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Detecting delaminations in concrete structures using velocity dispersion of laser generated Lamb waves

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ABSTRACT

There is growing concern about the deterioration of civil infrastructure. For sustainable management of infrastructure, stepped-up efforts are needed to improve the efficiency and reliability of inspections. However, conventional inspections depend on subjective and labor-intensive methods, such as visual inspections or hammering tests. The fact that severe accidents repeatedly occur after an inspection indicates the limit to conventional methods.

The laser-ultrasonic technique is based on the generation and detection of ultrasound with lasers. This technique allows remote inspection of concrete structures with high reproducibility of measurement.

We propose a non-destructive detection method for delaminations in concrete structures by analyzing the velocity dispersion of laser generated Lamb waves that propagate in plate-like structures of finite thickness.

Experiments for detecting several kinds of artificial flaws are carried out. As a consequence of the experiments, the effectiveness of the method is demonstrated. An application to concrete structure in service is also conducted.

Keywords: laser ultrasonics, velocity dispersion, Lamb waves, delaminations, non-destructive testing

INTRODUCTION

Nondestructive inspection techniques using ultrasonic waves play a key role in understanding mechanical properties or continuity condition of the structure. In spite of these remarkable features, the ultrasonic techniques did not find wide application in actual structure in contrast to laboratory test. There are several reasons for this: attenuation of ultrasound in concrete, instability of acoustic coupling to the object, inconvenience of acoustic coupling medium.

The laser-ultrasonic technique is based on the generation and detection of ultrasonic waves with lasers. This non-destructive testing (NDT) method allows remote inspection of concrete structures with high reproducibility of measurement, which is impossible with conventional ultrasonic techniques. This novel NDT technique has already been widely studied for many applications. Von Gutfeld and Melcher (1977) demonstrated the feasibility of laser ultrasonic techniques for flaw detection in a metallic sample. Monchalin et al. (1988) developed a thickness measurement and flaw detection system for seamless pipes. For the inspection of carbon fiber-reinforced composites (CFRC), Edwards et al. (2001) investigated the generation efficiency of ultrasonic waves and the threshold for damage-free generation. A laser-based inspection system for aircraft structures was studied for more than 10 years by major European aircraft companies (Guilliorit et al., 2004). In the area of railway maintenance, a laser-ultrasonic system was also developed and tested for rail inspections (Nielsen, 2004). In the experiments, artificial flaws in rails were detected, and the system was mounted on a specially designed railroad vehicle. Even though the laser-ultrasonic technique has been widely applied to metal or composite materials like CFRP, cases on application to concrete structures have rarely been reported. Concrete is a heterogeneous material containing micro-pores and aggregates. As is pointed out by Jacobs (1997), ultrasonic waves in concrete are scattered and strongly attenuated during propagation. Thus, a special technique is necessary to apply the laser-ultrasonic NDT to a concrete structure.

To overcome this problem, we adopted a suitable analyzing method of ultrasound in concrete. As the concrete surface is irradiated with a high-power pulsed laser, surface waves are efficiently generated in the concrete. Additionally, attenuation of surface waves is proportional to $r^{-1/2}$ (r: propagation distance), while attenuation of longitudinal or shear waves is proportional to r^2 (Richard et al., 1970). These features of surface waves are useful in the application of laser-ultrasonics to concrete NDT. If the inspected concrete has plate-like structures, for example delaminations, Lamb waves propagate between the top and bottom of the plate-like structure. The wave velocity of Lamb waves is a function of the frequency and the thickness of the plate and hence is dispersive. The phase velocity dispersion curve of Lamb waves is obtained from the non-contact measurement of surface vibrations at multiple points. The detection of flaws like delaminations is performed by analyzing the dispersion characteristics of Lamb waves.

This paper investigates the effectiveness of the laser-ultrasonic NDT we have proposed. Laboratory experiments for evaluating the proposed technique are conducted using various concrete specimens with artificial flaws. The laser-ultrasonic NDT is also applied to inspecting the delaminations inside water-conveying pipes in service.

NON-DESTRUCTIVE TESTING USING LASER-ULTRASONICS

Principle and properties of Laser-Ultrasonics. Laser-ultrasonics (laser generation and interferometric detection of ultrasound) is a novel technique developed for non-destructive inspection of various materials and structures. As a high power pulsed-laser is directed onto a material, minute quantities of the material gush out from the surface by absorbing the electromagnetic energy supplied from the laser pulse. In reaction to the gushing of material, ultrasonic waves are generated at the irradiated point of the material surface. By detecting the laser-generated ultrasonic waves with a laser interferometer, non-contact ultrasonic NDT becomes possible (Figure 1).

Pulse durations of the lasers in general are less than the order of microseconds, and the generated ultrasound has exceedingly broad frequency components. This feature is suitable for the detection of various anomalies in the material. The other favorable property of the laser-ultrasonic technique is the reproducibility of the measured waveforms. Conventional ultrasonic techniques require mechanical contact with the material and an acoustic coupling medium to reduce transmission loss. It is difficult to maintain consistent mechanical contact in every measurement to be compared, and the acoustic coupling medium decreases the efficiency of multi-point measurements. The high reproducibility of the laser-ultrasonic technique is suitable for multi-point, mobile, and automatic measurements.

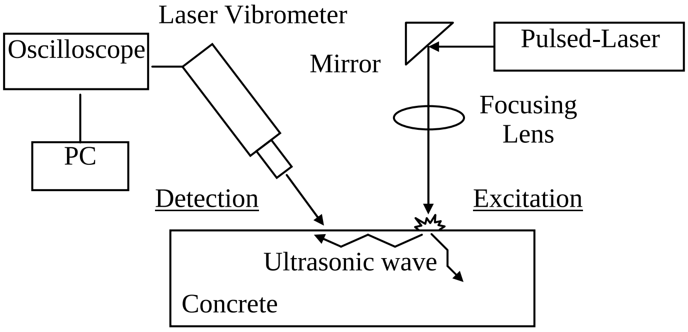


Figure 1. Schematic diagram of laser-ultrasonic technique

Velocity Dispersion Curves of Lamb Waves. Figure 2 is an example of a laser-generated ultrasonic wave in a thin concrete plate of 30 mm in thickness. A wave with large amplitude in the waveform seemed to be a guided wave from its large amplitude and wave velocity. To confirm the wave type, a laser beam was repeatedly irradiated at a fixed point, while measurement points of the laser-ultrasonic wave were shifted at a constant interval. Waveforms measured at multiple points with a constant interval are shown in Figure 3. The vertical axis in the figure corresponds to each measurement point. As the speed of the wave with large amplitude corresponded with the velocity of surface waves, the waves were presumed to be Lamb waves, namely guided waves propagating in plate-like structures.

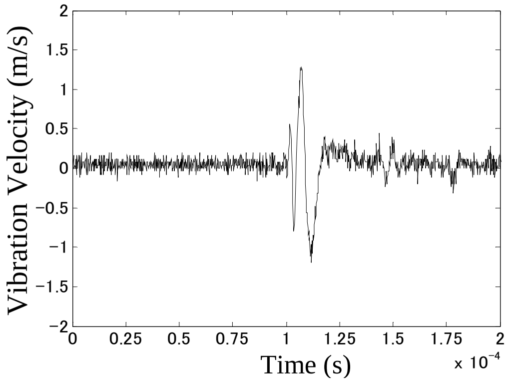


Figure 2. A waveform of laser-generated ultrasound

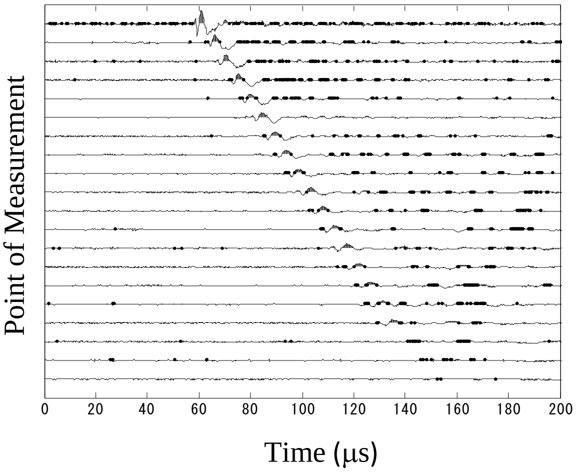
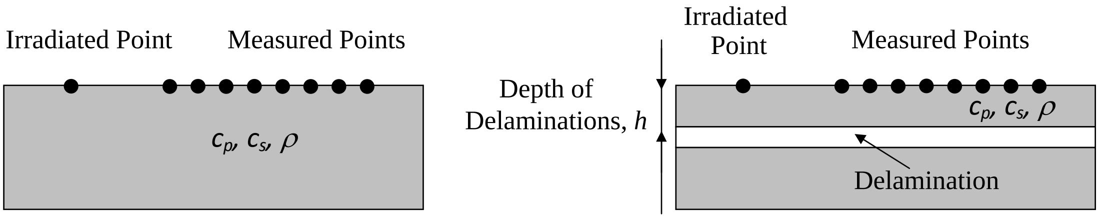


Figure 3. A wave set measured at multiple points

As mentioned above, Lamb waves are dispersive, and the wave velocity is a function of the frequency and the thickness of the plate. By using this property, the thickness of the plate-like structure, namely the depth of delaminations, can be derived from the relationship between velocity and the frequency of the wave as shown below.

For the velocity dispersion analysis, models that represent the sound portion and the portion with delaminations were assumed as shown in Figure 4. The fixed irradiated point and measurement points at even intervals are shown.



Sound Portion

with Delaminations

Figure 4. Schematic of analysis model

Fourier transformation is performed on a wave set (v (t, x_n)) obtained at each measurement-points (x_n), and a set of frequency spectrum (V (ω, x_n)) is given.

$$V(\omega,x_n)=\int v(t,x_n)\,e^{-j(\omega t-kx_n)}dt \tag{1}$$

After assuming velocity (c: phase velocity) of the wave propagating along each measurement point (x_n), summations of the frequency spectrum are performed while giving phase delays to each frequency spectrum (V (ω, x_n)). Then, updating the assumed value of propagation velocity (c) within the expected range of velocity, wave intensities on the frequency-velocity plane are derived from the summations of the frequency spectrum. Namely, the frequency dependence of the ultrasonic velocity will be obtained from the distribution of the wave intensities.

$$P(\omega,c)=\left|\sum_{n=1}^{N} V(\omega,x_n)\,e^{j\omega\frac{x_n}{c}}\right| \tag{2}$$

By displaying the wave intensities $P(\omega, c)$ on the frequency-velocity plane, velocity dispersion characteristics are found from the maximum value of the wave intensities.

Using these models, flaws can be determined from the velocity dispersion characteristics of the ultrasonic wave, and the depth of the delaminations, i.e. the depth to the air layer (thickness of the surface layer) can also be obtained. The depth of the defect is estimated by fitting of the theoretical curve and the measured curve with the depth of the defect, h, as a parameter.

The longitudinal wave velocity c_p (3750 m/s) and the shear wave velocity c_s (2340 m/s) of the specimens were determined from propagation time and distance, so that measured and analytical surface wave phase velocity would be consistent in the high frequency region, assuming the Poison’s ratio to be 1/6.

Theoretical dispersion curves of Lamb waves are shown in Figure 5. Lamb (1917) derived a dispersion equation of guided waves propagating in a free plate. Theoretical dispersion curves determined by the dispersion equation are function of frequency and phase velocity of waves, thickness of the plate.

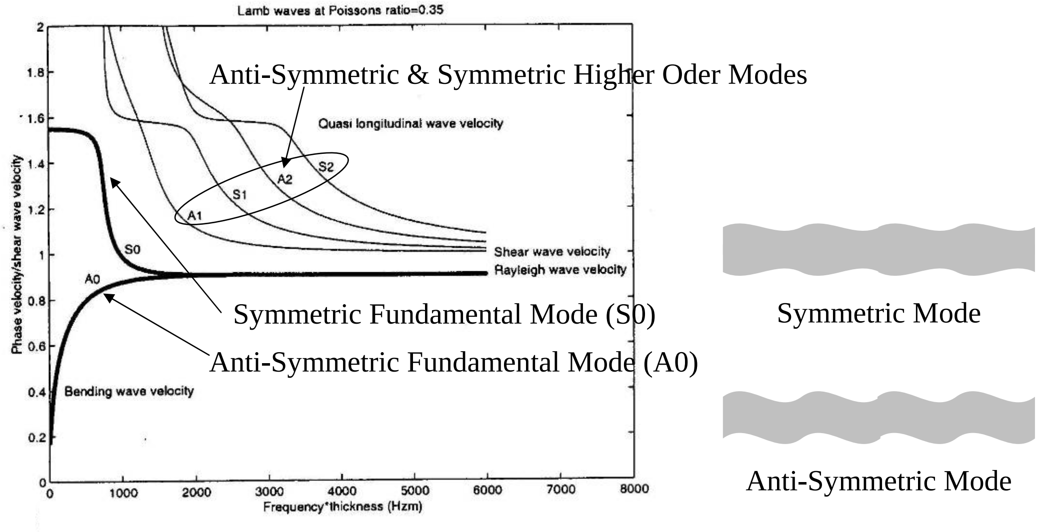


Figure 5. Theoretical Dispersion Curves of Lamb waves

[From Ryden N. et al. (2004)]

LABORATORY EXPERIMENTS

Experimental Setup. The experimental setup is shown in Figure 1. 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 waves. Laser beams leading to the specimen using a duct with mirrors inside were focused on the concrete surface using a ZnSe lens. The ultrasonic waves induced by irradiating the pulsed laser were measured using a laser Doppler vibrometer without contacting the concrete. The vibratory velocity waveforms measured with the vibrometer were 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 on a PC.

Experimental Specimen. In order to test the capability to detect internal defects in the concrete, such as delaminations, several types of specimens 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 6).

b) 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 7).

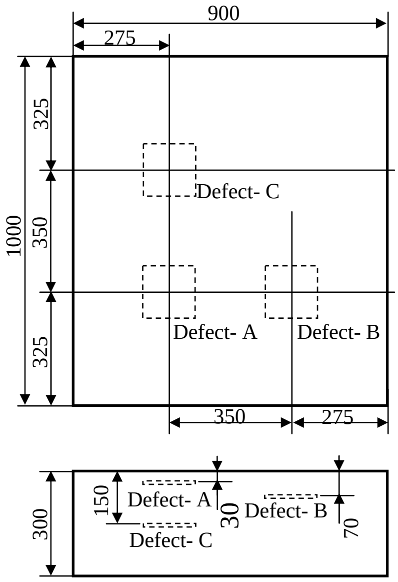


Figure 6. Schematic of specimen with artificial voids

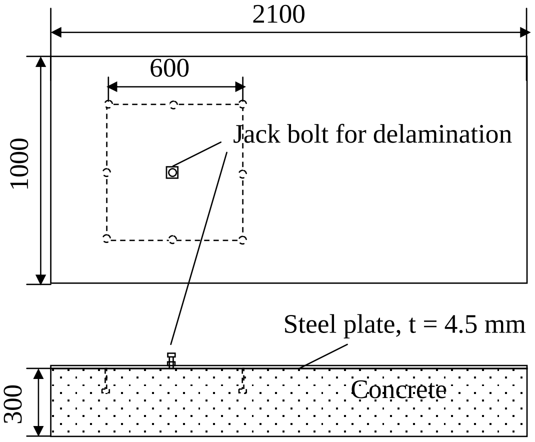


Figure 7. Specimen of steel plate reinforced concrete

Results of the Experiments. At first, an experimental result on the specimen with artificial voids is described. The dispersion curve for defect-A (depth of 30 mm) is shown in Figure 8. In the frequency range of about 0.07 MHz (70 kHz) or lower, large and small phase velocity modes are observed. These show good consistency within the theoretical dispersion curve (A0 and S0 mode in Figure 5) and measured dispersion characteristics in the experiment (Figure 8). On the other hand, branch of large phase velocity are not observed in dispersion characteristic of sound portion (Figure 9). By comparing measured dispersion characteristics with theoretical dispersion curves, it can be determined whether there is a defect from the change in the mode. It has been confirmed that symmetric fundamental (S0) mode is not observed in the velocity dispersion characteristic of sound portion.

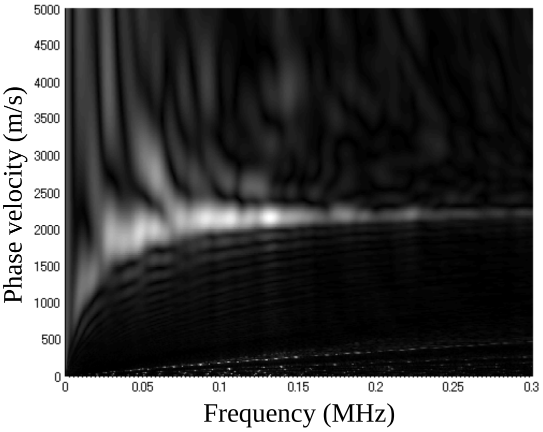


Figure 8. Velocity dispersion characteristics (defect-A)

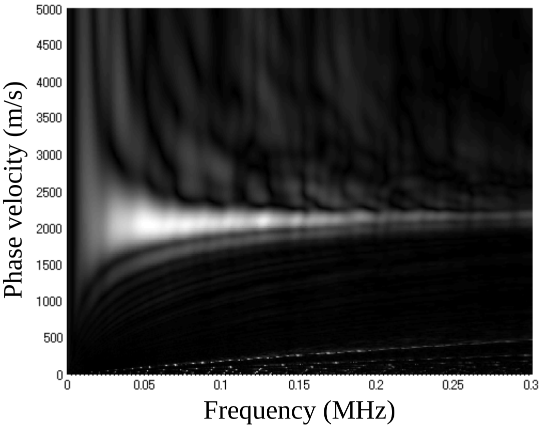


Figure 9. Velocity dispersion characteristics (without defect)

In order to examine the capability to estimate depth of the void, dispersion curves were obtained with assumed depth of the void, *h*, as a parameter for the defect model in Figure 4. These curves were compared with the measured data. The result is shown in Figure 10.

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 with high accuracy.

The steel-plate reinforced concrete shown in Figure 7 was tested. For simulating delaminations between the steel plate and the concrete, a bolt that penetrated through the steel of the specimen was used. Test results before and after the delamination are shown in Figure 11 and Figure 12, respectively. Comparing both figures, the Lamb waves propagate through the plate medium corresponding to the steel plate with a thickness of 4.5 mm as observed in the test result after delaminating. It has been shown that delaminations of the steel plate can be detected.

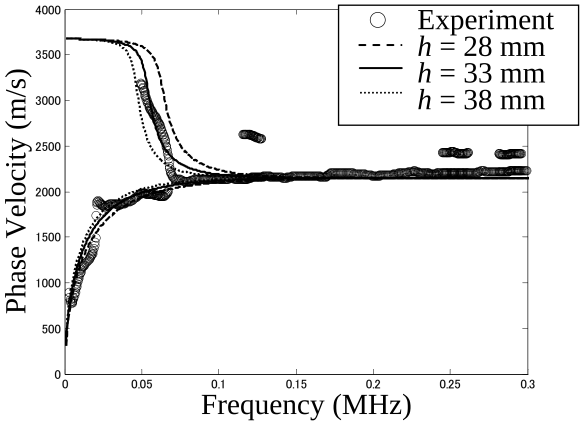


Figure 10. Velocity dispersion characteristics (defect-A)

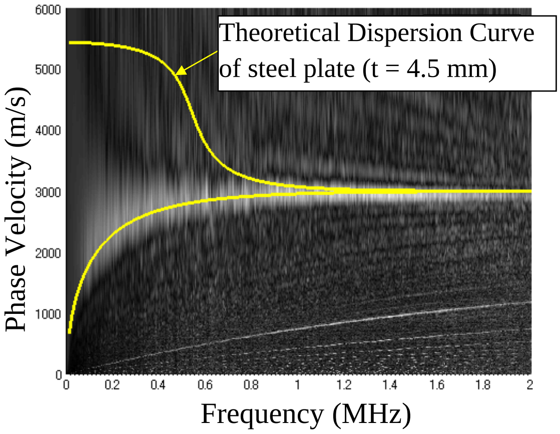


Figure 11. Velocity dispersion characteristics (before delaminating)

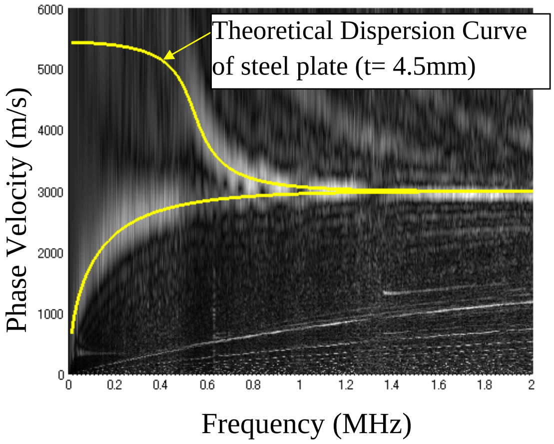


Figure 12. Velocity dispersion characteristics (after delaminating)

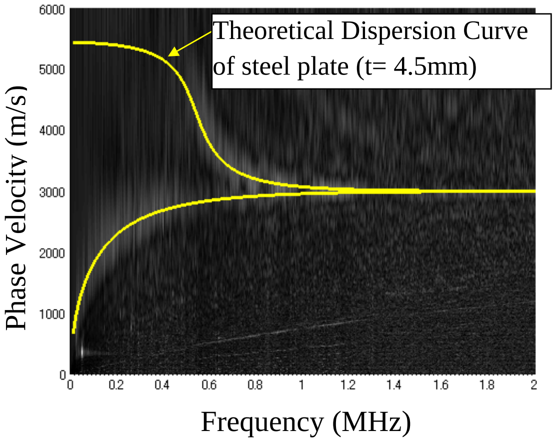


Figure 13. Velocity dispersion characteristics (after re-contact)

Then, the bolt that penetrated the steel plate to generate delaminations 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, but no definite difference was observed in the impact sound between the parts with and without the delaminations. The result of the laser-ultrasonic testing at the same position is shown in Figure 13. A slight sign of the delaminations was identified.

When attempting to measure the depth of the delamination by the fitting of theoretical dispersion curve, a curve corresponding to the S0 mode for steel plate with a thickness of 4.5 mm was easily identified (Figure 14).

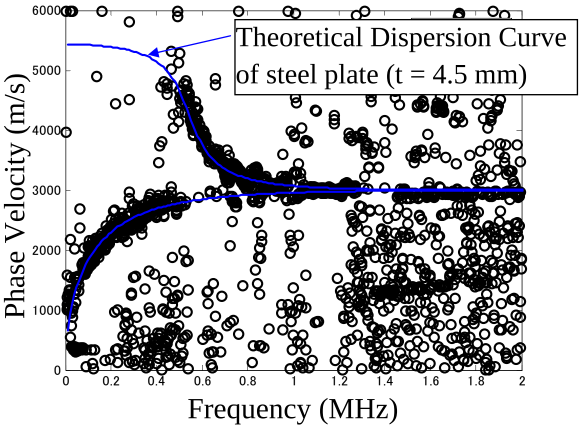


Figure 14. Estimation of depths of defect (after re-contact)

APPLICATIONS OF LASER-ULTRASONIC TECHNIQUE TO CONCRETE STRUCTURES IN SERVICE

Field Application of Laser-ultrasonic NDT. To verify the effectiveness of the laser-ultrasonic technique, a field experiment was conducted for detecting delaminations in cement-mortar linings of ductile iron pipes. The pipes are used for water supply, but concerns have arisen that the delaminations of cement-mortar linings are caused by deterioration. The pipes are 1200 mm in diameter, while the thicknesses of the cast-iron and cement-mortar linings are 17 mm and 10 mm, respectively. Because the pipes are in service and filled with water, a conventional thickness meter using ultrasonic pulse-echo reflection is not available.

Results Obtained in the Field Application. A similar procedure was followed in field applications of the laboratory experiments. A pulsed laser was directed toward the ductile pipe, and laser-generated ultrasound was measured at multiple points on the surface of the ductile pipe (Figure 15). Models that represent the sound portion and the portion with delamination are shown in Figure 4. Parameters of analysis model are given in Table 1.

Figure 16 shows a comparison of the measured dispersion characteristics and the theoretical dispersion curve, which is calculated by assuming the delaminated model. Because the measured dispersion characteristics seemed to fit the dispersion curve of the delaminated model, it was concluded that the mortar lining was delaminated.

At a later date, the pipe was dismounted and the inside of the pipe was examined by visual inspection. As a consequence, delaminations in the mortar lining have been found (Figure 17).

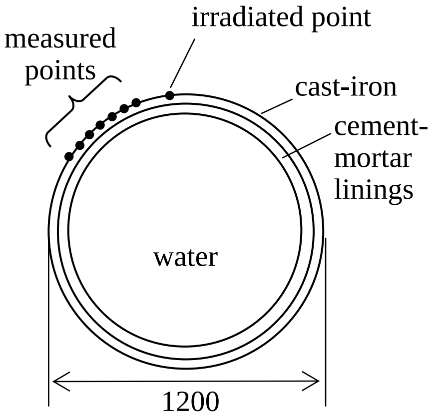


Figure 15. Diagram of the inspected water-conveying pipe

Table 1

cast-iron	thickness（m）	0.017
	density (kg/m^3)	7860
	P-wave velocity (m/s)	5950
	S-wave velocity (m/s)	3240
cement-mortar linings	thickness（m）	0.010
	density (kg/m^3)	2300
	P-wave velocity (m/s)	3100
	S-wave velocity (m/s)	1960

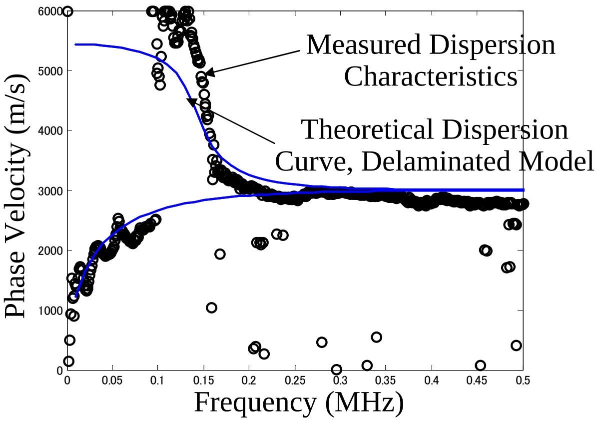


Figure 16. Velocity dispersion characteristics of mortar lining pipe

Figure 17. Verified delaminations of mortar lining (inside pipe)

CONCLUSIONS

For reliable and objective inspection of concrete structures, we developed a suitable laser-ultrasonic technique for concrete. The feasibility of the technique was examined by experiments using specimens with different types of defects often found in concrete structures. This method, based on a velocity dispersion analysis of laser-ultrasonic waves, accurately detected the existence and depth of defects in the concrete structure.

Development of a mobile inspection system is in progress. The system requires application expertise for continuous improvement of the technologies.

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