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Surface wave dispersion in large concrete structures

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ABSTRACT

The present paper discusses the repair characterization of large concrete surfaces based on the propagation of low-frequency elastic waves. A common repair method is cement injection. As a result, cracks and voids are eliminated increasing the measured average pulse velocity by about 5%. However, the central frequency of the pulses exhibits higher sensitivity to the repair increasing by about 15%. Additionally, the velocity of longitudinal waves exhibits a dependence on frequency. This dispersion is eliminated after repair being an indication of the repair efficiency, while Rayleigh waves are only slightly dispersive due to their long wavelength which enables them to travel below the shallow defects.

1. Introduction

The characterization of concrete structures by nondestructive testing (NDT) and specifically stress wave methods produces mainly qualitative results concerning distributed damage. The most widely used feature is pulse velocity, which is correlated with the damage degree. Despite its rough results, pulse velocity monitoring of large concrete structures is of great significance since it offers a general estimation of the condition and enables proper repair action. Therefore, the safe service life of a structure can be extended for decades. Empirical correlations between pulse velocity and damage or strength have been exploited for a long time [1] and have ceased to exhibit much scientific interest. It is accepted that pulse velocity is not sensitive enough to damage, being reduced only prior to final fracture [2]. Recently, frequency and dispersion features have been studied with the aim of more accurate characterization concerning the damage content and characteristic size. Dispersion originates from inhomogeneity, and hence the velocity dependence on frequency should be much more evident in damaged than in healthy media. Concrete is inhomogeneous by nature due to porosity and aggregates and slightly dispersive [3–5]. However, cracks exercise much stronger influence on wave propagation [6–8].

In the present paper, experimental measurements made on the surface of a large concrete structure are discussed. The structure was old and deteriorated mainly by freezing and thawing. The observation of numerous surface cracks indicated that repair should be conducted by cement injection. The main aim of elastic wave examination was the estimation of repair effect. Apart from the expected velocity increase, the frequency content of the pulses offered an additional and more sensitive descriptor of the material's condition. Additionally, pulse velocity showed a dependence on frequency. This kind of dispersion effects are attributed to inhomogeneity [3–5,9–11], and are eliminated after repair. This indicates that proper study of dispersion can provide additional features as to material characterization in-situ.

2. Repair

On the surface of the old concrete structure numerous cracks were observed. Repair was conducted by cement injection in three different ways. First, cement injection was conducted from the opening of the thicker cracks using syringes. As to thin cracks, they were repaired by surface application of cement. Finally, cement was injected in a pattern of boreholes on the surface using a constant pressure, as described in [12]. The actual result is that empty pockets in the structure created by cracks or extensive porosity were filled with cementitious material. Concerning initial crack depth evaluation, some of the cracks can be interrogated by longitudinal or Rayleigh waves [13,14]. However, given the large number of cracks this is not practical. A measure of the quality of the entire surface must be obtained in a time-effective manner.

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3. Wave measurements

In the specific case, three vertical arrays of four sensors were attached using a rectangular pattern to record the surface response, as seen in Fig. 1(a). All three dimensions of the concrete block (dam pier) were much larger than the monitored area and the wavelength, and therefore, no influence was expected to either longitudinal or Rayleigh waves. The excitation was consecutively conducted near each sensor (which acted as a trigger) and the rest acted as receivers. Therefore, several paths (all possible combinations between two individual sensors) with different lengths were examined. The horizontal spacing was 1.2 m, the vertical 1.5 m, while the longest paths corresponding to the largest diagonals of the whole monitored area were 5.1 m long. The sensors were acoustic emission transducers, namely Physical Acoustics, PAC, R6 sensitive at frequencies below 100 kHz. The acquisition system was a 16 channel PAC, Mistras operated on a sampling frequency of 1 MHz. The sampling time of 1 μs, resulted in an error lower than 0.3%, since even for the shortest distances of 1.2 m, the transit time was approximately 300 μs. The sensors were attached on the surface using electron wax. Excitation was conducted by a steel ball (35 mm in diameter) resulting in a frequency peak at approximately 10–15 kHz (see Fig. 1(b)) and a longitudinal wavelength of approximately 400 mm and a Rayleigh wavelength of 200 mm. Pulse velocity was measured by the time delay of the first detectable disturbance of the waveform. As to the Rayleigh velocity, the reference point used for the measurement was the first peak of the Rayleigh burst that stands much higher than the initial, weaker longitudinal arrivals [6,11,14] (see Fig. 1(c)).

4. Results

In Fig. 2, the dependence of central frequency on the distance is depicted. The central frequency, C, is calculated as the centroid of the FFT of the waveforms up to 40 kHz

$$C = \frac{\int_0^{40} fM(f)df}{\int_0^{40} M(f)df} \tag{1}$$

where f is the frequency, and $M(f)$ the magnitude of the FFT.

Fig. 2 includes the total population of points. For each specific distance the centroid is within a margin of 3–6 kHz. However, the decreasing trend with distance is clear since before repair, the average frequency is 12.5 kHz for 1.2 m propagation while it is reduced to 6.8 kHz for 5.1 m. The trend can be fitted quite well with a decaying exponential curve, and is attributed to the stronger attenuation of higher frequencies [6,9,15]. Measurements on the same points after repair showed a frequency increase of approximately 2 kHz for any distance, as seen again in Fig. 2. This can be attributed to the filling of the cracks which reduces the

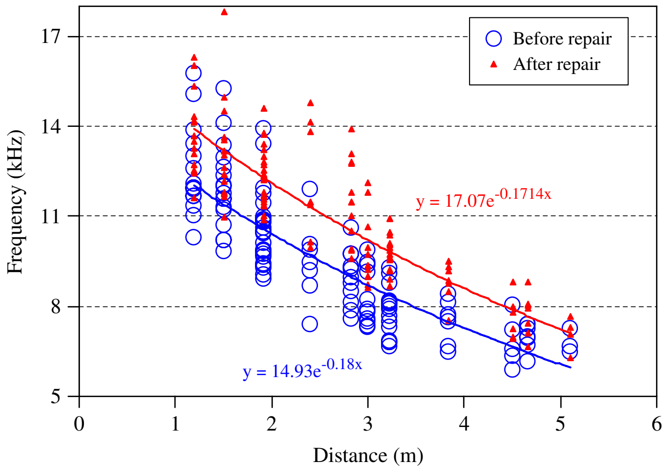

Fig. 2. Central frequency of pulses vs. propagation path.

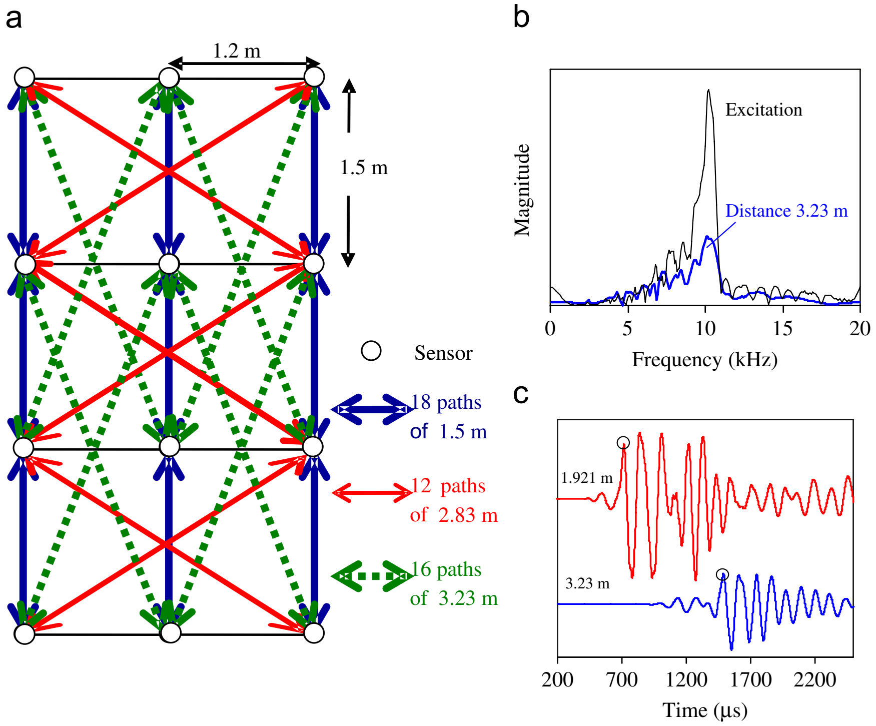

Fig. 1. (a) Pattern of sensor arrangement on concrete surface, (b) FFT of typical signals, and (c) typical waveforms collected at different distances from the excitation (the circle mark stands for the reference Rayleigh point).

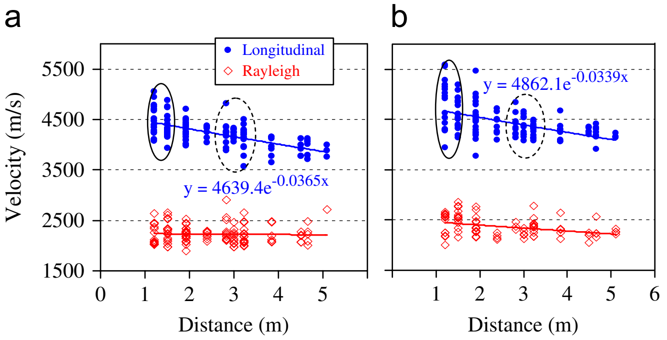

Fig. 3. Velocity vs. propagation path, (a) before repair, and (b) after repair.

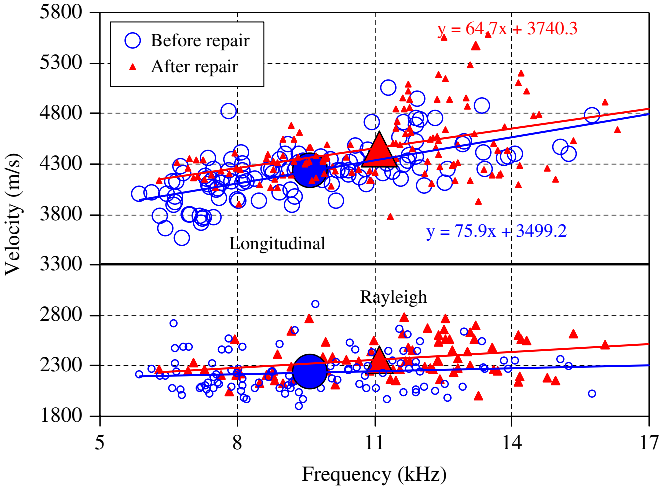

Fig. 4. Velocity vs. central frequency of all pulses.

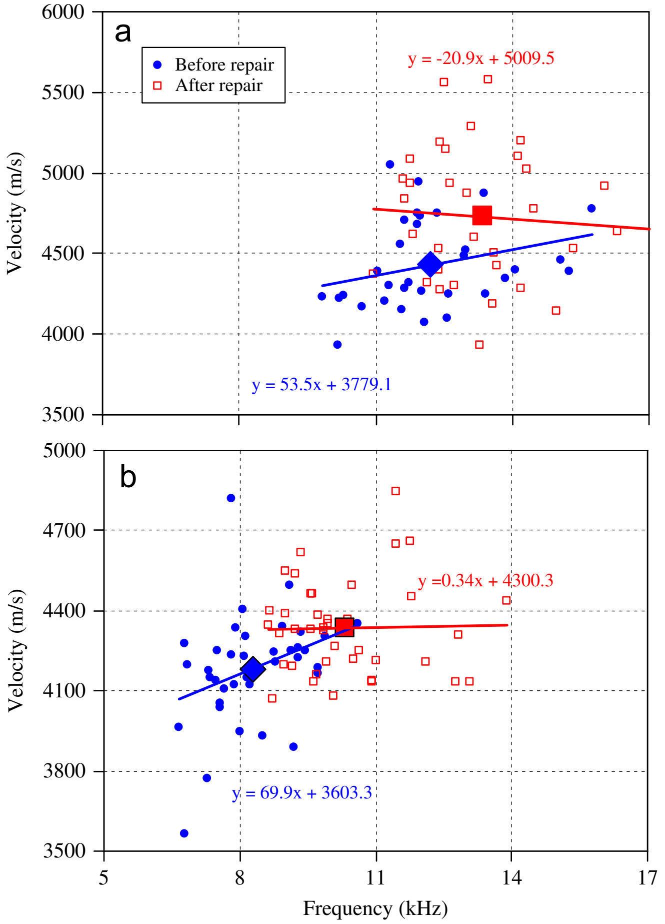

Fig. 5. Velocity vs. central frequency for pulses traveled (a) 1.2–1.5 m, and (b) 2.83–3.23 m.

material scattering attenuation. It should be mentioned that the frequency is not directly correlated with concrete strength or structural integrity. However, there is no NDT parameter directly related to strength. The importance lies on the comparison between the two stages (before and after repair). Since a frequency upgrade was evident this shows that there was a certain improvement on the structure's surface layer due to void elimination.

Similarly, the longitudinal velocity exhibits a strong dependence on the distance (see Fig. 3(a)). The average velocity measured for the short paths of 1.2 m before repair averages at 4500 m/s while for the longest paths of 5.1 m it is below 4000 m/s. After repair the curve is elevated by about 250 m/s, as seen in Fig. 3(b). As to Rayleigh waves, the dependence on the distance is much weaker both before and after repair, as seen again in Fig. 3(a) and (b). Concerning Rayleigh, the curve is elevated by about 100 m/s after repair.

One reason for the decaying trend of velocity with distance is that short distances are more likely to be crack-free than long ones and, therefore, exhibit higher velocity. Another reason should be the decreasing signal-to-noise ratio that hinders the correct identification of the waveform's leading edge for signals collected at large distances. This can be considered as an indirect effect of damage on the velocity, through the attenuation it imposes. It is mentioned that this reason does not apply for the Rayleigh waves, since they are measured by a strong reference peak (see Fig. 1(c)), much higher than the noise level.

5. Velocity–frequency relation

Both longitudinal velocity and frequency decrease exponentially with distance; thus they are correlated with each other, as seen in Fig. 4. The clusters consist of 130 points which is the total number of possible paths between the sensors. Due to inhomogeneity and locality effects there is a certain experimental scatter. However, it is clear that both before and after repair there is a positive correlation showing a certain dependence of velocity on frequency. Nevertheless, as seen by the large symbols in Fig. 4 the average velocity and frequency both increase after repair. In particular, the average longitudinal velocity increases from 4228 to 4455 m/s (5.36%). Central frequency increases from 9.6 kHz to 11.1 (15.6%) being much more sensitive than velocity. This kind of simultaneous examination of different features can enhance repair characterization as has been used in a number of occasions in the case of acoustic emission indices applied on this [12] and other large concrete structures [16].

It is understood that the correlations in Fig. 4 include the influence of distance since the top right points with the highest velocity and frequency are averaged from the shortest paths of 1.2 m, while the points with low velocity and frequency are taken from the longest distance of 5.1 m. In order to examine the frequency effect on the propagation velocity excluding the influence of attenuation, the information was processed in small groups of data collected over close distances. Two cases will be indicatively discussed. One group included the data collected at the shortest distances of 1.2 and 1.5 m (totally 34 points), while the other included approximately double distances of 2.83, 3 and 3.23 m (totally 40 points). These two groups are indicated by solid and dashed ellipses in Fig. 3. For each group, the velocity vs. frequency correlation is depicted in Fig. 5(a) and (b). Since the data are taken from similar distances, the effect of attenuation is eliminated allowing examination of pure dispersion within each group. The experimental scatter is high; however this is reasonable since each travel path in damaged concrete is unique due to inhomogeneity. The total population shows a trend that should not be ignored; there is a positive correlation between velocity and frequency before repair. Considering the linear function fitting the data of Fig. 5(a), the slope is 53.5 before repair. This suggests that for each increasing kHz pulse velocity increases by 53.5 m/s. The corresponding slope for Fig. 5(b) is even higher (70 m/s for each kHz). This trend may look impressive but is in agreement with recent dispersion studies on concrete [3,5,6,11]. They reveal that below 100 kHz the slope of the dispersion curve is steep, while for frequencies around or above 100 kHz the curve reaches a plateau.

After repair this correlation was eliminated as seen again in Fig. 5(a) and (b). The slope reduced close to zero (or even below). Injection filled cavities and cracks with cement eliminating inhomogeneity to a large extend. Thus, the structure behaved in a less dispersive way. From both figures it is again seen that repair enhanced the average velocity and frequency measured at short distances (up to 1.5 m) and longer (approximately 3 m). However, the repair-dependent dispersion should not be ignored as it shows the potential to enhance the rough characterization performed so far.

It is mentioned that all individual distance groups of data exhibited the velocity–frequency dependence. Fig. 5 contains the groups with the largest population.

The correlation of Rayleigh velocity with frequency and distance is much weaker than in the case of longitudinal as was seen in Figs. 3 and 4. One possible explanation is the long wavelength compared to the depth of surface-opening cracks. Some surface cracks with wide openings (i.e. 0.2–0.4 mm) were targeted using longitudinal and Rayleigh waves for depth measurement [13,14]. The depth of cracks never exceeded 100 mm while an average value for the depth of the cracks was 35 mm. Rayleigh waves propagating through a depth of more than 200 mm (similar to their wavelength) can “fly” below the shallow defects. Therefore, their dispersion in this case is weaker, since the highest degree of damage is concentrated near the surface, while the propagation of Rayleigh takes place also through deeper, more homogeneous zones. On the other hand, longitudinal waves traveling along the surface are influenced by each surface crack (even the smallest) as it poses a discontinuity on their path. This makes their dependence on frequency stronger, as was seen in Figs. 3 and 4. Dispersion should be further studied for material characterization since generally limited dispersion of Rayleigh should imply that defects are shallower than the Rayleigh wavelength offering a means of fast estimation for a large surface.

6. Conclusion

In the present paper, results of low-frequency elastic wave measurements on large concrete surfaces are discussed. The main aim is the characterization of repair effectiveness after cement injection. A pattern of acoustic emission sensors covered a large part of the surface allowing a quick and reliable scanning of the velocity structure. Velocity measurements revealed an increase of 5% to 6% after repair concerning both longitudinal and Rayleigh modes. However, the central frequency of the pulses increased by 15% showing better potential for repair characterization. The measured velocity of longitudinal depends clearly on the distance, something that implies attenuation and dispersion effects, which on the other hand are not clear for the Rayleigh waves. This indicated that the deteriorated zone was relatively narrow compared to the Rayleigh wavelength. After repair the longitudinal wave dispersion was eliminated offering an additional feature indicative of the repair effectiveness that should be further studied. A suggestion for future study is the application of low frequency accelerometers which, although not as sensitive as the acoustic emission transducers could prove more adequate for the low frequencies applied in concrete structures.

Nowadays, since waveform acquisition is standard to almost all ultrasonic equipment the rough characterization based on pulse velocity can be easily enhanced by features like frequency and dispersion. So far these have been applied successfully in laboratory conditions for material characterization but it is expected that their application in real structures will definitely improve NDT capabilities.

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