Determination of surface crack depth and repair effectiveness using Rayleigh waves

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ABSTRACT: Determination of surface crack depth and assessment of repair effectiveness are two non trivial tasks. In the present work, certain correlations between energy related characteristics and crack depth are observed, leading to a multivariate estimation approach. After repair, the same wave parameters are used to characterize the efficiency of repair, since propagation is restored after successful epoxy injection. As for in-situ application, wave inspection is described on a cracked concrete bridge deck, where the cracks were repaired with epoxy agent. It is concluded that the investigation demonstrated the efficiency of the injection, since wave energy and velocity were restored.

1 INTRODUCTION

Surface cracks are the most commonly seen kind of defects in concrete structures. The reason could be overloading, weathering, drying shrinkage, differential settlement, other degradation processes or combination of the above. The major threat they pose concerns the exposure of the metal reinforcement to environmental agents leading to its oxidation (Issa & Debs 2007, Hevin et al. 1998, Ono 1988, Kruger 2005, Shiotani et al. 2005). In order to seal the crack sides and protect the interior, along with structural strength restoration, injection of epoxy or other agent can be used (Aggelis & Shiotani 2006, Binda et al. 1997, Thanoon et al. 2005). However, the effectiveness of the filling as well as the initial determination of crack depth are not trivial tasks. Ultrasonic waves have been used as a non destructive technique in the case of crack characterization. The transit time of longitudinal waves diffracted by the tip of the crack can be used for the estimation of crack depth (Sansalone and Street 1997). However, due to attenuation in many cases the detection of the actual onset of the received waveform could be troublesome, leading to erroneous results. Apart from this, possible bridging points due to reinforcement or other materials could induce further error in the estimation (Liu et al. 2001, Malhotra & Carino 1991). Therefore, the use of Rayleigh waves has been studied extensively (Hevin et al. 1998, Wardany et al. 2004, Zerwer et al. 2005). The advantage of Rayleigh waves is that they carry higher amount of energy than bulk waves as well as their lower geometric spreading, allowing them to propagate at longer distances (Graff 1975). In many of the above studies and others (Doyle & Scala 1978, Achenbach and Cheng 1996, Edwards et al. 2006) amplitude or energy related parameters as well as frequency content has been related to artificial cracks' depth. However, there is no generally accepted and reliable treatment while the issue of non destructive evaluation of repair effectiveness has not been addressed.

In the present paper the correlation of waveform parameters with the depth of artificially machined slots in concrete specimens is studied. Certain trends are observed leading to a multivariate treatment of energy parameters in order to increase the accuracy of depth characterization. Due to the inherent difficulties the accuracy of estimation using one parameter is limited and therefore, combined analysis of different wave features is desirable, as current trends imply (Wu 2006). Additionally, filling of some slots with epoxy was conducted showing that waveform parameters are restored to a great degree while the partial filling of the slot is also examined. As an actual example, the examination of surface opening cracks on a concrete bridge deck before and after repair with epoxy is presented. The ultrasonic measurements reveal the efficiency of repair with the increase in propagation velocity and signal transmission.

2 EXPERIMENTAL SETUP

2.1 *Materials and geometry*

Two concrete specimens were casted using water to cement ratio of 0.43 and maximum aggregate size of

20mm. The specimens were of prism shape (150x150x500mm^3). After the completion of hydration (28 days in water), slots of different depths were machined, from 2mm up to 23mm, perpendicular to the longitudinal axis of the specimen. On opposite surfaces of each specimen 2 slots were cut with a sufficient distance of at least 150mm between them to avoid interactions. The slot width is 4mm.

2.2 *Sensors and excitation*

Although different configuration were tested, in this study results from pulse generator C-101-HV of Physical Acoustics Corp, PAC, with a main excitation frequency of around 115kHz, and the 1910 function synthesizer of NF Electronic Instruments are discussed. Concrete, due to attenuation, limits the propagating frequencies to bands around or below 100kHz. Therefore, sensitive sensors at this range were used, namely R6, of Physical Acoustics Corp., PAC. However, measurements with broadband sensors, i.e. Fujiceramics FC 1045S, were also conducted to confirm that the resulting trends were not dependent on the sensors frequency response. The representation of the experimental setup can be seen in Figure 1. In order to choose a suitable separation, different distances were tested in sound material (Aggelis & Shiotani, submitted). A separation of 60mm was chosen to avoid near field effects. The second receiver was placed 40mm away from the first. It is noted that excitation was conducted from both sides, resulting in similar trends.

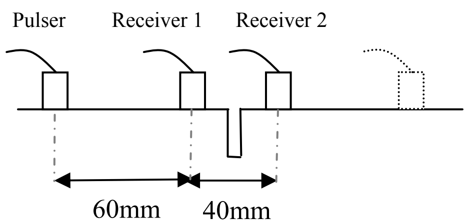

Figure 1. Representation of the experimental setup.

3 RESULTS

The aim of this experimental series is twofold; first to search for correlations between slot depth and wave parameters that could lead to characterization and second to check the validity of such a characterization. Therefore, the slots cut on one specimen (2mm, 9.5mm, 13mm, 23mm) as well as sound material were initially tested to establish some preliminary correlation curves. Afterwards, the slots of the other specimen were tested to examine if the initially observed correlations hold. Additionally, new measurements on the slots of the first specimen were done to check the repeatability of the whole procedure. Therefore, in the following figures, the preliminary curve obtained by the initial data is drawn in dotted line while the correlation curve obtained by the total population of measurements which is therefore considered more reliable is also presented.

In Figure 2 the waveforms of the first and the second receiver are depicted for different slot depths. It is seen that the major part of the energy is due to Rayleigh waves. For the sound material case the Rayleigh burst is clearly observed after the first longitudinal arrivals. The transit time between major peaks corresponds to the Rayleigh wave velocity of 2400m/s. For the case of 2mm slot the Rayleigh peaks are also clearly depicted, while for the 9.5mm their amplitude is certainly lower, although still detectable. For slots of 13.5mm or higher the Rayleigh burst is not clearly visible. It is noted that the main frequency peak is approximately 115kHz, corresponding to a wavelength of 20mm.

As seen in Figure 2, the energy and amplitude of the signal decreases with the slot depth. In Figure 3, the signal amplitude is plotted against the slot depth for all cases examined. This decreasing trend has been stated in previous works (Achenbach and Cheng 1996, Wu et al. 2003) for concrete as well as for metals (Edwards et al. 2006). Despite the experimental scatter, a certain master curve of the form of exponential decrease can be drawn to correlate the slot depth with the amplitude, as seen in Figure 2. It is also seen that up to the slots of approximately 10mm, there is noticeable difference in amplitude but for deeper slots the amplitude remains approximately constant. The slot of 9.5mm corresponds to approximately 0.5 of the wavelength as seen on the

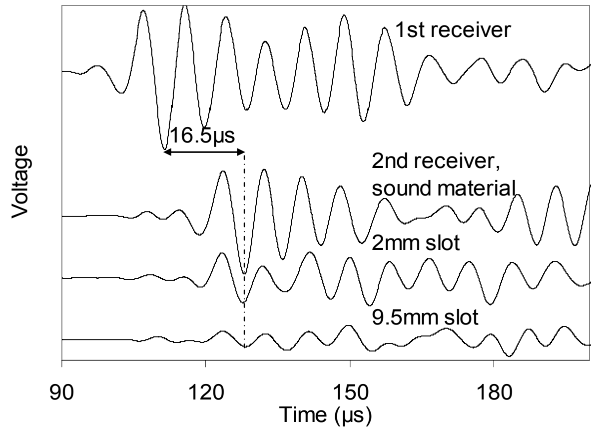

Figure 2. Waveforms collected at wave paths with different slots. The amplitude of the 1st receiver's waveform is reduced to 30% for fitting purposes.

second horizontal axis of Figure 3, while it is less than 10% of the specimen thickness. The second and third horizontal axes are drawn in order to investigate parameters other than solely the slot depth, since the wavelength and the specimen thickness may also influence the Rayleigh amplitude. The slightly decreasing trend of the amplitude for larger slots makes the characterization of larger cracks difficult by using only this parameter. Therefore, in order to characterize sufficiently the slot depth, other features should be used additionally to increase the accuracy.

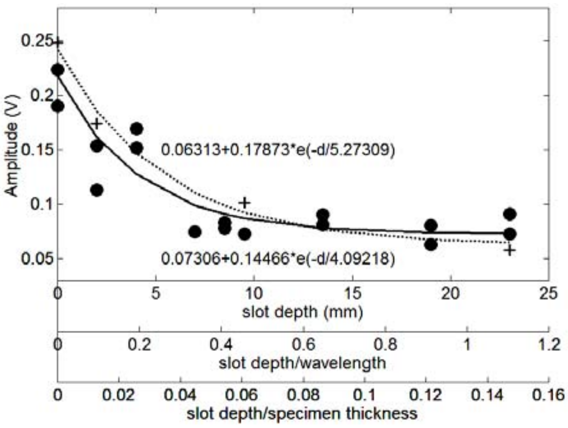

Figure 3. Correlation plot of waveform amplitude vs slot depth for excitation of 115kHz

From the above it is seen that there are correlations between slot depth and certain waveform parameters. However, these correlations are not strong enough to individually lead to accurate characterization. Therefore, a multivariate methodology was applied. For any slot tested, after the waveform was acquired, certain promising parameters were calculated as shown in the above figures. Totally five parameters were included in this analysis. Namely: i) the maximum amplitude, ii) the delay in central time in μs relatively to the central time of the 1st sensor waveform and iii) the inclination of accumulated amplitude, as presented in (Kruger 2005), iv) the absolute central time in μs and v) the time of the first positive peak of the waveform that precedes the Rayleigh peaks which is supposed to be from the refracted longitudinal wave at the tip of the crack.

After obtaining each waveform for a slot, the above mentioned five parameters were extracted. Using the exponential relations, as the example of Figure 3, five values for the depth of each slot were calculated. These were averaged in order to lead to a more reliable result. Applying this methodology for all the tested slots and using at least two individual measurements for each slot, in order to increase the population and check the repeatability, the correlation plot of Figure 4 was produced. There, the calculated depths are plotted vs the actual depths of the slots. It is seen that up to the slot of 13.5mm, the calculated values do not differ significantly from the actual, having an average error of 1.75mm. The slot depth of 13.5mm corresponds to 64% of the major wavelength and 9% of the specimen thickness. However, for the slots of 19mm and 23mm, the predictions are not nearly as accurate.

It is noted that use of only one individual curve for characterization (e.g. the amplitude vs slot depth curve of Figure 3) leads to a typical error of about 4mm or more. Therefore, the combination and averaging of results of different parameters has certainly positive effect on the accuracy. Additionally, new measurements on different slots would increase the population and thus make the correlation curves more reliable. As seen from Figure 3, the amplitude or any other parameter does not seem sensitive enough for the deepest slots. This is the reason for the reduced accuracy of calculation for slots larger than 13.5mm.

Considering the frequency content of the waveforms, no stronger correlations were observed. The major peak of 115kHz does not exhibit any downshift according to the slot depth, while its energy decreases up to the slot of 13.5mm but is slightly increased for the largest slot of 23mm. Therefore, this feature is not suitable for characterization.

Since, acceptable characterization is possible up to slot depth equal to about 65% of the wavelength, see Figure 4, slot of 13.5mm, it was assumed that using longer wavelength could expand the characterization to longer crack depths.

Therefore, the use of wave packets of 50kHz were applied among others with the function synthesizer 1910 of NF Electronic Instruments. In Figure 5 the amplitude vs slot depth for this excitation is depicted. Although the wavelength is nominally 50mm, it is seen that the decreasing trend stops again after the slot of 13.5mm and the larger slots exhibit slightly higher amplitude.

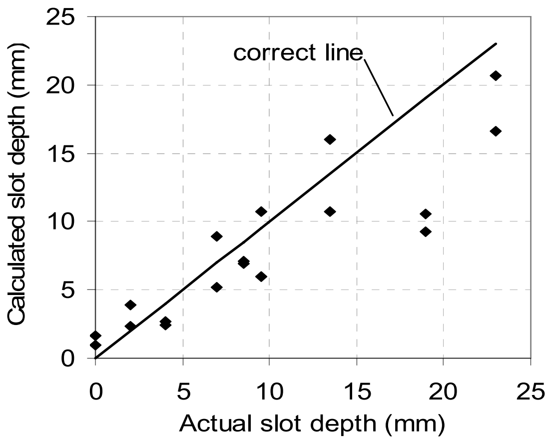

Figure 4. Correlation plot of predicted vs actual values of slot depths.

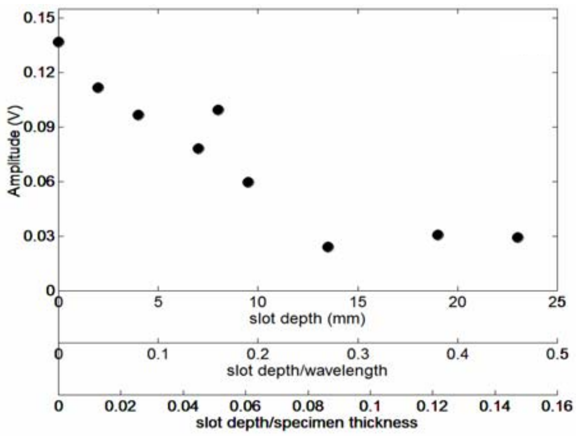

Figure 5. Correlation plot of waveform amplitude vs slot depth for excitation of 50kHz

This leads to some considerations concerning the Rayleigh penetration depth. It is generally accepted (Sansalone and Streett, 1997, Wardany et al. 2004, and can be calculated (Aggelis & Shiotani 2006) for the ideal non attenuative case, that the Rayleigh penetration depth is similar to the wavelength. However, this refers to the amplitude of the wave. The energy carried is proportional to the square of the amplitude. Therefore, taking also into account the attenuation, it is likely that the actual penetration depth is shorter than the one obtained theoretically. Although for the 50kHz excitation the amplitude decrease is more clear than the115kHz case, it seems that the amount of energy penetrating below the shallow layer of 10mm is not sufficient to distinguish different cracks of 13.5mm or larger, although the wavelength is nominally 50mm.

Another argument concerns the dimensions of the specimen. From the above it is seen that using frequency of 115kHz leads to clear characterization up to slot depth to wavelength ratio 0.5. For the case of 50kHz, the characterization holds up to depth/wavelength ratio of 0.3, see Figure 5. In both cases however, the decreasing trend stops at around the slot of 13.5mm. This implies a possible implication of the specimen thickness, since in any case the characterization cannot be performed for slots deeper than 10% of the specimen thickness. As stated in (Zerwer et al. 2005) wavelengths of close to half the specimen thickness do not propagate in the form of Rayleigh waves. For 50kHz or lower frequency, the wavelength is 50mm or higher approaching the limit of half the thickness. Therefore, considering that the exponential decay trend concerns Rayleigh waves, it becomes difficult to observe the same trend as the wavelength increases hindering the propagation of Rayleigh waves.

4 REPAIR EFFECT

4.1 *Complete filling*

A typical treatment of surface cracks is application of epoxy agent that seals the openings and protects the interior from environmental influence offering also improvement of structural strength (Issa and Debs 2007, Thannon et al. 2005). Two of the cracks were totally filled with two component epoxy adhesive suitable for concrete. The set time is 5min and sufficient hardening is obtained in 1hr at 20^{o}C. Measurements were conducted after 1 day when nominally the epoxy exhibits strength of 12MPa. In Figure 6 the waveform collected at the slot of 13.5mm after epoxy injection can be compared to the one obtained with the same configuration and setup before the application of epoxy, as well as to the sound material response. It is seen that the injection of epoxy, greatly enhances wave propagation, increasing the transmitted energy to almost the levels of the sound material. It seems that complete filling with the repair agent, restores the propagation since the total energy is of the same level with the sound material. The average increase in energy transmission due to complete filling of the crack with epoxy was 204%. Therefore, surface measurements can be used to characterize the efficiency of repair work. It is mentioned that in the frequency domain the energy was of course increased similarly as in the time domain, without however, any specific peak or band being more characteristic. In other words the filling of the crack enhanced the energy of all frequency bands the same way.

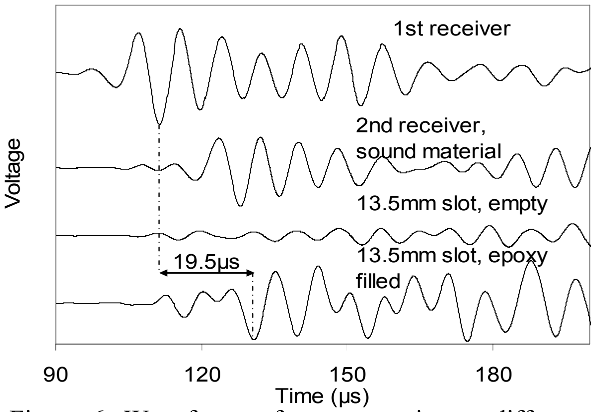

Figure 6. Waveforms after propagation at different wavepaths. The amplitude of the 1st receiver's waveform is reduced to 30% for fitting purposes.

Nevertheless, the Rayleigh peaks are again clearly visible, although delayed compared to the sound material case. They correspond to a velocity of 2050m/s, about 15% lower than the sound material's Rayleigh velocity. This is expected since concrete elastic properties are higher than epoxy's.

4.2 *Partial filling*

A case of interest is the partially grouted cracks. In many cases a large part of the crack remains unfilled especially if the injection is not conducted with an adequate pressure.

However, since the space near the mouth of the crack is filled with grout, this permits the propagation of stress waves resulting in difficulty to obtain information about the extend of grouting by transit time or amplitude data (Sansalone and Streett 1997). To study this case some slots were partially filled with epoxy at different depths. A thick piece of hard paper was wrapped in a Teflon sheet and placed inside the slot leaving an empty space on top. Afterwards, epoxy was placed and was let to set. Then the paper was removed by pulling from one side leaving only the epoxy layer on the top part of the slot as seen in the cross section of Figure 7a.

The cases examined concern filling of 2 and 9mm to the slot of 19mm and filling of 3 and 11mm to the slot of 23mm. Therefore, the filling ranges from

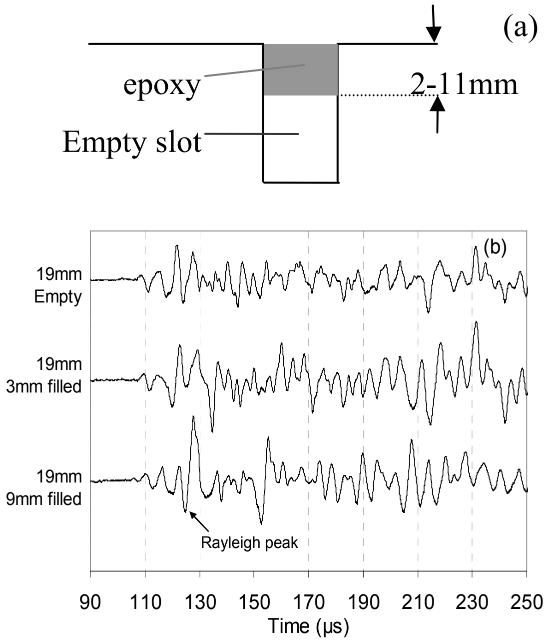

Figure 7. (a) Schematic representation of epoxy bridging, (b) waveforms recorded with different slot filling.

about 10% to 50%. Stress wave measurements were conducted using the configuration with the broadband sensors and the PAC pulser. In Figure 7b one can observe waveforms recorded at the slot of 19mm with different degree of filling. It is seen that the energy and amplitude of the waveforms increase according to the filling. However, only in the 9mm filling case a clear Rayleigh wave is visible. The position of this peak corresponds to a velocity of 2040m/s, being close to the Rayleigh velocity calculated for the fully injected slot of Figure 6. In the case of 3mm filling, a much weaker peak after the first arrivals is observed while it also arrives earlier than the Rayleigh velocity would allow. Therefore it should be attributed more likely to contributions of the longitudinal or even shear arrivals passing through the thin layer of epoxy.

In Figure 8, one can observe the increase of amplitude ratio of the second to first receiver according to the degree of filling for the slots of 19 and 23mm. The value of this ratio after measurement in sound material is 0.43, meaning that this value can be considered maximum. The depths of these slots are quite similar and therefore, measurements results in approximately the same amplitudes. Surface filling of the slot increases slightly the amplitude ratio (1-8%) as seen in Figure 8. Filling up to almost 50% of the initially empty volume of the slot increases further the amplitude ratio. Therefore, approximately half filling of the slot results in raising this parameter to approximately half of its maximum.

Anyway, from the above it can be concluded that surface wave measurements can supply information concerning the degree of filling after repair. From the above experiments it is seen that as the filling

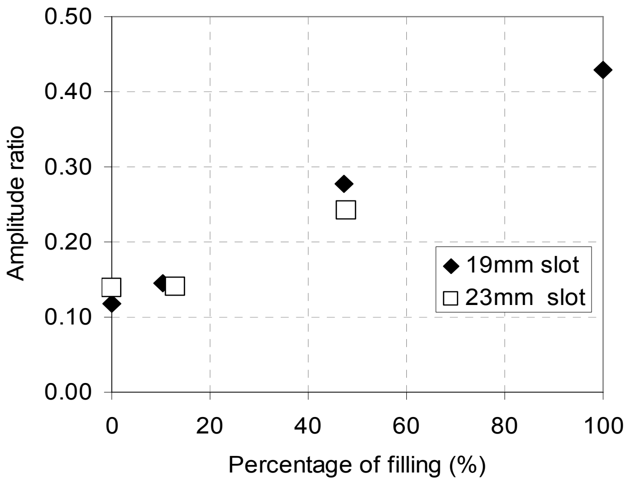

Figure 8. Relation between the waveform amplitude and the degree of epoxy filling of the slot

percentage gets higher, so do the amplitude and energy of the transmitted wave approaching the energy of the sound case. It is noted that this relationship holds for the specific cases examined and it could be dependent on the initial slot depth, wavelength and member thickness. However, it demonstrates that the characterization of the filling percentage of cracks after repair is possible using wave energy parameters of surface measurements. This correlation should be further examined since there is no other way of obtaining information about the efficiency of repair.

5 IN SITU APPLICATION

As an example of surface measurements conducted for evaluation of the injection efficiency, the following case is presented. Through the thickness cracks were observed in a concrete bridge deck. The engineers at the site decided to treat with epoxy applied from one side by means of syringes through the crack mouth opening of 0.2mm. Since both the sides of the bridge deck were available, through the thickness measurements were conducted with symmetri-

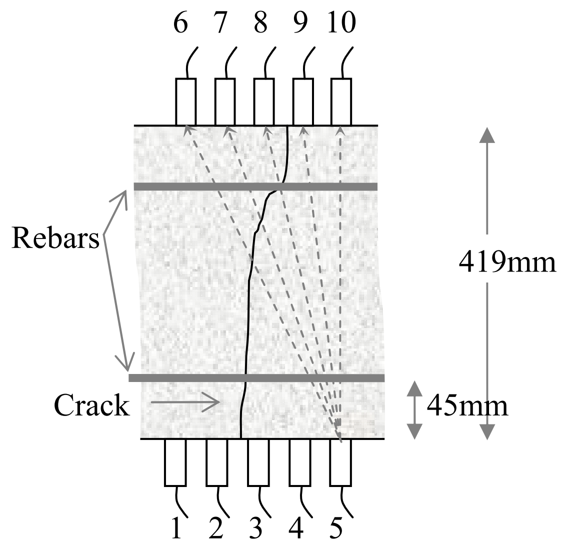

Figure 9. Representation of the sensor arrangement on the concrete deck.

cally arrayed sensors (Aggelis & Shiotani 2006), see Figure 9. Additionally, surface measurements were also performed before and after the injection using an array of 5 sensors with 50mm separation distance where the crack was located between the 3rd and 4th. In Figure 10a the response of the five sensors is depicted before the repair. It is obvious that not enough energy is transmitted through the crack as revealed by the very weak waveforms of sensors 4 and 5 (see 150 and 200mm in Figure 10a). After the injection, the energy was much enhanced as can be seen in Figure 10b demonstrating that the surface portion through which Rayleigh waves propagate was sufficiently filled. In case the filling was only shallow, as shown in the previous section, no clear Rayleigh wave would be observed. In order to yield more specific information, one should examine the frequency content of the waveforms.

The used excitation provides a wide spectrum of frequencies, with the major peak at 115kHz. However, propagation in an attenuative and dispersive medium like concrete may induce alterations in frequency content (Jacobs & Owino 2000), mainly causing downshift of the frequencies. Therefore, considering also the time period of the Rayleigh peaks (Aggelis and Shiotani 2006), see the arrows in Figure 10b, it becomes broader with propagation. Thus, it is concluded that the dominant wavelength increases with propagation distance. Specifically, near the impact, the period of the Rayleigh peak is measured at 8.8μs, (main frequency 113kHz), while after propagation of 200mm the period is 23.2μs (frequency of 43kHz). Therefore, the wave facing the crack, 125mm away from the excitation (between 3rd and 4th sensor) exhibits a major wavelength of 35-40mm considering a Rayleigh velocity of 2600m/s that was measured in sound material. It is accepted that Rayleigh waves propagate along the surface and sufficient energy penetrates to a depth similar to the wavelength. If this statement holds, the restoration of Rayleigh waves after the epoxy injection is indicative that the surface portion of 35-40mm of the crack was adequately filled.

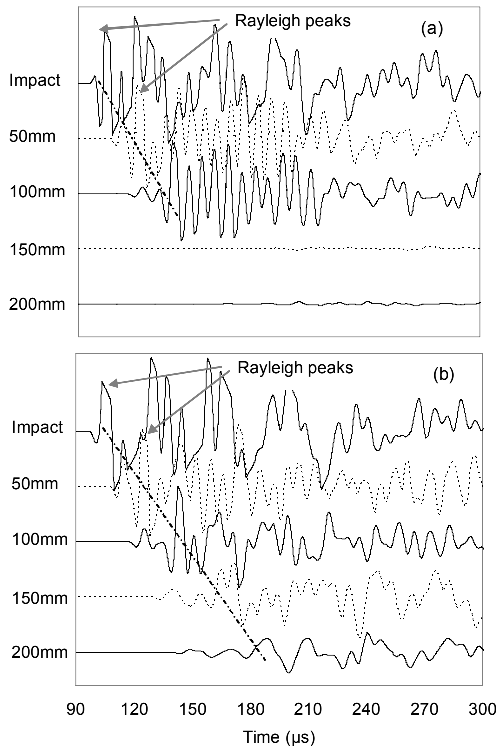

Figure 10. Waveforms collected at different distances from the excitation (a) before and (b) after epoxy injection in material with surface breaking crack between 100 and 150mm.

The velocity calculated from the peaks is 2414m/s. Using the same configuration sound material the velocity was measured at 2660m/s. It is reasonable to expect a drop in velocity of epoxy filled crack compared to the sound material. However, the specific crack's width was 0.2mm. Considering the propagation velocity of epoxy, sound concrete and the corresponding travel paths at the different materials, the measured Rayleigh velocity for the case of repaired crack should not be reduced by more than some m/s, being within the measurement error. Therefore, the further clear decrease of more than 200m/s should be attributed to other effects such as the fracture process zone, which expands several cm away from both sides of the crack (Mihashi et al 1991). In such a case wave propagation takes place not only through the sound concrete and the epoxy filled crack but also through a zone of deteriorated material at both sides of the crack. The thickness of this zone is dependent on the aggregate size and for concrete with 20mm aggregate, as is the material in the bridge it can be estimated to the order of 4-5cm (Mihashi et al 1991). The expansion of this zone to several centimeters justifies the clear decrease in velocity.

In the specific case since both sides were accessible, through the thickness measurements were also conducted to ensure the filling of the interior. Therefore two arrays of sensors were placed on the top and bottom side of the deck. Using pencil lead break excitation at each sensor position, the transit times for the wave to reach each of the opposite side surface sensors were determined and applied to special-

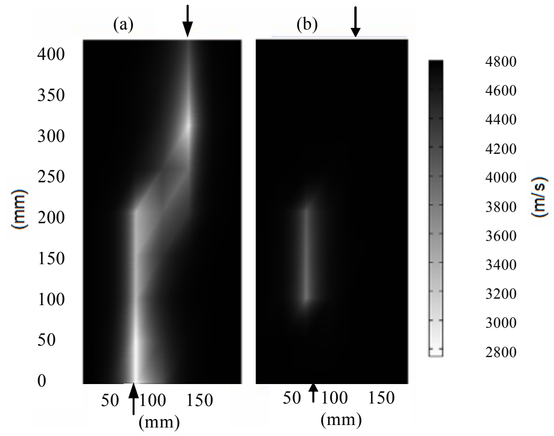

Figure 11. Velocity tomograms of the vicinity of the crack (a) before and (b) after repair. The arrows correspond to the actual position of crack openings.

ized tomography software (Kobayashi et al. 2006).

This way, the velocity structure of the cross section, namely tomogram, is constructed, see Figure 11. The first case (Figure 11a) concerns the cracked situation, while Figure 11b concerns the case after repair. It is seen that the velocity is sufficiently elevated, while only some remaining traces of the crack can be identified after repair. Anyway, due to the different mechanical properties of epoxy compared to those of concrete, it is impossible the velocity to be absolutely restored to the condition of sound material. Also, as mentioned above, except the major crack, the existence of the fracture process zone influences the measurements increasing the overall transit time. Despite these factors, the calculated velocity after epoxy injection exhibits clear increase, demonstrating that at least a substantial volume of the crack was successfully filled. The use of 5 sensors at each side leads to a number of 50 wave paths examined that provide sufficient information about the interior. However, the density of wave rays near the surface, is not as high as in the interior and therefore the reliability of the results concerning the portion near the surface is not secured. Accordingly, the surface wave examination was essentially conducted in order to obtain information about the surface layer.

6 CONCLUSIONS

In the present paper the non destructive characterization of surface opening cracks is addressed. Surface wave measurements offer a means of non invasive characterization. In such cases, the energy propagates mainly in the form of Rayleigh waves and the amplitude, energy and other features are dependent to a certain degree on the crack depth. Correlation curves between wave parameters and crack depth are established while new measurements on different cracks will increase the reliability of these correlations.

Although larger slot depths are accompanied by lower amplitude and delay in energy transmission, inherent difficulties like the inhomogeneous nature of concrete or ultrasonic coupling variations lead to certain experimental scatter. Therefore, it is reasonable to enhance the characterization by a simple multivariate analysis of 5 different features decreasing the error in depth estimation to less than ± 2mm. The characterization capacity however, is weakened for slot depths approaching the major wavelength. More important however, seem to be the dimensions of the concrete member, since slots exceeding 10% of the thickness result in approximately the same amplitude or energy regardless of the wavelength. For such large slots in many cases the amplitude is unexpectedly increased compared to the smaller cracks.

Further experiments on larger scale would clarify if the observed trends can be generalized for any case sharing the same slot depth to wavelength ratio as is usually suggested (Edwards et al. 2006, Wu 2006). Also search for other wave parameters that are sensitive to the slot depth could increase the accuracy in a more elaborate pattern recognition approach employed. Repair works with injection of epoxy, which is commonly used in practice, can be monitored using the same configuration, since wave propagation takes place also through the new layer of repair material, increasing the energy transmitted to a level similar to that of the sound material. Observation of energy and Rayleigh peaks can yield information concerning the degree of filling. The above findings hold to an actual case of through the thickness cracks in a bridge deck. Surface measurements revealed almost no energy transmitted though the crack in the form of Rayleigh waves initially. Injection with epoxy restored the propagation and Rayleigh waves were clearly observed through the repaired crack, demonstrating that the surface portion was sufficiently filled. If circumstances allow access to both sides of the deck, additional information for the filling of the interior can be supplied, as in the example presented herein. In this case tomography led to a visualization of velocity structure on the cross section revealing the necessary information about the efficiency of repair. Undergoing is the numerical simulation of wave propagation in cases of surface cracks in order to obtain better understanding of the propagation mechanics and increase the characterization accuracy.

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