Non-Destructive Testing of Concrete Based on Analysis of Velocity Dispersion of Laser Ultrasonics

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Abstract. With growing concern about aging of the infrastructure, efficient maintenance is becoming increasingly important. We propose a non-destructive testing method based on velocity dispersion analysis of laser ultrasonic waves for non-contact and quantitative inspection of concrete structures. This article outlines the proposed method and then reports experiments for detecting internal defects in concrete such as voids or delamination.
Experiments have been conducted to examine the feasibility of the method. Three kinds of specimens were used for the experiments: concrete incorporating Styrofoam to simulate voids, concrete cracked in compressive test, and steel plate reinforced concrete with delamination. The experimental results verified that internal defects can be detected and their depths accurately estimated.

1. Introduction

A large amount of infrastructure is now reaching the end of its design service life. For the effective investment of limited funding in infrastructures, effective surveys and structural integrity inspections are considered to become increasingly important. Conventional inspections, however, often involve labor-intensive techniques depending on the subjective judgment of the inspectors. Therefore development of more quantitative and effective inspection techniques is an urgent issue.

The laser ultrasonics is a unique technology that can transmit vibration to structures and measure the vibration without contacting the structure. Focusing on the laser ultrasonics, we developed a technique to detect internal defects based on analysis of velocity dispersion for the development of an effective, quantitative inspection technique. This paper describes the result of feasibility tests of the technique.

2. Laser Ultrasonics

It is well known that, when focused pulse laser is irradiated on a concrete surface, the temperature is raised or ablation is caused at the irradiated point. This generates ultrasonic wave in the concrete due to thermal strain or counteraction of a shock wave. By measuring the ultrasonic wave with an optical vibrometry, non-destructive inspection that achieves both non-contact transmission and reception of the vibration will be possible. This technique, called the laser ultrasonics, has recently been highlighted as a non-destructive inspection technique [1]. The laser ultrasonics does not require an acoustic coupling medium in objects concerned for the transmission and reception of ultrasonic wave, and has good reproducibility of measured ultrasonic waveforms. Thus it is expected to be applied for high accuracy inspection of large-scale structures.

3. Experiment

3.1 Experimental Setup

Instrumental setup of the experiment is shown in Figure 1 and Figure 2. The TEA CO_2 Laser (Transversely Excited Atmospheric Pressure Laser, wavelength: 10.6 μm, maximum energy; 4 J/pulse, maximum repetition rate: 20 Hz) was used to generate ultrasonic wave. Laser beams, lead to the specimen using an arm with mirrors in it, were focused on the concrete surface using a ZnSe lens (focal length: 200 mm). The ultrasonic waves induced by irradiating pulsed-laser were measured using a laser Doppler vibrometry (maximum detection frequency: 2 MHz) without contacting the concrete. The vibratory velocity waveforms measured with the vibrometry was sent to the digital oscilloscope, and synchronous averaging was then applied, synchronized to the time when the TEA CO_2 laser was irradiated. These waveforms were recorded in a PC.

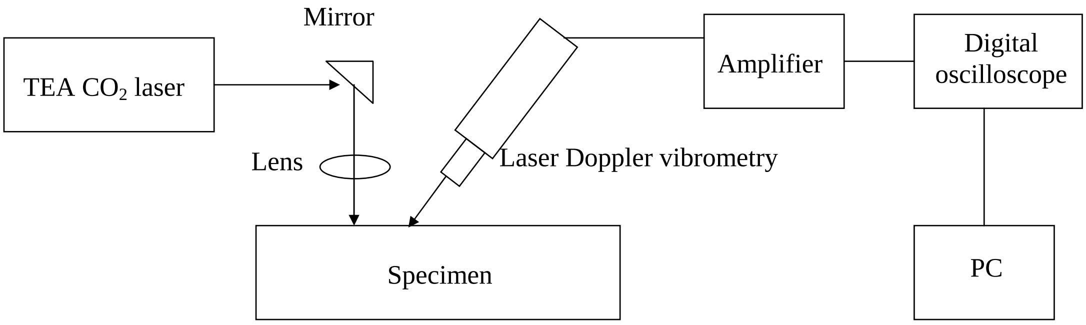


Figure1. Instrumental setup of the experiment

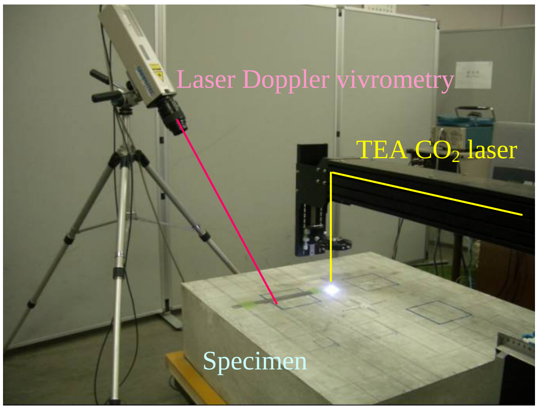
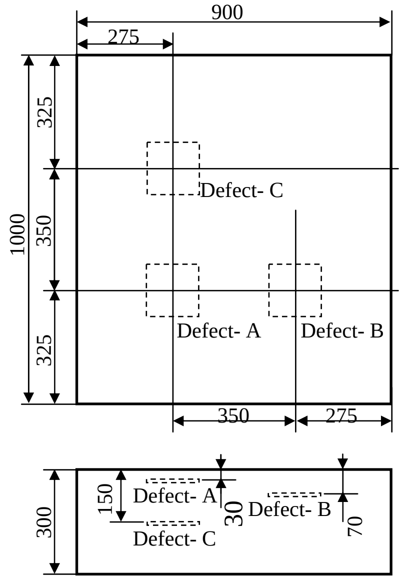


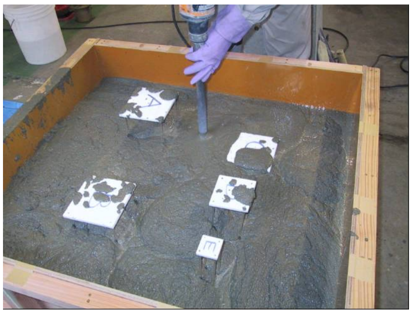
Figure2. Experimental arrangement

3.2 Specimen

In order to test the capability to detect internal defects in the concrete such as void and delamination, three types of specimen were prepared as shown below.

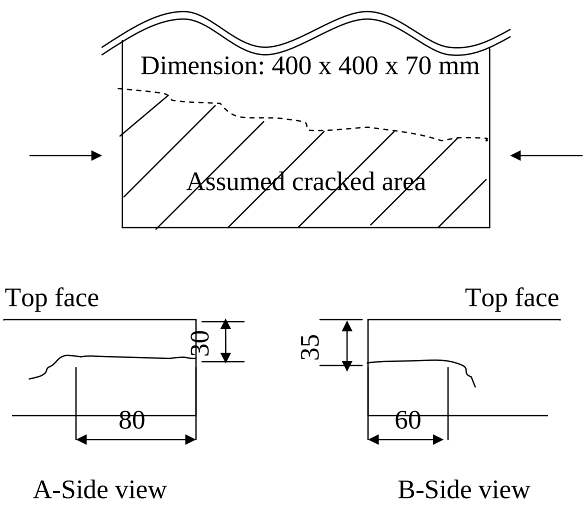
a) Specimen with artificial voids: Thin Styrofoam plates (150 x 150 x 10 mm) were embedded at different depths in concrete (Figure 3).
b) Specimen with a crack generated by a compression testing machine: Cracks were generated in the specimen using a compression testing machine (Figure 4).
c) Steel plate reinforced concrete with a delamination: A delamination was generated between the steel plate and concrete using a jack bolt. The gap between the steel plate and the concrete can be controlled by turning the jack bolt (Figure 5).





Fabrication of artificial voids

Figure 3. Specimen with artificial voids



Appearance of cracking

Figure 4. Specimen with crack

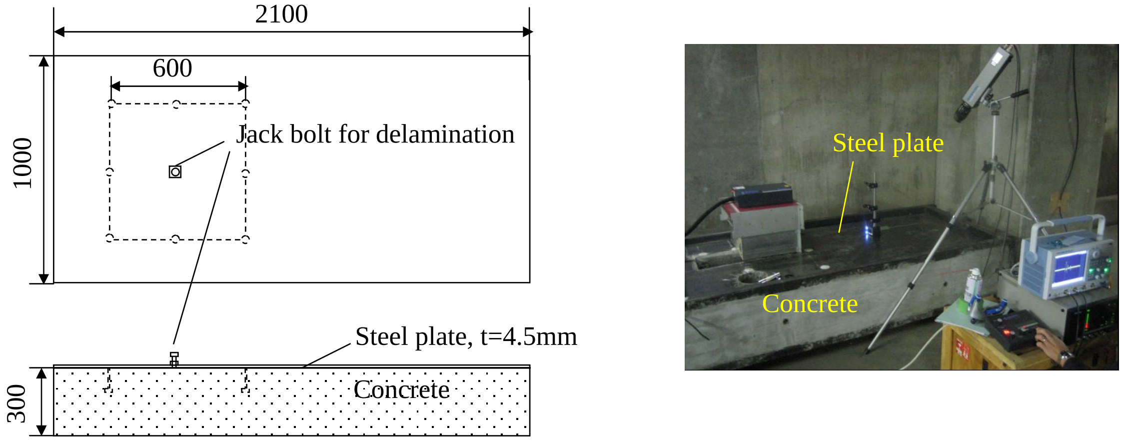


Figure 5. Specimen of steel plate reinforced concrete

4. Analysis of Velocity Dispersion of Laser Ultrasonic waves

Taking advantage of the laser ultrasonics, with the features described above, techniques to detect internal defects in the concrete were developed.

As a first step, ultrasonic waveforms were compared for the parts with and without a defect in the specimen shown in Figure 3. The defect (defect-A) was simulated with the Styrofoam plate embedded in the concrete at 30 mm depth from the surface. The distance from the irradiated point to the measured point was set at 40 mm. Laser ultrasonic waveforms were measured for the part with a defect in the specimen and sound portion (Figure 6).

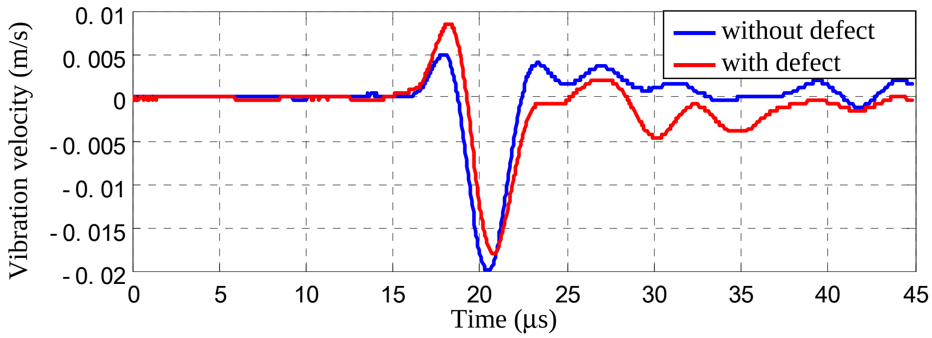


Figure 6. Comparison of waveforms between with and without defects

The propagation velocity obtained from propagation distance and the arrival time for the wave with large amplitude (with onset at around 16 μs, Figure 6) was almost the same as that of the surface wave. The waveforms after the arrival of this wave are different for the parts with and without a defect. In addition, no arrival of P-wave nor S-wave was identified.

As preliminary test confirmed that the difference between defected and sound portions can be judged by comparison of surface wave post-arrival waveforms, and as attention to large amplitude waves which are relatively easy to detect is advantageous on the point of S/N, multi-channel analysis[2], a technique to estimate velocity profile of a medium from velocity dispersion, was applied.

4.1 Measurement Procedure

A laser beam was repeatedly irradiated at a fixed point, while measurement points of the laser ultrasonic wave were shifted at a constant interval. Figure 7 shows waveforms measured at points with a minimum interval of 2 mm and a maximum interval of 150 mm. The vertical axis in Figure 7 corresponds to each measurement point. For this experiment, synchronous averaging was applied to the 64 waveforms measured at each measurement point synchronous to the time when the laser was irradiated.

The data were obtained for the specimen shown in Figure 3 (defect-A).

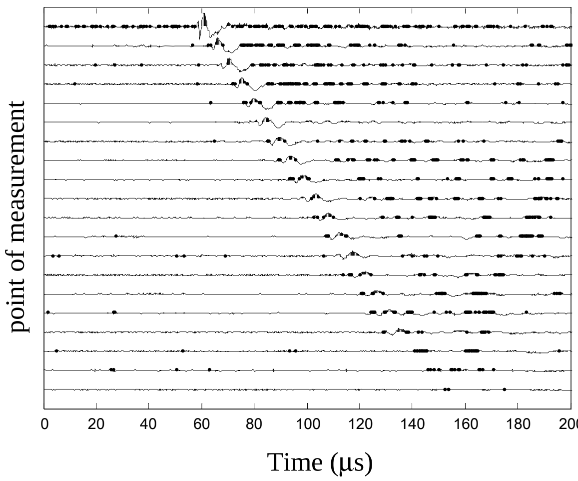


Figure 7. Measured waveset (defect-A)

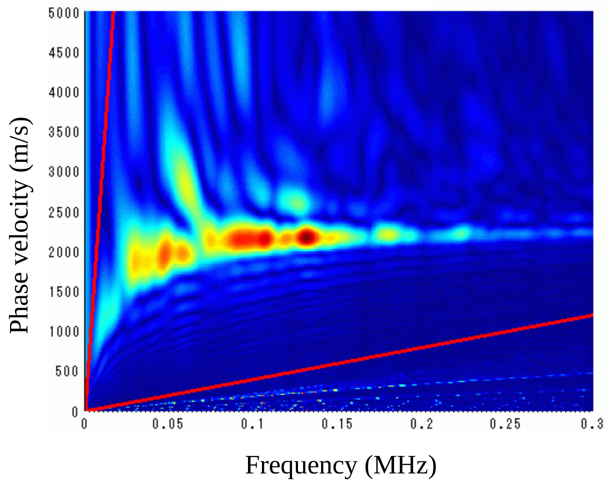


Figure 8. Velocity dispersion curve (defect-A)

4.2 Analysis Model

For the application of the velocity dispersion analysis, models that represent the sound portion and the portion with a defect were assumed as shown in Figure 9. The fixed irradiated point and measurement points at even intervals are shown.

Using these models, a defect can be determined by the presence of the air layer, and the depth of the defect, i.e. the depth to the air layer (thickness of the surface layer) can also be obtained. The depth of the defect could be estimated by, at first obtaining theoretical dispersion curve of the Lamb wave, the wave that propagates through a laminar medium as shown in Figure 9, and then fitting of the theoretical curve and the measured curve with the depth of the defect, *h*, as a parameter.

The compressional wave velocity c_p (3750 m/s) and the shear wave velocity c_s (2340 m/s) of the specimens were determined so that measured and analytical surface wave phase velocity would be consistent at the high frequency region, assuming the Poison's ratio to be 1/6.

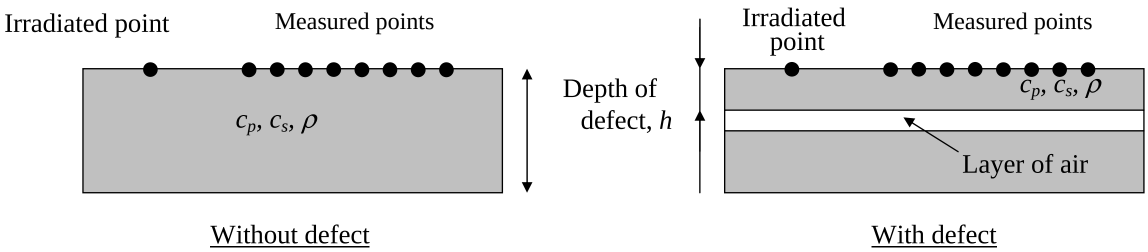


Figure 9. Schematic of analysis model

5. Experimental Results and Discussion

5.1 Detection of artificial Voids in Concrete

In the dispersion curve for the defect-A (depth of 30 mm) as shown in Figure 8, large and small phase velocity modes are observed in the frequency range of about 70 kHz or lower. These show good consistency with the dispersion curve of the Lamb wave curve that propagates in the shallower part than the defect (air layer) in the specimen as shown in Figure 9. By comparing this with the dispersion curve obtained for the part without a defect, it can be determined whether there is a defect or not from the change in the mode.

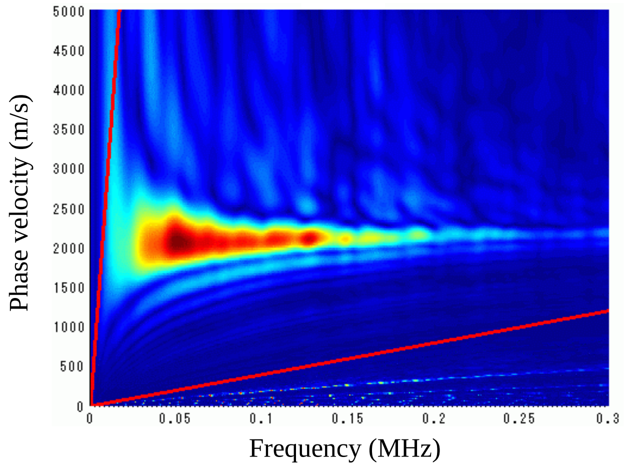


Figure 10. Velocity dispersion curve (without defect)

In order to examine the capability to define the depth of the void, dispersion curves were obtained with the thickness of specimens, *h*, as a parameter for the defect model in Figure 9. These curves were compared with the measured data. The result is shown in Figure 11. The measured data shown as open circles in the figure were the maximum values extracted from the contour in Figure 8. The value of *h*, which yields the best-fit curve to the measured value, was estimated to be the depth of the void. As a result, h was determined to be 33 mm. This implies that the depth of the void can be estimated at a high accuracy. When applied to the defect B and C, defect B could be detected at an error of 14 %, while defect C could not be detected. Expanding maximum interval of the receiving points of the vibration is considered in order to detect deeper defects.

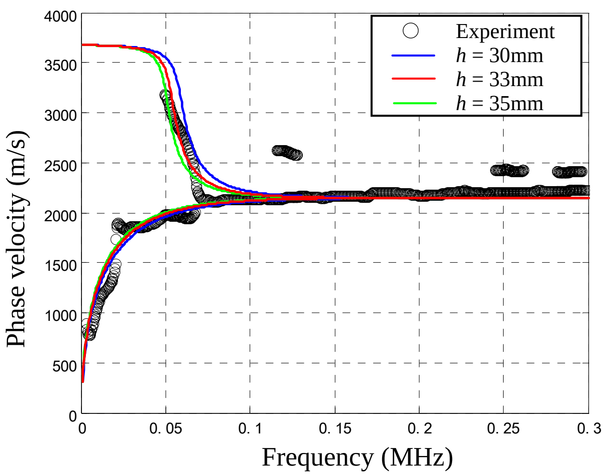


Figure 11. Estimation of depth of defect-A

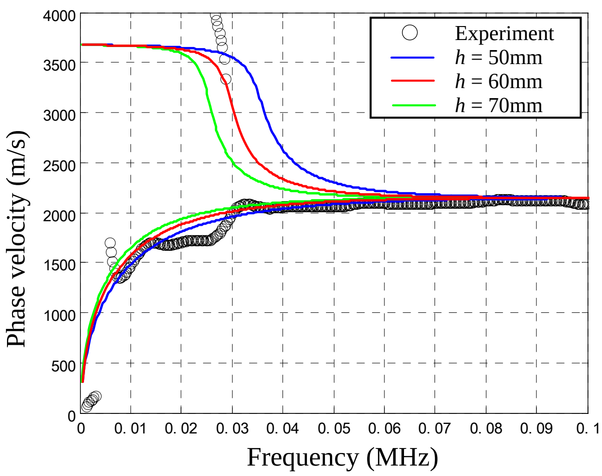


Figure 12. Estimation of depth of defect-B

5.2 Detection of Crack in Concrete

Using specimens prepared to simulate actual cracks (Figure 4), similar attempts were made. The dispersion curve obtained for the part with a crack is shown in Figure 13. Theoretical and measured dispersion curves obtained by putting the depth of the crack, *h*, as a parameter were compared as shown in Figure 14. The actual depth of the crack was in the range of 30 – 35 mm (Figure 4). The result indicates that the depth of the crack could be estimated accurately using this technique.

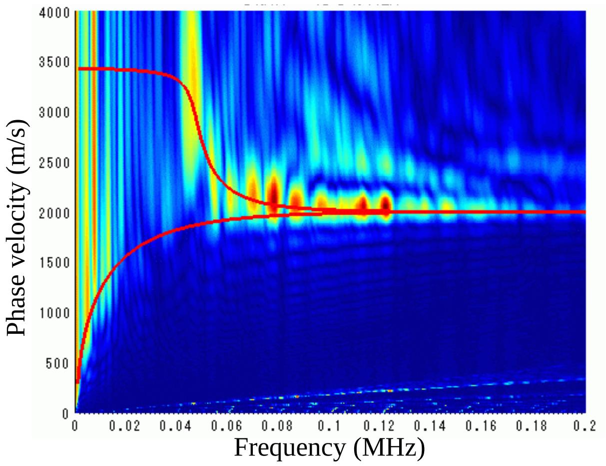


Figure 13. Velocity dispersion curve (cracked specimen)

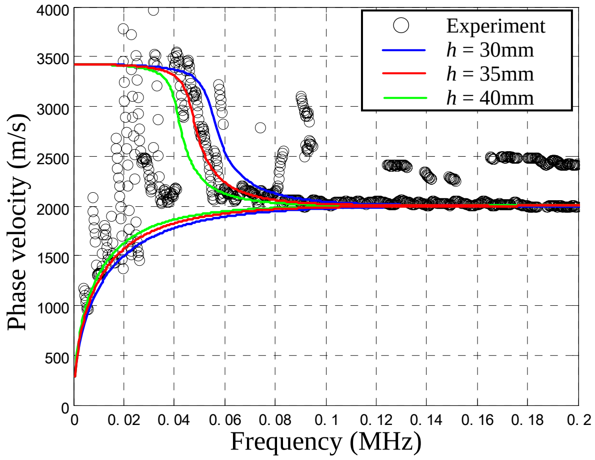


Figure 14. Estimation of depth of crack

5.3 Detection of Delamination between Concrete and Steel Plate for Reinforcement

The steel plate reinforced concrete has been applied or is planned for application for seismic retrofit of bridge pier or structures of next generation nuclear power plants. For such structures, since delamination between steel plate and the concrete can be a problem, various non-destructive test methods have been applied.

For the specimen shown in Figure 5, a simulated delamination was generated between the steel plate and the concrete using a bolt penetrated through the steel of the specimen. Test results before and after the delamination are shown in Figure 15 and Figure 16 respectively.

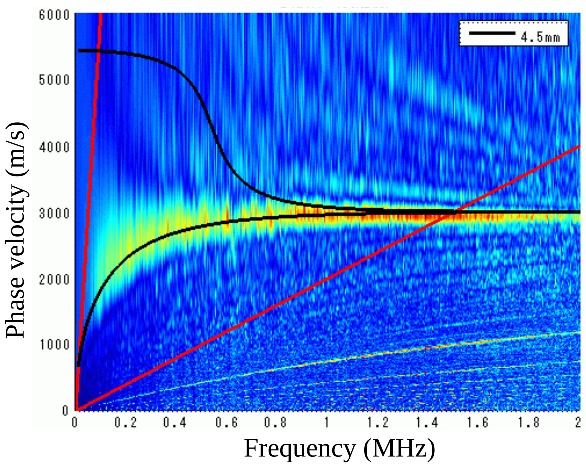


Figure 15. Velocity dispersion curve (before delamination)

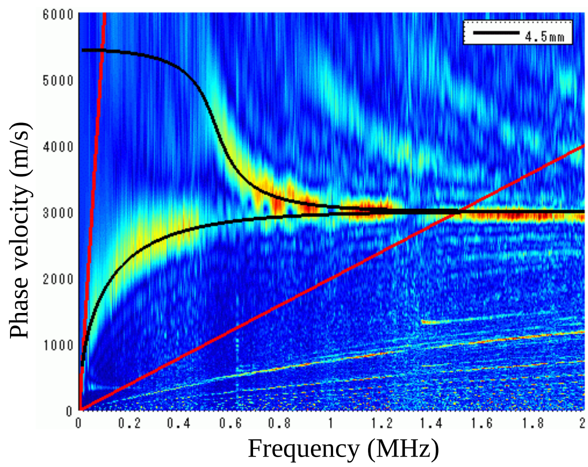


Figure 16. Velocity dispersion curve (after delamination)

Comparing both figures, it is indicated that Lamb wave that propagates through plate medium corresponding to the steel plate with a thickness of 4.5 mm is observed in the test result after the delamination. This implies that delamination of the steel plate could be detected.

Then the bolt penetrated the steel plate to generate delamination was put back in place to re-contact the steel plate with the concrete again. Under these conditions, the location near the bolt was hit with a hammer, and no definite difference was observed in the impact sound between the parts with and without a delamination. The result of the laser ultrasonic testing at the same position is shown in Figure 17. A slight sign of the delamination was identified.

When attempted to measure the depth of the delamination by the fitting of theoretical dispersion curve, a curve corresponding to the depth of 4.5 mm - the thickness of the steel plate - was easily identified (Figure 18).

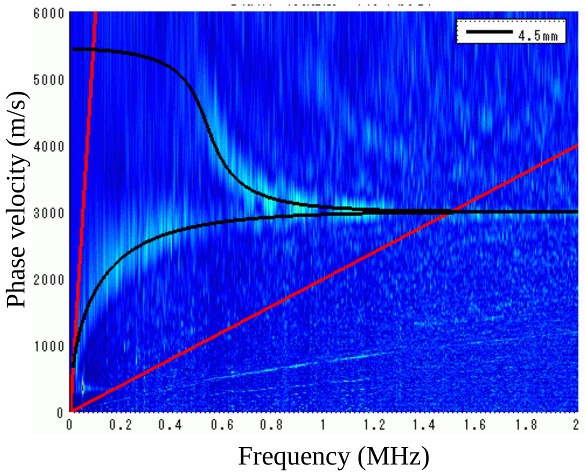


Figure 17. Velocity dispersion curve (after re-contact)

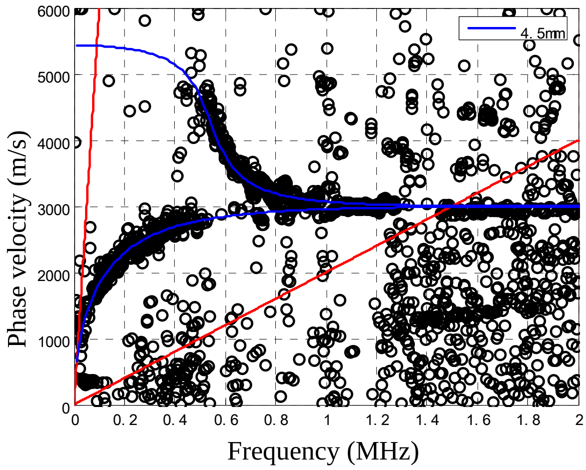


Figure 18. Estimation of depths of defect (after re-contact)

These results indicate that closed delamination, which is difficult to identify by the hammering test, could be detected using the laser ultrasonics that generates and detects wide band ultrasonic wave.

6. Conclusion

The laser ultrasonics developed has unique features of non-contact, and high reproducibility for the effective inspection of the integrity of concrete structures. Feasibility of the technique was tested for specimens with different types of defects often found in concrete structures. This method, based on velocity dispersion analysis of laser ultrasonic waves, was demonstrated to be able to accurately detect the existence and depth of defects in the concrete structure.

Demonstration of this technique for actual structures is being planned after the development of a portable system. For commercialization of the technique, development of a system applicable outdoors and improvement of measuring methods will be required.

References

[1] Davis S J, et al., 1993, Laser-generated ultrasound: its properties, mechanisms and multifarious applications: J. Phys. D: Appl. Phys., 26, 329-348.

[2] Park C B, et al., 1999, Multichannel analysis of surface waves: Geophysics, 64, 800-808.