-concrete interface.[1,2] For compressive strengthening of RC elements, it has also been reported that various modes of failure can occur by core concrete cracking, crumbling and delamination depending on the various degree of confinement pressures provided by the jacket.[3] Furthermore, possible air pockets and voids that may have been created during the manufacturing at the FRP-concrete interface would affect post-peak behavior and the failure mode. Concrete damages in the interface vicinity, bond delamination between layers of a FRP jacket and those in overlap joints can lead to abrupt, brittle failures of the strengthened FRP-concrete system. To prevent these failures from happening, reliable NDE technologies are needed for the early detection of defects (e.g., air pockets/voids, FRP delamination/debonding) in FRP-concrete systems.

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Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2010, edited by Peter J. Shull, Aaron A. Diaz, H. Felix Wu, Proc. of SPIE Vol. 7649 76491J · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.847630

The objective of this paper is to report the development of a distant acoustic-laser NDE technique utilizing a high powered standoff parametric acoustic array (PAA) and laser Doppler vibrometry (LDV) for the detection of debonding and delamination in multi-layer FRP-concrete systems. In proposed approach, a high powered standoff parametric acoustic array (PAA) that can excite FRP-concrete systems from ranges exceeding 30 meters has been developed at the MIT Lincoln Laboratory. This acoustic source and a laser Doppler vibrometer offer opportunities to examine FRP-retrofitted concrete components that are difficult to reach such as bridge piers in water or for elevated roadways. The use of traditional contact transducers would make this process much more difficult if not impossible.

In this paper, various NDE techniques for the inspection of delamination/debonding in FRP-concrete systems are first reviewed. Inspection methodology and system components of the proposed acoustic-laser NDE techniques are introduced. Performance of the technique has been validated by laboratory measurements on glass FRP-wrapped concrete cylinder specimens with artificial defects. Finally, research findings are discussed in the summary section.

2. REVIEW OF NDE TECHNIQUES FOR FRP-CONCRETE SYSTEMS

Currently, several NDE techniques have been developed for their application on civil engineering structures such as bridges and buildings, including stress wave (acoustic), infrared (IR) thermography, radiography, and radar (microwave) techniques. These applications are briefly reviewed in the following.

Acoustic methods are based upon elastic wave propagation in solids, including pulse-echo, impact-echo, ultrasonic, acoustic emission, and spectral analysis of surface waves (SASW) techniques. Disadvantages in conventional acoustic methods include the need of intimate contact between the equipment and subject, the use of sound couplant, as well as the existence of multiple paths through the same subject.[4–7]

Infrared (IR) thermography is based on the detection of heat flow in the subject in which air gaps resulting from delamination act as insulators, which block out the proper heat flow. Data interpretation is complicated because of varying ambient temperature conditions and surface emissivity variations, which is a function of surface properties.[8,9] Additionally, thermography provides lower resolutions than those by other techniques such as laser vibrometry.

Radiographic methods use high frequency electromagnetic (EM) radiation (beta rays, neutron beams, X-rays, and Gamma rays) passing through the subject and exposing it onto a film on the other side of the subject. When applied to FRP-concrete systems, limitations include the need to access both sides of the subject, the need of safety precautions, and long exposure.[10,11]

Radar (microwave) methods have been used for site characterization in geotechnical engineering in the past, as well as to evaluate concrete structures, pavements, and bridges.[12,13] Radar methods use the reflection and/or transmission of EM signals to characterize materials and to extract structural features for evaluation purposes, either by near-field contact,[14] or near-field non-contact,[15] or far-field non-contact[16–18] measurements. High frequency EM signals are constrained by near-surface penetration in FRP-concrete systems, although higher resolution can be achieved when compared with the use of low frequency EM signals.

The laser Doppler vibrometer technique has been studied to a limited extent for detecting delamination in composite specimens. The technique is based on Doppler shifts effect which characterizes the frequency changes owing to movement of the source, receiver, propagation medium, or intervening reflector or scatter. The technique has been applied to the detection of delamination in ceramic tiles[19] and composites structures.[20] These previous developments generally dealt with all composite/epoxy specimens. Reported work also includes the use of sound and focused sound to excite frescos on masonry together with the use of scanning laser for measurements.[21] In these tests, the excitation source was in contact or in close range with the sample either at the top or side edge, and the method relied on the propagation of sound waves through the material to the damaged area. Furthermore, this development was not particularly developed for FRP-concrete systems.

We propose the development of a novel and effective technique for the nondestructive evaluation of multi-layer FRP-epoxy-concrete systems using an acoustic-laser technique which will utilize a remote excitation and measurement approach, such as from a shoreline or from a barge looking up, involving large distances more than

30 m (greater than the far-field distance). In this approach, we use an airborne acoustic wave to excite the direct location of the damage underneath the FRP sheets/plates and in the concrete substrate using a focused sound beam. The target vibration is measured using laser Doppler vibrometry. Figure 1 shows the inspection scheme in a field configuration. The details of the proposed approach will be discussed in the following sections.

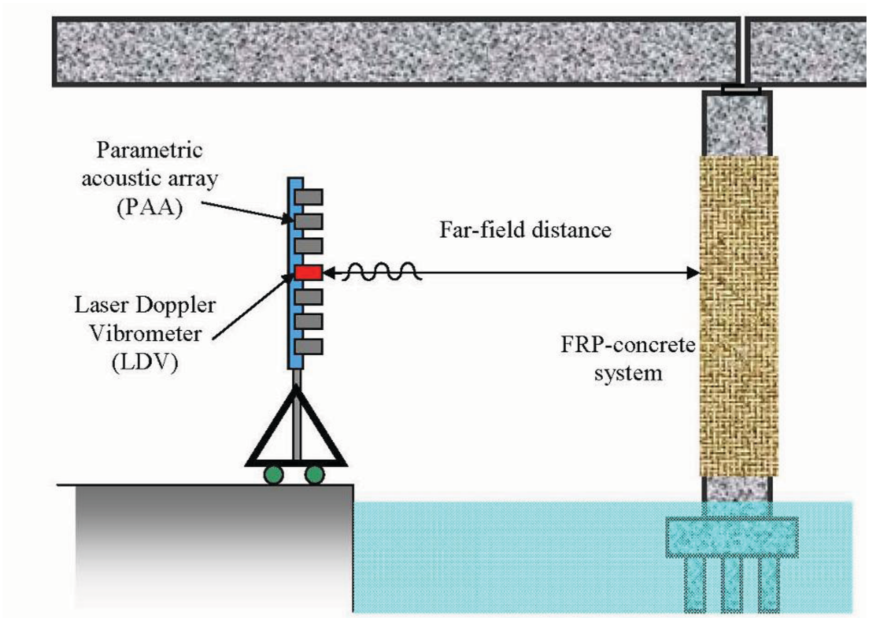

Figure 1. Distant inspection of the acoustic-laser NDE technique

3. DISTANT ACOUSTIC-LASER NDE TECHNIQUE

In proposed acoustic-laser NDE technique, we use a high powered standoff parametric acoustic array (PAA) capable of exciting the FRP-concrete system from ranges exceeding 30 meters and a laser Doppler vibrometer measuring the surface dynamic signature of the system. A focused sound beam is generated by the PAA such that the beam diameter can be controlled to directly and locally excite the surface area where damages/defects are embedded in the FRP-concrete systems. The PAA source is shown in Figure 2. Flaws and structural damages embedded underneath the externally bonded FRP plates or wrapped FRP sheets will be detected through the acoustically excited vibration launched by the system (Figure 3). Surface dynamic signatures (Rayleigh waves) of damaged and intact regions are collected by laser Doppler vibrometer and analyzed for damage detection. The laser vibrometer beam size provides us the opportunity to obtain spatial resolution on the order of a millimeter. The PAA has two sources of sound; one source is high frequency which is generated directly from one or more high-frequency transducers (2 kHz∼7 kHz); the other is low frequency which is generated from nonlinear effects in the volume of air in front of the transducer (500 Hz∼2 kHz). The PAA source can provide a practical means to deliver the necessary level of acoustic power in air to the void underneath the FRP sheet while minimizing system size and weight, reducing the sound level imposed on personnel close to the source. To be able to detect the voids of small size between FRP and concrete, the use of PAA source exhibits potential advantages on this particular application.

3.1 Theoretical Basis

Propagation of acoustic waves in media can be described by the following governing equation representing the free vibration of a three-dimensional uniform circular plate with fixed edge supports. Its analytical solution can be found and used as an approximation to the problem.[22]

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

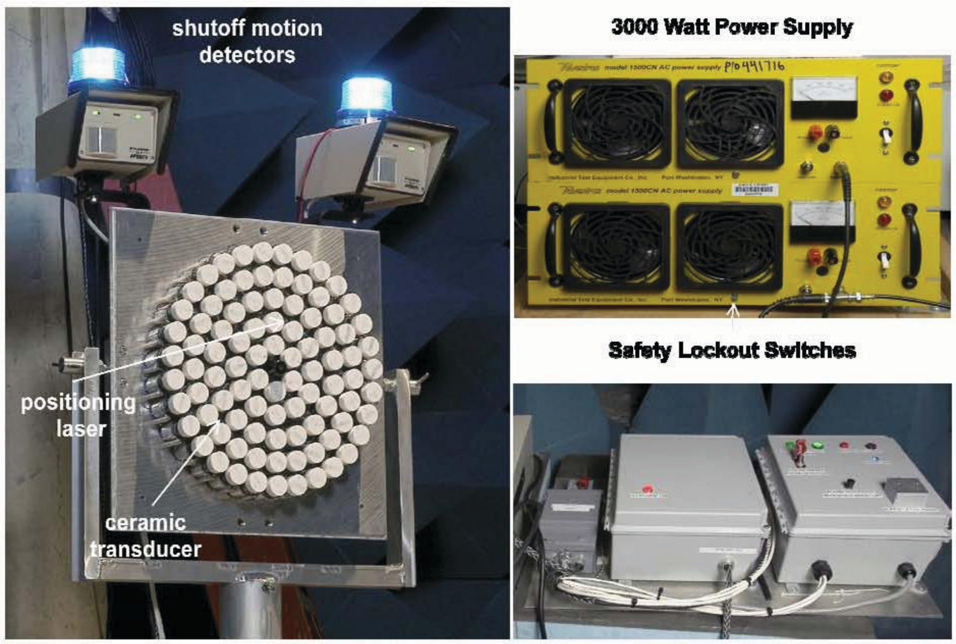

Figure 2. Parametric acoustic array (PAA) [Courtesy of MIT Lincoln Laboratory]

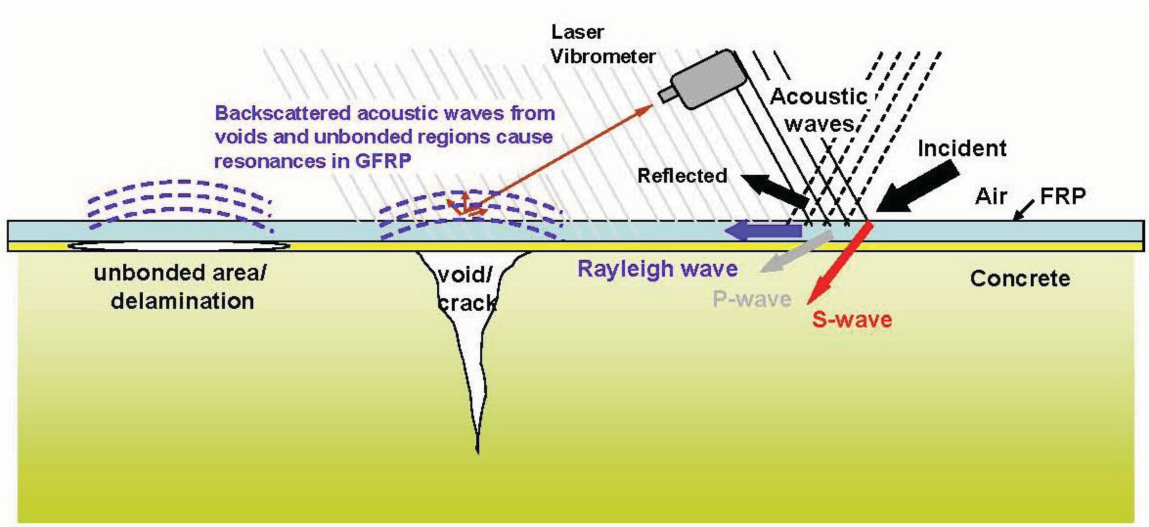

Figure 3. Distant PAA excitation and LDV measurements in the damaged and intact regions

where $D = \dfrac{Eh^3}{12(1-\omega^2)}$ = flexural rigidity of the circular plate, E = Young's modulus, h = thickness of the plate, ν = Poisson's ratio, ρ = density of the material, $w = w(r, \theta, t)$ = transverse displacement in cylindrical coordinates as the function of spatial variables (r, θ) and time t. The natural frequencies are

$$\omega_{mn} = \frac{(\lambda a)_{mn}^2}{a^2}\sqrt{\frac{D}{\rho h}} \tag{2}$$

The value of $(\lambda a)_{mn}$ for the $m-th$ order natural frequency can be determined by the frequency equation.

$$J_n(\lambda a)\frac{dI_n(\lambda a)}{dr} - I_n(\lambda a)\frac{dJ_n(\lambda a)}{dr} = 0 \tag{3}$$

where a = the radius of the circular plate, λ = eigenvalue of the frequency equation, $J_n(\lambda a)$ = Bessel function of the first kind, and $I_n(\lambda a)$ = modified Bessel function of the first kind. For the GFRP-concrete specimens used in this research, thickness of the GFRP layer is 0.25 cm. Young's modulus of the GFRP layer is 148 GPa (21.465 psi). The density of GFRP is 1.5 kg/m^3 (1.3906 lb/in^3), and the Poisson's ratio of GFRP is 0.25.

3.2 Acoustic Radiation Patterns

To better understand the efficiency of acoustic energy transmission and focusing by the PAA source at distant ranges, the acoustic radiation patterns of the PAA are measured and shown in Figure 4. In Figure 4, the acoustic radiation patterns of the PAA source at two particular frequencies were measured at 7 kHz (audible) and 26.3 kHz (ultrasonic) in the unit of sound pressure level (SPL).

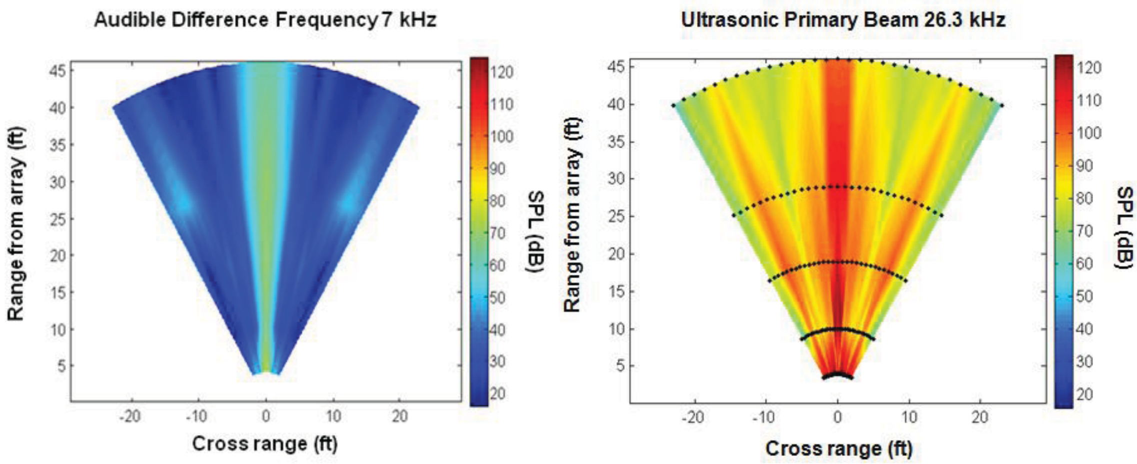

Figure 4. Acoustic radiation patterns of the PAA source at different ranges

4. EXPERIMENTAL VALIDATION

The feasibility and performance of the acoustic-laser NDE technique is validated and examined using laboratory measurements on glass FRP (GFRP)-wrapped concrete cylinder specimens. Two cylinder specimens were manufactured and subjected to laboratory acoustic-laser measurements. Details of laboratory measurements are provided in the following sections.

4.1 Specimen Preparation

Two specimens were designed and manufactured for laboratory acoustic-laser measurements; specimen AD1: GFRP-concrete cylinder with artificial defect type 1, and specimen AD2: GFRP-concrete cylinder with artificial defect type 2. Portland Type I cement was used, and the mix ratio of concrete was water:cement:sand:aggregate = 0.45:1:2.52:3.21 (by weight). The diameter of concrete core was 15.24 cm, and the heights were 30.4 cm and 38.1 cm. Specimens AD1 and AD2 are shown in Figure 5. Concrete cores of these specimens were cast with an artificial defect and cured in clean water for 14 days. Artificial defect type 1 was cubic-like (3.8cm-by-3.8cm-by-2.5cm), and artificial defect type 2 was delamination-like (7.6cm-by-7.6cm-by-0.5cm). These two artificial defects were created at the interface between GFRP sheet and concrete substrate in the GFRP-concrete systems. After the curing period the concrete cores were wrapped with GFRP sheet according to the manufacturer's specifications. A unidirectional glass fabric system (Tyfo® SEH-51A by Fyfe Co. LLC) was used and molded with epoxy resin (Tyfo® S Epoxy) to form the GFRP-epoxy sheet wrapped on the surface of the concrete core. The volumetric ratio of epoxy:GFRP was 0.645:0.355. The thickness of the GFRP-epoxy sheet was 0.25 cm. Single layer configuration scheme was adopted.

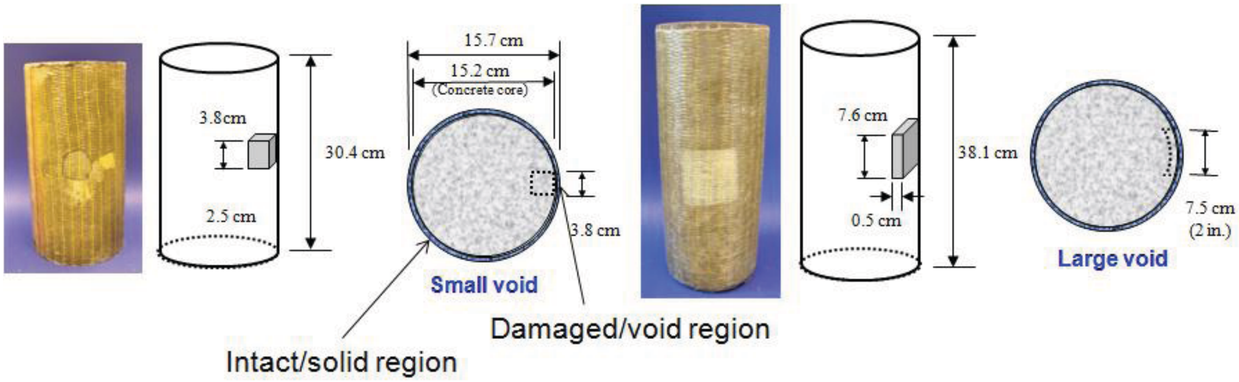

Figure 5. Description of two GFRP-concrete specimens

4.2 Measurement Results

The surface velocities in the damaged (void) and intact (solid) regions of the GFRP-concrete cylinders were excited by the PAA source and measured by the laser Doppler vibrometer at 50∼7000 Hz. Figure 6 shows the surface vibration signatures (velocities) of the damaged and intact regions from 50 Hz to 2000 Hz, while Figure 7 shows from 2000 Hz to 7000 Hz. In these figures, the vibration velocities measured at single locations are illustrated; one directly over the void (red curve) and over a solid concrete region (black curve) as a function of acoustic excitation frequency.

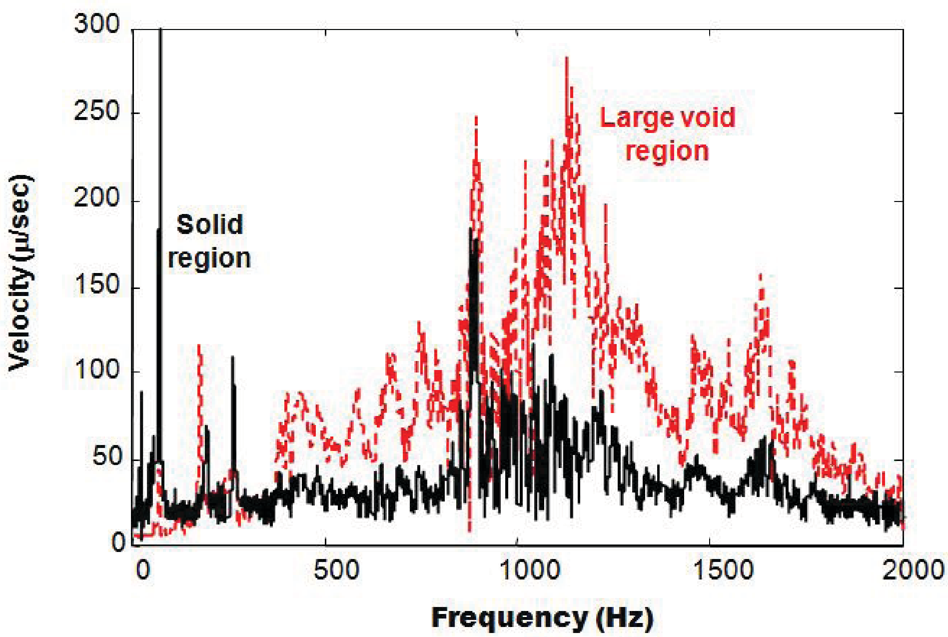

Figure 6. Low frequency surface acoustic responses of damaged (void) and intact (solid) regions

It is found that the vibration signature over the void exhibits a larger velocity amplitude than that of the intact region and may be useful for detecting an anomalous region in the multi-layer GFRP-concrete system. The dynamic response of the void excited by a higher acoustic frequency band (2000∼7000 Hz) using the PAA exhibits a large resonance velocity at 4322 Hz . The velocity amplitude at the peak resonance is over 30 dB greater than the return from an intact region. Intact response (solid region) is differentiated from the damaged response (void region) in both Figures 6 and 7, especially in Figure 7 where significant differences are observed.

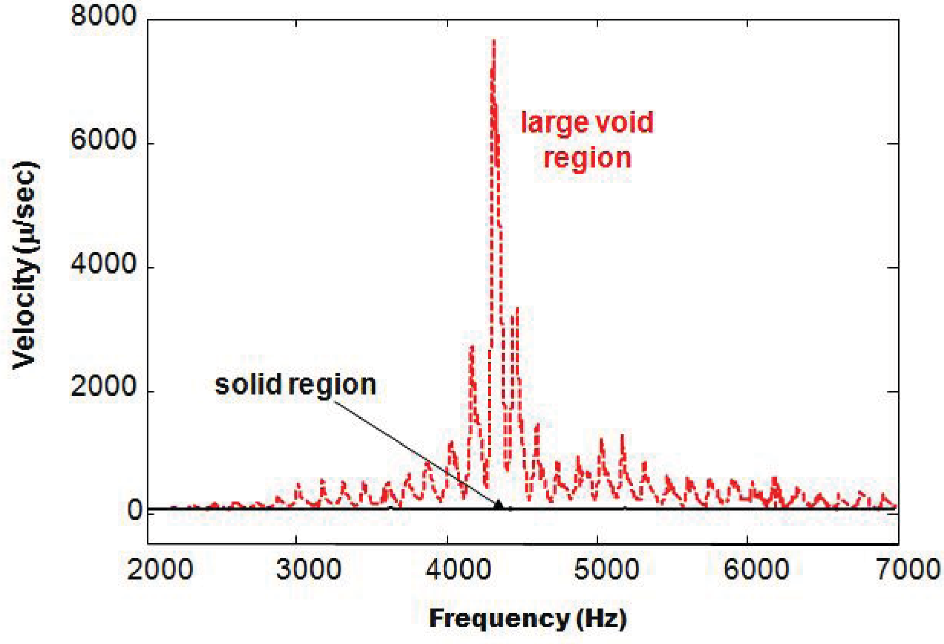

Figure 7. High frequency surface acoustic responses of damaged (void) and intact (solid) regions

Additionally, it is noteworthy to point out that the size of large void (7.6cm-by-7.6cm-by-0.5cm) can also be inferred from the peak resonance frequency by Eq.(2). Using a sound speed of 340 m/s shows that the half-wavelength of the resonance is found close to 2 inches (7.5 cm) at 4512 Hz which is close to the measured 4322 Hz. The difference is attributed to the non-perfect shape of the void defect and the variation at the support condition.

5. SUMMARY

A distant acoustic-laser NDE technique for the condition assessment of FRP-concrete systems is proposed. The technique consists of a high powered standoff parametric acoustic array (PAA) that can excite FRP-concrete systems from ranges exceeding 30 meters and a laser Doppler vibrometer for the accurate distant measurements of surface vibrations on the FRP-concrete systems. From the laboratory validation, it is found that the proposed technique is capable of remotely exciting GFRP-concrete cylinder specimens and collecting their surface velocities. High velocity measurements were observed at the delamination/debonding location and at the resonant frequency relating to the defect geometry. Consequently, a database connecting surface velocity measurements and defect characteristics can be established for the rapid interpretation of results in practice. Future research issues include the performance of the acoustic-laser NDE technique in a noisy environment (low signal-to-noise ratio), application on smaller defects/damages, and detection of surface concrete cracking and steel corrosion.

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