



Study on Damage Evaluation of Laminated Rubber Bearings using AE Method

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Abstract

Recently, some problems of degradation in the laminated rubber bearings have become obvious. The damage inside a rubber bearing causes its fracture when an earthquake occurs. However, there are few studies on the evaluation of damage inside rubber bearings. To prevent fracture due to an earthquake, an appropriate method to detect internal damage is urgently required. In this study, the acoustic emission (AE) method, one of the non-destructive testing methods, was utilized to evaluate the damage inside a rubber bearing.

The rubber bearings made of natural rubber, which conducted the shear test, were used. After the shear test, the rubber bearings conducted the cyclic compressive loading test which was assumed the traffic vibration on the bridge girder. During the test, AE monitoring performed as shown in Fig. 1. Finally, the rubber bearings cut and the cross-section observed using a microscope to compare the AE data with the microscopic observation results to determine the damage condition.

The number of AE hits was compared with before and after the shear test as shown in Fig. 2. The results showed that more AE hits were detected after the shear test. Also, several fractures, which were thought to crack due to shear test, were observed in the rubber bearings from the microscopic observation. These results indicated that the AE method could be used to evaluate the damage of the rubber bearings.



Fig. 1 – AE monitoring

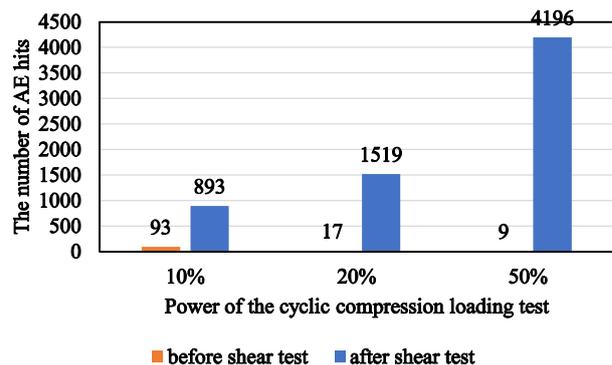


Fig. 2 – Results of AE hits

Keywords: acoustic emission, AE parameter analysis, before/after shear test, microscope, rubber bearing,



1. Introduction

Since the 1995 Kobe Earthquake, laminated rubber bearings (hereinafter referred to as “rubber bearings”) have been actively used in bridges as members that do not basically require maintenance. However, more than 20 years have passed since then, and the age-related deterioration of rubber bearings has become apparent [1]. Rubber bearings are continuously subjected to external forces, and aging due to ozone degradation and fatigue caused by earthquakes have been cited as deterioration factors. In addition, there have been several reports of rupture due to earthquakes. For example, the rupture due to the 2011 Tohoku Earthquake [2] and the rupture due to the 2016 Kumamoto Earthquake have been reported [3]. The rubber bearing installed near the ruptured rubber bearing is not ruptured. The problem is that there is no index to determine whether an unbroken rubber bearing can continue to use. Furthermore, the rubber bearings currently in use may have internal deterioration or damage due to traffic vibration, environmental loads, or deformation caused by earthquakes. Because of the above, there is a growing interest in the maintenance and repair of rubber bearings, which previously do not almost consider. However, there are very few studies on the evaluation of damage inside rubber bearings because there is no partial repair method for rubber bearings and replacement is not easy. Therefore, no precise method has been established to diagnose the degree of internal damage and maintain the rubber bearing [4][5].

In previous studies, rubber bearings were subjected to shear tests to the extent of the rupture. Cyclic compressive loading tests simulating traffic vibration were conducted before and after the shear tests, and AE measurements were taken during the tests. However, it has not observed the actual damage and to correlate the detected AE data. In this study, the detected AE data were organized, and AE parameters were analyzed before and after the shear test. After the cyclic compressive loading, the specimens were cut, and microscopic cross-sectional observations were made.

2. Laminated Rubber Bearings

The laminated rubber bearing consists of alternating layers of rubber material and steel plates, which are vulcanized and bonded together. The vertical load is suppressed by the adhesive force between the rubber and steel plates and the tensile stiffness of the steel plates, while the steel plates do not interfere with the shear deformation of the rubber and deform by the elasticity of the rubber itself against the horizontal load. Therefore, the laminated rubber bearing is stiff in the vertical direction and soft in the horizontal direction.

The rubber bearing used in this study is a natural rubber-based laminated rubber bearing, and its internal structure is shown in Fig. 3. Although natural rubber has excellent elongation and tensile strength, it is not ozone-resistant and has little damping performance, which requires a damper device.

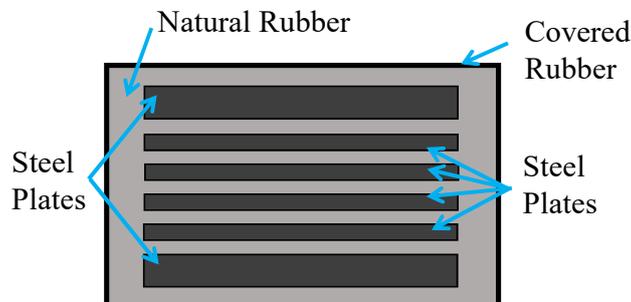


Fig. 3 – Internal structure of rubber bearing



3. AE Method

AE consists of Acoustic Emission, which means "the phenomenon of elastic waves generated by the release of previously stored strain energy when a solid is deformed or fractured, or the elastic behavior generated in this way" [6]. In a cyclic compressive loading test of a rubber bearing, the void inside the bearing opens and closes when the bearing is loaded and unloaded. The elastic waves released are detected by an AE sensor installed on the surface of the rubber bearing to obtain AE signals such as AE waveforms.

One of the analysis methods using the AE method is to use various parameters obtained from AE signals. By comparing the time variation of the measured parameters and the combination of multiple parameters, the AE characteristics generated inside the material can determine and the damage evaluation can perform.

Fig. 4 shows a typical AE waveform, and the typical AE parameters and their characteristics are shown as follows [6]:

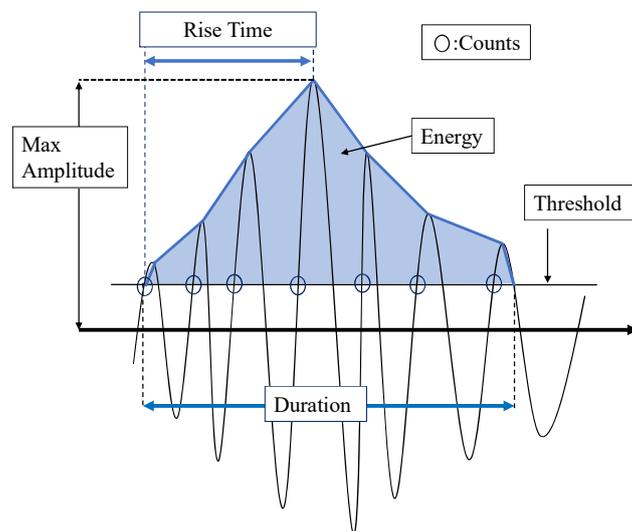


Fig. 4 – A typical AE waveform

- i. **Threshold:** This value is set to eliminate mechanical and electrical noise in AE measurement.
- ii. **The number of AE hits:** The number of AE signals detected. A larger number of AE hits indicates a larger number of wave sources, which in turn indicates a larger possibility of damage.
- iii. **Energy:** The area of the envelope detection waveform of the AE signal indicates the scale of the AE phenomenon; a larger value indicates a greater possibility of damage.
- iv. **Amplitude:** It is the magnitude of vibration caused by the event that generated the AE. The maximum amplitude value indicates the largest amplitude value of the AE signal, and a larger value indicates the possibility of a larger scale.
- v. **Rise Time:** It is the time from the start time of AE signal measurement to the maximum amplitude value for that AE signal.
- vi. **Duration:** It is the time from the start of measurement when the AE signal first crosses the threshold to the end of measurement when the AE signal last crosses the threshold.
- vii. **Counts:** Number of times the threshold value is exceeded during the duration time.



4. Method

4.1 Outline of specimen

The cross-section and top views of the specimen used in this study are indicated in Fig. 5, and the specimen specifications are shown in Table 1.

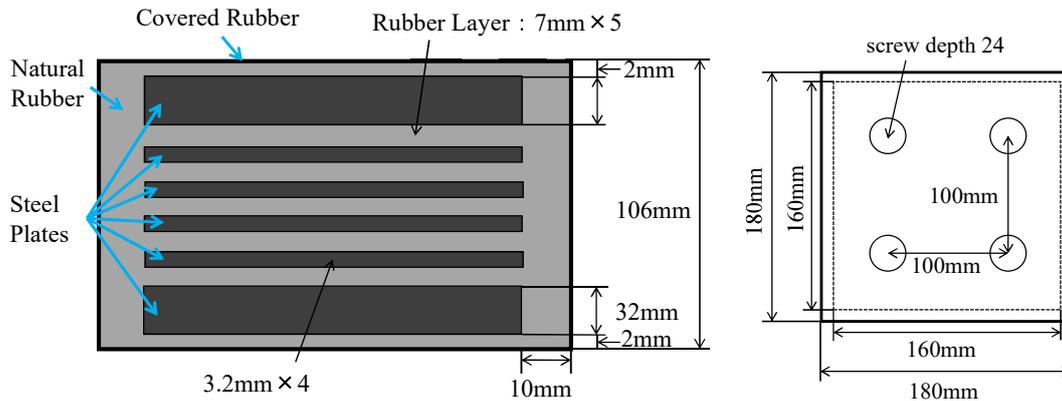


Fig. 5 – Outline of the specimen (left: cross-section view, right: top view)

Table 1 – Specimen specifications

Dimensions (mm×mm×mm)	180×180×106
Rubber layer thickness (mm)	7
Steel plates thickness (mm)	3.2

4.2 Shear test

The rubber bearings used in this study were subjected to shear tests as shown in Table 2, with excitation at shear strains of 175%, 250%, and 300%. The specimens used in this experiment were borrowed by Civil Engineering Research Institute for the cold region for their experiments, and AE measurements were carried out on the specimens before and after the shear tests. Thus, the specimens were stored at -30°C for 8 hours in a temperature-controlled room before the shear tests were conducted. AE measurements were conducted on the specimens before and after the shear tests. Therefore, the shear tests were conducted under low-temperature conditions to simulate cold regions. AE measurements were carried out on specimens that did not fracture during the shear tests, and although residual shear deformation was observed, no surface cracks were observed.

Table 2 – Outline of shear test

Shear strain (%)	Number of oscillation cycles
±175	3
±250	6
±300	3

4.3 AE Measurement in cyclic compressive loading tests

In this study, the rubber bearings were subjected to cyclic compressive loading tests in the vertical direction under the assumption of traffic vibrations on an on-site bridge. AE measurements were applied based on the assumption that elastic waves are generated by the opening and closing of internal voids. It is a practical



method to evaluate the rubber bearing in service on a bridge without stopping traffic, if the internal damage can be evaluated by AE measurements using cyclic compressive loading tests assuming traffic vibration. Fig.1 and Fig. 6 show the experimental conditions of the cyclic compressive loading test. The load was applied from the minimum load value to the maximum load value in 10 cyclic cycles. The minimum load value is considered a compressive force equivalent to a dead load and a live load equivalent to a surface pressure of 6MPa. Therefore, the minimum load value was set to 153.6kN (=160mm × 160mm × 6MPa) for this study. The maximum load value is calculated from the allowable maximum compressive stress, which is determined by the primary shape factor of the rubber bearing. The relationship between the primary shape factor and the allowable maximum compressive stress is shown in Table 3, and the primary shape factor of this specimen is 5.71. The specimen used in this study has a maximum allowable compressive stress of 8N/mm², so the maximum allowable load value is 259.2kN (=180 mm × 180 mm × 8MPa). The minimum load value of 153.6kN was subtracted from this value to obtain a value of 105.6kN (=259.2kN-153.6kN). 10.6kN, which is 10% of this value, was added to 153.6kN to obtain a value of 164.2kN as the maximum load value, which was named the 10% cyclic compressive load test. Similarly, the 20% and 50% portions of 105.6kN were added to 153.6kN, and the maximum load values were 174.8kN and 206.6kN, which were named the 20% cyclic compressive test and 50% cyclic compressive test, respectively. AE measurements were performed using the above 10%, 20%, and 50% cyclic compressive tests.

Eight AE sensors with a resonant frequency of 60kHz were used for AE measurements, four at the height between the upper steel plate and the inner rubber, and four at the height between the lower steel plate and the inner rubber. The coordinates of the AE sensor locations are shown in Table 4. The threshold value for AE measurement was set at 40dB. Among the AE phenomena obtained, AE phenomena with an AE parameter count of 1 and an AE energy of 0 were eliminated as noise. In addition, AE phenomena that occurred during the time before the first exceedance of 153.6kN were also eliminated as out of the target time.

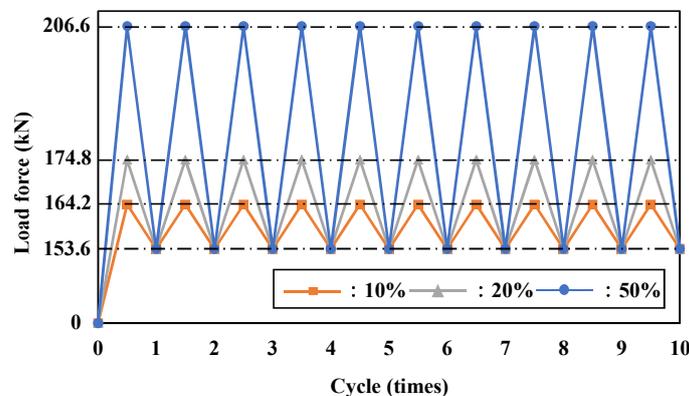


Fig. 6 – Experimental overview of cyclic compressive loading tests

Table 3 – Primary shape factor and allowable maximum compressive stress

S_1 : Primary shape factor	Allowable maximum compressive stress (N/mm ²)
$S_1 < 8$	8
$8S_1 < 12$	S_1
$12S_1$	12



Table 4 – Coordinates of AE sensors installation location

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
x (mm)	30	30	150	150	30	30	150	150
y (mm)	0	0	0	0	180	180	180	180
z (mm)	72	34	72	34	72	34	72	34

5. Results

5.1 Number of AE hits

The number of AE hits in the 10%, 20%, and 50% cyclic compressive tests are compared before and after the shear tests as shown in Fig. 7. The number of AE hits after the shear test is significantly larger than that before the shear test, indicating that the AE sensor detects more AE phenomena. The higher number of AE hits indicates more AE phenomena detected by the AE sensor, thus indicating an increase in the number of AE sources, i.e., internal damage, after the shear test than before the shear test. Therefore, based on the comparison of the number of AE hits before and after the shear test, it can be concluded that the internal damage increased due to the shear test.

Then, the results were compared in terms of the number of AE hits at each sensor before and after the shear test. The results are shown in Table 5, where the overall number of AE hits is higher after the shear test than before the shear test, similar to the overall comparison. After the shear test, the number of AE hits on CH4 is significantly higher, indicating that the number of AE hits varies depending on the specific sensor. This indicates more damage in the vicinity of the sensors where a large number of AE hits are detected. Furthermore, AE hits are higher for the sensor on the lower steel plate side than for the sensor on the upper steel plate. Looking only at the sensors on the upper steel plate side, several sensors with the same number of AE hits as before the shear test, suggesting that the upper steel plate side is hardly damaged by the shear test based on the results of AE phenomena alone.

The above results indicate that the number of AE hits after the shear test was larger than that before the shear test, indicating that the shear test caused internal damage. Also, a comparison of the number of AE hits for each sensor shows that a large number of AE hits were detected in the sensor on the lower steel plate side, while some sensors on the upper steel plate side only detected the same number of AE hits as before the shear test, suggesting that there was little damage on the upper steel plate side and a lot of damage on the lower steel plate side.

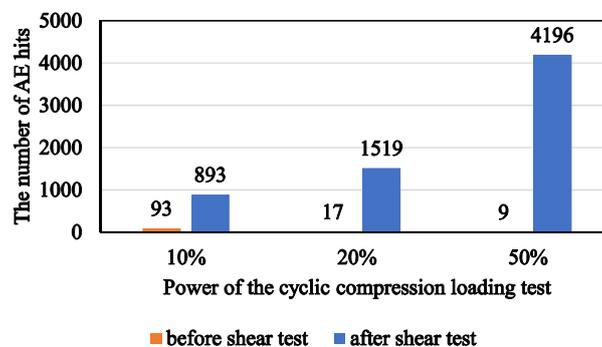


Fig. 7 – Comparison of the number of AE hits before and after the shear test



Table 5 – Comparison of the number of AE hits in each sensor

load force	shear test	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
10%	before	3	22	5	13	2	23	1	24
	after	3	93	19	294	3	270	21	190
20%	before	0	4	1	3	0	4	0	5
	after	1	110	5	790	1	368	15	229
50%	before	0	3	0	2	0	2	0	2
	after	1	863	22	1586	4	1003	15	702

5.2 Maximum amplitude value and AE energy

The increase in the number of AE hits from before the shear test indicates that the damage to the specimen has increased. This section focuses on the maximum amplitude value and AE energy to evaluate the damage in more detail. Both the maximum amplitude and AE energy are parameters related to the magnitude of AE phenomena, and higher values of each parameter indicate the greater damage. Therefore, if both the maximum amplitude and AE energy are large, it is considered that there is a possibility that a large amount of damage exists.

Therefore, the relationship between the maximum amplitude values and AE energy in the 10%, 20%, and 50% cyclic compressive loading tests were compared before and after the shear test. The results are shown in Fig. 8 to Fig. 10. The AE energy after the shear test is higher than that before the shear test for all the specimens under all the loading forces. For the maximum amplitude values, especially at 10% and 20%, larger values are detected before the shear test, and there is no significant difference in the distribution between before and after the shear test. In particular, after the shear test, as the maximum amplitude value increases, a significant value of AE energy is also detected, and the AE energy suddenly decreases after a specific maximum amplitude value is exceeded. Therefore, the larger the maximum amplitude value at the time of maximum AE energy value, the higher the degree of damage.

Fig. 11 shows the relationship between the maximum amplitude values and AE energy of the sensors on the lower steel plate side for the 10% cyclic compressive loading test. The maximum amplitude value at the time of the maximum AE energy is also the highest at CH4, suggesting that the area around CH4 may be more damaged than other sensors.

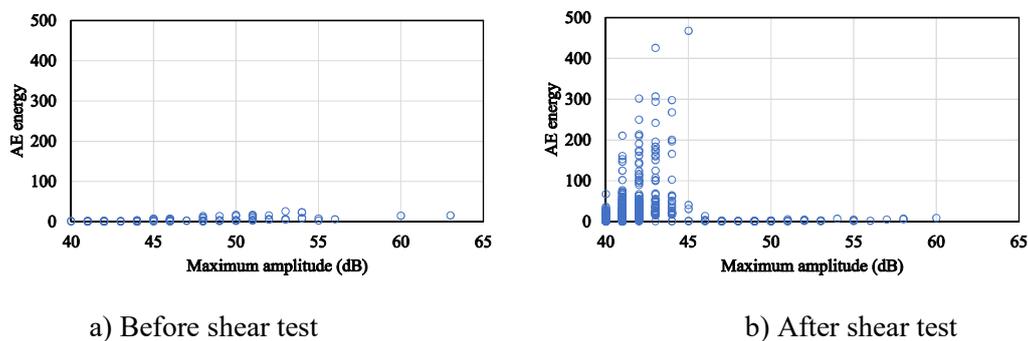


Fig. 8 – Relationship between maximum amplitude values and AE energy in 10% cyclic compressive loading tests

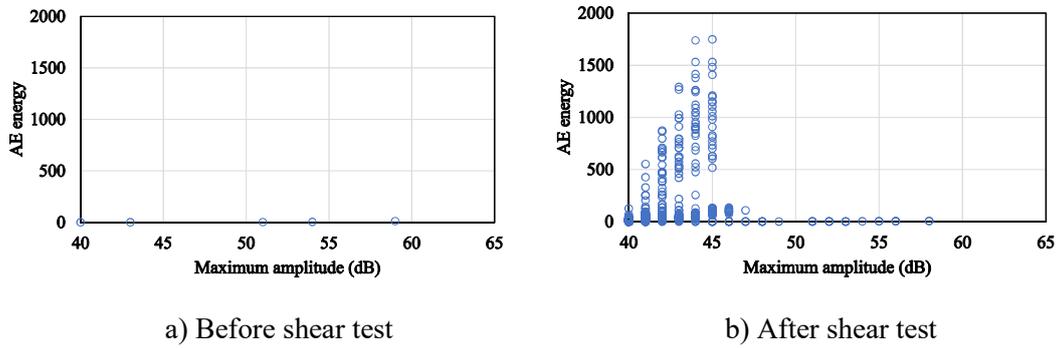


Fig. 9 – Relationship between maximum amplitude values and AE energy in 20% cyclic compressive loading tests

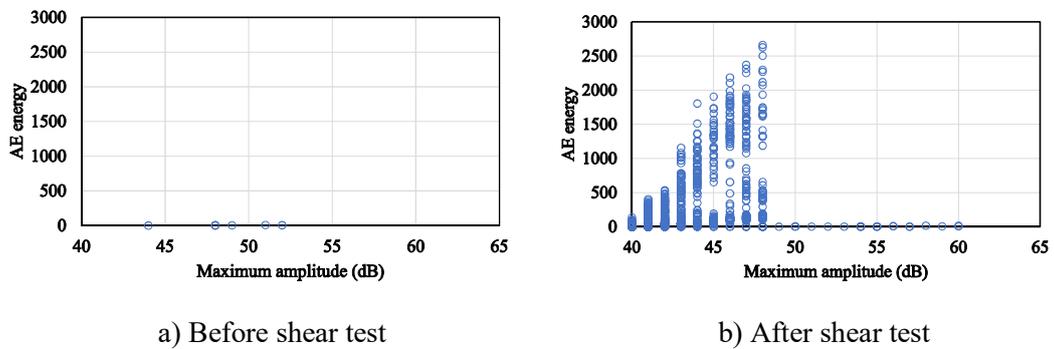


Fig. 10 – Relationship between maximum amplitude values and AE energy in 50% cyclic compressive loading tests

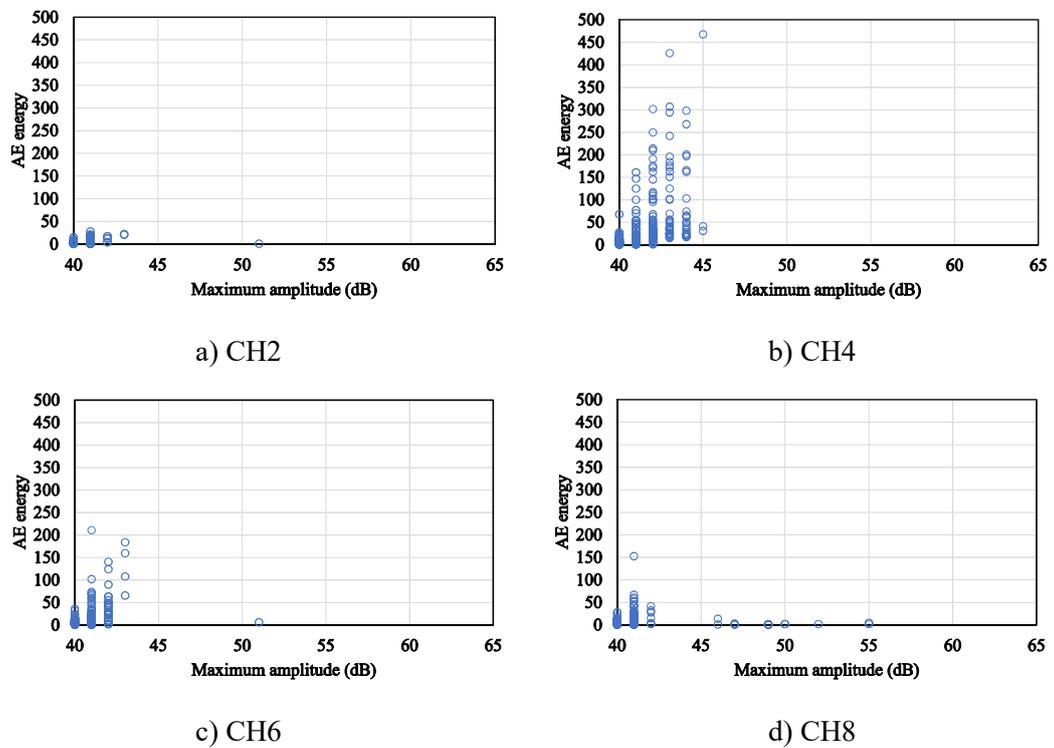


Fig. 11 – Relationship between maximum amplitude value and AE energy of sensors on the lower steel plate side



6. Microscopic observation of rubber bearing cross section

6.1 Observation outline

The purpose of the microscopic observation of the rubber bearing cross-section was to compare the results of the damage evaluation by AE measurement with the actual damage level of the cross-section and to verify the reliability of the AE measurement results. After the shear test, the specimens were cut and observed with a 500x microscope. The cross-section of the specimen is shown in Fig. 12, and the observation area is the red circle, which is considered to be the most damaged area by the shear test and is also near the location of the AE sensor.



Fig. 12 – Observation points

6.2 Observation results

This study focused on the direction and number of cracks. Horizontal cracks are considered to be caused by the shear test and cutting marks made during cutting, while vertical and diagonal cracks are considered to be caused by the shear test and the extension of horizontal cracks just before rupture. The other cracks were mostly round cracks like air bubbles that were thought to be mixed in during the manufacturing of the rubber bearings, and a few cracks that were thought to be caused by the shear test.

The results of the distribution of crack directions are shown in Fig. 13. Since horizontal cracks are caused by the shear test, vertical and oblique cracks are just before fracture, and the shear test may cause other cracks. It thought that the shear test caused internal damage. Therefore, the results shown in Chapter 5 for the number of AE hits indicate an increase in internal damage.

Then, the results of the number of cracks for each sensor are shown in Fig. 14. The actual cross-section of the specimen is not biased, and some sensors have fewer cracks on the lower steel plate side and some sensors have more cracks on the upper steel plate side. Also, compared with the results of the damage level in Chapter 5, similar results were obtained, and it was found that there was a large amount of damage near CH4. Therefore, it can be evaluated the degree of damage based on the relationship between the maximum amplitude value and AE energy.

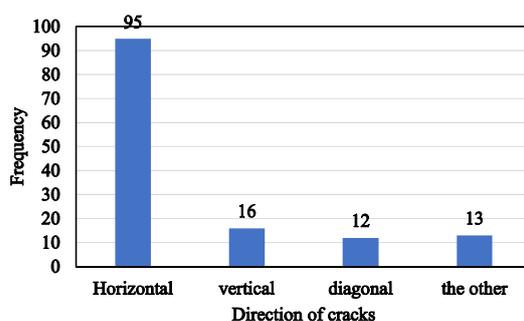


Fig. 13 – Distribution of cracks direction

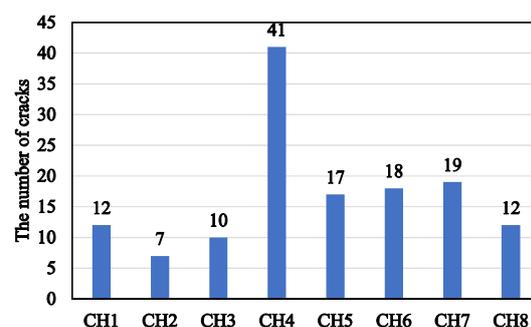


Fig. 14 – Number of cracks for each sensor



7. Conclusion

The conclusions drawn from this study are as follows.

- (1) Since the number of AE hits was significantly higher after the shear test than before the shear test, and many cracks caused by the shear test were observed in the actual cross-section, the number of AE hits was considered an increase in internal damage.
- (2) There was no difference in the distribution of the maximum amplitude values before and after the shear test, but there was a significant change in the AE energy. Therefore, the larger the maximum amplitude value at the time of the maximum AE energy value indicates, the higher the degree of damage.
- (3) When the degree of damage was evaluated for each sensor, the results obtained by the relationship between the maximum amplitude value and AE energy agreed with the results observed in the actual cross-section, suggesting that the relationship between the maximum amplitude value and AE energy is effective in evaluating the degree of damage.

8. Acknowledgments

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9. References

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