

Vibration characteristics of spalling defects in concrete lining

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Abstract

The mechanization of the hammering test, which checks the delamination or damage of concrete using a hammer, is required to improve the efficiency of inspections. To realize mechanization, the characteristics of defects with high risk of spalling must be quantified. The objective of this study was to investigate the vibration characteristics. To this end, concrete specimens with inclined detachment were prepared and the vibration measurement, detachment process, and loading were repeated until spalling occurred. In the loading process, it was assumed that the defect existed at the tunnel crown, and the self-weight was considered. The natural frequencies, damping ratios, and response amplitudes for each state are presented in this paper. Additionally, numerical analysis results are presented to supplement the experimental results. The experimental results reveal that spalling did not occur until the adhesion area and frequency of the lowest mode significantly decreased. The frequency of the lowest mode just before spalling is expected to be less than 100 Hz. Based on the simulation results obtained for an actual severe concrete spalling accident in Fukuoka Tunnel, it is concluded that the ability to detect defects with the response amplitude of 1 mm/s/N is required to mechanize the hammering test.

Keywords: Vibration, Plain concrete, spalling defects, Hammering test, Maintenance

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1. Introduction

Periodic inspections are required and often mandated to maintain the good operating condition of concrete structures over a long period of time. In Japan, a severe concrete spalling accident in the Fukuoka tunnel in 1999 (Asakura and Kojima, 2003; Tsuno and Kishida, 2020) has highlighted the importance of inspections. After the accident, the inspection regime was updated and major accidents related to concrete spalling caused by deterioration over time have not occurred to date. Human inspection combining visual inspection and the hammering test, which checks for delamination or damage such as cracking, distortion, and spalling, has a proven track record and is considered to be reliable. However, the number of structures requiring inspection increases, owing to the increase of construction and aging, while the number of skilled technicians decreases. Therefore, improving the efficiency of inspection has become an important concern. Alternative technology for completing the task currently carried out by the hammering test is under development. For example, an infrared method (Sakagami and Kubo, 2002; Clark et al., 2003; Maierhofer et al., 2006; Meola, 2007; Omar and Nehdi, 2017; Afshani et al., 2019; Ishikawa et al., 2021; Chun and Hayashi, 2021), a mobile robotic system (Menendez et al., 2018; Loupos et al., 2018; Moreu et al., 2018; Nakamura et al., 2019), a non-contact acoustic method (Mori et al., 2002; Zhu and Popovics, 2007; Oh et al., 2013; Sugimoto et al., 2019), and a laser sensing method (Kurahashi et al., 2018; Yasuda et al., 2020, 2021; Wakata et al., 2022) have been proposed.

Soundness evaluation using the hammering test, which is the method used at present, is based on a qualitative approach. To realize mechanization, it is important to quantify the characteristics of defects with high spalling risk. Tsuno and Kishida (2020) quantitatively evaluated the safety against spalling by comparing the shear stress acting on the joint surfaces of the concrete cracks to the shear capacity of the joint surfaces under the assumption that enormous chunks of already detached lining concrete are held by friction. Except for the above-mentioned study, no other studies have proposed a method for quantitatively evaluating the safety against spalling. However, because skilled technicians use hammering sound and the tactile sensation for evaluation, a relationship must exist between the vibration characteristics of defects and the spalling risk degree.

This study investigated the vibration characteristics of defects with high risk of spalling. Concrete specimens with an inclined detachment were pre-

pared and the vibration measurement, the detachment process, and loading were repeated until spalling occurred. In the loading process, it was assumed that the defect was at the tunnel crown, and the self-weight was considered. The natural frequencies, damping ratios, and response amplitudes were estimated for each state. Additionally, the vibration characteristics of a spalling defect that existed in the Fukuoka tunnel were estimated by numerical analysis.

2. Materials and methods

2.1. Outline of concrete specimens

Table 1 lists the concrete specimens used in the laboratory experiments. Figure 1 shows the detailed dimensions of specimens No. 2 and No. 5. Five types of specimens with an inclined detachment were prepared. The adhesion area is defined as the attachment part on the extension line of the detachment. The maximum weight of the specimens was approximately 80 kgf, as determined by considering the portability. Under the assumption that spalling is caused by the detachment along the adhesion area, the maximum weight of the spalling mass is considered to be approximately 30 kgf. For specimens No. 1 and No. 2, the shape of the adhesion area was varied. For No. 2 to No. 4, the relative size was varied. Three specimens were prepared for No. 3 and No. 4 to assess the variation in the aggregate arrangement. The inclined detachment angle of No. 1 to No. 4 was 15 degrees, and that of No. 5 was 10 degrees. The weights of the spalling mass of No. 3 and No. 5 were approximately the same and amounted to approximately 15 kgf. The detachment was made by embedding Styrofoam when placing the concrete and removing the Styrofoam after curing. A nut (P Insert M8, Japan Life) was inserted at the center of each specimen to fix an eyebolt for loading.

The concrete mix proportions are summarized in Table 2. The maximum size of the coarse aggregate was 20 mm, and the design compressive strength was 18 N/mm². The compressive and tensile strength at the age of 28 days was approximately 28 N/mm² and 2.4 N/mm², respectively. The material properties of concrete are listed in Table 3. These properties were obtained by carrying out physical property tests with the same concrete as the specimens, and were used in numerical (FEM) analysis.

2.2. Specimen preparation procedure

Figure 2 shows the process of preparing the specimens. A nut was set in a wooden formwork tilted by 10 or 15 degrees, and concrete was poured. Immediately after pouring, a Styrofoam sheet was placed on the concrete to model the detachment. Concrete was poured again until the Styrofoam sheet was fully embedded. Then, the formwork was set to the horizontal position, and concrete was poured up to the top. Before hardening, the separately poured concrete was integrated using a vibrator. After curing, the hardened concrete was removed from the formwork. Finally, the Styrofoam was removed and a notch was made by cutting the concrete surface.

2.3. Experimental procedure

The experimental procedure was designed in accordance with the accident in the Fukuoka tunnel in 1999. The assumed cause of concrete spalling is discussed below (Asakura and Kojima, 2003; Tsuno and Kishida, 2020). Discontinuities such as the cold joint and fracture surface exist immediately after construction and gradually develop until spalling occurs, owing to water leakage, temperature changes, repeated vibrations, and air pressure fluctuations caused by trains. To simulate this situation, the vibration measurement, detachment process, and loading were repeated until spalling occurred.

Vibration measurement (surface velocity measurement) was carried out using a laser Doppler vibrometer (RSV-150, Polytec). During the measurement, anti-vibration gel (GD15-100, EXSEAL) was inserted between the specimen and the ground to suppress the wobbling caused by the unevenness at the bottom of the concrete specimen. An impact hammer (086C03, PCB) was used to produce vibration excitation. Figure 4 shows the excitation and measurement points. The vibration was excited at a fixed point, and vibration measurement was carried out at three points. The relative positions of the excitation and measurement points of specimens No. 3 and No. 4 were the same as those of specimens No. 1 and No. 2. The data were obtained at the sampling frequency of 48 kHz. The 5 kHz low-pass filter built into the laser Doppler vibrometer was used for measurement.

The detachment process was modeled by gradually cutting on the adhesion area from both the left and right sides using a saw (FUN-N2, Funaso), as shown in Figure 3. The cut length on both sides was kept the same at every stage. The loading was carried out by applying a tensile load to the center of the specimen to simulate the self-weight acting on the spalling mass. A load cell (ZTS-LU-500N, Imada) was used to measure the applied load.

2.4. Application of tensile load

The tensile load was applied in the vertical direction on the surface of the specimen through a rope tied to the eyebolt, which was inserted at the center of the specimen. A pulley was constructed on the opposite side of the rope, and the load was gradually applied by suspending the weight. If only the self-weight is considered, the spalling risk increases when the defect is placed at the tunnel crown. The reason for this is that the tensile load produced by gravity tends to act on the adhesion area and trains are more likely to be damaged when spalling occurs. The loading simulated this situation, and the effect of the repeated vibrations and air pressure fluctuations caused by trains was ignored in this experiment because the evaluation and modeling would be very challenging otherwise.

The tensile loads applied to each specimen are listed in Table 4. Each loading magnitude was assumed to be constant, regardless of the cut length, and approximately the same as the weight of the spalling mass. Because the loading position was at the center of the specimen and below the center of gravity of the spalling mass, the tensile load in Table 4 was sufficiently large to model the situation of the defect being placed at the tunnel crown.

2.5. Analysis conditions

Numerical analyses were carried out to supplement the experimental results. Modal analysis was carried out to determine the natural frequency and mode shape, and harmonic response analysis (the mode superposition method) was carried out to determine the steady-state response (frequency response). The analyses were conducted in the commercial software ANSYS as linear elastic analyses. The harmonic response analysis was carried out using the results obtained by modal analysis. Hence, the FEM mesh and boundary conditions were the same for both analyses. The concrete was meshed using a 3-D 20-node structural solid element (SOLID186). The anti-vibration gel used in the vibration measurement was not modeled, and was instead simulated by not constraining the displacement. Consequently, the boundaries were not constraint and the specimen was considered as floating concrete.

3. Results

Figure 5 shows the hammer-induced force signals in specimen No. 2 before the cut. Figure 6 shows the hammer-induced force signals in specimen

No. 4-a, which is one of three identical specimens in this group. The data acquisition began 0.02 s before the hammer excitation and lasted for approximately 0.34 s (16,384 measurement data points). The average values of the maximum excitation force in specimens No. 2 and No. 4 were approximately 390 N and 320 N. The excitation force in No. 4 was smaller by approximately 20 % compared with that in No. 2. Although the volume of No. 4 was only approximately 20 % of the volume of No. 2, there was no significant difference between the corresponding Fourier spectra, which are strongly affected by the contact time. Figure 7 shows the hammer-induced force signals in specimen No. 2 after a cut of 39 cm, which significantly reduced the adhesion area. The excitation force after the cut of 39 cm was smaller by approximately 20 % compared with that before the cut. Although the adhesion area after the 39 cm cut was only 2.5 % of that before the cut, there was no significant difference between the corresponding Fourier spectra.

Figure 8 shows the hammer-induced vibrations at measurement point A of specimen No. 2 before the cut. The average value of the maximum velocity was approximately 60 mm/s, and the maximum amplitude of the spectrum was approximately 1.8 mm/s. The waveforms include many oscillation modes because characteristic peaks can be observed in the Fourier amplitude spectrum. Additionally, their amplitudes are directly proportional to the magnitude of the excitation force. Subsequently, the frequency response functions were used in the evaluation of the vibration characteristics to eliminate the hammering influence.

Figure 9 shows the frequency response functions in specimen No. 2 before the cut. Only the results up to 3000 Hz are shown, because that is where sufficient excitation amplitude was obtained. Each result is the average value of five measurements. The response differed depending on the excitation point. The response at point A, which was closest to the edge, is remarkably large at low frequency. The maximum amplitude in the vicinity of 300 Hz (the lowest mode) at point A was approximately 20 times larger than that at point C.

Figure 10 compares the frequency response functions before the cutting of the specimens with different size and shape. All measurements were made at point A. For specimen No. 3, variation existed in the results, and the variation in the high-order modes is more significant compared with that in the lowest mode. Similar results were obtained for specimen No. 4. The main reason for this is the shape distortion of the spalling mass caused by the Styrofoam subsidence resulting from the weight of concrete. The thickness

of the spalling mass tended to be thicker than that of the original design. By comparing the results obtained for No. 2 and No. 4, it was found that No. 4, for which the length of each side was 60 % of that of No. 2, had a higher natural frequency and larger response amplitude. The lowest frequency of No. 4 was approximately two times larger than that of No. 2, and the amplitude response was also approximately two times larger. By comparing the results obtained for No. 3 and No. 5, it was found that No. 3, for which the detachment angle was larger than that of No. 5, had a higher natural frequency and smaller response amplitude.

Figure 11 shows the change in the frequency response functions as the cut length increased. The spalling of No. 1 and No. 2 occurred when loading was applied after the cuts of 36 cm and 39 cm, respectively. Both specimens exhibited similar trends. Each natural frequency decreased with the adhesion area, and the rate of decrease differed depending on the mode. The amplitude change depended on the mode. The amplitudes of the low-order mode did not change significantly as the adhesion area decreased. For specimen No. 2, the amplitudes of the low-order modes sharply decreased just before spalling occurred.

Based on field measurements (Yasuda et al., 2021), the estimated frequency of the lowest mode is considered as the most useful index for defect evaluation. Therefore, the responses to the two low-order vibration modes, which are shown in Figure 12, are discussed below. Modes A and B correspond to the lowest and second-lowest mode in Figure 11 (a).

Figure 13 shows the change in the frequencies of the low-order vibration modes as the cut length increased. The frequencies were estimated from the frequency response functions using the least-squares complex frequency-domain (LSCF) method (Van Der Auweraer et al., 2001; Verboven et al., 2004). The figure also shows the natural frequencies obtained by modal analysis. The natural frequencies of the experiment and FEM analysis are generally in good agreement, although the results of the FEM analysis tend to be higher. The frequencies decreased as the cut length increased, and the rate of decrease in mode B was faster than that in mode A. Except for No. 1, mode B eventually became the lowest mode.

Table 5 summarizes the experimental results that were obtained when spalling occurred. The adhesion area, frequency of lowest mode, and applied load are listed. Except for specimen No. 1, spalling did not occur even when the width of the adhesion area was 1 cm. Notably, when the adhesion area becomes small, the rate of the cut length error increases and spalling may

occur during the cut. Hence, up to twice the amount that was initially planned was loaded when the width became 1 cm. If spalling did not occur, another cut of 0.3 cm was made and the specimen was loaded until spalling occurred. For No. 1, the adhesion area and applied load were 20 cm² and 301 N, while those for No. 2 were 10 cm² and 501 N. The adhesion area of No. 1 was twice that of No. 2, although the applied load of No. 1 was 60 % of that of No. 2. Specimen No. 1 was more prone to destruction. This difference is mainly attributed to the different forms of destruction. As shown in Figure 14, the destruction of No. 1 avoided the aggregates and occurred off the adhesion area. In contrast, the destruction of No. 2 penetrated into the aggregates and occurred in the adhesion area. Except for No. 1, all forms of destruction were the same as those of No. 2. For specimens No. 3 to No. 5, the precise adhesion area and frequency just before spalling were not obtained in this experiment. However, the frequency of the lowest mode before spalling was 100 Hz at most.

Figure 15 shows the estimated damping ratios of the low-order vibration modes before the cut. The damping ratios were estimated using the least-squares complex frequency-domain (LSCF) method (Van Der Auwerker et al., 2001; Verboven et al., 2004). These values were estimated along with the natural frequencies. Although variation existed, the overall average was approximately 1 %. Figure 16 shows the change in the estimated damping ratios as the cut length increased for specimen No. 1. The results include modes C and D in addition to modes A and B. The deformation in the x direction is shown in Figure 17. The large amplitudes in the vicinity of 1200 Hz and 2000 Hz in the 0 cm cut shown in Figure 11 (a) correspond to modes C and D, respectively. For modes A and B, the damping ratios increased with the cut length. In particular, the damping ratios increased rapidly just before spalling occurred. For modes C and D, the damping ratios did not significantly increase, except just before spalling.

4. Discussion

In the hammering test, the tactile sensation is considered as a soundness evaluation indicator. However, in this experiment, there was almost no change in the tactile sensation even just before spalling occurred and a solid hammering response always existed even just before spalling occurred. This can be confirmed from the results shown in Figures 5 to 7. Therefore, the

tactile sensation is not a fully reliable indicator of the spalling risk degree, but is still a useful indicator.

The specimens used in this experiment are expected to cause spalling with a relatively large adhesion area, because large stress concentration occurs under bending tension. Nevertheless, it was observed that spalling did not occur until the adhesion area significantly decreased, as presented in Table 5. Let us consider the results of specimen No. 1 as an example. The weight of the spalling mass was 30 kgf and the adhesion area was 20 cm² when spalling occurred. The weight of the concrete supported by the unit adhesion area was estimated as 1.5 kgf/cm². Therefore, spalling did not occur until the adhesion area significantly decreased. In conclusion, defects with high spalling risk can always be identified provided that the cracks on the concrete surfaces are periodically monitored.

In this experiment, the detachment angles were set to be larger than they actually are. Additionally, the tensile load just before spalling was sufficiently large to model the situation of the defect being placed at the tunnel crown, as presented in Tables 4 and 5. Based on the results obtained by this study, the frequency of the lowest mode just before spalling is expected to be less than 100 Hz. Therefore, spalling does not occur until the frequency of the lowest mode significantly decreases.

The estimated damping ratios were approximately 1 %, as shown in Figures 15 and 16, and tended to be higher than those observed in a previous laboratory experiment, which used concrete specimens with an internal defect (Yasuda et al., 2020), wherein most damping ratios were less than 1 %. Defects with an opening are more likely to dissipate energy compared with defects with an internal opening. In contrast, in this experiment, the estimated damping ratios tended to be lower than those obtained by a field test on a reinforced concrete tunnel lining (Yasuda et al., 2021), wherein most damping ratios were larger than 1 %. Notably, actual defects are more likely to dissipate energy compared with artificial defects. Considering that the damping ratios increased with the cut length, it is hypothesized that additional energy dissipation occurred around the edge of the adhesion area. The edge of the artificial defect was not sharp compared with the actual defect. This seems to be the reason for the damping ratios of the artificial defects tending to be lower than those of actual defects. Furthermore, considering the variations of three identical specimens in No. 3 and No. 4, the arrangement of the aggregate around the edge of the attachment part also seems to have influenced the energy dissipation.

The experimental results varied owing to the shape distortion of the specimen and the arrangement of aggregates. Numerical analysis can effectively eliminate these effects. Figure 18 shows the numerically estimated frequency response functions. The damping ratios for each mode δ_n were assumed to be the same and constant, although they are generally different. The corresponding experimental results are shown in Figure 10(a). The comparison of these results shows that they are reasonably consistent. The results shown in Figure 18 reveal that, when the damping ratios are the same, the natural frequencies of No. 2 are 0.6 times equal to those of No. 4, while the amplitudes of No. 2 are 0.36 times equal to those of No. 4. Additionally, when the damping ratios double, the amplitudes are halved. In theory, when the damping ratios are the same and the length of each side becomes N times, the natural frequencies become $1/N$ times and the amplitudes related to the velocity response become $1/N^2$ times. Additionally, when the damping ratios become N times, the amplitudes become approximately $1/N$ times.

In this experiment, the change in the frequency response function was investigated by decreasing the width of the adhesion area. As shown in Figure 11, the amplitude of each mode did not change significantly as the adhesion area decreased. However, the response was not experimentally investigated in the case wherein when the adhesion area increased. Instead, numerical analysis was carried out to investigate this case. Figure 19 shows the change in the numerically estimated frequency response functions at measurement point A. The adhesion lengths of 50 mm and 100 mm correspond to specimens No. 1 and No. 2. The comparison of the spectral amplitudes reveals that there was no significant difference from 50 mm to 350 mm. In contrast, the amplitudes rapidly decreased when the adhesion length changed from 350 mm to 400 mm. Regarding the lowest mode, the amplitude was approximately one-third during the transition from 50 mm to 300 mm, and one-tenth during the transition from 300 mm to 350 mm. The increase in the velocity response amplitude caused by the growth of detachment was gradual compared with the beginning of detachment.

In reality, the size and shape of the defects widely vary, and the defects may be larger than those prepared for this experiment. Moreover, some defects may be small vibrational excitations, which are difficult to measure. Therefore, it is necessary to elucidate the performance requirements, because machines have limited excitation force and detection performance. To estimate the performance that the machine should achieve, an actual spalling accident was considered as a reasonable criterion. The concrete lining block

that spalled in Fukuoka tunnel had a particular defect, which was large and thick. Among actual defects, the spalling defect is considered to face difficulty in exciting vibration. Hence, the frequency response functions of the concrete block that caused the spalling accident in the Fukuoka tunnel were estimated by numerical analysis. Figure 20 shows the concrete lining block model. Details regarding the location and configuration of the actual block can be found in Asakura and Kojima (2003) and Tsuno and Kishida (2020). The numerical properties were assumed to be the same as those listed in Table 3. Notably, the compressive strength of the spalled concrete was approximately 28 N/mm^2 , and quality problems did not exist. The calculated mass of the block model was approximately 270 kg. The cold joint and fracture surface are discontinuities that already exist immediately after construction. Based on the results obtained by the concrete neutralization test, it was estimated that some parts of areas 1 and 2 were attached until just before spalling occurred. The adhesion areas of areas 1 and 2 were approximately 856 cm^2 and 1200 cm^2 , respectively. Relatively large adhesion areas were assumed because the actual situation was unknown. Points 1 to 3 are the excitation and measurement points, respectively. For simplicity, the excitation and measurement points were assumed to be the same.

Figure 21 shows the frequency response functions for the concrete lining block with varying adhesion areas. The adhesion was modeled by completely fixing the displacement. The damping ratios for each mode were assumed to be 3%, considering the result just before the spalling of mode A, as shown in Figure 16. From (a) to (c), the response amplitudes in the low-order mode are approximately 1 mm/s/N , which is not very different to the experimental results obtained for specimens No. 1 and No. 2, as shown in Figure. 11. Therefore, the ability to detect defects with the response amplitude of 1 mm/s/N is considered as a requirement for the mechanization of the hammering test. In contrast, in (d), where the concrete block can be considered as almost healthy, the response amplitudes are quite smaller and can be considered as zero.

5. Conclusions

This study investigated the vibration characteristics of defects with high spalling risk. The adhesion area of the concrete specimens was decreased until spalling occurred. The natural frequencies, damping ratios, and response amplitudes were obtained and are presented in this paper. Additionally,

results obtained by numerical analysis are presented to supplement the experimental results. The following conclusions were drawn from this study:

- (1) The tactile sensation in the hammering test is not a fully reliable indicator of the spalling risk degree.
- (2) Spalling did not occur until the adhesion area is significantly decreased. Defects with high spalling risk were always identified provided that the cracks on the concrete surfaces were periodically monitored.
- (3) Spalling did not occur until the frequency of the lowest mode significantly decreased. The frequency of the lowest mode just before spalling is expected to be less than 100 Hz.
- (4) The increase in the velocity response amplitude caused by detachment growth was gradual compared with the beginning of detachment.
- (5) The ability to detect defects with the response amplitudes of 1 mm/s/N is considered as a requirement for mechanizing the hammering test.

High reliability is required as a standard for mechanizing the inspection. The results obtained by this study are simply a starting point, and it is expected that more results will be obtained by other methods under different conditions.

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Table 1: Outline of concrete specimens.

Number	Overall size (mm)	Adhesion area (mm)	Comment
No. 1	500×400×175	50×400	Detachment angle was 15° and the opening was 5 mm
No. 2		100×400	
No. 3	400×320×140	80×320	Length of each side was 80% of No. 2
No. 4	300×240×105	60×240	Length of each side was 60% of No. 2
No. 5	450×400×150	80×400	Detachment angle was 10° and the opening was 4 mm

Table 2: Summary of concrete mix proportions.

Water cement ratio (%)	Fine aggregate ratio (%)	Water (kg/m ³)	Cement (kg/m ³)	Fine aggregate (kg/m ³)	Coarse aggregate (kg/m ³)	Admixture (kg/m ³)
68	46	190	270	800	990	2.7

Table 3: Material properties of concrete.

Young's modulus (GPa)	Poisson's ratio	Density (kg/m ³)
29	0.20	2300

Table 4: Application of tensile load equivalent to self-weight.

Number	Weight of spalling mass (kgf)	Applying load (N)
No. 1	30	300
No. 2	30	300
No. 3	15	150
No. 4	6.5	70
No. 5	14	150

Table 5: Summary of experimental results obtained when spalling occurred.

Number	Adhesion area (cm ²)	Frequency of the lowest mode (Hz)	Applied load (N)
No. 1	20 (5×4)	84	301
No. 2	10 (10×1)	38	501
No. 3-a	8 (8×1)	98	225
No. 3-b	8 (8×1)	71	300*
No. 3-c	8 (8×1)	65	214
No. 4-a	4.2 (6×0.7)	98	176
No. 4-b	4.2 (6×0.7)	92	180
No. 4-c	4.2 (6×0.7)	101	170
No. 5	4.2 (8×0.7)	50	178

* It was spalled on moving the specimen after 300 N loading.

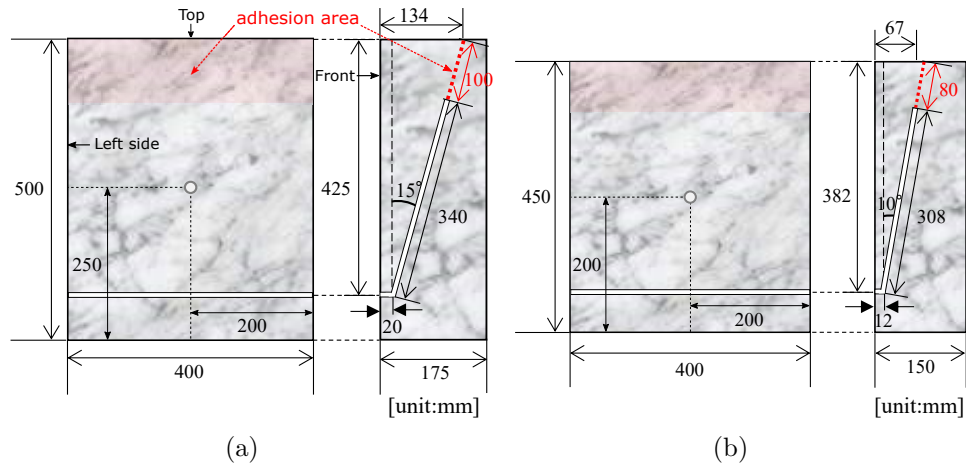


Figure 1: Detailed dimensions of specimens: (a) No. 2 and (b) No. 5.

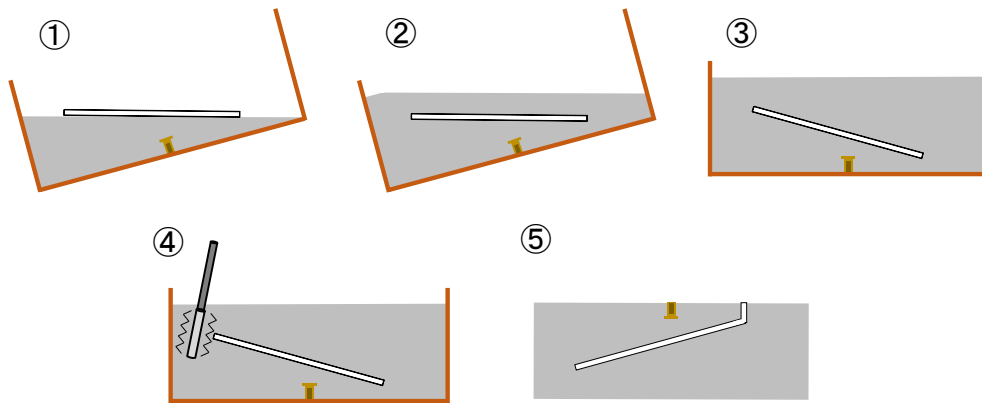


Figure 2: Specimen preparation procedure.

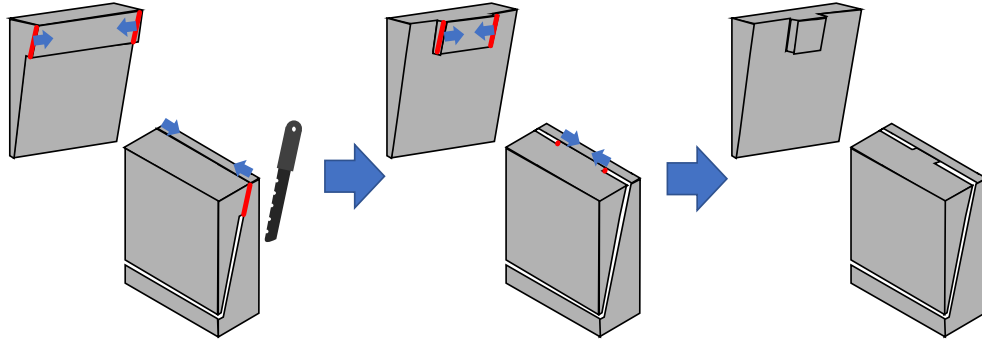


Figure 3: Specimen cutting procedure.

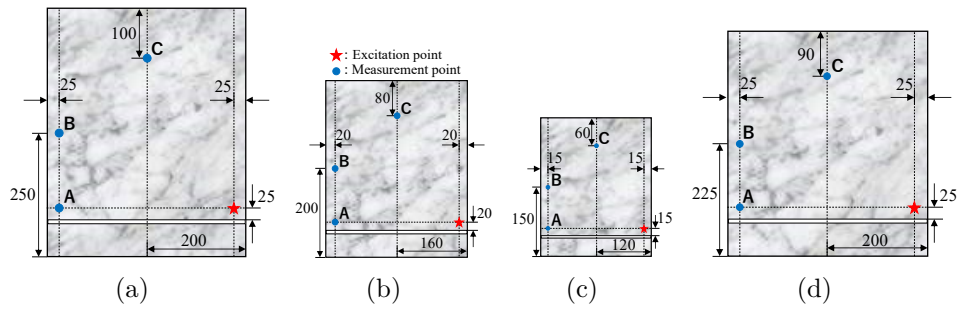


Figure 4: Excitation and measurement points on specimens: (a) No. 1 and No. 2; (b) No. 3; (c) No. 4; (d) No. 5.

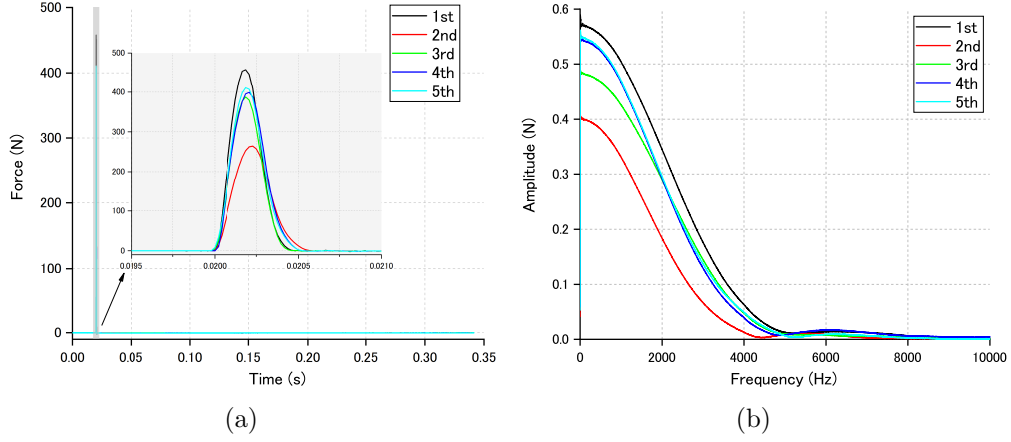


Figure 5: Hammer-induced force signals in specimen No. 2 before the cut: (a) time history waveforms for five measurements; (b) Fourier spectra of these waveforms.

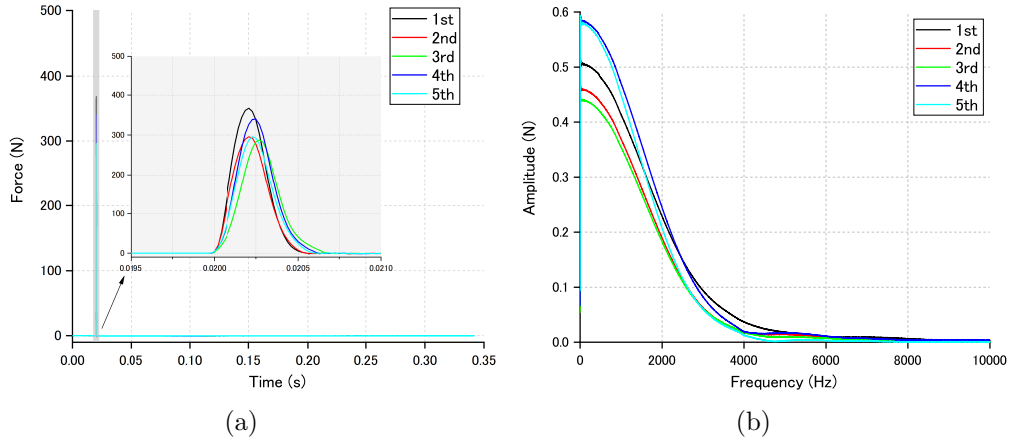


Figure 6: Hammer-induced force signals in specimen No. 4-a before the cut: (a) time history waveforms for five measurements; (b) Fourier spectra of these waveforms.

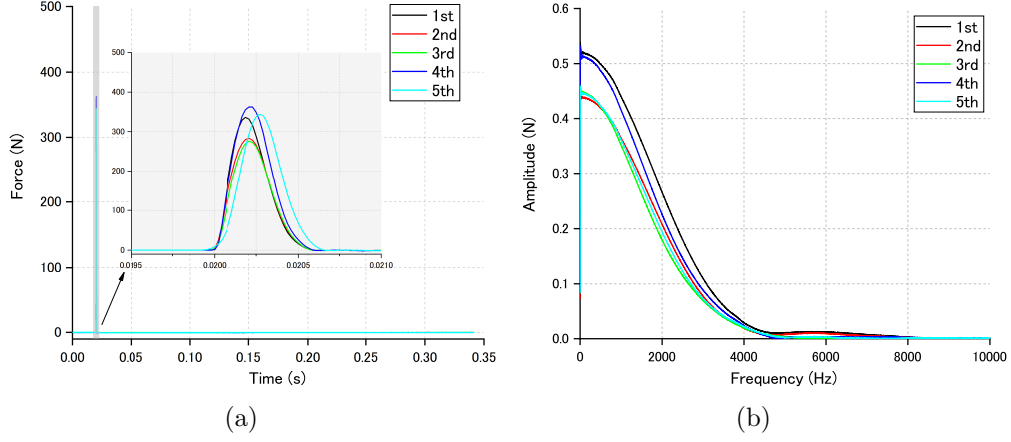


Figure 7: Hammer-induced force signals in specimen No. 2 after cut of 39 cm: (a) time history waveforms for five measurements; (b) Fourier spectra of these waveforms.

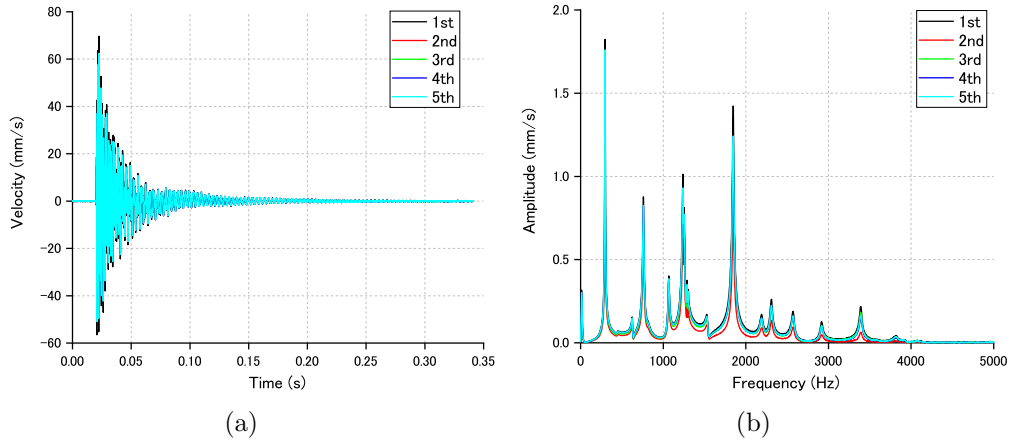


Figure 8: Hammer-induced vibrations at measurement point A in specimen No. 2 before the cut: (a) velocity waveforms for five measurements; (b) Fourier spectra of these waveforms.

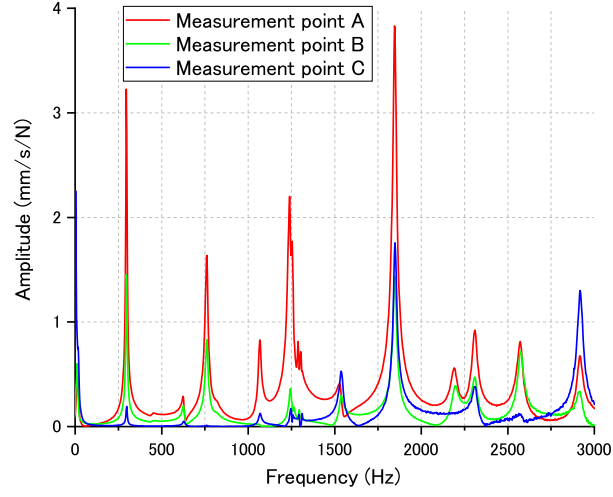


Figure 9: Frequency response functions in specimen No. 2 before the cut.

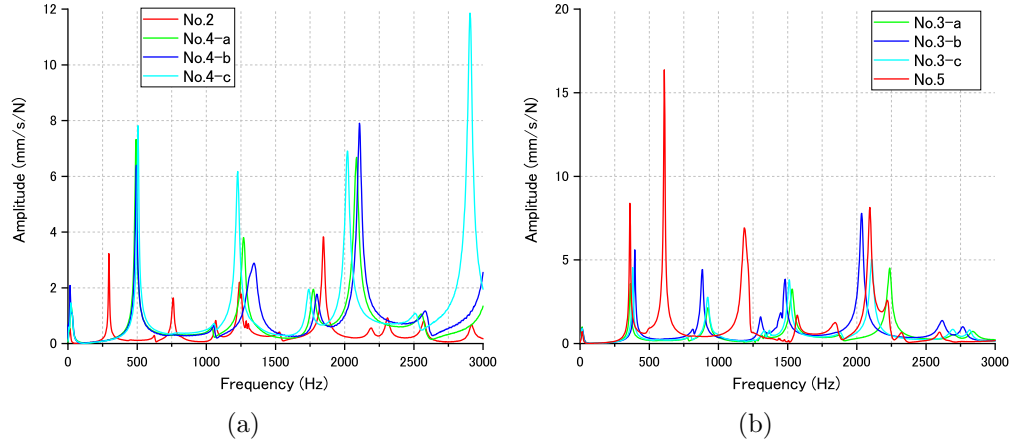
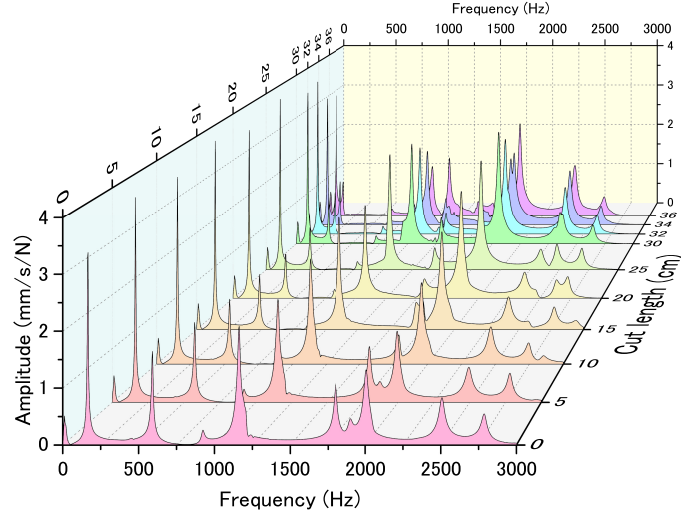
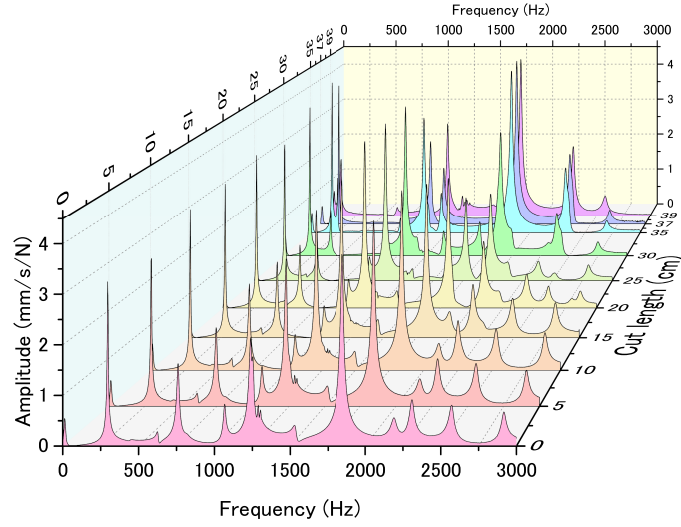


Figure 10: Comparison of frequency response functions before the cut: (a) No. 2 and No. 4; (b) No. 3 and No. 5. All measurements were made at point A.



(a)



(b)

Figure 11: Change in frequency response functions with increase of cut length: (a) No. 1 and (b) No. 2. The measurement was made at point A.

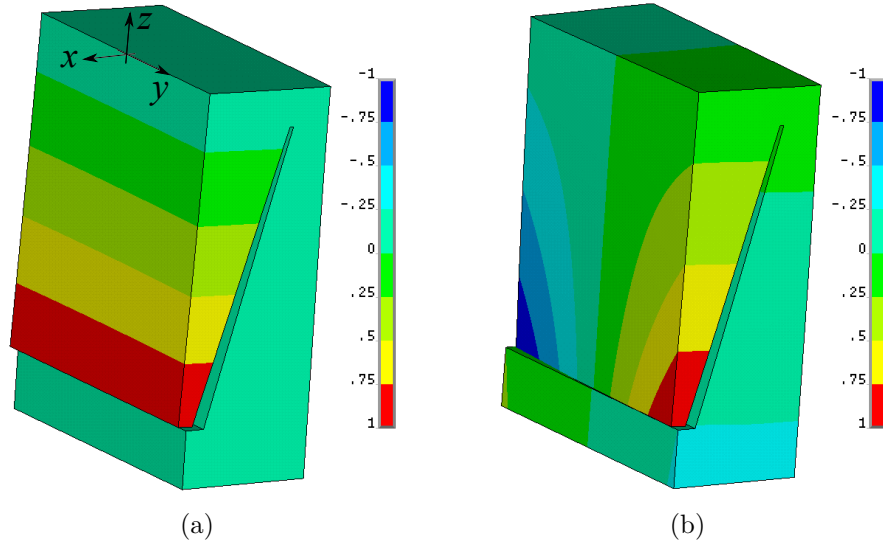


Figure 12: Deformation in x direction of low-order vibration modes in specimen No. 1 before the cut: (a) mode A and (b) mode B.

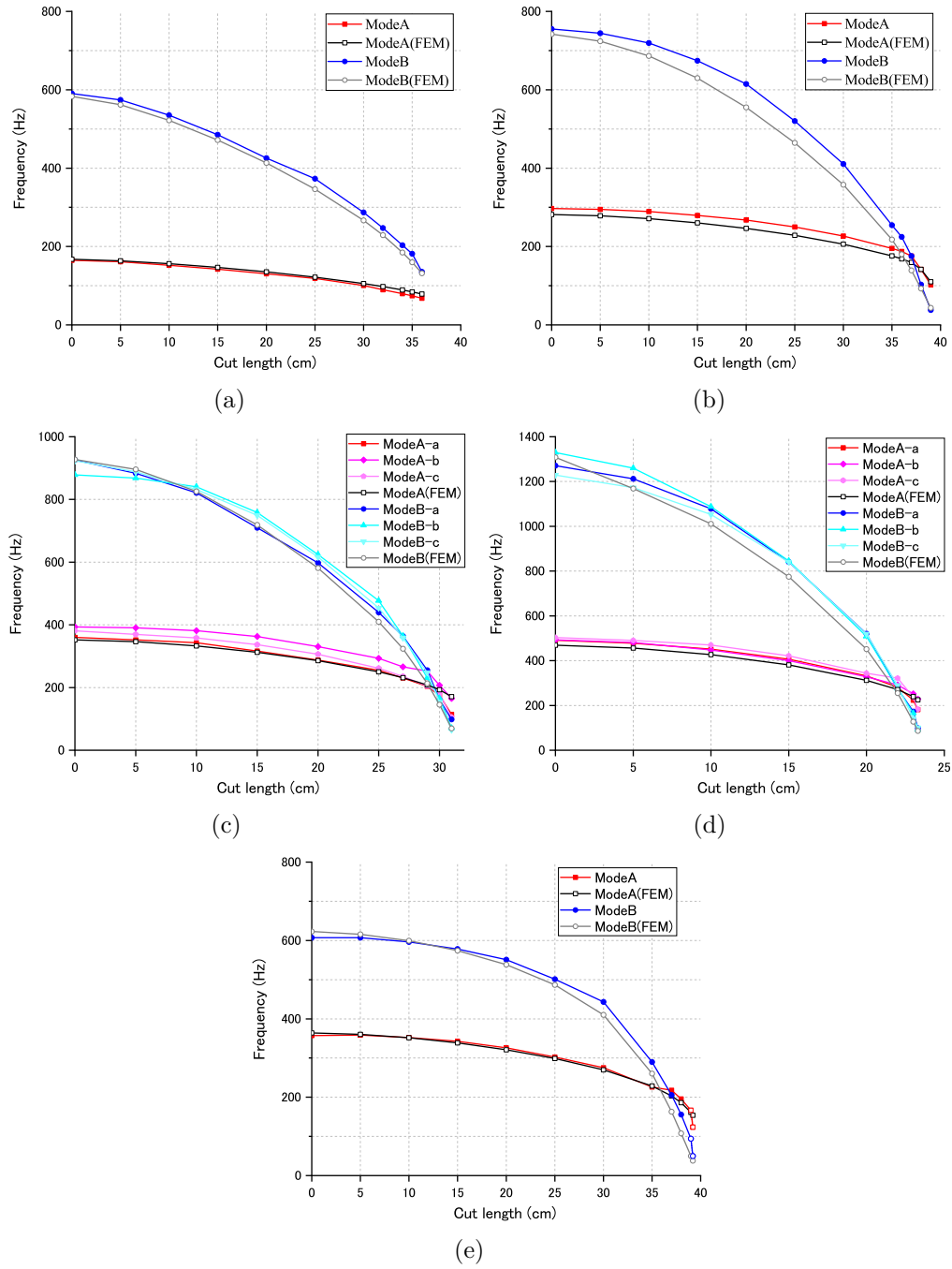


Figure 13: Change in frequencies of low-order vibration modes with increase of cut length: (a) No. 1; (b) No. 2; (c) No. 3; (d) No. 4; (e) No. 5.

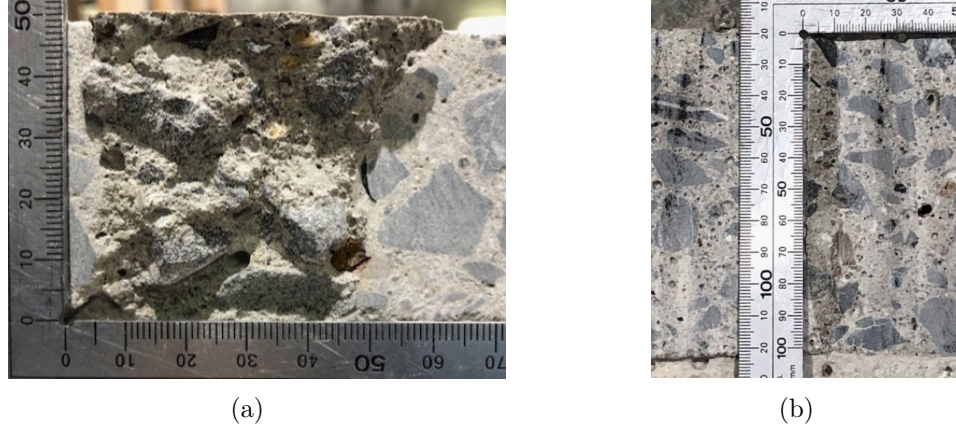


Figure 14: Photograph of vicinity of adhesion area after spalling: (a) No. 1 and (b) No. 2.

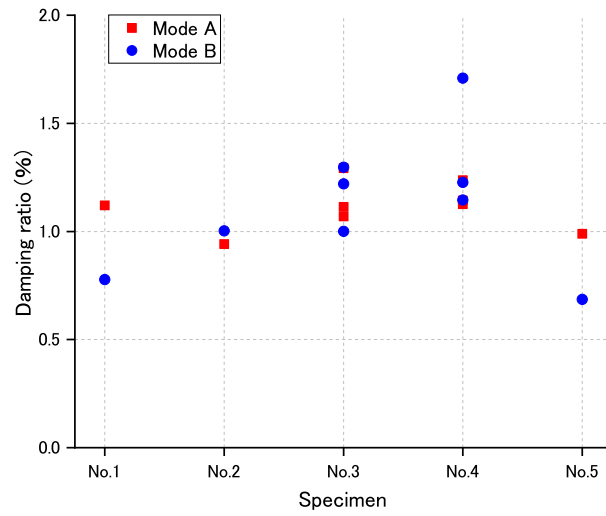


Figure 15: Estimated damping ratios of low-order vibration modes before the cut.

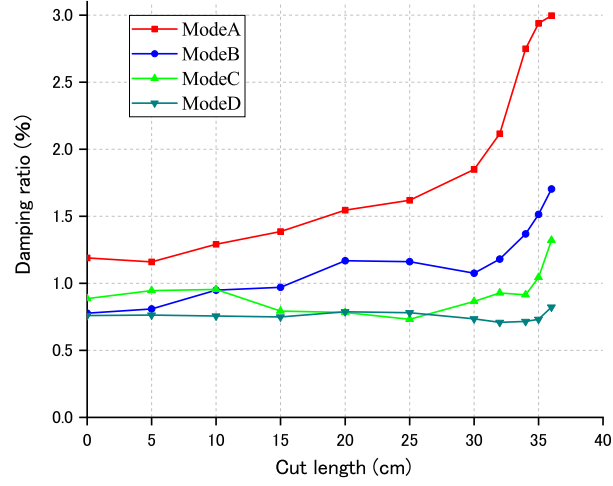


Figure 16: Change in estimated damping ratios with increase of cut length in specimen No. 1.

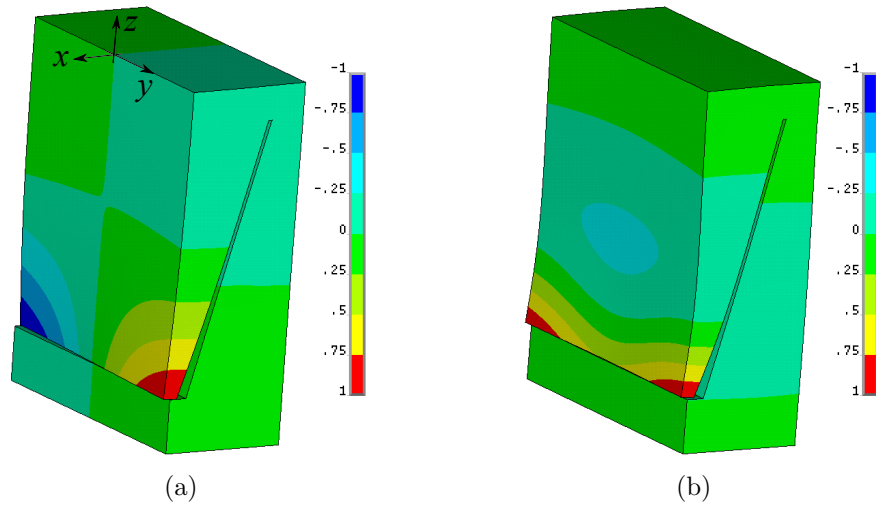


Figure 17: Deformation in x direction of vibration modes in specimen No. 1 before the cut: (a) mode C; (b) mode D.

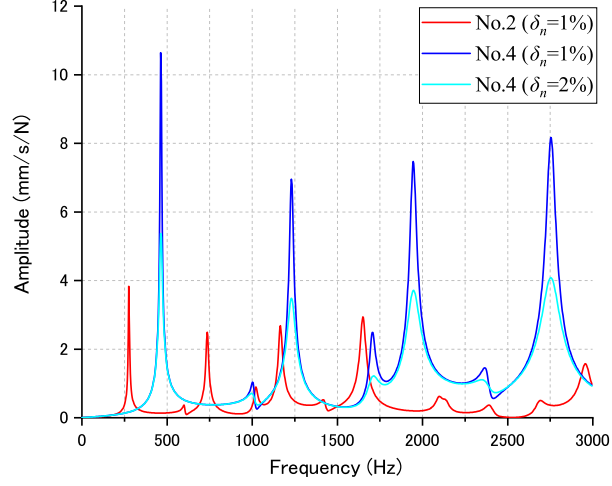


Figure 18: Numerically estimated frequency response functions at measurement point A. The damping ratios for each mode δ_n were assumed to be constant.

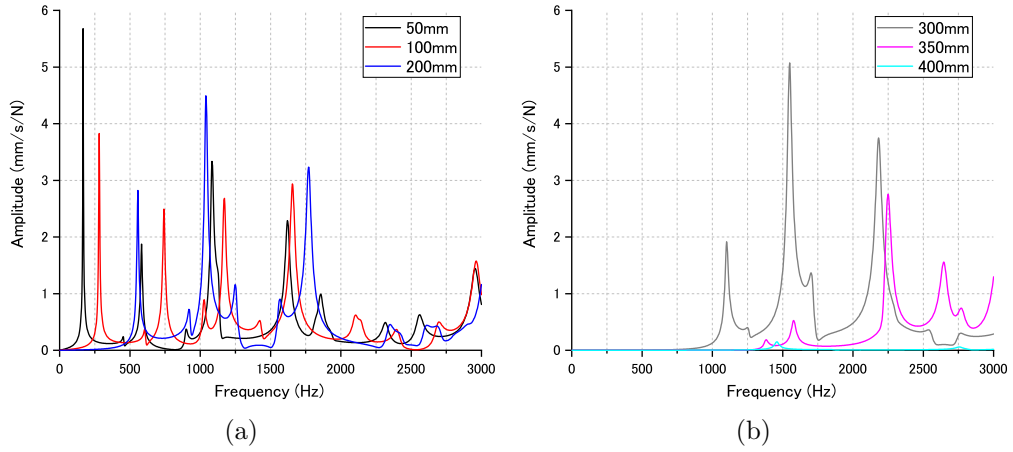


Figure 19: Change of numerically estimated frequency response functions at measurement point A with increase of adhesion area. The adhesion length is (a) 50 mm-200 mm and (b) 300 mm-400 mm. The adhesion lengths of 50 mm and 100 mm correspond to specimens No. 1 and No. 2. The damping ratios for each mode are assumed to be 1%.

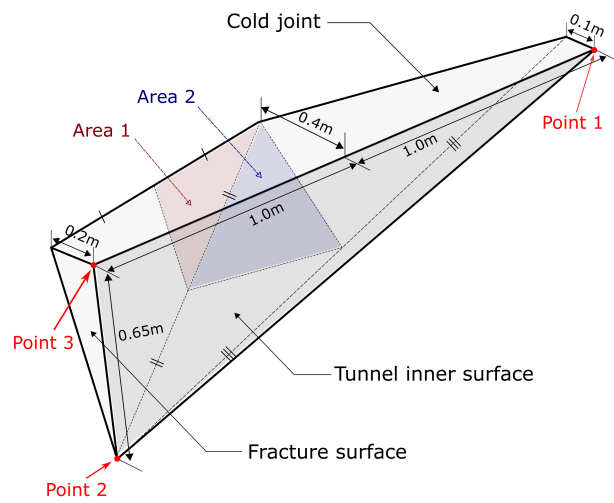


Figure 20: Concrete lining block model of spalling accident in Fukuoka Tunnel.

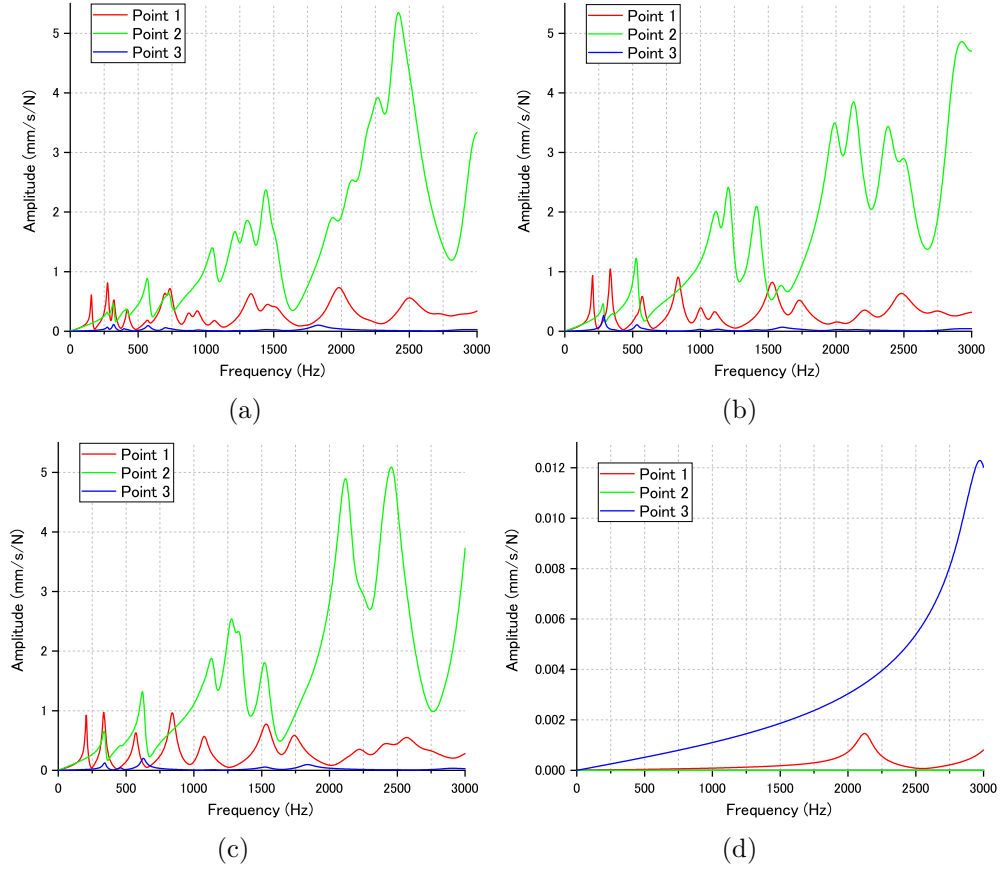


Figure 21: Frequency response functions for concrete lining block. The adhesion is (a) Area 1, (b) Area 2, (c) Areas 1 and 2, and (d) all areas except for the cold joint, fracture surface, and tunnel inner surface. The damping ratios for each mode are assumed to be 3%.