Characterization of CFRP strengthened concrete plate and gap detection with piezoelectric based sensory technique

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Abstract

In this paper, a piezoelectric based sensory technique is proposed for detection of gap between surfaces of CFRP plate and concrete specimen and characterization of shrinkage of early-age concrete. The proposed technique uses propagation properties of the guided waves in the CFRP plate excited and received by piezoelectric based transducers attached to the external surface of the CFRP-strengthened concrete specimen. Measurement is conducted with fresh and hardened early-age concrete specimens and two CFRP plates at different gaps. A piezoelectric actuator is excited using sine burst signal and the generated wave is received by a sensor after propagation along the specimen. The received signal at different gap values is used to detect a gap. To quantify gap, damage indexes including correlation coefficient, peak-to-peak amplitude of resultant signal and root mean square deviation are used. The shrinkage of concrete is detected and predicted by comparing the damage indices at different gaps with the indices at different stages of early-age concrete. The proposed technique is

relatively simple with small transducers, one-sided, non-destructive, and cost-effective solution for gap detection and concrete characterization.

Keywords: concrete characterization, CFRP, structural health monitoring, debond, gap, piezoelectric transducers, guided waves, non-destructive testing

1. Introduction

Fiber reinforced polymer composites are used for the external bonding of concrete members for strengthening concrete structures[1-5]. The most common composites used for this purpose are carbon fiber reinforced polymer (CFRP) laminates and plates. CFRP composites are light, have a high resistance to corrosion and can be applied using a relatively simple technology, for instance, FRP wrapping of concrete beams or external bonding of FRP plates or laminates to a concrete surface[1-3]. Other applications of CFRP composites are concrete-filled CFRP tubes (CFFTs)[4] and reinforced concrete beam-column joints strengthened with CFRP jacketing [5]. However, the poor construction quality, aging, shrinkage of concrete and deterioration due to moisture may cause flaws such as debonding and gap between CFRP composites and concrete surfaces[6]. These flaws significantly degrade the structural integrity and safety of these composite structures.

The behaviour of concrete inside the CFRP, especially at an early age where the properties of concrete changes rapidly due to the loss of water and evaporation is critical[7]. Shrinkage of concrete can cause a gap and debonding of the concrete and CFRP member. Therefore, characterization of concrete inside the CFRP is an important issue. There have been several studies to investigate the early hydration of concrete structure which result in shrinkage of concrete[8, 9]. Several techniques have also been developed and applied for detecting the gaps/debonds between CFRP composites and concrete. Recently, an impact-echo method has been applied to detect debonding flaws at the epoxy-concrete interfaces in near-surface mounted CFRP strengthening beams[10]. However, this method needed an external impact source. Acoustic-laser technique was also used to detect gaps in CFRP bonded concrete structure by vibrating the target with an acoustic excitation and characterizing the vibration behavior with laser beam [11]. The method is particularly suitable for detecting the air voids near the surface of CFRP since the size of the artificial defect used in this paper was 50 mm × 50 mm × 30 mm but not suitable to detect smaller defects. Pulsed infrared thermography method was used for inspection of CFRP-concrete composites beams[12] but this method required artificial heating in laboratory which applicability in practice is questionable. A dual polarized near-field microwave reflectometer was proposed and applied for detecting debond between CFRP laminates and concrete in lab and in an actual bridge using two-dimensional images of the structure under test [13]. However, this technique needed bulky mechanical systems such as scanners to perform raster scanning of antenna over the specimen under test. Another potential non-destructive testing technique for the inspection of CFRP-concrete interfaces is a piezoelectric based technique which has been conventionally used as an embedded sensor to detect debonds[14, 15]. However, the sensors need to be embedded into the concrete to detect the debonds which requires a special preparation of the structures. An electro-mechanical impedance-based technique for identification of the debonding conditions of a CFRP laminated reinforced concrete beam using PZT ceramic patches was proposed[16]. This technique demonstrated promising results but could only detect debonding near the patches in a small area.

However, the study of hydration and shrinkage of concrete inside the CFRP and simultaneous detection of gaps/debonds using non-destructive approach is a challenging task and has not been investigated. This paper has addressed the limitation of existing technique using an advanced piezoelectric based sensor technique. The proposed technique uses propagation properties of the guided waves in the CFRP plate excited and received by piezoelectric transducers attached to the external surface of the plate attached to the concrete specimen. The technique is utilized to detect gaps/debonds in the composite structure and ultimately predict the shrinkage of concrete inside the CFRP reinforcement. The proposed technique is fully non-destructive, external, one-sided and relatively simple.

2. Specimens and measurement approach

The specimens for this investigation included early-age concrete structure and two different CFRP plates. One specimen consisted of a 5-mm thick CFRP plate of dimensions 240 mm x 100 mm (referred to as specimen 1) while the other specimen consisted of a 2-mm thick CFRP plate of the dimensions 150 mm x 50 mm (referred to as specimen 2). A 200-mm concrete cube was prepared by mixing cement, sand, coarse aggregates and water, and placed inside a mold for casting. Then, a CFRP plate was placed on top of the cube.

The measurement system used in this investigation consisted of two circular piezoelectric transducers, a signal generation unit and data acquisition unit as shown in Figure 1. Each transducer had a diameter of 6.35 mm with a resonant frequency of 300 kHz in radial mode. Both transducers were attached to the external surface of a CFRP plate of the specimen under test. One transducer was used as an actuator (A1) and the other as a sensor (S1). These transducers were connected to a signal generation and data acquisition unit from Acellent Inc. which was in turn connected to a computer as shown in Figure 1. The command for signal generation was given with specific parameters from the computer. A sine burst signal with 5 peaks was generated and transmitted through the actuator. The peak-to-peak amplitude of this actuation signal was set to be 8 V. To determine the optimum frequency for excitation, the frequency sweep from 100 kHz to 500 kHz with a step size of 100 kHz was applied. The generated wave propagated along a CFRP plate of the specimen under test and was partially received by the sensor. It was observed that the received signal had highest amplitude at a frequency of 300 kHz which matched the resonant frequency of the transducer and was used as an excitation frequency. This received signal was transmitted to the computer through a data acquisition unit at a sampling rate of 48 x 10^6 Samples/s. A gain of 40 dB was used to amplify the received signal. The changes in the received signal at the computer was used to determine the presence of a gap between CFRP plate and concrete due to the shrinkage of early-age concrete with time.

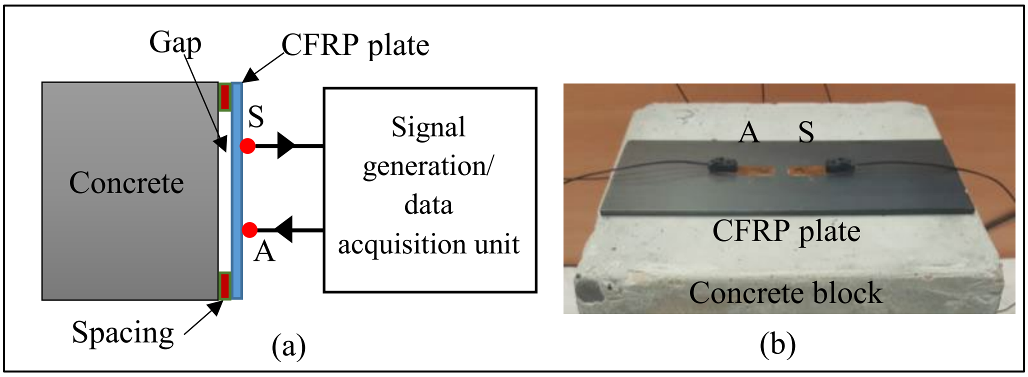

Figure 1 Experimental setup for detection and monitoring of gap between CFRP plate and concrete using transducers: (a) schematic and (b) picture of the specimen 1 with transducers after 72 hours (A – Actuator and S – sensor).

First, we introduced damage indices to quantify different gaps. For this, multiple measurements were taken at no gap (0 mm) and with gap values: 0.1 mm, 0.2 mm, 0.3

mm and 0.4 mm. Then, the average of these measurements vs time and standard deviation were calculated. Damage indices including a correlation coefficient, peak-to-peak (P2P) amplitude and root-mean-square deviation (RMSD) were used for quantitative analysis of the gap.

Next, we investigated how the received signal and the corresponding damage indexes changes with increasing time by comparing the signal at 1, 2, 6 and 24 hours after concrete casting. The gaps were generated over time due to the natural shrinkage of concrete. For this, multiple measurements were taken at no gap (0 mm) before the shrinking started and when the gap widths were: 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm which increased with increasing time interval. The gap values were measured using a Vernier calliper.

3. Results and discussion

Figures 2(a) and 2(b) show the average voltage measurement vs time at no gap and 0.2-mm gap for specimens 1 and 2, respectively. These are the first received wave by the receiver within 4 ms. It can be seen from Figure 2 that there is a difference between the average reference signal and average signals with gap which indicated the presence of a gap for both specimens and this difference is larger for specimen 2 than for specimen 1. This can be attributed to the fact that the CFRP plate in specimen 1 is thicker than the CFRP plate in specimen 2 which leads to higher concentration of stress wave inside the thicker plate and lower sensitivity to the small change of CFRP plate-concrete interface. The maximum standard deviation of reference signal and signal at gap values of 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm were determined to be 0.35, 0.21, 0.33, 0.36 and 0.39, and 0.11, 0.09, 0.13, 0.12 and 0.11, for specimen 1 and specimen 2, respectively. The results show that the standard deviation in specimen 2 is lower for each gap than in specimen 1. Again, this can be attributed to the lower sensitivity of the proposed technique to the gap for a thicker CFRP plate.

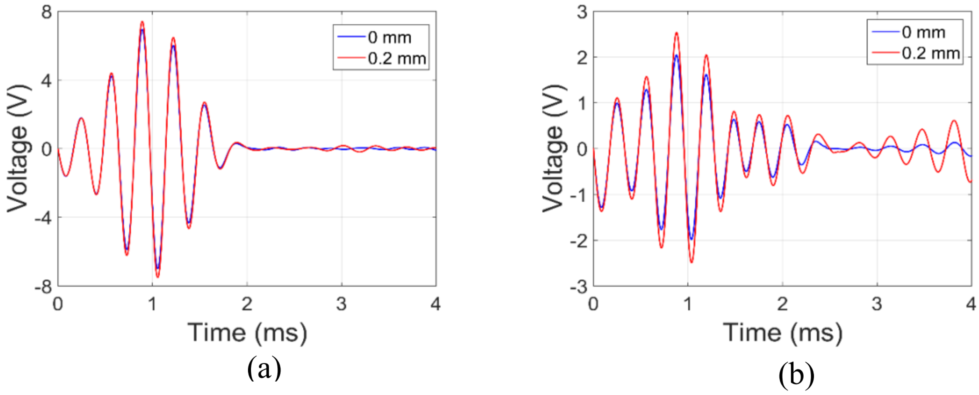

Figure 2 Average output voltage vs time in (a) specimen 1 and (b) specimen 2 at gap values: 0 mm and 0.2 mm.

3.1 Comparison of damage indices with respect to the gap value

The correlation coefficient[17] was determined between the average reference signal and average signal for each gap in specimens 1 and 2 to determine the similarity/difference between these signals. The correlation coefficient plot at different gap values in specimen 1 and specimen 2 is shown in (left) Figures 3(a) and 3(b), respectively. It can be seen from the plots that the correlation coefficient decreases with increasing gap value which shows that the dissimilarity between the reference signal and signal with gap increased. Further, linear fitting was carried out. The coefficient of determination (R^2) for specimen 1 was determined to be 0.99 and for specimen 2 was determined to be 0.88 which imply that the corresponding gap and the shrinkage of concrete inside the CFRP plate can be predicted from this fitted curve. The second damage index was P2P (peak-to-peak) amplitude. To get P2P amplitude, resultant signal was obtained at each gap value by subtracting the average signal at different gap values against the average reference signal. The P2P amplitude of this resultant signal was plotted and linear fitting was applied. The P2P amplitude plot for specimens 1 and 2 at different gaps is shown in (right) Figure 3(a) and 3(b), respectively. It can be clearly seen from these figures that the P2P amplitude increases with increasing gap. From linear fitting, R^2 was determined to be 0.95 in specimen 1 and 0.81 in specimen 2.

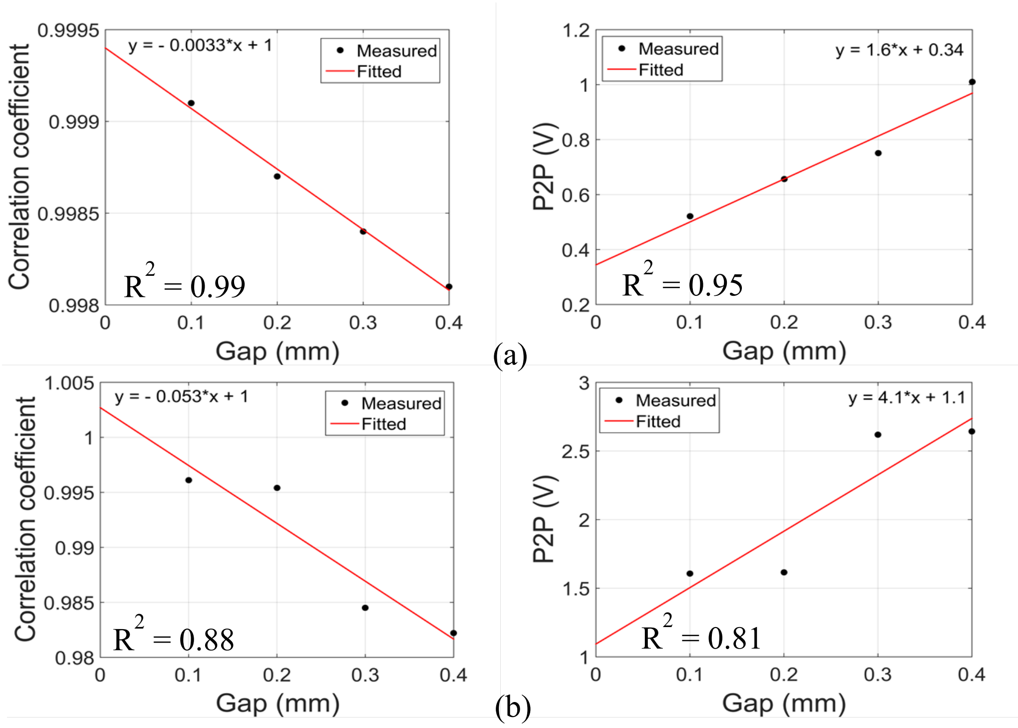

Figure 3 Correlation coefficient (left) and change in P2P voltage of the resultant signal (right) with fitted curves at different values of gap in (a) specimen 1 and (b) specimen 2.

The third damage index used to quantify the gap was the root-mean-square-deviation (RMSD). For this purpose, RMSD was given by,

$$RMSD\ (\%) = \sqrt{\frac{\sum_{i=0}^{t}\left(z(i) - z_0(i)\right)^2}{\sum_{i=0}^{t}\left(z_0(i)\right)^2}}x100$$

where, *z(i)* are $z_0(i)$ are average signal with gap and average reference signal, respectively for $i = 0$ to t sec.

The RMSD values at each gap at different stages of concrete were compared. Figure 4 shows the RMSD at different gaps at different time intervals of concrete casting for specimen 1 and specimen 2. For specimen 1 (cf. Figure 4(a)), the RMSD values increased from 0.14 to 0.19 for gap value ranging from 0.1 mm till 0.4 mm for 1-hour concrete. Similar trends were observed for 6-hour, 24-hour and 48-hour concrete. For 48 hour-concrete, the RMSD value increased from 0.21 for a 0.1 mm gap to 0.27 for a 0.4 mm gap. For specimen 2 (cf. Figure 4(b)), the RMSD values increased from 0.06 to 0.15 for gap values ranging from 0.1 mm till 0.4 mm for 1-hour concrete. In 48-hour concrete, RMSD values increased from 0.20 to 0.35 for gap value ranging from 0.1 mm till 0.4 mm. This shows that increasing the gap gave a larger RMSD value. These RMSD values can be correlated with the gap values and can be used as a gap value index. Further it should be noted that as the time of concrete casting increased, the RMSD level also increased which proves that the indication of gap in concrete based composite structures is more prominent as the time of concrete casting increases.

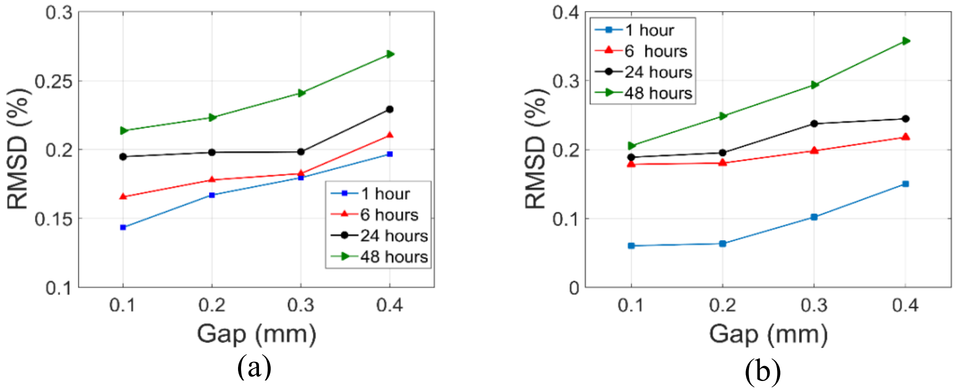

Figure 4 RMSD values at different time of concrete casting at different values of gap for (a) specimen 1 and (b) specimen 2.

3.2 Effect of the duration of concrete casting on gap size

To determine the effect of duration after concrete casting on gap size, the correlation coefficient at each time interval was compared for a day after concrete casting. The correlation coefficient with linear fitting at different time interval from 1 hour to 24 hours of concrete casting in specimen 1 and 2 is shown in Figure 5(a) and 5(b), respectively. The R^2 value for specimen 1 and specimen 2 were determined to be 0.98 and 0.95 respectively. The decrease in correlation coefficient with time indicates that the difference between the reference signal and damage signal is more once the fresh concrete starts to settle. This proves that the gap between the CFRP and the concrete due to the shrinkage of concrete in concrete based composite structure is more prominent as the time of concrete casting increase.

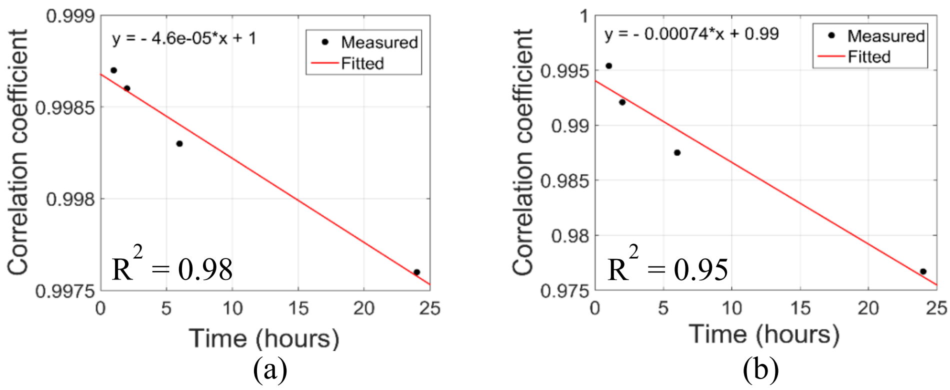

Figure 5 Change in correlation coefficient over time (hours) in (a) specimen 1 and (b) specimen 2.

Based on the results above, the correlation coefficient of the resultant signals at different gap values at different stages of concrete were then compared. For this, the damage indices obtained for gap values were directly compared with the damage indices obtained at different hours after concrete casting. Based on this training dataset, the corresponding gap values at different stages of concrete were determined. Further, linear extrapolation was carried out to estimate the gap values at different hours of concrete settling when two different CFRP plates were used. The estimation of gap values for specimen 1 is shown in Figure 6(a) and for specimen 2 is shown in Figure 6(b). The results accurately estimated the gap values at different stages of concrete. From the graph (cf. Figure 6), it was estimated that the concrete will shrink by 0.6 mm after 24 hours in specimen 1 and will shrink by 0.64 mm in specimen 2. These estimations were close to the real gap value after 24 hours which was measured to be 0.58 mm using Vernier calliper.

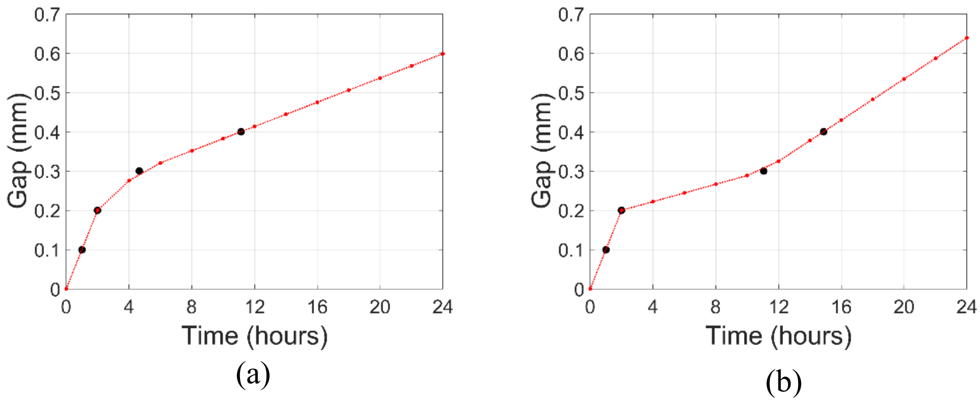

Figure 6 Estimation of gap between CFRP and concrete at different stages of concrete on (a) specimen 1 and (b) specimen 2.

The above results show the feasibility of the detection and evaluation of gap between CFRP plate and concrete using the proposed piezoelectric sensing system. Statistical analysis including correlation coefficient and P2P amplitude show that they vary with varying gap value. The high value of R^2 of the fitted curve implied that it can be used for measurement of gap value. The damage indices also show that the gap values can be correlated quantitatively with these indexes. The linear trend in change of correlation coefficient and RMSD values with time of concrete casting shows that gap indication is more prominent in settled concrete and implies its applicability in dry concrete as well. The accurate estimation of gap values proves the applicability of the technique to characterize the shrinkage of concrete inside the CFRP reinforcement.

4. Conclusion

The results of this paper showed that the proposed piezoelectric sensor technique was able to detect gap between CFRP and early-age concrete surfaces. The statistical indexes including correlation coefficient, P2P amplitude of resultant signal and RMSD showed good correlation with measured gap values. Further, the estimation of gap caused by the shrinkage of concrete inside the CFRP member also correlated with the actual gap. Overall, the proposed technique is (1) fully non-invasive technique as both actuators and sensors are only attached to the external surface of the specimen, (2) able to detect the gap between thick CFRP plate (≥ 5 mm) and concrete, (3) able to detect very small gaps (~ 0.1 mm) and (4) able to predict the extent of shrinkage of concrete inside the CFRP reinforcement. The results showed that the proposed technique is relatively simple and cost-effective solution to characterize the shrinkage and detect gaps in CFRP reinforced concrete structures and CFFTs. The detection of such small gaps is important for early retrofitting of structures preventing further damage and failure.

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