A photophone-based remote nondestructive testing approach to interfacial defect detection in fiber-reinforced polymer-bonded systems

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Abstract
Externally bonded fiber-reinforced polymer is an increasingly popular material to be used in strengthening and retrofitting aging structures. In such structures, debonding defects may occur at or near the interface between fiber-reinforced polymer and concrete. As such debonding in fiber-reinforced polymer-bonded systems is generally brittle in nature, there is a need of a reliable inspection technique that can provide early warning of interfacial defects such that premature failure of fiber-reinforced polymer-strengthened structures can be avoided. A remote nondestructive testing approach based on the working principle of a photophone is presented here as an economical alternative to laser Doppler vibrometry for detecting interfacial defects. Concrete specimens retrofitted with fiber-reinforced polymer are excited acoustically by white noise, while the surface of the structure is illuminated by a light source. If an interfacial defect exists beneath the surface, the surface will exhibit a frequency response different from an intact surface. The surface of the fiber-reinforced polymer portrays the role of flexible mirror in a photophone, which encodes information about surface vibration into amplitude-modulated light signal. A light detector then captures the irradiance of the reflected beam, and the amplitude modulation is converted into frequency domain in post-processing. With this technique, defect dimensions and thus damage extent can be inferred from the frequency spectrum obtained. The obtained results correspond well with the theoretical calculation, demonstrating the robustness and the applicability of the proposed technique in civil infrastructure.

Keywords
Acoustic-laser, amplitude-modulated modal analysis, fiber-reinforced polymer, interfacial defect, nondestructive testing, photophone

Introduction
The maintenance of aging structures is a challenging issue faced by many nations.¹ In most cases, strengthening and retrofitting of these deteriorated structures may be more economical than reconstruction, especially in situations involving the preservation of historic sites. The use of fiber-reinforced polymer (FRP) composites as an externally bonded element to retrofit structural elements such as beams, columns, slabs, and bridge decks in order to restore the design capacity and structural redundancy of deteriorated structures has emerged as a popular strengthening and retrofitting technique. FRP, as a thin sheet of composite material, has a lot of desirable properties when compared with the conventional bulk construction materials, such as high strength-to-weight ratio, good environmental resistance, and excellent resistance against fatigue. Because externally bonded FRP becomes more popular in retrofitted structures, the failure modes of FRP-bonded systems have thus been studied extensively to better understand the mechanical behavior of such composite structures.²–⁶ Failures in FRP-bonded reinforced concrete (RC) beams can be classified into

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two major mechanisms: (1) flexural failures of critical sections, such as crushing of concrete and FRP rupture and (2) debonding of FRP from the RC beams. The near-surface debonding defects resulting from the latter case will be referred to as interfacial defects in this article, and they are the focus of this study. Interfacial defects often occur in regions with high stress concentration and/or shear stress discontinuity, which are positively correlated with (1) regions of material discontinuity, (2) poor installation including inadequate surface preparation of the substrate, and (3) the presence of cracks (e.g. propagation of flexural or flexural-shear cracks from the concrete substrate to the FRP-concrete interface, resulting in delamination). The failures modes due to interfacial defects are brittle in nature and will result in premature failures of FRP-strengthened elements if not promptly resolved.

Current nondestructive testing (NDT) approaches developed for civil engineering application include the use of ultrasound, X-ray and neutron radiography, near-field and far-field radar, and infrared thermography. However, these techniques may not always be optimal for the remote detection of interfacial defects. Passive thermography typically has insufficient spatial resolution to resolve small interfacial defects. Radiography involves the use of hazardous ionizing radiation. The radar approach may have issues if carbon fiber–reinforced polymer (CFRP) sheets being penetrated by radar are not arranged in a parallel orientation as CFRP is a highly conductive material at microwave frequencies. Finally, while near-field radar and ultrasound are promising approaches, they require a close proximity to the subject. Recently, high-speed video in conjunction with motion magnification has been applied to remotely evaluate modal behavior. Despite being promising in detecting larger scale damages, as of the moment of writing, the maximum frequency measurement demonstrated by the high-speed video technique is 2500 Hz, which is below the typical fundamental frequencies of interfacial defects as explored in this article. To complement existing NDT approaches, an acoustic-laser technique has been devised specifically to detect interfacial defects from a distance based on their vibrational behavior.

It has been shown that interfacial defects in FRP-bonded systems can be modeled as a combination of a clamped plate (representing the FRP surface) and an acoustic cavity (representing the air gap at the interface), resembling the physics of a drum. In such defects, the fundamental mode of vibration lies typically at the order of kHz. However, the dedicated setup used in previous acoustic-laser studies may cost a million US dollars and might prove an obstacle to the commercialization of the acoustic-laser technique. This study presents an economical augmentation to the previous works based on the design of a photophone. Electronic parts required to assemble the NDT device put forward in this article can readily be purchased from consumer electronics retailers, and the total cost of a functioning setup is around a hundredth of the original work.

Originally conceived by Alexander Graham Bell who invented the telephone in 1880, a typical photophone concentrates sunlight onto a flexible mirror which reflects the sunlight to a remote receiver (Figure 1). Excited by the speaker’s voice, the flexible mirror modulates the reflected sunlight’s radiant intensity by flexing convex and concave according to the changing sound pressure, dispersing, and converging the beam of sunlight. This amplitude-modulated radiant intensity is converted back to an audio signal when detected by the receiver. The photophone eventually achieved the first wireless telephone communication, predating the first spoken radio transmission by almost two decades and laying the groundwork for fiber-optic communication a century later. Although considered by Bell to be one of his greatest achievements, even more superior than the telephone, the photophone never went into mainstream usage and it is found mostly in military use. Nowadays, the photophone is commonly known as the “spy microphone” in hobbyist projects, with few real-life applications. In this article, the interest in photophone is renewed by considering an NDT application in the detection of interfacial defects in FRP-bonded systems. The working principle of the modified photophone will first be introduced with the relation to previous acoustic-laser studies, followed by experiments with artificially induced delamination-like interfacial defects on FRP-bonded concrete specimens. Finally, benefits and limitations of this photophone-based technique will be addressed based on experimental results, and future research direction including an extension of this technique to general modal analysis will be discussed.
The acoustic-laser technique

Although previous acoustic-laser studies focus on detecting debonding defects located at or near the interface between a sheet of FRP and its substrate, it is in fact a general NDT method for remote evaluation of structures that can be excited acoustically and would induce a vibration on an exposed measurable surface. Defects are identified based on the frequency response of the surface vibration. Previous works involve exciting the FRP-bonded structure by a frequency sweep from a high-power standoff parametric acoustic array (PAA), and the resulting vibration is monitored remotely by a laser Doppler vibrometer (LDV) with the peaks in the frequency response spectrum corresponding to vibration modes of the defect. The benefits of this design include the ability of long-range measurements up to 30 m, the robustness against environmental noise as the technique is based on interference, and the ability to connect measurement result (surface vibration velocity) with defect characteristics for intuitive interpretation of experiment results.

However, the technique measures only surface vibrations. Therefore, to obtain a holistic view of the structure’s health, the acoustic-laser technique must be combined with other NDT techniques to reveal subsurface defects.

The photophone-based approach and experiment setup

In this study, the measurement setup is refined to demonstrate the flexibility in deployment and commercial viability of the acoustic-laser technique (Figure 2(a)). An ordinary loudspeaker is used in place of the PAA as the acoustic excitation source given that the fundamental modes of interfacial defects have been shown to be in the order of kHz, thus can be excited by consumer-grade electronics. White noise is introduced for acoustic excitation instead of a frequency sweep to cover a wide range of frequencies in a short period of time. The LDV is replaced by the low-cost photophone-based measurement system proposed in this article, exchanging frequency modulation (FM) in an LDV system with amplitude modulation (AM), with
a tradeoff in accuracy and precision. Although the setup in previous works involving PAA and LDV produces highly precise results, the cost of the setup is over a million dollars. At around a hundredth of the original cost, the current setup provides comparable performance, albeit at the expense of the resistance to environmental noise, as expected in an AM system.

Although the photophone was intended for voice transmission, it is realized that the transmission carries not only the voice but also information regarding the vibrational characteristics of the flexible mirror. Through white noise excitation or a frequency sweep, the modes of resonance of the mirror can be probed. Furthermore, it is noted that all reflective surfaces can act as the flexible mirror, allowing modal analysis on a general object based on the principle of a photophone. If a surface is dull, a retroreflective sticker or reflective paint can be applied to the surface to enhance reflection. If a surface is rough, a lens system can be included to focus the diffuse light reflected from the vibrating surface.

The working principle of our photophone-based method is illustrated in Figure 2. The specimen is excited acoustically by white noise and is simultaneously illuminated by a beam of laser for vibration measurement at a single point (Figure 2(a)). If a structure is acoustically ideal in an open area and it is excited by white noise, the resulting vibration would have equal energy at every frequency bin, reproducing the incident white noise. However, in reality, all objects have a set of resonance modes, and therefore, the frequency response is not flat. To be precise, spikes in the frequency response correspond to resonance frequencies of the object, save for a minor shift due to the effect of damping. The vibration of the surface results in the periodic variation of the surface normal, which in turn causes the reflected beam of light to converge and diverge at the same frequency as the vibration, resulting in an amplitude-modulated beam of reflection carrying information about the surface vibration (Figure 2(b) and (c)). The reflected light is picked up by a photodiode circuit, amplified, and collected by a data logger as voltage signal. The frequency-domain view of the modulated signal is obtained via fast Fourier transform (FFT), and vibration modes are identified by locating response peaks in a plot of the frequency spectrum.

Defect dimensions and damage extent are inferred from the frequency spectrum as interfacial defects can be modeled as a clamped plate with an acoustic cavity from the frequency spectrum as interfacial defects can be modeled as a clamped plate with an acoustic cavity. According to Cheng and Lau, the vibration magnitude of the FRP surface could be probed and the location of the defect is not known in advance. In this scenario, the FRP surface could be illuminated by sunlight, a light emitting diode (LED) array, or equivalent even lighting setup (Figure 3(a)). Focusing the reflected rays with a lens system, the single photodiode detector can be replaced by a light sensor array, such as a high-speed camera, to obtain an image of vibration activity over the entire area under inspection. Significant response peaks observed in the spectrum would indicate existence of defects (Figure 3(b)), prompting further investigation using the single-point laser technique to localize the defect. It should be noted that in principle the illumination source is not limited to visible light but applicable to the entire electromagnetic (EM) wave spectrum.

### Experiment

**Specimens**

Three square concrete slabs with edge lengths of roughly 300 mm are casted with various interfacial defects manifested as near-surface voids induced by inserting Styrofoams onto the mold of the concrete.
The use of air voids is a common strategy to emulate interfacial defects. The specimens are cured for approximately 28 days in a water tank and then dried at 50°C in an oven for 3 days. The surfaces of the specimens are sanded to reduce surface roughness and are bonded to three layers of CFRP (TORAY UT70-30) using epoxy (Sikadur®-300). The bonded specimens are further allowed to cure for a minimum of 7 days before measurements are made.

(Figure 4). FRP-bonded concrete slab specimens with artificial interfacial defects are shown here. The FRP is bonded to the surface facing the reader but is omitted in this illustration to reveal the underlying defects. Interfacial defects of three types of area: 25 × 25, 37.5 × 37.5, and 50 × 50 mm² are investigated, together with five types of depths: 5, 10, 20, 30, and 40 mm.

### Procedure

A white noise recording with a sample rate of 48 kHz is played over a period of 11 s at 102.1 ± 0.2 dB (sound pressure level (SPL)), while the environmental noise is fluctuating around 65–71 dB (SPL). Two control recordings without acoustic excitation of the same duration are recorded before and after the experiment to identify the influence of environmental noise. Over the entire period of recording, the FRP surface under inspection is illuminated by either a beam of 532 nm laser at a power of 80 mW or direct sunlight. When a laser is used for illumination, the source of acoustic excitation, a studio monitor (Yamaha MSP7 Studio), is placed 0.96 ± 0.01 m away from the specimen surface at an angle +15° ± 5° from the surface normal, while the laser and light detector are placed 1.80 ± 0.01 and 1.7 ± 0.1 m, respectively, away from the specimen and located at +25° ± 1° and −20° ± 10° on either side of the specimen. The position of the light detector has a larger variation as the reflection path is dependent on the specimen surface normal. A laser line filter and collimator are required as the light detector can easily be saturated by the 100 Hz or 120-Hz frequency of ambient lighting (50 or 60 Hz mains electrical supply rectified), which would have limited indoor use. Under sunlight, the studio monitor and the light detector are placed 1.0 ± 0.1 m in front of the three specimens. A photodiode connected to an amplification circuit is placed in the path of the reflected light ray from the specimens. The data are recorded on a computer via a data logger system operating at a sample rate of 50 kHz, giving a Nyquist frequency of 25 kHz. In post-processing,
the data are converted into frequency domain using FFT of size 1024, multiplied by Hanning window, and averaged using Welch’s method with an overlapping region of 50%. The FFT size is chosen to optimize smoothness of the resulting spectrum rather than maximizing signal-to-noise ratio (SNR), as the latter would result in a highly jagged curve, a well-known artifact of FFT. As the specimen is small in scale, the concrete slab has a high fundamental mode of vibration around 2 kHz, resulting in low-frequency noise during the measurement. Furthermore, aliasing toward the high-frequency end of the frequency spectrum is strong. Therefore, on each end of the frequency spectrum, a 2.5 kHz portion was cropped from the result.

Results

The measurement results from single-point laser measurement with white noise excitation are shown in Figure 5. The measurements of 50 × 50, 37.5 × 37.5, and 25 × 25 mm² defects are plotted in Figure 5(a) to (c), respectively. Each solid curve represents a measurement of a different defect specimen, while the dotted line represents the average of all frequency responses of each defect area. The response peaks appear to cluster together even though the scale of signal magnitude varies across specimens. As this photophone-based technique depends on measured irradiance, and the voltage output of the photodiode depends heavily on the reflectivity of the measured surface and the positioning of the light detector. Thus, reproducing the result in terms of absolute irradiance is difficult to achieve as the measured specimen is not a smooth surface (i.e. an FRP fabric consisting of interweaving fibers). Although repeatability in terms of measured voltage is degraded and the noise floor is not constant across measurements, the clarity and consistency in the frequency domain are high. In Figure 5(d), the frequency of each peak in the cluster is plotted as a ratio to the peak with the lowest frequency, further visualizing the effect of the clustering of peaks and implying that the distribution of peaks is not random. Taking the peak with the lowest frequency to be the fundamental mode of vibration, it is plotted against the inverse of defect area (Figure 5(e)). A linear relationship with $R^2 = 0.971$ is observed, indicating strong correspondence to plate theory. However, as the FRP, epoxy, and concrete are all much stiffer and denser than the trapped pocket of air at the interface, the SNR is too low for defect depth to be decoupled from the current measurement.

Figure 5. Measurement results using the photophone-based technique. (a–c) The frequency response of 50 × 50, 37.5 × 37.5, and 25 × 25 mm² defects, respectively, are shown. The behavior of each specimen is shown in the background as translucent curves, and the averaged response for each set of defect areas is displayed as a dotted line. (d) The frequency of each peak in the cluster is plotted as a ratio to the fundamental mode, further visualizing the effect of this clustering and implying that the distribution of peaks is not random. (e) The peak with the lowest frequency is taken to be the fundamental mode of the defect and is plotted against the inverse of defect area for obtaining a linear relationship with $R^2 = 0.971$. 
In Figure 6, the magnitude of acoustic excitation is varied. Although generally a stronger excitation will result in a larger response but the increase in SNR is not linear. Occasionally, a higher mode may have a stronger response than the fundamental mode (e.g. the third mode in Figure 6(a)). This observation is due to the fact that even though the photophone-based technique has a high correlation with the specimen’s resonance modes, it is an indirect measurement of the specimen’s vibration. A mode that results in the highest contrast in its reflection of the illumination source to the light detector is favored. When a flat surface is displaced (e.g. due to vibration), the direction of reflection remains unchanged. However, as the FRP surface is rough, the displacement of the surface amplifies the variation of the reflected light intensity, which may explain the nonlinear increase in SNR (Figure 6(b)). It is also possible that the laser fall in between two carbon fibers, and the direction of reflection is erratic (Figure 6(b)).

In Figure 7, the excitation duration is varied. It is observed that the longer the excitation, the smoother the response. In the particular signal processing method used in this study (i.e. Welch’s method), however, even though the duration is increased exponentially, the signal strength is only increased marginally. Judging from the result, an exposure of 2.6 s is optimal for manual trigger, while an excitation duration below 0.2 s is possible for computer trigger. It should be noted that the latter is only a loose upper bound as the excitation and recording are manually synchronized in this study; results below 0.2 s can be significantly influenced by human error.

In Figure 8, the measurement of the specimens illuminated by sunlight is shown. The excitation duration is reduced to 5 s, and the response from a frequency sweep from 100 to 20,000 Hz is also shown for comparison. Resonance modes of various defects are found to have superimposed on each other. However, a minor frequency offset of around 500 Hz is observed, which is possibly due to the specimens being clamped differently from the indoors single-point laser measurement, thereby altering the damping coefficient of the system. Moreover, it is found that white noise excitation results in a higher SNR than using frequency sweep, justifying the use of white noise for excitation in place of frequency sweep.

Discussion

From the consistency in inferring defect dimensions, the capacity of the measurement technique introduced
in this article as a low-cost alternative to the original acoustic-laser technique is validated. Although only square interfacial defects are investigated in this study, it is anticipated that a similar relationship between resonance frequencies and defect dimensions would exist for other defect shapes. Indeed, supported by the evidence that known analytical solutions to other defect shapes (e.g., circular, triangular) behave similarly, it has been suggested empirically that an inverse relationship exists for all regular polygon-shaped interfacial defects between resonance frequencies and defect area, which differs only by a shape-dependent factor.

From the review of existing remote NDT approaches in the introduction of this article, it can be seen that many of such techniques penetrate the specimen. In radiography and infrared thermography, the resulting image contains information regarding the entire depth of the structure; in radar imaging, although the penetration depth can be reduced by adjusting the frequency of the radar, the measurement still covers a certain depth of the structure. As concrete is a material containing coarse aggregates, the resulting scattering would most certainly result in a degradation in such techniques’ resolution. It may thus be difficult to distinguish a subsurface defect from an interfacial defect, which has different failure modes, if access is restricted to the anterior surface (e.g., when measuring a wall). Fortunately, the acoustic-laser technique, the current modification inclusive, is based entirely on surface reflection. This ensures that the measured response is predominantly due to interfacial defects. Therefore, a full picture of both interfacial and subsurface defects can be obtained when the acoustic-laser technique is paired with other penetrating NDT techniques. Previous attempts have been made to combine different NDT techniques to offer a more comprehensive understanding of structural health, however, the techniques utilized remain penetrating in nature.

As the design of the photophone-based technique is in an early stage, multiple improvements are possible for future studies. Due to the simplicity of the design, the setup can be further miniaturized as an all-in-one handheld device. If sunlight is used for illumination, the device can be plugged into a smartphone via its microphone input as the signal is compatible by design, with the defect being excited via the smartphone’s speaker. The frequency spectrum can be obtained via existing audio-processing software with modal identification in real time. A prototype has already been demonstrated while still using laser for illumination and is capable of providing a comparable level of measurement (Figure 9). If a stabilized drone is available, the device can be mounted on the drone for automated airborne areal measurement. Environmental noise such as highway traffic can also be considered as a source of acoustic excitation. Moreover, noting that FRP is a thin material, the loudspeaker or PAA can in fact be omitted in the setup and replaced by a modulating illumination source, utilizing photoacoustic effect to generate mechanical vibration from a long distance with minimal dispersion. In this scenario, from the experience of war-time development with the aid of high-powered light sources, the device is potentially capable of NDT over a range of kilometers. As a further improvement, instead of a single light detector, the FRP surface of interest can be focused by a lens system onto a detector array to obtain a two-dimensional (2D) vibration map of the entire surface, visualizing the mode shape without the need of a scanning laser system as in a scanning LDV. Similarly, the recording of a high-speed camera can be processed by treating each pixel as an independent light detector for the same purpose, or the entire video is processed collectively using the technique of motion magnification.

It is envisioned that this photophone-based technique can be applied to a wider range of NDT applications, including general modal analysis. The current application of the technique in FRP, which is a fabric material, is already one of the worst possible scenarios for technologies based on surface reflection. Although the absolute comparison across results measured in different conditions is challenging for FRP surfaces, the robustness and consistency in frequency domain are high. Hence, this technique is most suited for measurements focusing on the frequency domain. In retrospect, if interferometry is considered as a frequency-modulated measurement technique, this proposed photophone-based technique has the potential to be
developed into the amplitude-modulated counterpart of interferometry.

**Conclusion**

A low-cost augmentation to the acoustic-laser technique is developed and demonstrated in this study by applying the technique for the detection of interfacial defects in FRP-bonded systems. As part of the modification, a photophone-based measurement device is conceived for analyzing surface mechanical vibration at a distance. Various parameters and their influence on SNR are investigated. The FRP-bonded specimen is excited acoustically and its frequency response is measured remotely using the aforementioned photophone-based device. The result corresponds well with theoretical prediction, allowing defect dimensions to be inferred based on the measured frequency response. If interferometry is considered as a frequency-modulated technique, this proposed technique has the potential to be developed into the amplitude-modulated counterpart of interferometry.

**Declaration of Conflicting Interests**

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