

Applicability of non-contact inspection using laser ablation-induced vibration in a reinforced concrete tunnel lining

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Abstract

This paper considers the applicability of remote laser sensing to reinforced concrete tunnel linings with suspected corrosion of the reinforced steel. As an alternative to the hammering test, this approach represents a non-contact inspection method that provides quantitative evaluation. Remote laser sensing uses two types of lasers: an impact laser to induce vibrations in the measurement target by laser ablation and a detection laser to measure these induced vibrations. The validity of the method is verified by comparison with the results of a hammering test. It is shown that remote laser sensing can be successfully applied to a reinforced concrete tunnel lining, although the induced vibrations decay faster and the noise level are higher in the field than in the laboratory. Changes in natural frequency are occasionally observed; these are believed to be a results of changes in temperature and nonlinear vibrations. Based on the results of on-site laser measurements, the estimated

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frequency of the lowest mode is found to be the most useful index for the quantitative evaluation of defects.

Keywords: Non-contact inspection, Laser ablation, Reinforced concrete, Tunnel, Vibration

1. Introduction

Concrete is one of the most durable and frequently used structural materials in civil engineering. Structures made of concrete, such as tunnel linings and segments, typically have a long service life, but may deteriorate through the processes of aging, water leakage, and unexpected pressure. Therefore, periodic inspections are required to ensure that the concrete remains functional for long-time use (Asakura and Kojima, 2003; Bergeson et al., 2015).

Tunnel maintenance is usually performed by trained inspectors, although human inspection is time-consuming and the results vary depending on the inspectors. At present, to improve productivity and accuracy, the development of interdisciplinary technologies for tunnel inspection is accelerating (Montero et al., 2015; Menendez et al., 2018; Fujino and Siringoringo, 2020). In particular, technology related to the photography of tunnel linings and automatic defect detection from these photos have made remarkable progress (Attard et al., 2018; Protopapadakis et al., 2019; Jiang et al., 2019), and this approach has been used in practical applications as an alternative or supplement to visual inspection. In contrast, technology related to the hammering test, which checks for delamination or damage (e.g., cracking, distortion, spalling) using a hammer, requires further development (Sugimoto et al., 2015; Kurahashi et al., 2018; Menendez et al., 2018; Afshani et al., 2019; Ya-

suda et al., 2020), because more accurate machine control and more precise measurements are needed for comparison with the photographic records.

Remote laser sensing is one alternative to the hammering test. This method uses two types of laser: an impact laser to induce vibrations in the measurement target by laser ablation, and a detection laser to measure these induced vibrations. In this way, remote laser sensing can be used to realize non-contact inspection and quantitative evaluation. The usefulness of remote laser sensing has been confirmed in laboratory experiments using concrete specimens with and without internal defects (Yasuda et al., 2020). However, real tunnel environments are somewhat different from the laboratory and are often unsuitable for precise measurement devices because of the dust, dirt, and uneven surfaces. Additionally, the vibration characteristics of actual defects may differ from those of artificial defects. Therefore, it is necessary to confirm the applicability of remote laser sensing in the field.

This paper considers the applicability of the remote laser sensing method in a reinforced concrete tunnel lining. The results of field experiments, carried out in sections where corrosion of the reinforced steel had been observed, are reported. The measurement results are compared with those from a hammering test to verify the validity of the remote laser sensing approach. The differences between the field and laboratory results, and data processing methods for use in the field, are also considered.

2. Outline of experiments

The experiments were conducted near the portal of a Shinkansen (bullet train) tunnel. The lining was reinforced concrete in which deterioration as a

result of rebar corrosion had been observed. Fig. 1 shows a schematic diagram of the experiment. The measurements were performed from the center of the double-track tunnel. The maximum distance from the laser devices to the tunnel lining was approximately 8 m. The impact laser was a high-power pulsed Nd:YAG laser (SLT-ND-EOQ-AMR, Sparkling Photon) with a wavelength of 1064 nm (invisible light) and a pulse width of approximately 10 ns. This laser was used to excite laser ablation, which is the process of material removal from a solid surface by high-power pulsed laser irradiation. The laser energy in front of the lining was approximately 3 J. This laser device was specially developed for use in tunnels, and so its size is relatively compact compared with that of commercial high-power laser devices. Two types of detection lasers were used to measure the induced vibrations: a laser Doppler vibrometer (RSV-150, Polytec), which uses a laser with a wavelength of 1550 nm (invisible light) and has an output of 10 mW or less, and a laser photorefractive interferometer (Shimada and Kotyaev, 2012), which uses a continuous-wave laser with a wavelength of 532 nm (green light) and has a maximum output of 5 W. The latter is the more powerful of the two, and is expected to be more noise-tolerant.

A carrier for the laser devices that can move along the central passage of the Shinkansen tunnel was developed, as shown in Fig. 2. The train-type carrier consisted of four cars. The system was powered from batteries installed in every car, so that the carrier was able to travel via the central passage and perform the inspection for several hours. The first and last cars were towing vehicles, and the laser systems were placed in the two middle cars. One car contained the impact laser and the laser Doppler vibrometer (LDV),

while the other car contained the photorefractive interferometer. Each car also had a laser range finder to measure the distance to the tunnel lining surface and focus the laser. On top of each car, there was a window for laser irradiation and a mirror for reflecting the laser to the intended irradiation point. Because the impact laser and the LDV were coaxial, they were not able to determine the irradiation point independently.

Experiments were conducted at four locations in the upper half of the tunnel, as shown in Fig. 3. Concrete delamination had been evaluated using the hammering test three days before the experiment using lasers. At that time, the laser irradiation positions were marked in advance of the laser experiment. As it was difficult to perform a detailed investigation in the operating tunnel, the validity of the laser measurements was verified by comparison with the results of the hammering test. The zones indicated by the yellow lines were judged to be defective. The points marked in red circles with numbers were determined to be delaminated, while those in yellow circles were found to be slightly delaminated. Those areas in white squares were judged to be sound. The green and red circles denote the points actually measured by the lasers. The two detection lasers overlapped at the measurement points to allow their results to be compared. There was no interference from this overlapping, as the wavelengths of the two lasers are different. The measurements covered a total of 24 points, excluding point 8. The measurement at point 8 was discarded because one of the two detection lasers was blocked by the overhead systems. For the same reason, some measurement and excitation points were slightly different from the points marked in advance.

The measurement results of the two detection lasers were almost the same, although the photorefractive interferometer was slightly more resistant to noise. The LDV is much smaller and lighter than the interferometer. Additionally, the LDV is an eye-safe laser, posing a relatively low hazard to the human eye, whereas the interferometer is a class 4 device, which can cause devastating and permanent eye damage as a result of direct, diffuse, or indirect beam viewing. Therefore, we judged the LDV to be better for practical use. In the following, we only present the data measured by the LDV in considering the applicability of the remote laser sensing method. The data acquisition was performed at a sampling frequency of 100 kHz with a 10 Hz high-pass filter, which is built into the device. Note that the gray squares next to some of the points marked in advance are optical reflective sheets. These were not used in the experiments, but were prepared in case the amount of reflected light from the detection lasers was insufficient to acquire the necessary data.

3. Experimental results

Fig. 4 compares the laser-induced vibrations at points 2 and 5. Point 2 is judged to be delaminated, whereas point 5 is judged to be sound. Fig. 4(a) shows a velocity waveform averaged over five measurements, which covers a period of 0.04 s (4000 measurement data points). The impact laser is radiated at 0.0010 s in the figure. Fig. 4(b) shows the Fourier spectrum of the velocity waveform. The pulse-like response caused by an instantaneous reduction in the detection of reflected laser light (Yasuda et al., 2020) is observed immediately after laser irradiation. Damped oscillations can be observed

immediately after laser ablation at point 2. This oscillation includes several modes, because characteristic peaks can be observed in the Fourier amplitude spectrum. In contrast, no damped oscillations can be observed at point 5. A characteristic waveform is plotted in the Fourier phase spectrum at both points.

Figs. 5 and 6 show the laser-induced vibrations at points 2 and 5. The data begin 0.0010 s after laser irradiation starts so as to avoid any dead time before the onset of laser radiation and to cut the pulse-like response occurring immediately after laser irradiation. The velocity waveforms are from five measurements and cover a period of approximately 0.020 s (2048 measurement data points). The Fourier spectra correspond to these waveforms. The data obtained from point 2 are reproducible and the phase change within the vicinity of the natural frequency can be evaluated. In contrast, the data obtained at point 5 are not reproducible.

Fig. 7 shows the stabilization diagrams for the laser-induced vibrations at points 2 and 5. Each diagram is obtained from the five Fourier spectra shown in Figs. 5(b) and 6(b) using the least-squares complex frequency-domain (LSCF) method, which is a fast-stabilizing parameter estimation method for modal identification problems (Van Der Auweraer et al., 2001; Verboven et al., 2004). The horizontal axis represents the frequency and the vertical axis represents the assumed order of the model. The estimated natural frequencies are visualized for the different model orders. The frequencies used for estimation range from 0–3125 Hz. The red line represents the amplitude spectrum, which is the average of five shots. The symbols *, $\triangle$, and $\circ$ are plotted when the estimated solution is physically meaningful, i.e.,

when both the estimated frequency and the damping ratio are positive. The distinction is based on the relationship between the estimated solutions and those obtained from the previous modal order: * corresponds to a new pole, $\triangle$ indicates that the pole frequency is close to its previous value (frequency within 2%), and $\circ$ indicates that both the frequency and the damping ratio are close to their previous values (frequency within 2% and damping ratio within 5%). The stability of the estimated solutions can then be estimated from the arrangement of these symbols. The $\triangle$ and $\circ$ are arranged vertically in a column in four places at point 2. In contrast, few symbols are arranged vertically at point 5.

Fig. 8 shows the estimated modal frequencies for all measurement points and the value of N , which is the number of consecutive $\circ$ or $\triangle$ symbols arranged vertically in a column. Each result is derived from the five Fourier spectra. For simplicity, no distinction is made here between $\circ$ and $\triangle$, although the reliability increases as the number of $\circ$ symbols increases. The value of N provides a useful indicator for estimating the presence or absence of damped oscillations. It is assumed that N should be at least 11 to determine that damped oscillations are actually present. The symbols are plotted where N is greater than or equal to 11. The values of the estimated frequencies are for the highest modal order of each column. The color of the horizontal lines depends on the judgment determined from the hammering test. Red, yellow, and blue lines indicate delaminated, slightly delaminated, and sound, respectively. At all points judged to be delaminated by the hammering test, many symbols are plotted. At the points judged to be sound, no symbols are plotted, except for points 16 and 17. Square symbols, indicating

$N = 13$, are plotted at points 16 and 17, although these are sound parts.

Fig. 9 shows the distribution of the estimated natural frequencies and the damping ratio of the defects from points 1–4. The assumed model order used for the calculations ranges from 28–32 for each point. The estimated natural frequencies are stable; in comparison, the estimation accuracy of the damping ratios is low. There are variations in the estimated damping ratios.

When the remote sensing method is applied in the field, the locations of defects are unknown, and area measurement is required for inspection. As a simulation of the actual inspection process, multi-point observations were performed in the vicinity of locations 1 and 4.

Fig. 10 shows the measurement points and excitation points at location 1'. These measurements were performed ten days after the laser measurement at location 1, the results of which are shown in Fig. 3(a). The temperature was approximately ten degrees lower than before. The irradiation positions were set to be evenly spaced by moving the reflection mirror of the lasers. However, they were not actually evenly spaced because the movement was calculated assuming a flat, rather than a curved, surface. In addition, the detection laser and the impact laser were irradiated from different cars. As a result, the distance between the two lasers was not constant.

Fig. 11 compares the laser-induced vibrations around point 8, which is almost the same position as point 2 in location 1. A slight position change causes a significant difference in the velocity amplitude. The amplitude of each mode also differs depending on the location. Fig. 12 summarizes the estimation results at location 1'. Symbols are plotted between points 7 and 17. The estimated frequencies around 1000 Hz are stable, whereas the estimated

frequencies above 1500 Hz are not stable.

Fig. 13 shows the measurement points and excitation points at location 4'. These measurements were performed two days after the measurement at location 4, for which the results are shown in Fig. 3(d). The temperature was almost the same. Fig. 14 compares the laser-induced vibrations around point 10. Although the spectral values are large at points 9 and 10, there are no clear peaks above 1000 Hz. A summary of the estimation results at location 4' is shown in Fig. 15. Symbols are plotted between points 9 and 13 and between points 16 and 20. The estimated frequencies for lower vibration modes are more stable than those for higher vibration modes, similar to the result at location 1'.

4. Discussion

The presence of a defect can be estimated from damped oscillations in the measurement data, as shown in Fig. 4. The presence or absence of these damped oscillations can be estimated using the LSCF method, as shown in Fig. 7. Additionally, when a defect is present, the natural frequencies and damping ratios can be estimated, as shown in Fig. 9. In particular, the estimated natural frequencies are stable. These are basically the same as for the laboratory experiment using concrete specimens with artificial defects (Yasuda et al., 2020). The estimation results for the presence or absence of a defect show good agreement between the laser measurement and the hammering test, as shown in Fig. 8, Figs. 10 and 12, and Figs. 13 and 15. Therefore, remote laser sensing can be successfully applied to reinforced concrete tunnel linings, as in laboratory experiments. Nonetheless, there are

some differences in the measurement results obtained in the field and in the laboratory.

One of the main differences is the damping ratio of the vibrations. Most of the estimated damping ratios in the field were greater than 1%, as shown in Fig. 9. In contrast, those in the laboratory were less than 1% (Yasuda et al., 2020). The vibration decay is faster in the case of actual defects. It is presumed that friction at the boundary between the adhering part and the delaminated part contributes to this fast decay.

The other main difference is the amount of noise. Fig. 16 shows velocity waveforms for five measurements at point 9 in location 2. The data for the second shot have clearly been disturbed. This disturbance is believed to be caused by the instantaneous reduction of reflected laser light by dust in the air. Such a disturbance can always occur, especially in the field. The disturbance reduces the estimation accuracy, as shown in Fig. 17.

Fig. 18 compares the vibration energy for five shots at each point. The energy is defined as the sum of squares of the velocity waveform, and includes 2048 data from 0.0010 s after the onset of laser irradiation. At each point, this value is normalized according to the minimum value of the five shots. The magnitude of the energy provides an index that indicates the disturbance of the measurement data. Most of the normalized energy values are less than 2.0. However, some values are greater than 3.0. Such data are considered dubious and should not be used for evaluation. The energy of the first and second shots tends to be larger. This is because of dirt on the concrete surface—the darker the surface, the higher the energy absorption of the laser light. Repeated laser ablation cleans the surface, thus reducing the

energy absorption rate. The data from the first and second shots are usually better because the excitation vibration is larger. In contrast, these data are sometimes unreliable because the material removed from the concrete surface blocks the laser light and causes disturbances.

In this experiment, regular noise was also observed. Fig. 19 shows the measurement results at point 16 in location 3. No characteristic vibrations were expected to be excited, as shown in Fig. 6, because this area was known to be sound. However, a characteristic vibration, as opposed to a damped vibration, can be observed from the laser irradiation after a short time. Because of this vibration, a characteristic response occurs in the phase spectrum, which causes incorrect estimation results in the stabilization diagram. Although there are many $\triangle$ symbols and the stability is not high, the $\circ$ or $\triangle$ symbols are arranged vertically in a column. This estimation result is not caused by the actual vibration of the concrete, but by the instantaneous refraction of laser light. When laser ablation occurs on the concrete surface, a compression wave is radiated into the air. Near point 16, some inner lining reinforcement was installed for protection against rebar corrosion, as shown in Fig. 20. The compression wave is reflected by the edge of the reinforcement, where the thickness is approximately 10 cm. When the reflected wave crosses the laser beam, it is instantaneously distorted by refraction, and the fake response is observed. This response was also observed at point 17. This is a special case, as there is generally no difference in the level of the tunnel lining surface. However, it is necessary to assume such a situation for practical use. Evaluation using the LSCF method is not suitable for waveforms that may be subject to a sudden changes, such as the case illustrated by

Fig. 19(a). Thus, it may be necessary to combine another algorithm, such as machine learning, to improve the accuracy of evaluation.

As shown above, for actual defects in the field, the induced vibrations decay faster and the noise level is higher. Therefore, it can be difficult to obtain data comparable quality to that obtained from artificial defects in the laboratory. In addition, changes in natural frequency, as a result of changes in temperature and nonlinear vibrations, were occasionally observed in this experiment.

From a comparison of Figs. 8 and 12, it can be seen that the estimated modal frequencies around point 2 in location 1 had clearly decreased after only ten days. This must have been caused by the change in temperature, because it is very unlikely that the corrosion would have progressed rapidly in such a short period of time. It is believed that the contact conditions around the areas of delamination had been affected by the decrease in temperature of approximately 10 degrees.

Fig. 21 shows velocity waveforms for five measurements at point 19 in location 4. The data begin 0.0010 s before the onset of laser irradiation. This point produced the largest-amplitude measured vibrations among all 24 measured points (see Fig. 8). Stabilization diagrams for this point are shown in Fig. 22. The data used for the derivation of Fig. 22(a) cover approximately 0.020 s (2048 measurement data points) from 0.0010 s after the onset of laser irradiation. Fig. 22(b) is derived from data taken 0.0020 s after laser irradiation starts. The estimated result in Fig. 22(b) is better than that in Fig. 22(a), although the vibrations decrease and the quality of the data deteriorates over time. It can be inferred that the data measured

immediately after vibration excitation contain nonlinear vibrations. As the estimation procedure using the LSCF method assumes linear vibrations, it is not suitable for data containing nonlinear vibrations. It is thought that these nonlinear vibrations are caused by changes in the contact conditions around the areas of delamination.

Other possible effects of nonlinear vibration have been observed. The estimated frequencies for lower vibration modes are more stable than for higher vibration modes at locations 1' and 4', as shown in Figs. 12 and 15. It is believed that the higher vibration modes are more susceptible to changes in the contact conditions. The amplitude of the laser-excited vibrations is small, and it is considered that nonlinear vibrations are unlikely to occur. However, nonlinear vibrations were occasionally observed.

The primary purpose of the hammering test is to evaluate the degree of risk of spalling. Therefore, an index for evaluating the quality of defects is required in order to discuss the applicability of the remote laser sensing.

In this experiment, the location where the risk of spalling was highest was around point 19 in location 1. White powder (presumed to be powdered concrete) was ejected from the surrounding cracks during the hammering test. The data from point 19 show the largest-amplitude measured vibrations and the smallest estimated frequency of the lowest mode among all measured points (see Fig. 3). It is believed that, as the risk of spalling increases, the estimated natural frequency of the lowest mode decreases and the amplitude of the induced vibrations increases. Therefore, it is concluded that the location with the highest risk of spalling can be predicted from the measurement data.

Based on the results of on-site measurements by lasers, the estimated natural frequency of the lowest mode is the most useful index for quantitatively evaluating defects. This is because it can be estimated stably, regardless of the noise level, and is less susceptible to nonlinear vibrations and the vibration node, where the amplitude of the mode becomes zero. The amplitude of the measured vibration is not a suitable index for evaluating defects because it is strongly influenced by the measurement and excitation positions and the performance of the impact laser.

The relationship between the estimated natural frequency of the lowest mode and the risk of spalling will be examined in future studies. In this experiment, no spalling occurred during the hammering, although a low frequency of 200 Hz was observed. Considering this fact, it seems that spalling does not occur until the frequency becomes very low.

5. Conclusions

This paper has considered the applicability of remote laser sensing for identifying defects in reinforced concrete tunnel linings. Experiments were conducted near the portal of a Shinkansen tunnel, where corrosion of the reinforced steel had been observed. The measurement results were compared with the evaluation derived from a hammering test. Measurement and data processing methods suitable for use in the field were also considered. The following conclusions can be drawn from this study:

- (1) Remote laser sensing can be successfully applied in a reinforced concrete tunnel lining, as in laboratory experiments.

- (2) The main difference between the field and the laboratory is the damping ratio of the vibration and the amount of noise. For actual defects in the field, the induced vibrations decay faster and the noise level is higher.
- (3) Changes in natural frequency, as a result of changes in temperature and nonlinear vibrations, were occasionally observed. It is believed that these are caused by changes in the contact conditions around the areas of delamination.
- (4) The estimated natural frequency of the lowest mode is the most useful index when quantitatively evaluating defects, because it can be estimated stably, regardless of the noise level, and is less susceptible to nonlinear vibrations and the vibration node.

References

- Afshani, A., Kawakami, K., Konishi, S., Akagi, H., 2019. Study of infrared thermal application for detecting defects within tunnel lining. *Tunnelling and Underground Space Technology* 86, 186 – 197.
- Asakura, T., Kojima, Y., 2003. Tunnel maintenance in japan. *Tunnelling and Underground Space Technology* 18, 161 – 169.
- Attard, L., Debono, C.J., Valentino, G., Castro], M.D., 2018. Tunnel inspection using photogrammetric techniques and image processing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing* 144, 180 – 188.
- Bergeson, W., Ernst, S.L., et al., 2015. Tunnel operations, maintenance,

- inspection, and evaluation (TOMIE) manual. Technical Report. United States. Federal Highway Administration.
- Fujino, Y., Siringoringo, D.M., 2020. Recent research and development programs for infrastructures maintenance, renovation and management in japan. *Structure and Infrastructure Engineering* 16, 3–25.
- Jiang, Y., Zhang, X., Taniguchi, T., 2019. Quantitative condition inspection and assessment of tunnel lining. *Automation in Construction* 102, 258 – 269.
- Kurahashi, S., Mikami, K., Kitamura, T., Hasegawa, N., Okada, H., Kondo, S., Nishikino, M., Kawachi, T., Shimada, Y., 2018. Demonstration of 25-hz-inspection-speed laser remote sensing for internal concrete defects. *Journal of Applied Remote Sensing* 12, 015009.
- Menendez, E., Victores, J.G., Montero, R., Martínez, S., Balaguer, C., 2018. Tunnel structural inspection and assessment using an autonomous robotic system. *Automation in Construction* 87, 117 – 126.
- Montero, R., Victores, J., Martínez, S., Jardón, A., Balaguer, C., 2015. Past, present and future of robotic tunnel inspection. *Automation in Construction* 59, 99 – 112.
- Protopapadakis, E., Voulodimos, A., Doulamis, A., Doulamis, N., Stathaki, T., 2019. Automatic crack detection for tunnel inspection using deep learning and heuristic image post-processing. *Applied Intelligence* 49, 2793–2806.

- Shimada, Y., Kotyaev, O., 2012. Remote sensing of concrete structure using laser sonic waves. *Industrial Application of Laser Remote Sensing* , 153–169.
- Sugimoto, K., Akamatsu, R., Sugimoto, T., Utagawa, N., Kuroda, C., Katakura, K., 2015. Defect-detection algorithm for noncontact acoustic inspection using spectrum entropy. *Japanese Journal of Applied Physics* 54, 07HC15.
- Van Der Auweraer, H., Guillaume, P., Verboven, P., Vanlanduit, S., 2001. Application of a fast-stabilizing frequency domain parameter estimation method. *Journal of dynamic systems, measurement, and control* 123, 651–658.
- Verboven, P., Cauberghe, B., Parloo, E., Vanlanduit, S., Guillaume, P., 2004. User-assisting tools for a fast frequency-domain modal parameter estimation method. *Mechanical systems and signal processing* 18, 759–780.
- Yasuda, N., Misaki, N., Shimada, Y., Yamaoka, D., 2020. Detection and characteristics estimation of defects in concrete structures using laser ablation-induced vibration. *Tunnelling and Underground Space Technology* 103, 103460.

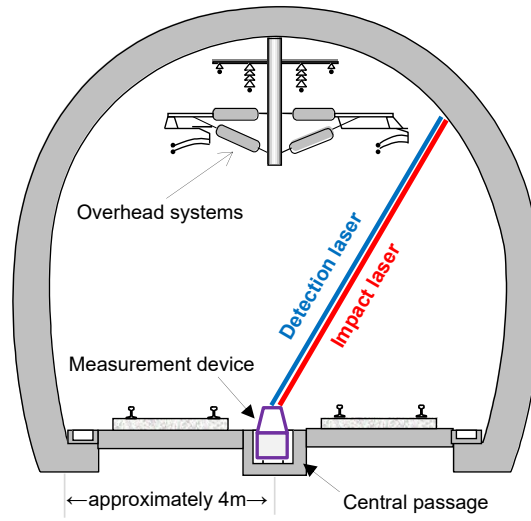
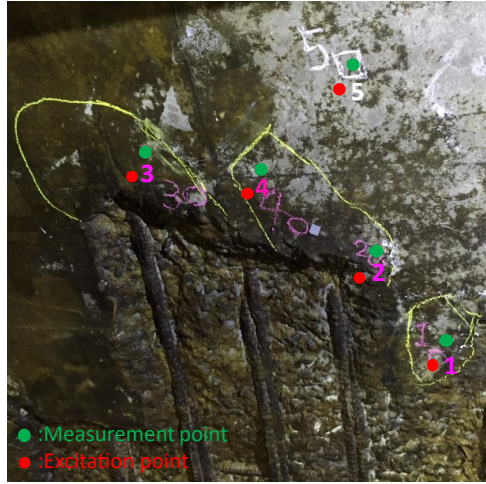


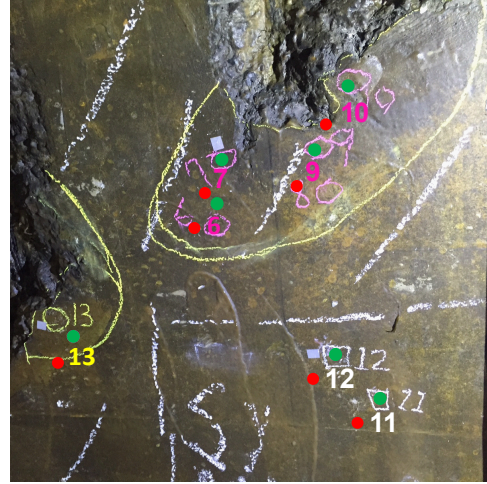
Figure 1: Schematic diagram of the experiment.



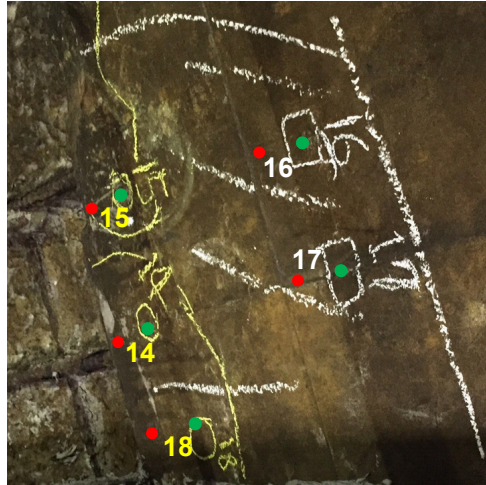
Figure 2: Experimental environment.



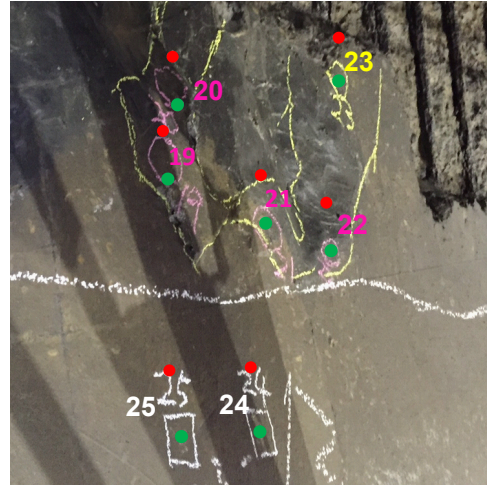
(a)



(b)



(c)



(d)

Figure 3: Experiment locations. (a) Location 1, (b) Location 2, (c) Location 3, and (d) Location 4. The zones surrounded by the yellow line were judged to be defective by the hammering test. Green and red circles are points actually measured by lasers.

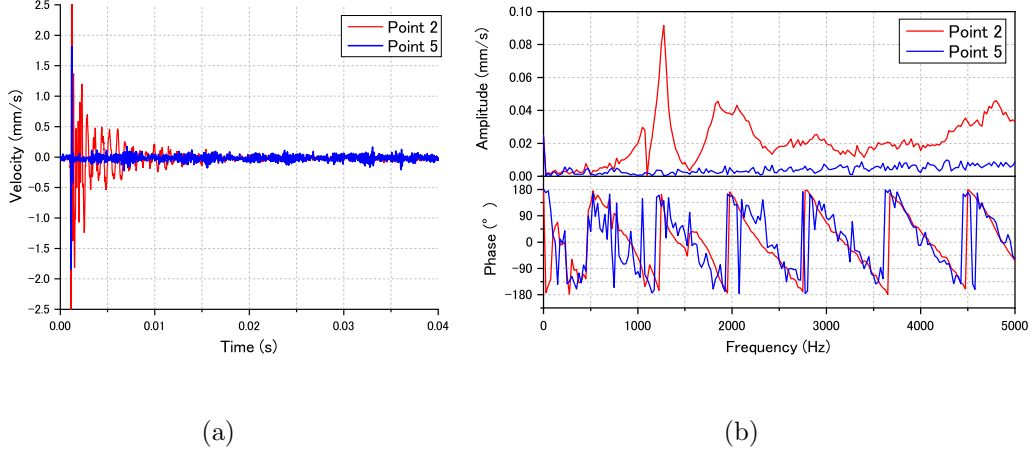


Figure 4: Comparison of laser-induced vibrations at point 2, where the concrete is delaminated, and point 5, where the concrete is sound. (a) Velocity waveform averaged over five measurements and (b) Fourier spectrum of the waveform.

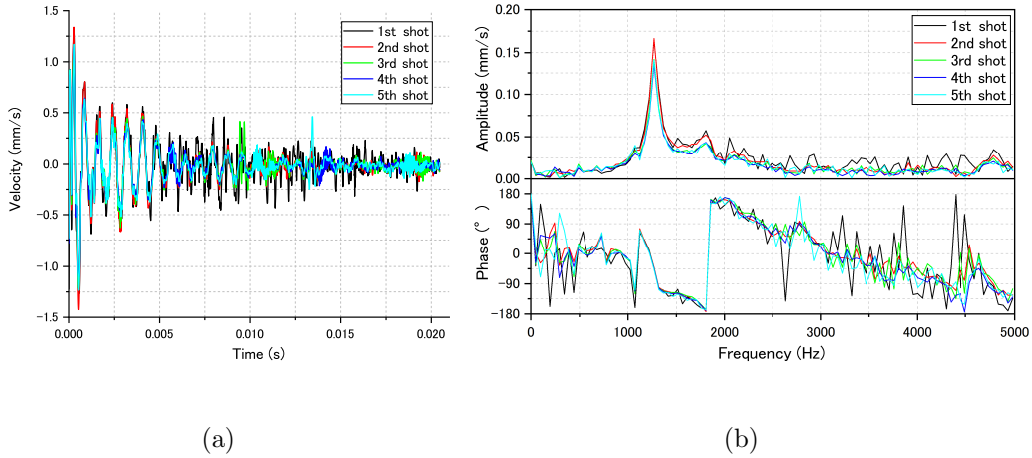


Figure 5: Laser-induced vibrations at point 2. (a) Velocity waveforms for five measurements and (b) Fourier spectra of these waveforms. The data begin 0.0010 s after laser irradiation starts.

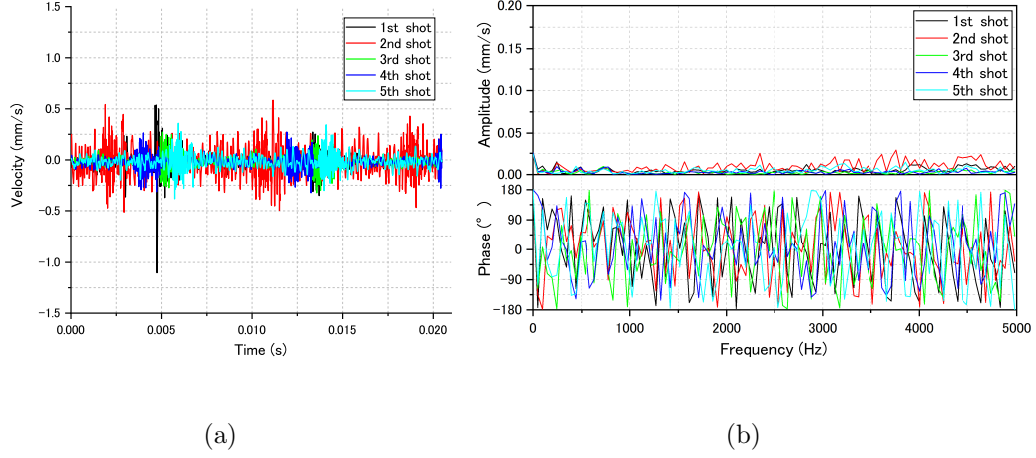


Figure 6: Laser-induced vibrations at point 5. (a) Velocity waveforms for five measurements and (b) Fourier spectra of these waveforms. The data begin 0.0010s after laser irradiation starts.

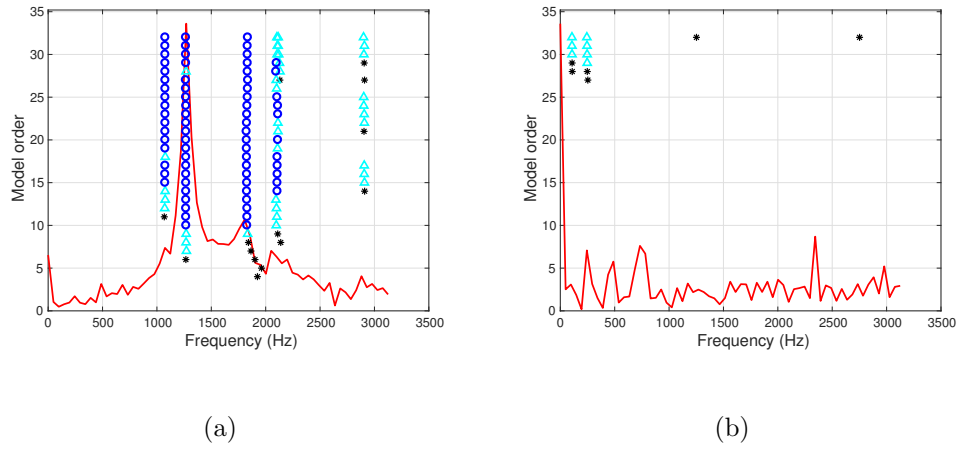


Figure 7: Stabilization diagrams at (a) point 2 and (b) point 5.

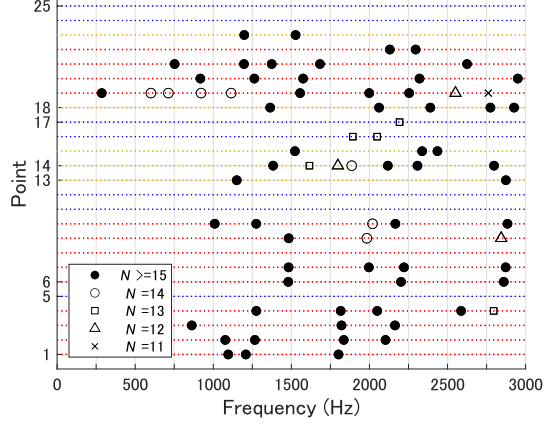


Figure 8: Estimated modal frequencies for all measurement points and the number of N , which is the consecutive number of $\circ$ or $\triangle$ symbols arranged vertically in a column.

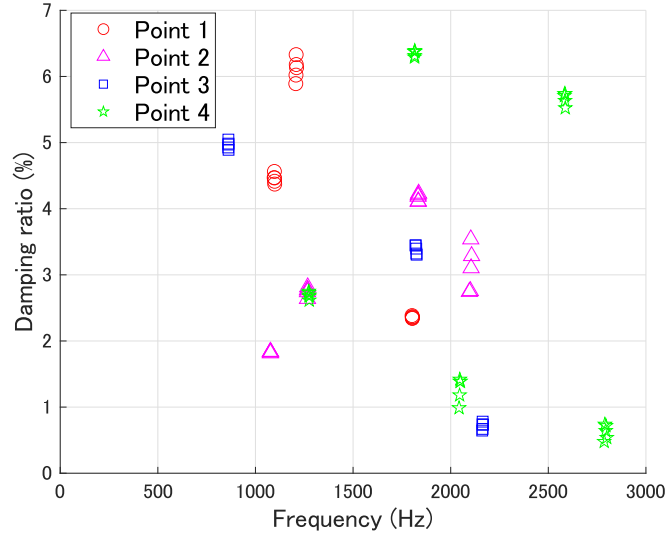


Figure 9: Distribution of estimated natural frequencies and damping ratio of defects from points 1–4. The assumed model order used for the calculations ranges from 28–32 for each point.

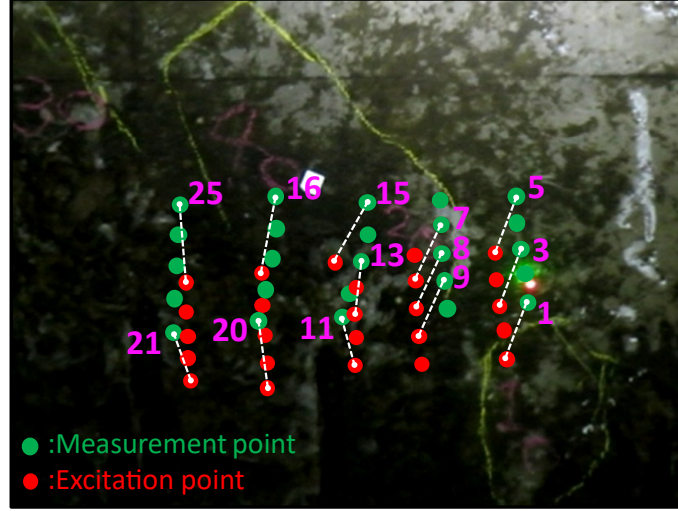


Figure 10: Experiment location 1'.

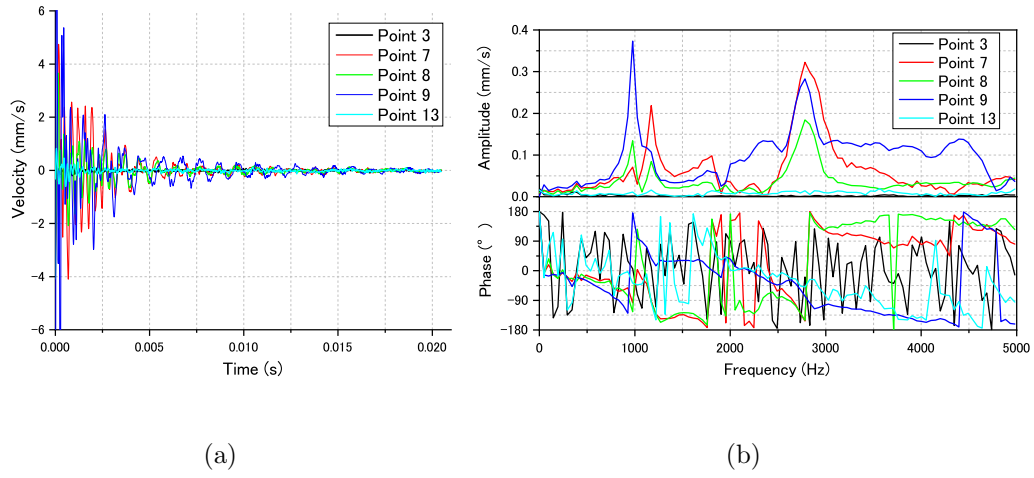


Figure 11: Comparison of laser-induced vibrations around point 8 in location 1'. (a) Velocity waveform averaged over five measurements and (b) Fourier spectrum of the waveform. The data begin 0.0010 s after laser irradiation starts.

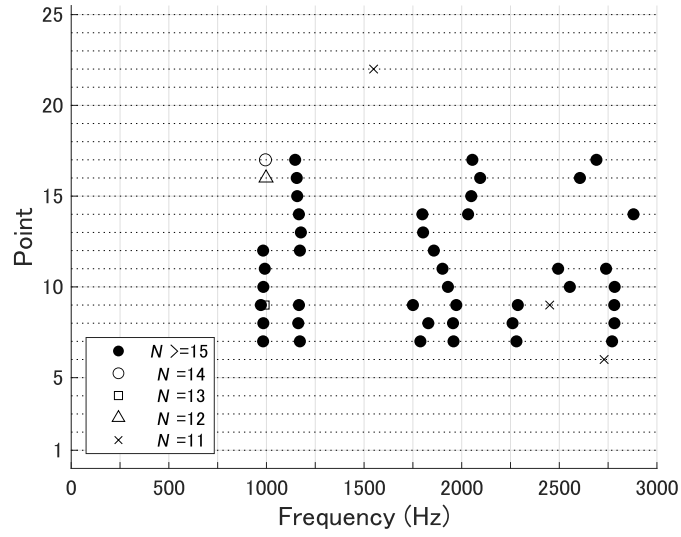


Figure 12: Summary of estimation results at location 1'.

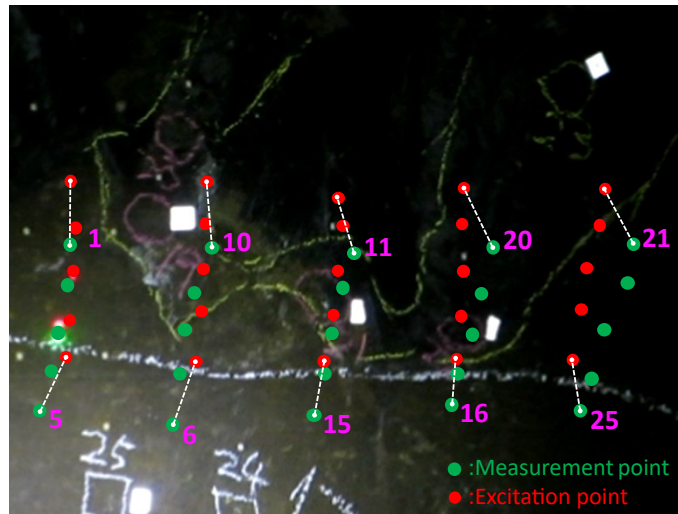


Figure 13: Experiment location 4'.

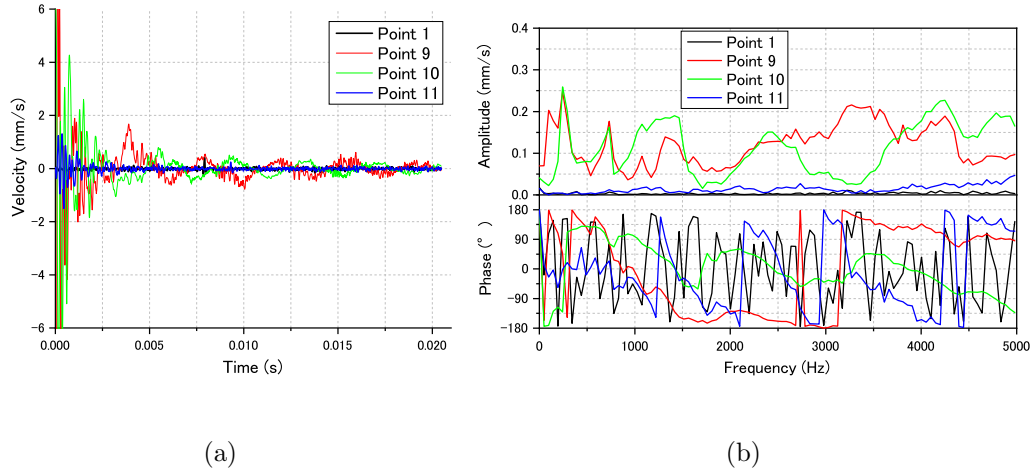


Figure 14: Comparison of laser-induced vibrations around point 10 in location 4'. (a) Velocity waveform averaged over five measurements and (b) Fourier spectrum of the waveform. The data begin 0.0010s after laser irradiation starts.

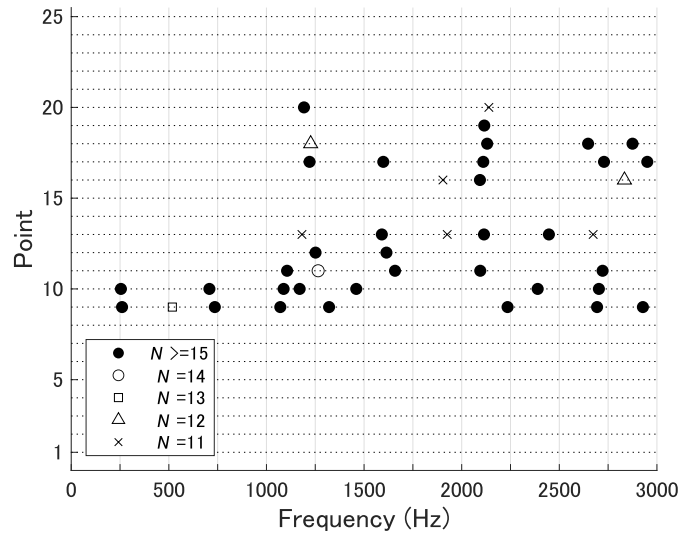


Figure 15: Summary of estimation results at location 4'.

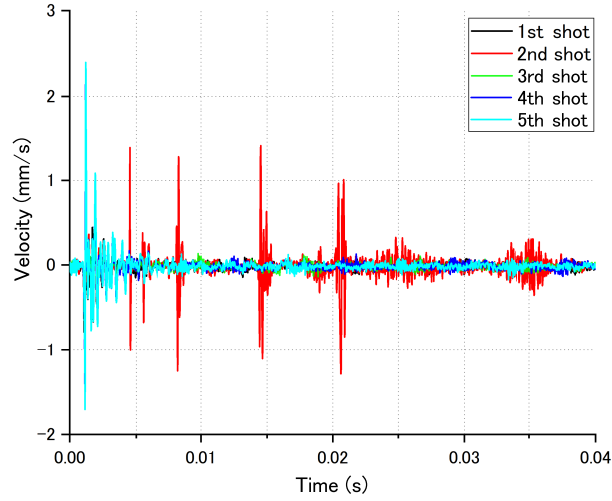
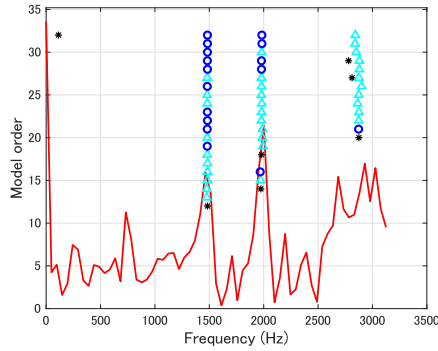
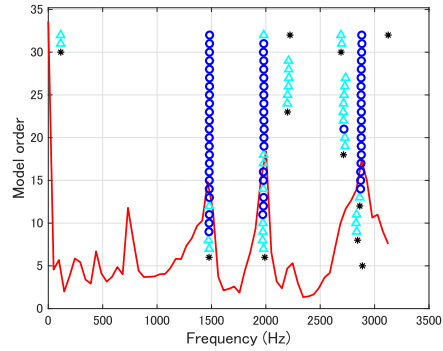


Figure 16: Velocity waveforms for five measurements at point 9 in location 2. The data begin 0.0010 s before laser irradiation starts.



(a)



(b)

Figure 17: Stabilization diagrams at point 9 in location 2. The data used to derive this figure cover approximately 0.020 s from 0.0010 s after laser irradiation starts. (a) Five shots used for derivation and (b) four shots (second shot omitted) are used.

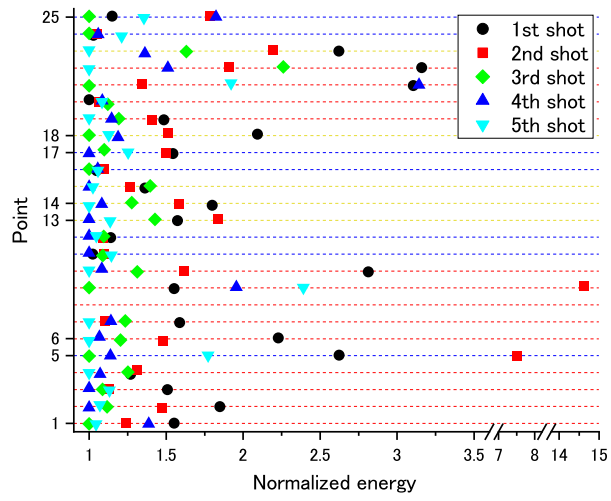
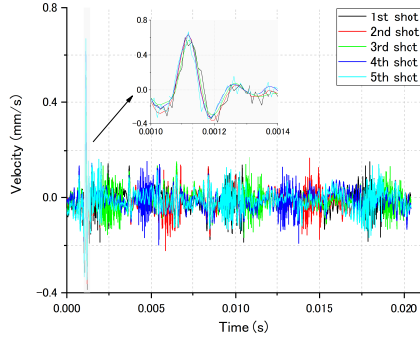
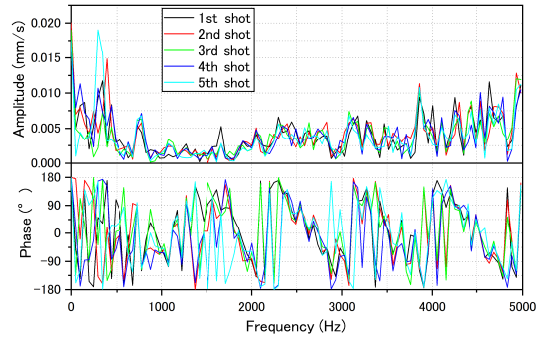


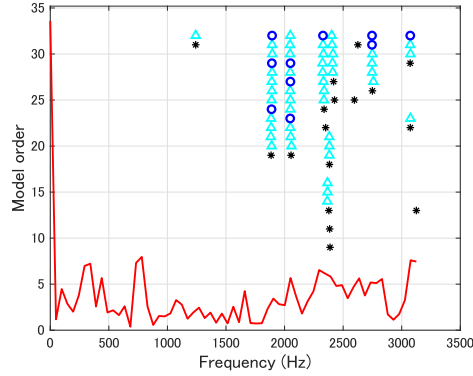
Figure 18: Comparison of vibration energy.



(a)



(b)



(c)

Figure 19: Measurement results at point 16 in location 3. The data begin 0.0010 s after laser irradiation starts. (a) Velocity waveforms for five measurements and (b) Fourier spectra of these waveforms. (c) Stabilization diagram.



Figure 20: Tunnel lining around experiment location 3.

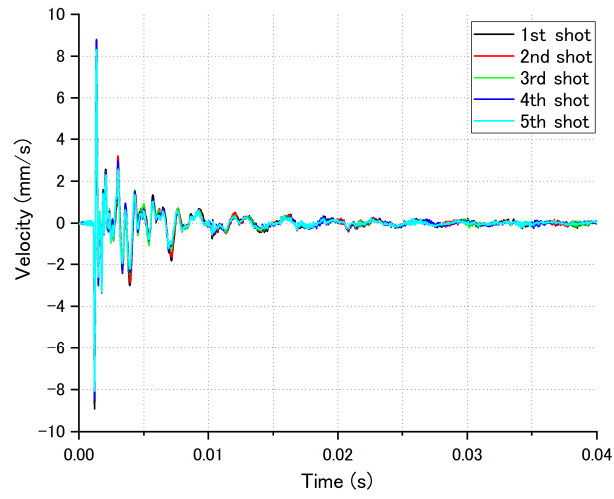
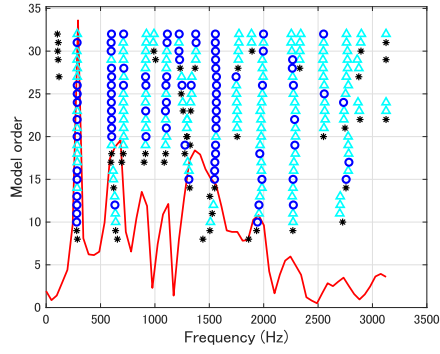
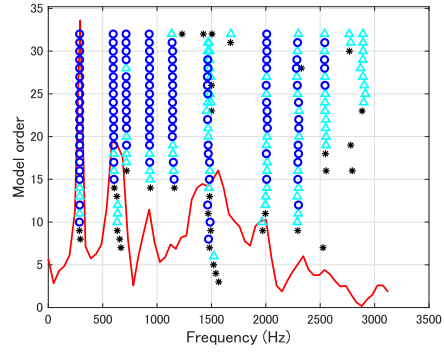


Figure 21: Velocity waveforms for five measurements at point 19 in location 4. The data begin 0.0010s before laser irradiation starts.



(a)



(b)

Figure 22: Stabilization diagrams at point 19 in location 4. The data used for derivation cover approximately 0.020 s (a) from 0.0010 s after laser irradiation starts and (b) from 0.0020 s after laser irradiation starts.