



EXPERIMENTAL MODAL ANALYSIS USING SHAKE TABLE OF SMALL-SCALED GYMNASIUM WITH SIMULATED DAMAGES

J. Fujiwara⁽¹⁾, A. Kishida⁽²⁾, T. Aoki⁽³⁾, R. Enokida⁽⁴⁾ and K. Kajiwara⁽⁵⁾

⁽¹⁾ Senior Research Fellow, Earthquake Disaster Mitigation Research Division, NIED, Japan, j.fujiwara@bosai.go.jp

⁽²⁾ Senior Research Fellow, Earthquake Disaster Mitigation Research Division, NIED, Japan, akiko_kishida@bosai.go.jp

⁽³⁾ Research Fellow, Earthquake Disaster Mitigation Research Division, NIED, Japan, taoki@bosai.go.jp

⁽⁴⁾ Associate Professor, International Research Institute of Disaster Science, Tohoku University, Japan

(Visiting research fellow, NIED, Japan), enokida@irides.tohoku.ac.jp

⁽⁵⁾ Manager, Earthquake Disaster Mitigation Research Division, NIED, Japan, kaji@bosai.go.jp

Abstract

Many school gymnasiums in Japan are expected to be used as evacuation shelters, when natural disasters, for examples earthquakes, typhoons, concentrated heavy rains and so on, occur. In case of earthquake, school gymnasiums themselves may have damage. By 2011 Tohoku earthquake, more than 140 gymnasiums had damages due to the earthquake^[1]. It is important to judge immediately after earthquakes whether gymnasiums can be used as shelters.

Many studies have been conducted to measure and analyze response accelerations, displacements and so on, and detect locations and degrees of structural damages. This kind of technique is called as structural health monitoring. In the field of building structures, structures are mostly modeled as mass - shear spring model or similar. It is known that seismic behaviors of large-spanned structures such as gymnasiums are totally different from general building structures. Thus, it is difficult to simplify large-spanned structures to conventional models. Hamamoto *et. al.* proposed a damage detection method for spatial truss structures. In that study, however, they focused only on roof structures.

Our final goal of this research is to develop a structural health monitoring method for gymnasiums. As the first step, we conduct an experimental modal analysis of small-scaled gymnasium. The testing specimen for full-scale shake table test conducted at E-Defense in 2014^[3] is the original gymnasium model and reduced to a small-scaled model. The dimensional similarity is 1 / 4. The weight is adjusted so that the major frequencies of the model follow similarity rule. The excitation is by the large shaking table held by NIED, Tsukuba, Japan. Four kind of measured ground motion, Kobe, El Centro, Hachinohe and Tomakomai, are scaled to JMA seismic intensity scale 2 - 4, and input to the small-scaled model. Response accelerations are measured and modal parameters such as frequencies and vibration modes are identified. In addition, shake table tests and modal parameter identifications of the small scaled model with simulated damages are also conducted. Structural damages are simulated by detaching joint plates or cross bracings. It is discussed from the result whether modal parameters are changed due to simulated damages and locations of damages can be estimated from the changes.

Keywords: Gymnasium, Structural health monitoring, Experimental modal analysis, Shake table test, Simulated damage



1. Introduction

Many school gymnasiums in Japan are expected to be used as evacuation shelters, when natural disasters, for examples earthquakes, typhoons, concentrated heavy rains and so on, occur. In case of earthquake, school gymnasiums themselves may have damage. By 2011 Tohoku earthquake, more than 140 gymnasiums had damages due to the earthquake^[1]. It is important to judge immediately after earthquakes whether gymnasiums can be used as shelters.

Many studies have been conducted to measure and analyze response accelerations, displacements and so on, and detect locations and degrees of structural damages. This kind of technique is called as structural health monitoring. In the field of building structures, structures are mostly modeled as mass - shear spring model or similar. It is known that seismic behaviors of large-spanned structures such as gymnasiums are totally different from general building structures. Thus, it is difficult to simplify large-spanned structures to conventional models. Hamamoto et. al^[2]. proposed a damage detection method for spatial truss structures. In that study, however, they focused only on roof structures.

Our final goal of this research is to develop a structural health monitoring method for gymnasiums. As the first step, we conduct an experimental modal analysis of small-scaled gymnasium. The testing specimen for full-scale shake table test conducted at E-Defense in 2014^[3] is the original gymnasium model and reduced to a small-scaled model. The dimensional similarity is 1 / 4. The weight is adjusted so that the major frequencies of the model follow similarity rule. The excitation is by the large shaking table held by NIED, Tsukuba, Japan. Four kind of measured ground motion, Kobe, El Centro, Hachinohe and Tomakomai, are scaled to JMA seismic intensity scale 2 - 4, and input to the small-scaled model. Response accelerations are measured and modal parameters such as frequencies and vibration modes are identified. In addition, shake table tests and modal parameter identifications of the small scaled model with simulated damages are also conducted. Structural damages are simulated by detaching joint plates or cross bracings. It is discussed from the result whether modal parameters are changed due to simulated damages and locations of damages can be estimated from the changes.

2. Plan of shake-table test

A shake-table test is conducted at Large Scale Earthquake Simulator, which is a uniaxial shake-table held by National Research Institute for Earth Science and Disaster Resilience (NIED), Tsukuba, Japan.

2.1 Test specimen

The gymnasium model, which is the test specimen of full-scale shake-table test conducted at E-Defense in 2014^[3], is reduced in size to 1/4. The overview of target structure is illustrated in Fig. 1. The section profiles of main frame (columns and girders) and braces are an I-beam of width 100, height 100, web thickness 6 and flange thickness 8 mm, and an angle of width 50 and thickness 4 mm, respectively. The specimen is bolted to the foundation beam, and the foundation beam is bolted to the shake-table. To induce span- and longitudinal direction vibrations simultaneously, the test specimen is inclined to the excitation direction (see Fig. 2).

Here, it is assumed that the elastic modulus and density of scaled model are the same as the original model. Therefore, the similarity rule is summarized as shown in Table 1. The scale in size is denoted by λ . The values in parentheses in Table 1 indicate the actual values of the scaled specimen. Since it is difficult to choose standard steel members with exactly similar section profile, here some steel weights are added so that the fundamental frequencies in span, longitudinal and vertical directions follow the similarity rule.

To investigate how modal parameters change due to structural damage, it is simulated by detaching flange plates at I-beam joints as shown in Fig. 3. The positions of simulated damages are shown as a triangle in Fig. 4.

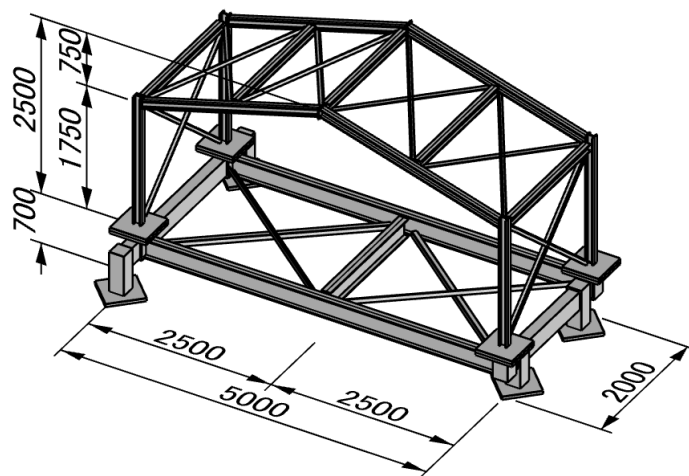


Fig. 1 – Overview of test specimen

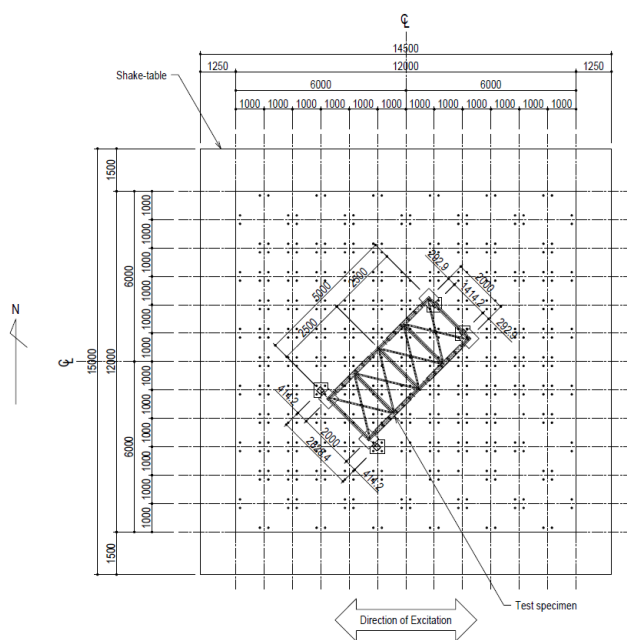


Fig. 2 – Layout of test specimen

Table 1 – Similarity rule

Length	λ (1/4)	Acceleration	$1 / \lambda$ (4)
Elastic modulus	1 (1)	Mass	λ^3 (1/64)
Density	1 (1)	Force	λ^2 (1/16)
Time	λ (1/4)	Stiffness	λ (1/4)
Velocity	1 (1)	Stress	1 (1)

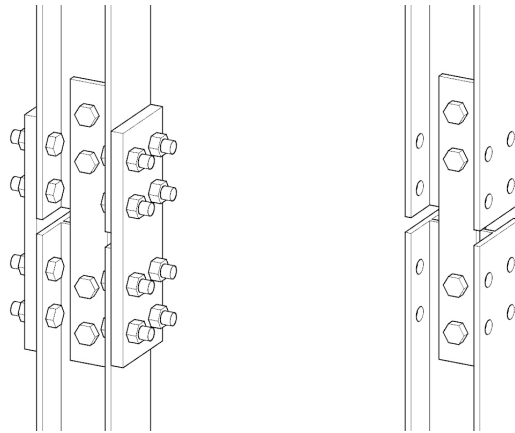


Fig. 3 – Simulated damage (left: not damaged, right: damaged)

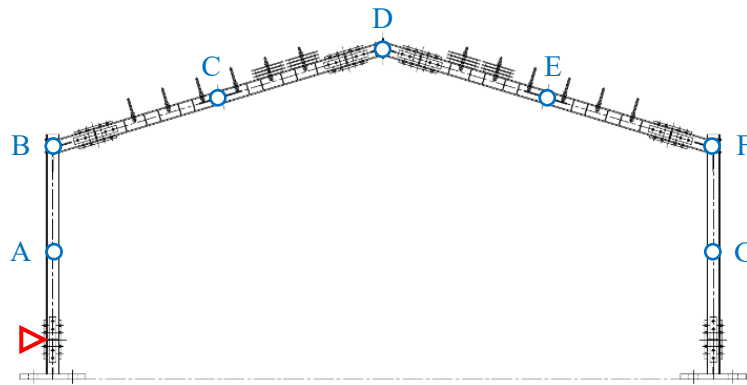


Fig. 4 – Positions of simulated damage (triangle) and accelerometers (circles)

2.2 Measurement

The acceleration of shake-table and response accelerations at positions A to G shown in Fig. 3 are measured using triaxial wireless MEMS accelerometers. The sampling frequency is 1000 Hz. No filter is applied in the measurement.

2.3 Excitation

In the shake-table test, four observed earthquake ground motions, JMA Kobe NS^[4], El Centro NS^[5], Hachinohe NS^[5] and K-Net Tomakomai NS^[6], which was observed in 2003 Tokachi earthquake at K-NET Tomakomai site (HKD129), are considered. They are scaled so that the JMA seismic intensity are equivalent to 2.0 and 4.0. After the adjustment of seismic intensities, they are scaled in time- and acceleration axes according to the similarity rule shown in Table 1. The acceleration time-histories and response spectra ($h=0.05$) are plotted in Figs. 5 - 8. In addition, a random excitation, the band of which is from 0.3 to 30 Hz, is also used. The Excitations are listed in Table 2.

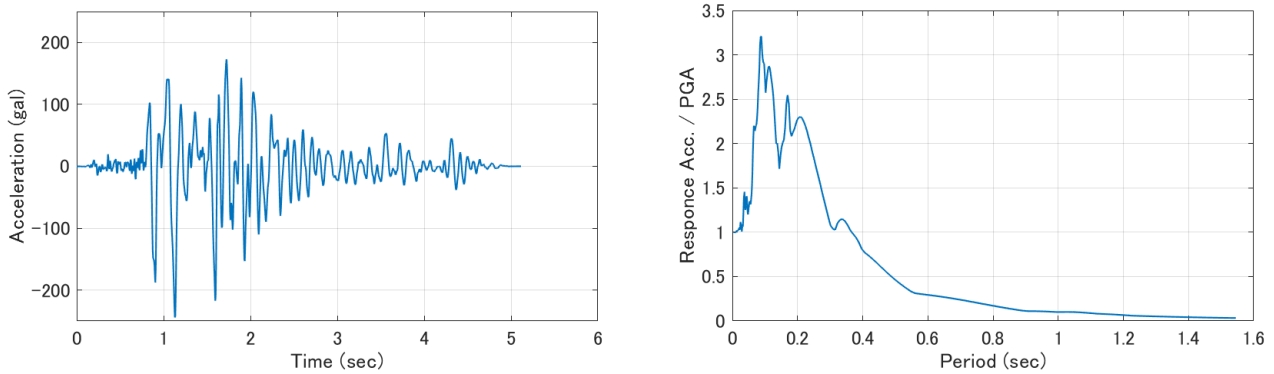


Fig. 5 – Time-history of acceleration (left) and response spectrum (right, $h = 0.05$) of JMA Kobe NS adjusted to JMA intensity 4.0, and scaled according to similarity rule)

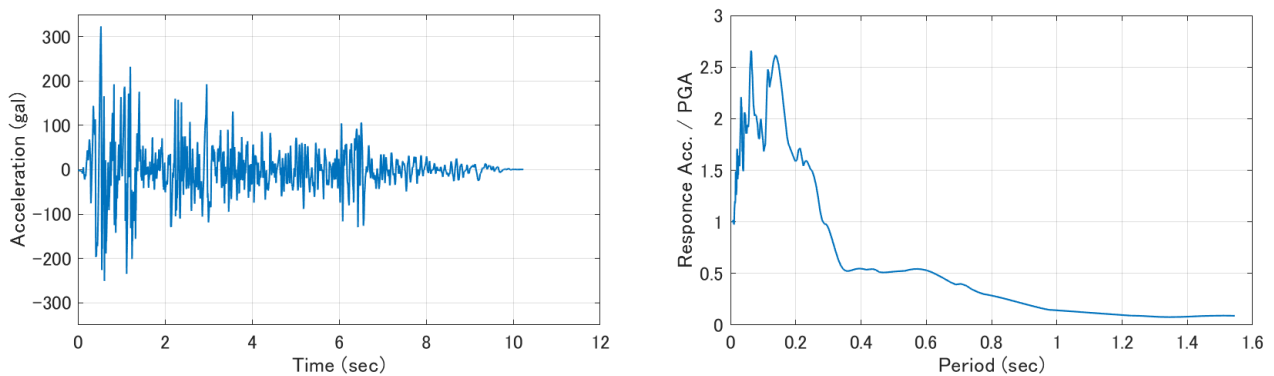


Fig. 6 – Time-history of acceleration (left) and response spectrum (right, $h = 0.05$) of El Centro NS (adjusted to JMA intensity 4.0, and scaled according to similarity rule)

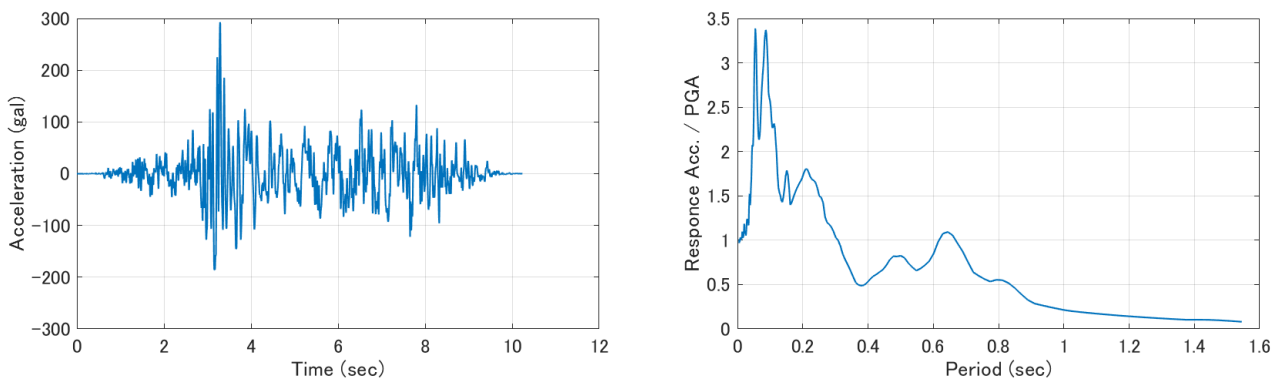


Fig. 7 – Time-history of acceleration (left) and response spectrum (right, $h = 0.05$) of Hachinohe NS (adjusted to JMA intensity 4.0, and scaled according to similarity rule)

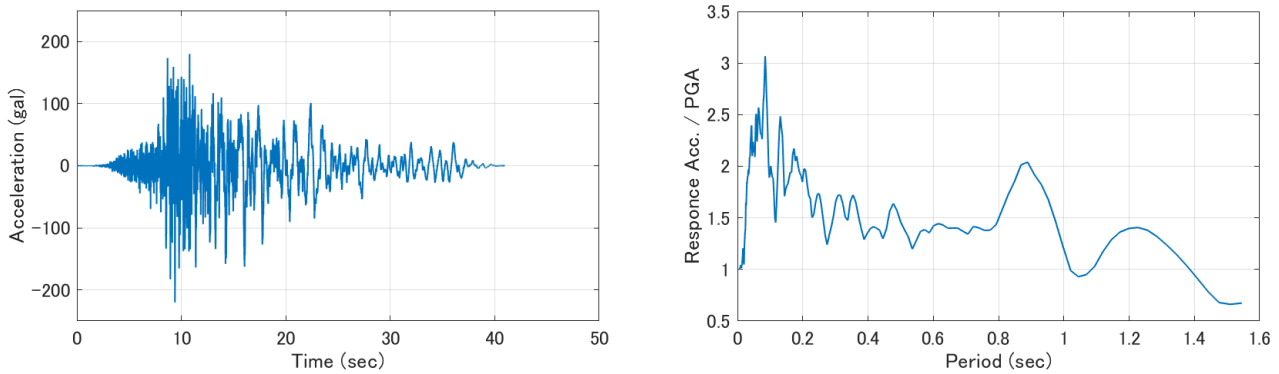


Fig. 8 – Time-history of acceleration (left) and response spectrum (right, $h=0.05$) of K-NET Tomakomai NS (adjusted to JMA intensity 4.0, and scaled according to similarity rule)

Table 2 – List of excitations

No	Damage	Seismic wave	Intensity
1	No	Random	150 gal
2	No	Kobe NS	4.0
3	No	El Centro NS	4.0
4	No	Hachinohe NS	4.0
5	No	Tomakomai NS	4.0
6	No	Kobe NS	2.0
7	No	El Centro NS	2.0
8	No	Hachinohe NS	2.0
9	No	Tomakomai NS	2.0
10	Yes	Random	150 gal
11	Yes	Kobe NS	4.0
12	Yes	El Centro NS	4.0
13	Yes	Hachinohe NS	4.0
14	Yes	Tomakomai NS	4.0



3. Result of shake-table test

Transfer functions under the excitation listed in Table 2 are calculated. Here, the input is the acceleration of shake-table in span direction, and the outputs are the acceleration responses in span-, longitudinal and vertical directions at roof top (accelerometer D shown in Fig. 4). The transfer functions are plotted in Figs. 9 – 22 and the obtained fundamental frequencies are summarized in Table 3.

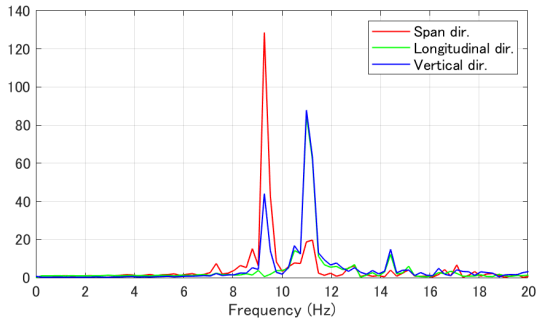


Fig. 9 – Transfer function, Not damaged, Random excitation

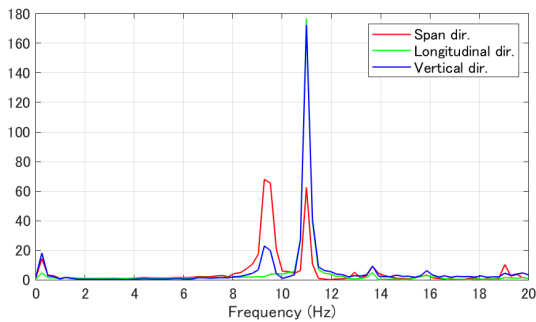


Fig. 10 – Transfer function, Not damaged, JMA Kobe NS, Intensity 4.0

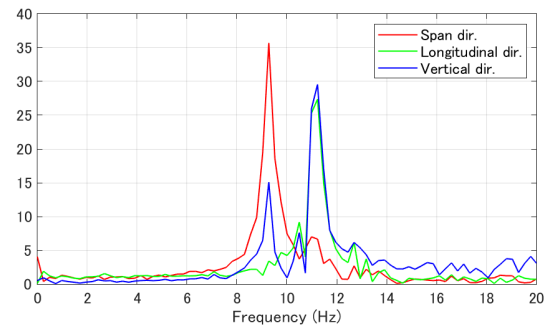


Fig. 11 – Transfer function, Not damaged, El Centro NS, Intensity 4.0

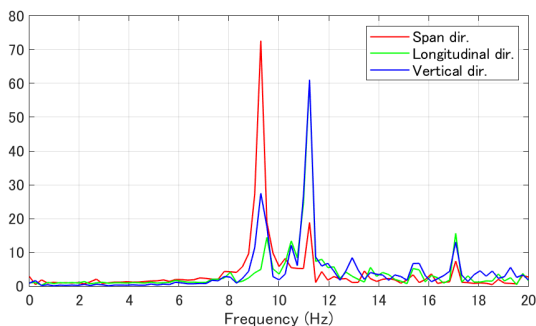


Fig. 12 – Transfer function, Not damaged, Hachinohe NS, Intensity 4.0

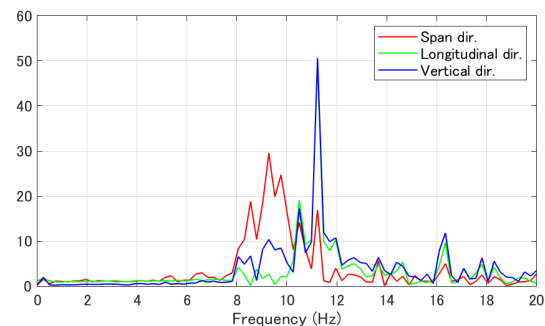


Fig. 13 – Transfer function, Not damaged, K-NET Tomakomai NS, Intensity 4.0

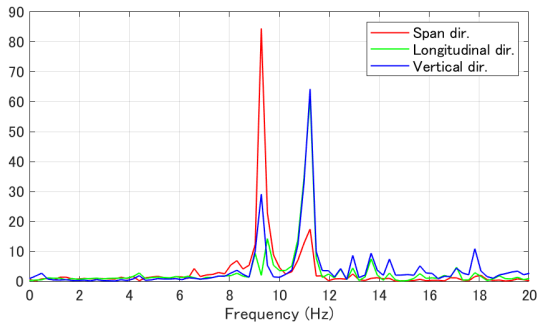


Fig. 14 – Transfer function, Not damaged, JMA Kobe NS, Intensity 2.0

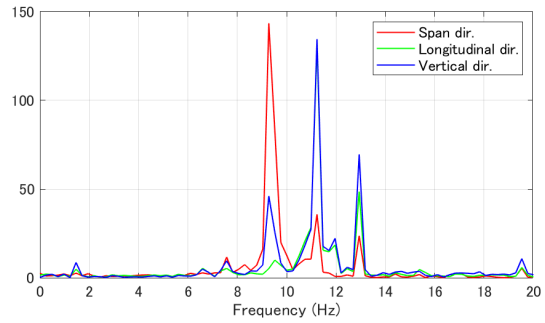


Fig. 15 – Transfer function, Not damaged, El Centro NS, Intensity 2.0

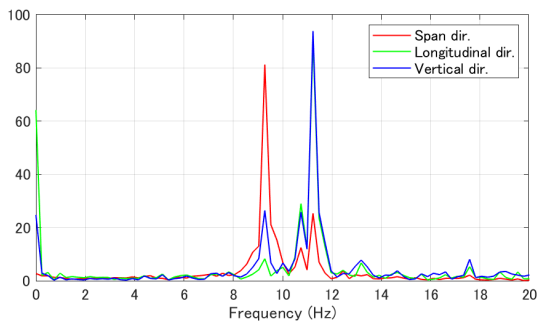


Fig. 16 – Transfer function, Not damaged, Hachinohe NS, Intensity 2.0

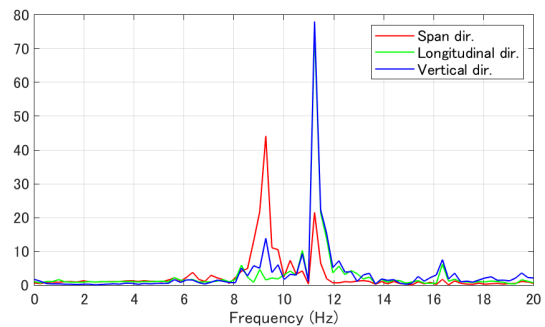


Fig. 17 – Transfer function, Not damaged, K-NET Tomakomai NS, Intensity 2.0

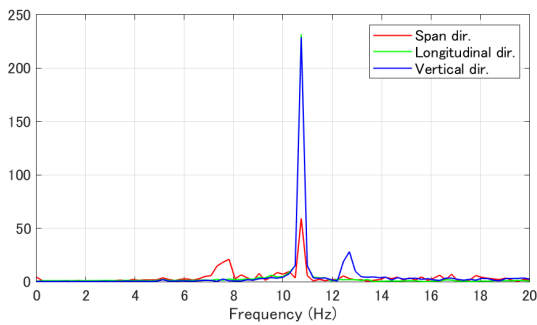


Fig. 18 – Transfer function, Damaged, Random excitation

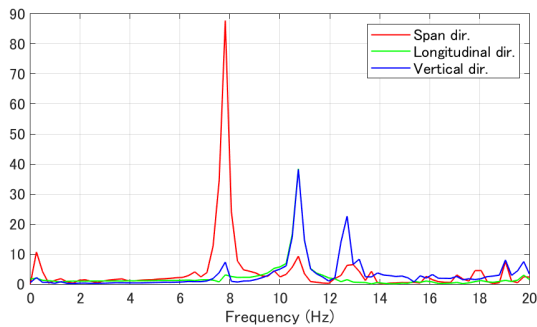


Fig. 19 – Transfer function, Damaged, JMA Kobe NS, Intensity 4.0

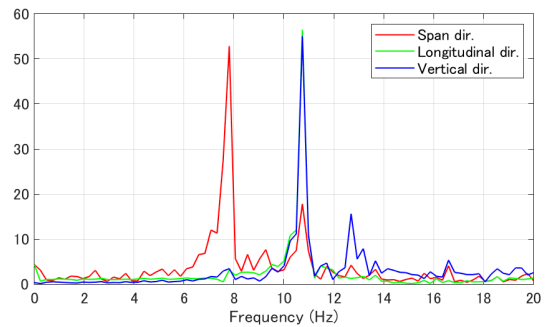


Fig. 20 – Transfer function, Damaged, El Centro NS, Intensity 4.0

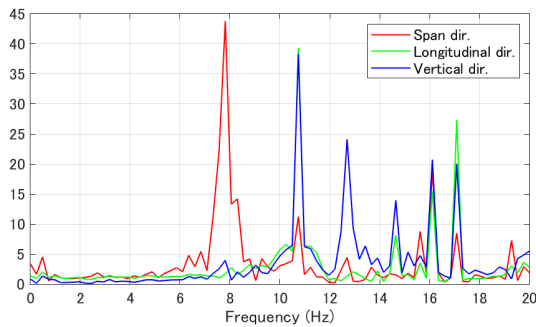


Fig. 21 – Transfer function, Damaged, Hachinohe NS, Intensity 4.0

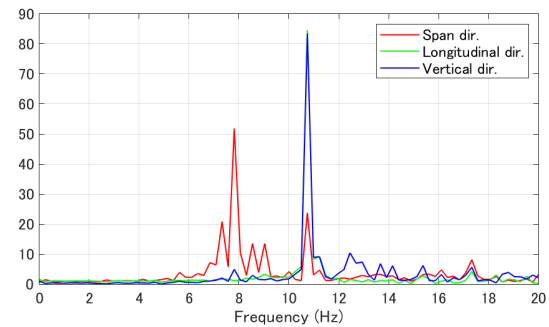


Fig. 22 – Transfer function, Damaged, K-NET Tomakomai NS, Intensity 4.0

Table 3 – Identified fundamental frequencies in span-, longitudinal and vertical directions

No	Damage	Seismic wave	Intensity	Frequency in span dir. (Hz)	Frequency in longi. dir. (Hz)	Frequency in ver. dir. (Hz)
1	No	Random	150 gal	9.28	11.0	---
2	No	Kobe	4.0	9.28	11.0	---
3	No	El Centro	4.0	9.28	11.2	---
4	No	Hachinohe	4.0	9.28	11.2	---
5	No	Tomakomai	4.0	9.28	11.2	---
6	No	Kobe	2.0	9.28	11.2	---
7	No	El Centro	2.0	9.28	11.2	---
8	No	Hachinohe	2.0	9.28	11.2	12.9
9	No	Tomakomai	2.0	9.28	11.2	---
10	Yes	Random	150 gal	10.7	10.7	---
11	Yes	Kobe	4.0	7.81	10.7	12.7
12	Yes	El Centro	4.0	7.81	10.7	12.7
13	Yes	Hachinohe	4.0	7.81	10.7	12.7
14	Yes	Tomakomai	4.0	7.81	10.7	---

From Figs. 9 – 17 and Table 3, the fundamental frequencies in span- and longitudinal directions have been identified, independently of type and intensity of excitations. In some cases, however, the fundamental frequency in vertical direction has not been obtained. The fundamental frequency of original gymnasium model^[3] in span-, longitudinal and vertical directions are 2.51, 2.72, 2.98 Hz, respectively. The identified frequencies from this shake-table test correspond to the ideal values when the scaled model exactly follows the similarity rule.



From Figs. 18 – 22, the fundamental frequencies of damaged model have been also obtained stably irrespective of the excitation. The damage around column base have effected only on the span-directional vibration. This tendency is the same as the result of hammering test conducted by the authors^[7].

4. Conclusions

A shake-table test of scaled gymnasium model has been conducted. From the measured accelerations, the fundamental frequencies in span, longitudinal and vertical directions have been identified. The target structure is a 1/4 scaled model of test specimen of a full-scale shake-table test conducted at E-Defense^[3]. To investigate how structural damage can effect on the dynamic characteristics and if the change can be detected, a shake-table test with a simulated damage has also been carried out. Several types and intensities of excitations are considered. The result is summarized as follows:

1. The fundamental frequencies in span- and longitudinal directions have been identified, independently of type and intensity of excitations.
2. In some cases, however, the fundamental frequency in vertical direction has not been obtained.
3. The identified frequencies from this shake-table test correspond to the frequencies of original model.
4. The fundamental frequencies of damaged model have been also obtained stably irrespective of the excitation.
5. The simulated damage around column base have effected only on the span-directional vibration.

Acknowledgements

This research has been partially supported by JSPS KAKENHI No. JP17K06666.

References

- [1] Yamada S., Matsumoto Y., Iyama J., Ikago K., Kishiki S., Ikenaga M., Shimada Y., Koyama T., Minami S. and Asada H., “Reconnaissance of damaged steel school buildings due to the 2011 Tohoku earthquake, Outline of the reconnaissance”, *AIJ Journal of Technology and Design*, Vol. 18, No. 40: 935-940, 2012. (in Japanese)
- [2] Hammoto T., Kondo I. and Kanno R., “Damage detection of spatial structures using system identification approach”, *Journal of Structural Engineering*, Vol. 40B, pp. 189-196, 1994.3 (in Japanese)
- [3] Sasaki T., Aoi A., Kajiwara K., Tagawa H. and Sato D., “Collapse mechanism of wide-area suspended ceiling in school gymnasium”, *Proceedings of the IASS Annual Symposium 2016 “Spatial Structures in the 21st Century”*, Tokyo, Japan, 2016.
- [4] Japan Meteorological Agency, Strong motions in 1995 Kobe earthquake, https://www.data.jma.go.jp/svd/eqev/data/kyoshin/jishin/hyogo_nanbu/index.html, (in Japanese, accessed 2019.04.19)
- [5] Building Performance Standardization Association, <https://www.seinokyo.jp/jsh/top/>, (in Japanese, accessed 2019.04.12)
- [6] National Research Institute for Earth Science and Disaster Resilience, Strong-Motion Seismograph Networks (K-NET, KiK-net), <http://www.kyoshin.bosai.go.jp/>, (accessed 2019.04.15)
- [7] J. Fujiwara and K. Kajiwara, Experimental Modal Analysis and Damage Estimation of Large-Span Structures by Hammering, *Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, Structure I*, pp.805-806, Sep., 2019 (in Japanese)