An Investigation on the Pre- and Post- Repair Vibrational Characteristics of Two Gymnasiums Damaged by the 2011 Great East Japan Earthquake

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Summary:
Microtremor measurements and earthquake response measurements were conducted on two gymnasiums damaged by the 2011 Great East Japan Earthquake. This paper investigates the change in predominant frequency between pre- and post-repair observed in the measurements. The predominant frequency of the microtremor measurements are higher than the earthquake response results. It is presumed that this is due to the amplitude dependence of the response characteristic. The measurements are compared with numerical simulations using a frame model conducted in a commercial structural analysis software. The simulated results show the same trend in the change of predominant frequency between pre- and post-repair as the measurements when the amplitude of vibration is small.

Keywords: Steel Gymnasium, Vibrational Characteristics, Predominant Frequency

1. INTRODUCTION

From a structural calculation perspective, when the braces of a purely braced frame structure lose their load-bearing capacity, the structure is assumed to have zero force resistance. However, it has been observed that some braced frame structures severely damaged by strong earthquake ground motion not only did not collapse but tolerated several aftershocks even after all of its load bearing braces had fractured. This is due to redundant load resisting factors which have not been accounted for. In order to understand this redundancy as well as the effect of repair on the restoration of the load bearing capacity, pre- and post-repair microtremor and earthquake response measurements of two gymnasiums damaged by the 2011 Great East Japan earthquake have been collected. These measurements are compared with numerical simulations using a frame model.

2. OVERVIEW OF THE GYMNASIUMS INVESTIGATED

The two investigated gymnasiums A and B, shown in Figure 1, are located in Sukagawa City, Fukushima. For both gymnasiums, the 1st story consists of a reinforced concrete moment resisting frame and the 2nd story a steel gable frame in the transverse direction and a steel braced frame in the longitudinal direction. Gymnasium A has rod bracing in 6 of its 14 longitudinal bays and gymnasium B equal leg single angle bracing in 4 of its 12 longitudinal bays. The structural elements used in both gymnasiums are described in Table 1. The emergency repair of gymnasium A was carried out in June, 2012 and the emergency repair of gymnasium B was carried out in February, 2012.

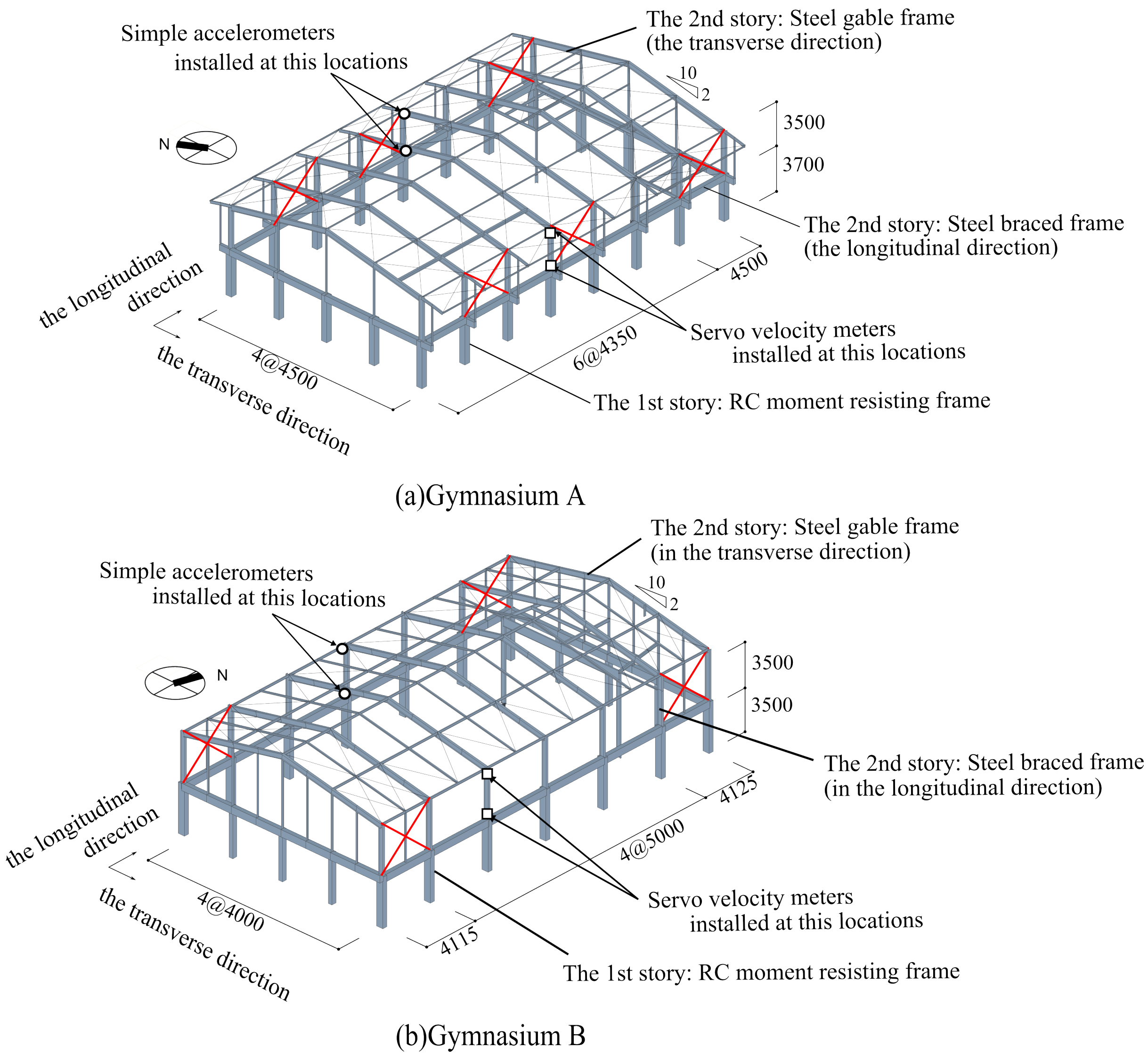


Figure 1. Diagram of the gymnasiums

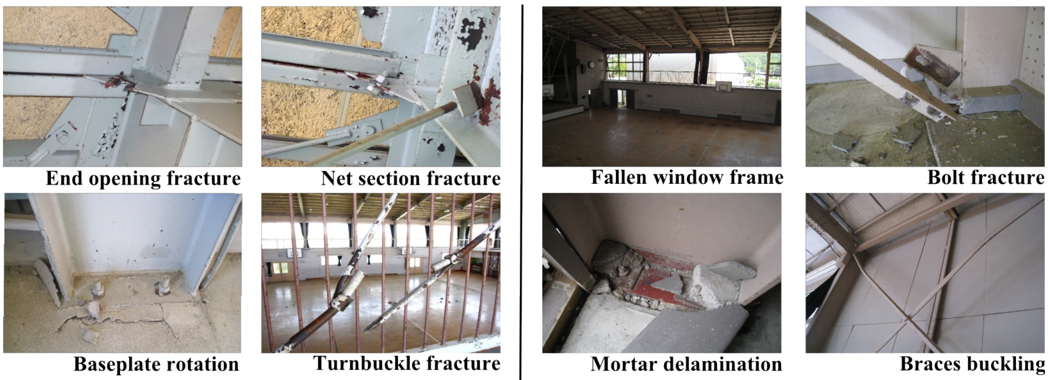
Table 1. Column, beam, and brace sizes of the gymnasiums

Elements	Gymnasium A	Gymnasium B
Column	H-396×199×7×11	H-350×175×7×11
Beam in the transverse direction	H-396×199×7×11	H-350×175×7×11
Beam in the longitudinal direction	2C-100×50×20×2.3	H-150×75×5×7
Vertical brace	φ19, tightened with a turnbuckle and connected to the gusset plate by regular bolts.	L-50×50×6

3. DAMAGE CAUSED BY THE 2011 GREAT EAST JAPAN EARTHQUAKE

Figure 2 shows the modes of failure observed in gymnasium A and B after the 2011 Great East Japan Earthquake. The braces of both gymnasiums were severely damaged. For gymnasium A, the turnbuckle fractured in 2 bays and the bolted brace-to-gusset connection suffered net section failure in

1 bay, end opening fracture in 1 bay, and bolt fracture in 2 bays. For gymnasium B, the bolt fractured in all 4 of its bays. The base plate of several columns to which the braces were fixed had slightly rotated for both gymnasiums. Damage such as yielding could not be observed in the roof bracing by simple visual inspection. As for non-structural damage, only the windows broke in gymnasium A while the window frame completely fell off in gymnasium B.



(a)Gymnasium A **(b)Gymnasium B**

Figure 2. Observed failure modes

4. EMERGENCY REPAIR

Figure 3 shows the emergency repair which was conducted on several of the damaged locations. In gymnasium A, the turnbuckles, gusset plates, and bolts of the rod braces which had fractured were replaced and the nuts corresponding to anchor bolts which had yielded and extended were tightened. The base plates which had rotated were enlarged and the number of anchor bolts were increased. In gymnasium B, the L-50×50×6 braces were replaced with L-65×65×6 braces, the mortar which had delaminated from the column base was repaired, and a new window frame was installed to replace the one that fell off.

(a)Gymnasium A **(b)Gymnasium B**

Figure 3. Emergency repair

5. VIBRATION MEASUREMENTS

5.1 OVERVIEW

Microtremor and earthquake response measurements were conducted on gymnasium A and B. Table 2 shows the dates and period of the measurements.

Servo velocity meters were installed at the locations designated with a □ in Figure 1 to measure the microtremor. The microtremor of gymnasium A was measured twice, once on May 25, 2011 (pre-repair) and once on July 9, 2011 (post-repair). Two 5 minute cycle measurements were conducted on each day. The microtremor of gymnasium B was measured twice, once on July 8, 2011 (pre-repair) and once on March 27, 2012 (post-repair). Three 5 minute cycle measurements were conducted on each day.

To obtain the dynamic response characteristics at large displacements under earthquake ground motions, accelerometers were installed at the locations designated with a ○ in Figure1 since July 9, 2011 in gymnasium A and July 8, 2011 in gymnasium B. The pre-repair earthquake measurements for gymnasium B could not be obtained because the repair had been performed before the measurement equipment was installed. In this paper, the earthquake response records from the installation date of the accelerometers to March 28, 2012 are considered. Table 3 shows the number of earthquakes measured in each gymnasium organized by their Japan Meteorological Agency (JMA) seismic intensity scale at the nearest observatory. Seismic measurements which do not have an intensity declared by JMA are categorized as undefined.

Table 2. The dates and periods of the measurement

Gymnasium	Microtremor measurements		Earthquake response measurements	
	Pre-repair	Post-repair	Pre-repair	Post-repair
A	May 25, 2011	July 9, 2011	-	From July 9, 2011 to March 28, 2011
B	July 8, 2011	March 27, 2012	From July 8, 2011 to December 22, 2011	From March 27, 2012 to March 28,2012

Table 3. Number of earthquakes obtained from the earthquake response measurements

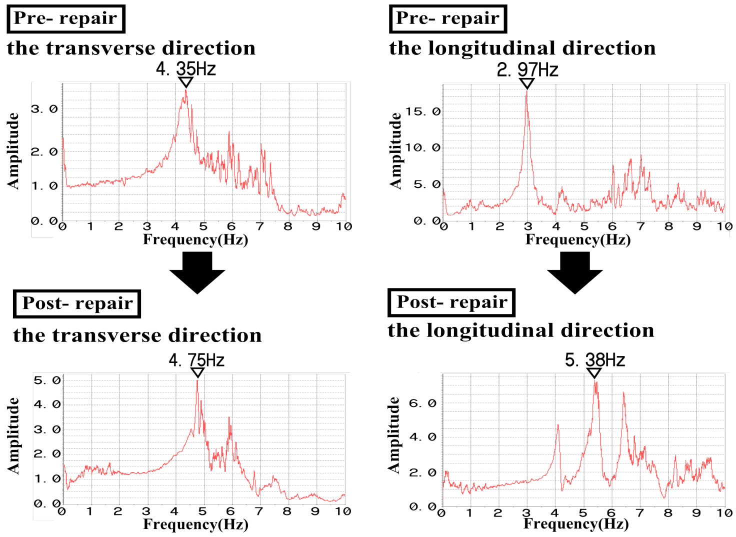
Seismic intensity	4	3	2	1	undefined	sum
Gymnasium A	0	6	12	13	11	42
Gymnasium B	3	5	18	4	2	32

5.2 MICROTREMOR MEASUREMENTS

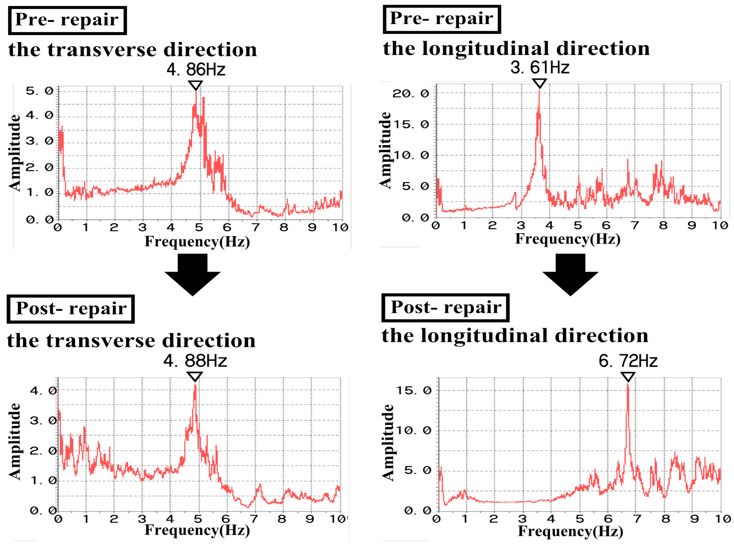
Fast-Fourier Transforms (FFT) were conducted to obtain the Fourier amplitude spectra from the measured microtremor response velocity time histories. The spectra were smoothed with a Hanning window of 0.1Hz, and used to obtain the transfer function between the column base and the column top. These are shown in Figure 4.

In the transverse direction, the pre-repair predominant frequency of gymnasium A is 4.35Hz, and the post-repair 4.75Hz. This small increase in frequency is assumed to be from the rise in stiffness caused by the enlargement of the base plate and increase in the number of anchor bolts. The pre-repair predominant frequency of gymnasium B is 4.86Hz and the post-repair 4.88Hz. In spite of having repaired the column base, the pre- and post- frequency has hardly changed. An increase in the weight of the gymnasium due to the installation of new window frames maybe a cause of this.

On the other hand, in the longitudinal (braced) direction the pre-repair predominant frequency of gymnasium A is 2.97Hz and the post-repair 5.38Hz. Those of gymnasium B are 3.61Hz and 6.72Hz, respectively. For both gymnasiums, the large increase in frequency is due to the repair of the vertical braces.



(a)Gymnasium A



(b)Gymnasium B

Figure 4. Response spectra from microtremer measurements

5.3 EARTHQUAKE RESPONSE MEASURMENTS

Figure 5 shows the transfer function spectra between the column base and the column top, calculated from the measured earthquake response time histories using the same method as in Section 5.2.

Figure 5(a) shows a post-repair response record of gymnasium A measured around 17:00 on October 10, 2011(the seismic intensity is 3). The predominant frequency is 4.00Hz in the transverse direction and 4.39Hz in the longitudinal direction. These values are smaller than the corresponding values obtained from the microtremor measurement results.

Figure 5(b) shows a pre-repair response record of gymnasium B measured around 11:45 on September 10, 2011(the seismic intensity is 2) and a post-repair response record measured around 20:00 on March 27, 2012(the seismic intensity is 2). These two records have been selected for comparison since they have a similar maximum acceleration at the column base. The predominant frequency in the transverse direction has increased slightly from 3.06Hz to 3.70Hz due to the repair. This trend was not observed in the microtremor measurement results. On the other hand, the predominant frequency in the longitudinal direction has increased considerably from 1.38Hz to 6.21Hz as in the microtremor measurement results.

One should note that the differences between the predominant frequencies of the microtremor and earthquake response results in each direction are smaller after the repair. Additionally, like gymnasium A, the frequencies are smaller than the corresponding microtremor measurement results.

The claims made here should be interpreted with care since there is a nonlinear dependence of the response characteristics on the amplitude and may not hold true in general.

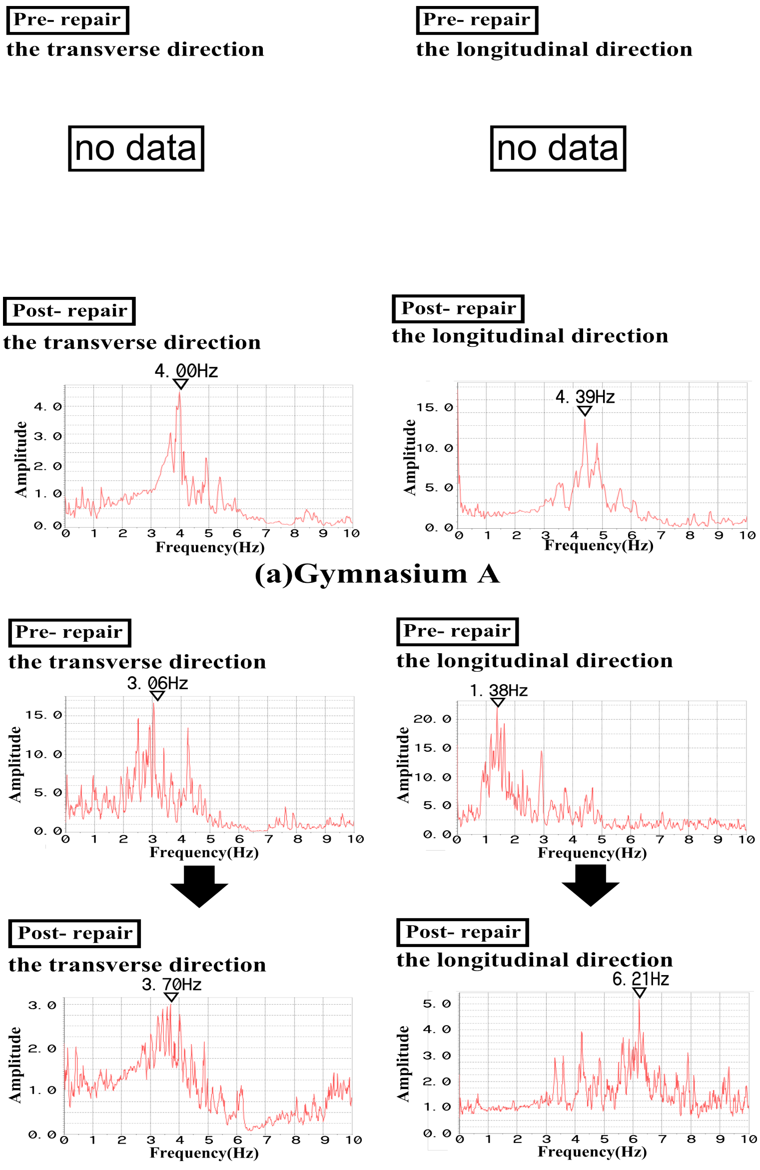


Figure 5. Response spectra from earthquake response measurements

6. FRAME MODEL ANALYSIS

6.1 ANALYSIS MODEL

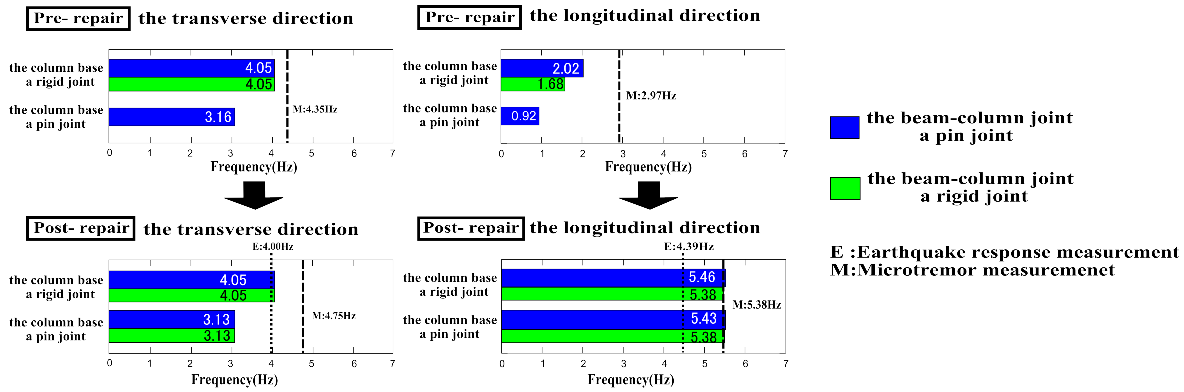
The dimensions and details of the frame model are based on the design plans at the time of construction. The mass distribution has also been deduced from the plans with the total weight of the roof equal to 208kN in gymnasium A and 139kN in gymnasium B.

The beam-end joints in the longitudinal (braced) direction are designed as a pin joint. Despite this fact, the building did not collapse even after all of the braces had fractured. This as well as the fact that significant sliding in the pin joint was not observed suggests that the joint has some rotational stiffness. Thus in the analysis, two cases were tested: one in which the joints are assumed rigid, and one in which the joints are assumed to be pinned. As for the column base, one can make an argument similar to the case of the beam-end joints. The column base is a pin joint by design but actually has some rotational stiffness. Thus in the analysis, two cases were tested: one in which the bases are assumed fixed, and one in which the bases are assumed to be pinned. In total, 4 variations of the frame model are analyzed.

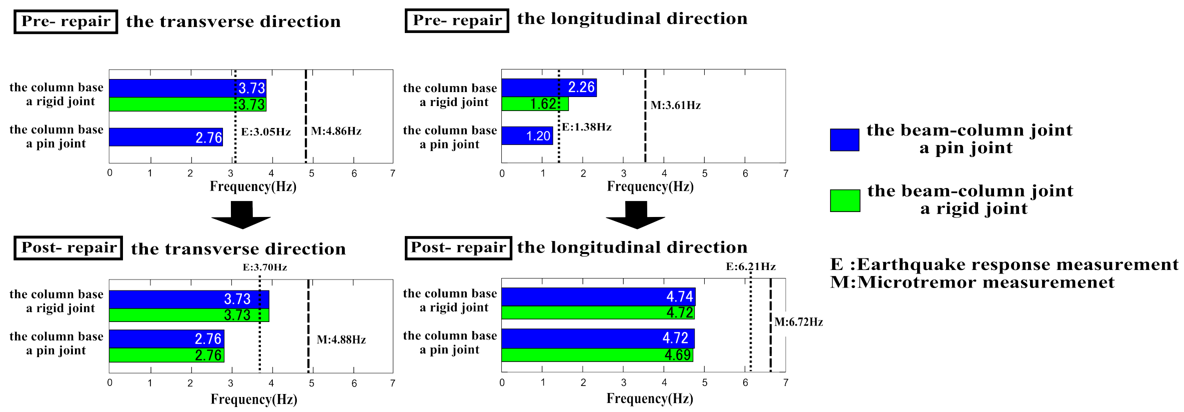
6.2 COMPARISON BETWEEN THE NUMERICAL RESULTS AND RESPONSE MEASUREMENTS

An eigenvalue analysis was conducted in a commercial structural analysis software. From the natural vibration modes obtained from the analysis, the fundamental modes in the transverse and longitudinal direction were chosen through visual inspection based on the criteria that they be probable modes.

Figure 6 shows the natural frequencies of vibration. The horizontal axis is the value of the frequency, and the vertical axis the analysis condition. Moreover, the thick dotted line shows the microtremor measurement results and the thin dotted line the earthquake response measurement results. In both gymnasiums, the change in natural frequency between pre- and post-repair is large in the longitudinal direction but small in the transverse direction. This is of course because the restoration only increased the stiffness in the longitudinal direction by inserting vertical braces. Since the eigenvalue analysis is a linear analysis and only considers the behaviour at small vibrations, the numerical results are only comparable with the microtremor measurements. The reason why the numerical frequencies are larger than the microtremor measurements may be because the mass was underestimated in the analysis due to neglect of the weight of the components other than the roof of the gymnasium.



(a)Gymnasium A



(b)Gymnasium B

Figure 6. Comparison between the numerical results and measurements

7. CONCLUSION

Microtremor measurements and earthquake response measurements on two gymnasiums damaged by the 2011 Great East Japan Earthquake were conducted before and after the repair. The measurement results were compared with numerical simulations using a frame model.

The microtremor measurement results revealed that even though the repair was an emergency measure, it was capable of greatly increasing the stiffness in the longitudinal (braced) direction of both gymnasiums and the numerical results show the same trend.

For gymnasium B, the predominant frequency in the transverse direction from the earthquake response measurements slightly increased between the pre- and post-repair but this trend was not observed in the microtremor measurements. And the predominant frequency of the microtremor measurements approach to the earthquake response measurements after repair. This is presumed that there is the amplitude dependence of the response characteristic and the amplitude dependence decreases by the repair.

To collect and analysis different amplitude data, it is necessary to study how a nonlinearity from the amplitude dependence can be evaluated.

REFERENCES

Japan Meteorological Agency (JMA). http://www.jma.go.jp/jma/index.html
Strong-motion Seismograph Networks(K-NET,KiK-net). http://www.kyoshin.bosai.go.jp/kyoshin/