PERFORMANCE EVALUATION OF A BUILDING STRUCTURE WITH NONLINEAR DAMPERS UNDER STRONG GROUND MOTION ON MARCH 11, 2011

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Abstract

This paper reports the earthquake data obtained from one of the facilities on the campus of Tokyo City University. The author started monitoring the response of the target building structure with a purpose of identifying its damping performance since it was constructed in 2004. There had been accumulated enough data to identify the damping factor and natural frequency of the system with nonlinear damping devices installed until Tohoku district experienced the major earthquake on March 11 in 2011. As was expected the monitoring system started recording the response of the structure as well as the ground motion. We have several other data obtained on the occasion of post quakes ever since then. These data enable us to compare the damping performance of the structure before and after the event. Especially the performance during the major quake is of first importance, and we eventually evaluated it. There are three issues discussed in this paper. The first one is the identification of the system: the network monitoring system successfully worked and can be used as a powerful tool to evaluate the performance of structures. The second one is how to design a damping structure: the nonlinear damping devices, compressive dampers, were thought to be equivalent to linear dampers when feedback algorithm was taken into consideration during the design phase of the project. The last issue discussed in this paper is how to optimize the installation of damping devices and how to estimate the performance as precise as possible even before their actual installation.

Introduction

In this paper, the author reports the damping performance associated with one of the facilities on the campus of Tokyo City University. The project was a complex building composed of a student dining hall and a gymnasium connected with an annex structure by way of damping devices. The structure was designed by the author's research team and constructed in 2004. It has a unique damping system so that it has been expected to have better earthquake resistance behaviour. The dampers have highly nonlinear dynamic characteristics that generate no tensile forces at all but only compressive reactions. The theoretically expected damping performance is roughly 0.05 to 0.10 in terms of damping factor with respect to the first modal vibration. The theoretical procedure for the damping augmentation in the design phase of the project was reported and published (Nishimura, 4th WCSC, 2006) and briefly reviewed in this paper. The damping evaluation procedure in the general theory was also reported by Nishimura at the previous *U.S.-Japan Workshop on Improvement of Structural Design and Construction Practices* in 2010. The unique feature of the damping system motivated the author to implement a monitoring system into the complex building system so that the dynamic properties such as modal frequencies and damping factors can be identified and compared with the analytical estimation conducted in the design phase. Shortly after the monitoring system started operation we successfully obtained response vibrations of the third floor of the structure as well as the ground motion. Ever since then we have accumulated many data on occasion of small earthquake events until March 11 in 2011 when Tohoku district experienced a major earthquake with magnitude 9.0. The monitoring system worked well and recorded important data that enable us to assess the damping performance of the structure. The long term observation makes it possible to certify the design procedure of passive damper installation and the actual earthquake resistance performance of the damper system.

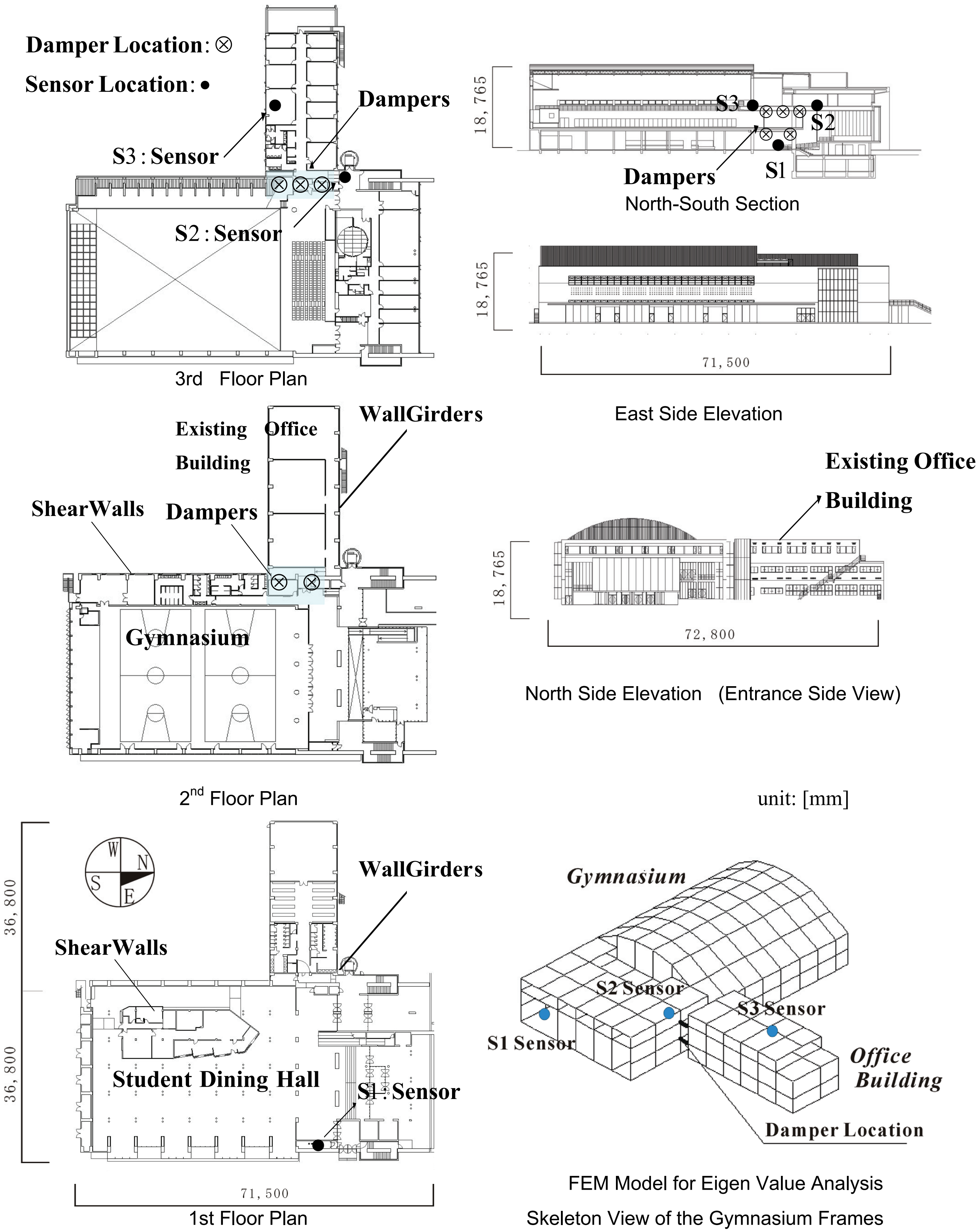


Figure 1. Sensor and Damper Locations

Table 1 Dynamic Characteristics of Linear Dampers and Compressive Dampers

System 1	$\omega_1 =$ 25.2 rad/sec; $k_1 =$ 3000 KN/mm; $m_1 = 4.7 \times 10^6$ kg
System 2	$\omega_2 =$ 70.0 rad/sec; $k_2 =$ 3000 KN/mm; $m_2 = 6.0 \times 10^5$ kg
Damper parameters	$k_d =$ 800 KN/mm; $\omega_\infty =$ 28.2rad/s; $\omega_{opt} =$ 26.7 rad/s; $k_{opt} =$ 400KN/mm
Linear Damper	$c_{opt} =$ 32.0 KN sec/mm; $\eta_{eq} = 0.055$
Compressive Damper	$c_N =$ 60 KN sec/mm (For compression only.); $k_d =$ 800 KN/mm

Table 2 Basic Dynamic Properties of Gymnasium and Office Building

Gymnasium Properties (Preliminary Study)	4th FL. 104.9m^2, 3rd FL. 1732.9 m^2 2nd FL. 2725.8m^2, 1st FL. 2633.3 m^2	Effective mass at 3rd FL. $m_1 = 4.7 \times 10^6$ kg Frequency $\omega_1 = 25.2$ rad/sec
Office Properties (Preliminary Study)	3rd FL. 430.9 m^2, 2nd FL. 518.3 m^2 1st FL. 518.3 m^2	Effective mass at 3rd FL. $m_2 = 6.0 \times 10^5$ kg Frequency $\omega_2 = 70.0$ rad/sec
Damper Specification	Damper stiffness 200KN/mm per one damper. Damping coefficient 15 KN sec/mm per one damper.	

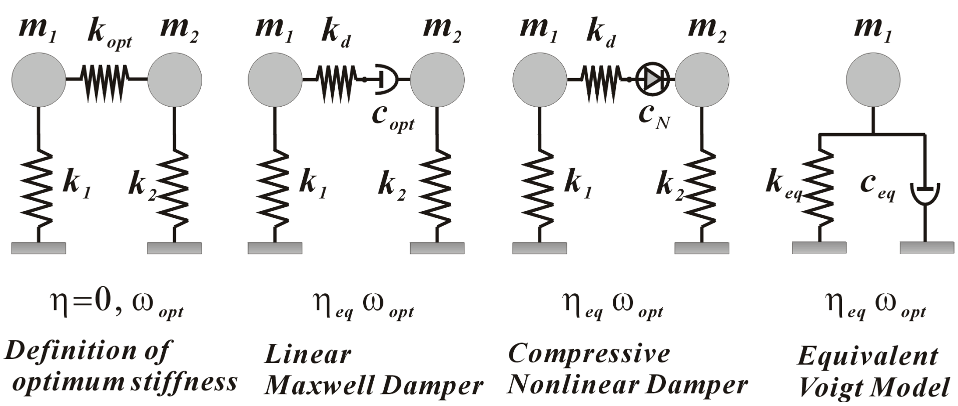


Figure 2. Mathematical models for the nonlinear damper devices in EW direction

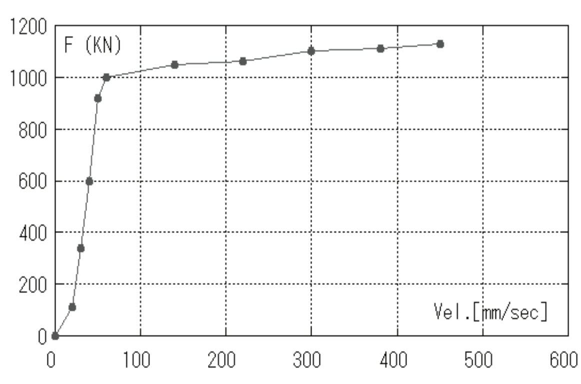


Figure 3. Test results of damper coefficient

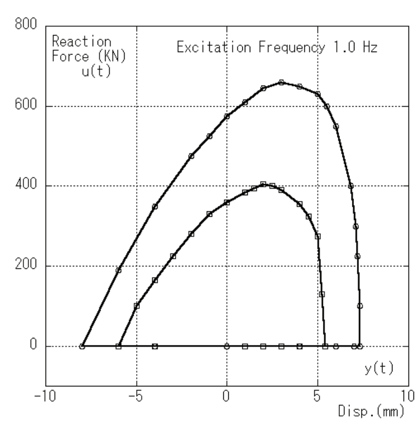
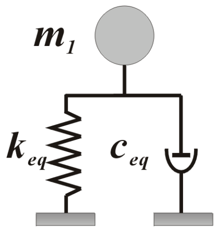


Figure 4. Cyclic loading test results



$\eta_{eq} = 0.06$

$\omega_{opt} = 26.7$ rad/s

Figure 5. Equivalent Voigt Model *Photo 1 Accelerometers* *Photo 2 Network data logger*

The dynamic property of the nonlinear dampers

We used a simple model in Figure 2 for designing the damper specification. Even though a better performance is roughly expected, carefully selecting their damping coefficient is still the key factor for achieving the best performance of the devices. According to the preliminary study, the appropriate compressive damping coefficient for one device should be around 15KN sec/mm, which is certified in Figure 3 that shows the dynamic test result before shipping and installation. The compressive damper characteristic is clearly seen in Figure 4, which is the result of dynamic loading tests with 1.0 Hz frequency.

Data acquisition system

The purpose of the structure health monitoring that the author adopted for this project is to evaluate the performance of building structures with compressive dampers. Special attention is paid to nonlinearity of the damping devices, because preliminary study showed that local nonlinearity would disappear naturally but change the global dynamics in an average sense. It is extremely difficult even impossible to identify the mathematical model that could explain cause and effect, but it would be much easier to create a mathematical model that could explain the observed phenomena. Both of them have clearly different objectives and purposes. In this project, the author started observing the earthquake response dynamics of the structure to create a model that could explain the phenomena not the cause-and-effect. The local area network sensor system is shown in photo 1 and Photo 2. It is composed of two accelerometers, 16-bit A/D converter with data logger PC, and another PC that works as a gateway computer with global IP address. (See Figure 6 and 7) There are three Local Area Network sensor systems (LAN) working individually so that none of them are synchronized and each one of them starts data acquisition according to its own trigger level.

Earthquake records of July 23 in 2005 and August 18 in 2005.

There were two noticeable events shortly after the author's research team started observation using the network sensors. One of them occurred on 23 July 2005, whose epicenter is located about 50km east of Tokyo and recorded magnitude 6.0 and intensity 5 according to JMA scale. Another one occurred about 300km away from Tokyo on 16 August 2005 with magnitude 7.2 and JMA intensity 4. The observed acceleration data on the ground floor are shown in Figure 12, and Figure 13, respectively. The acquired response acceleration histories on the 3^{rd} floor are shown in Figure 8 and Figure 9, respectively. There are also shown transfer functions of 3^{rd} floor from ground floor for each event. Even though the intensity levels are different, there is noticed little difference between the two transfer functions. Using the observed ground data and a simple Voigt Model shown in Figure 5, we can simulate the 3^{rd} floor acceleration responses shown in Figure 10 and Figure 11. The participation coefficient factor at the 3^{rd} floor with respect to the first mode is 1.10 according to the FME analysis. The damping factor in Figure 5 is determined by considering the participation coefficient 1.10.

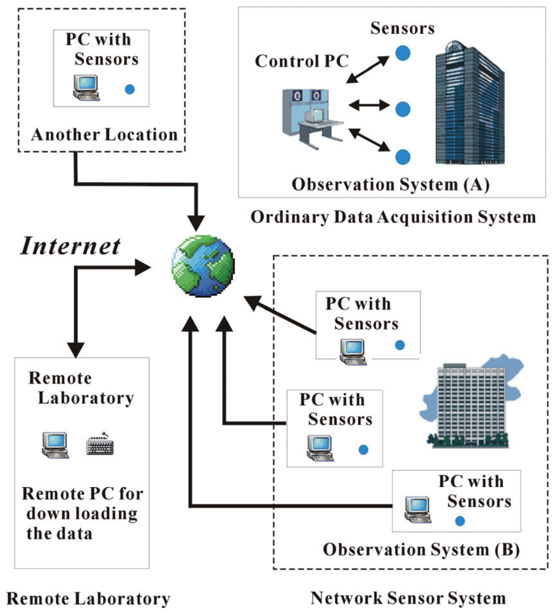


Figure 6 Global network sensor system

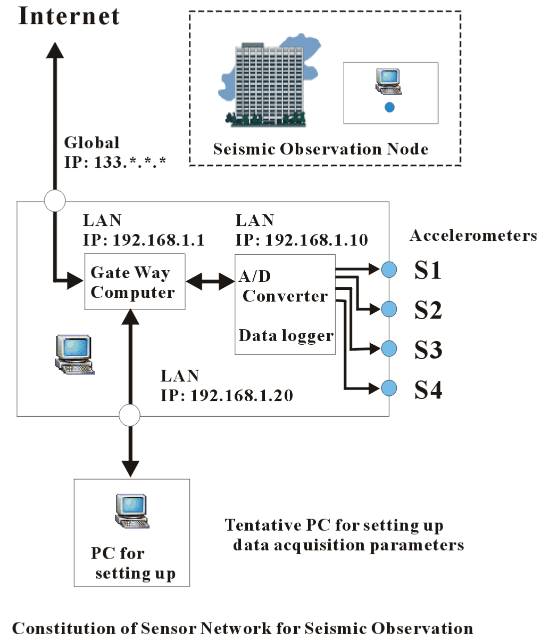


Figure 7 Local network sensor system

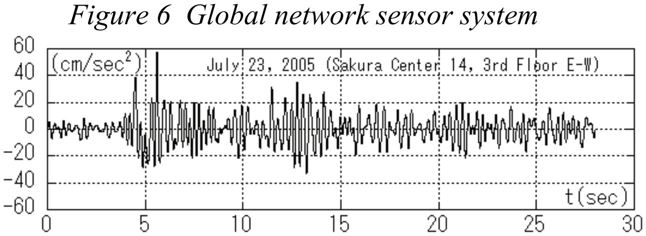


Figure 8 Observed Acc. on the 3rd FL

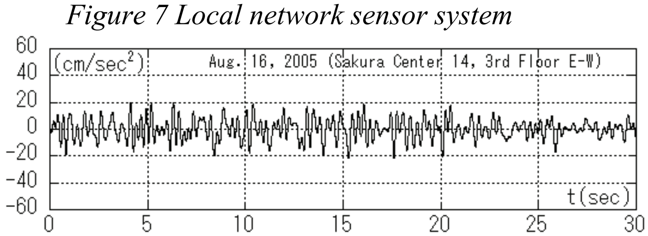


Figure 9 Observed Acc. on the 3rd FL

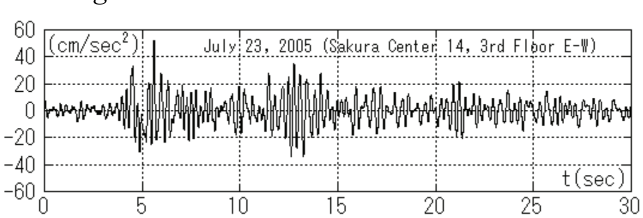


Figure 10 Simulated Acc. on the 3rd FL

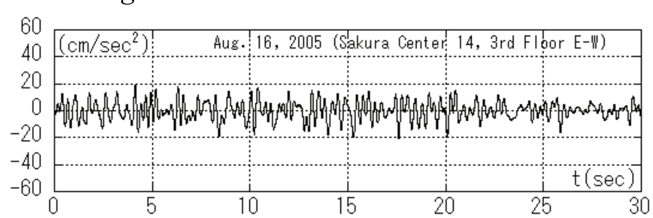


Figure 11 Simulated Acc. on the 3rd FL

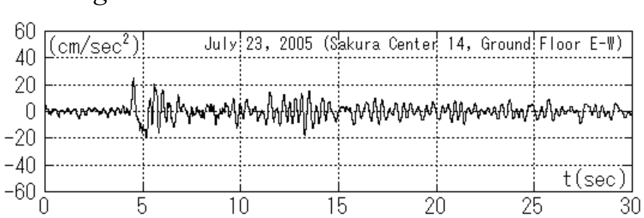


Figure 12 Observed Acc. on the Ground FL

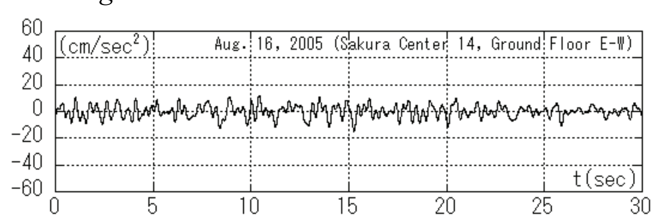


Figure 13 Observed Acc. on the Ground FL

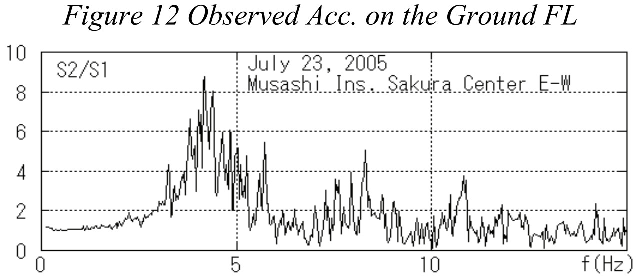


Figure 14 Transfer Function (3FL/GL)
Data recorded on July 23, 2005 (E-W)

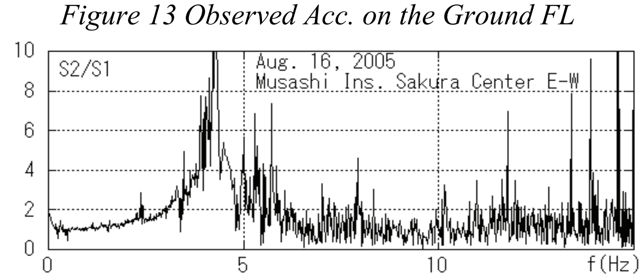


Figure 15 Transfer Function (3FL/GL)
Data recorded on August 16, 2005 (E-W)

General information of the Tohoku Earthquake on the March 11 in 2011

The epicentre of the event is about 125km offshore of the coastline of Tohoku district in the northern part of Japan. The location of the epicentre is 38.1N and 142.9E. The campus of Tokyo City University is located at 35.60N and 139.65E. They are roughly 400km away from each other. The recorded acceleration history on the ground floor of the gymnasium in EW and NS direction is shown in Figure 16 and Figure 17, respectively. The response acceleration spectra of those data are shown in Figure 18 and Figure 19. The velocity response spectra show a rather flat curve over a wide range of period in Figure 20 and Figure 21. It is quite interesting that the EW ground motion seems to be attenuated in the high frequency range as compared with the NS ground motion. The damping system in the structure seems to reduce the intensity over the high frequency zone in EW direction, when we compare the acceleration spectrum of EW direction with the counterpart in NS direction.

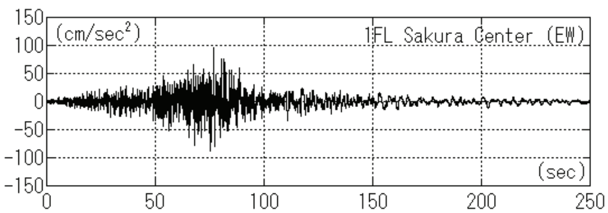


Figure 16 Observed Acc. on the Ground FL (EW)

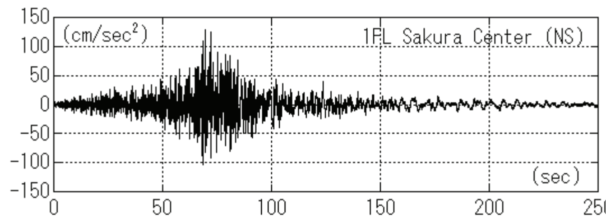


Figure 17 Observed Acc. on the Ground FL (NS)

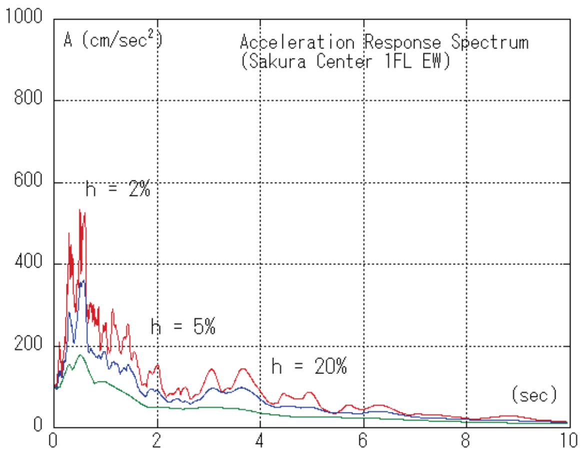


Figure 18 Acceleration Response Spectrum (EW)

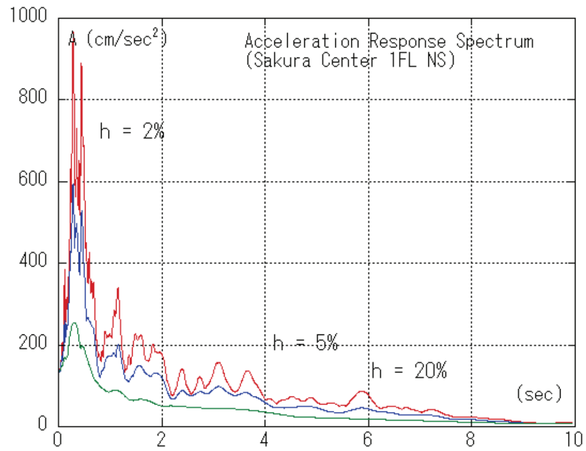


Figure 19 Acceleration Response Spectrum (NS)

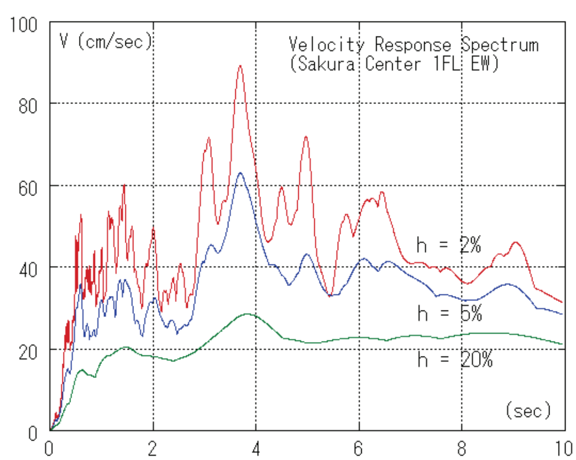


Figure 20 Velocity Response Spectrum (EW)

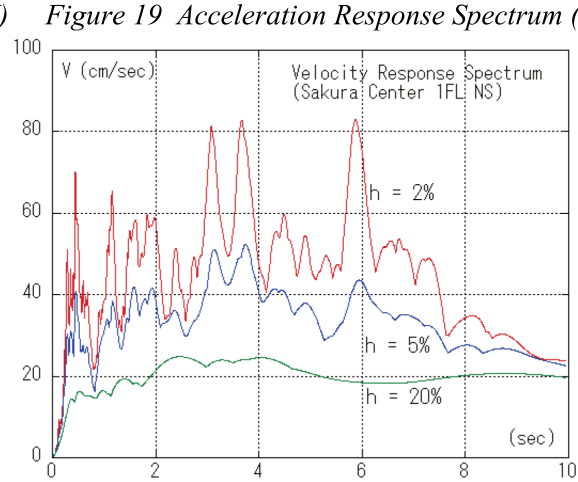


Figure 21 Velocity Response Spectrum (NS)

Response of the structure on March 11, 2011

The response data on the third floor of the structure are shown in Figure 22 and Figure 23. The transfer functions of the third floor from the ground floor are shown in Figure 24 and Figure 25 for east-west direction and north-south direction, respectively. The damping factor judging from the phase transfer function of Figure 26 is roughly 9.0 % and the first modal frequency is 3.8 Hz where the phase lag between the ground motion and the 3rd floor response is 90 degree in Figure 26. The damping factor is about 3% larger and the frequency is 8% smaller than the previously identified dynamic properties.

The transfer function in NS direction in Figure 25 does not show any noticeable peak that can be identified as the first modal frequency. As a matter of fact, the complex structure seems to be moving as a rigid body in NS direction and response of the 3rd floor in Figure 23 is even smaller than the input ground motion in Figure 17. The author could not create a simple model for explaining the observed data, however, the monitoring system can be used for judging whether the system experienced severe damage or not. Because there is no clear amplification over the frequency range less than 5Hz in Figure 25. In this case, the input energy from the ground to the structure in NS direction is extremely small because there is small phase lag between the ground motion and the floor response in Figure 27.

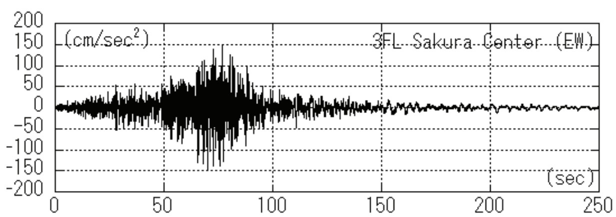


Figure 22 Observed Acc. On the 3rd FL (EW)

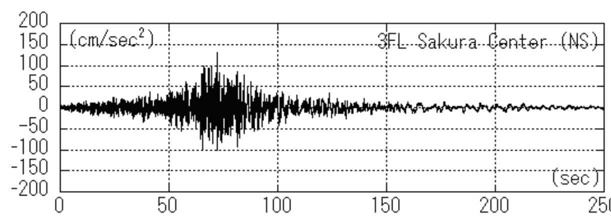


Figure 23 Observed Acc. On the 3rd FL (NS)

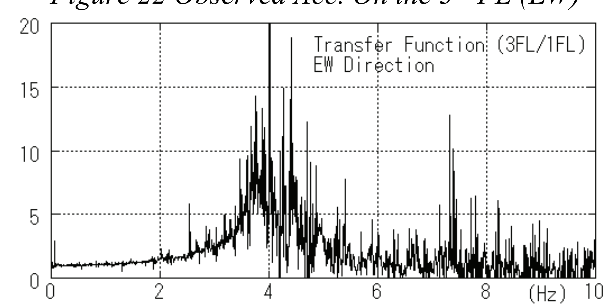


Figure 24 Amplitude transfer function of the 3rd FL from Ground FL (EW)

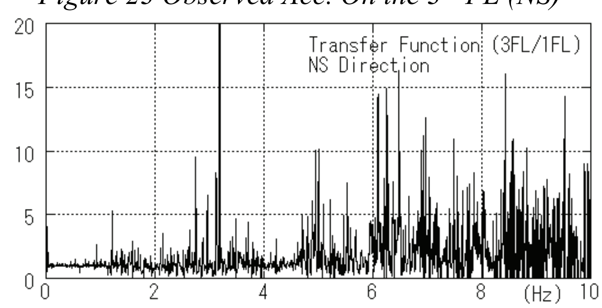


Figure 25 Amplitude transfer function of the 3rd FL from Ground FL (NS)

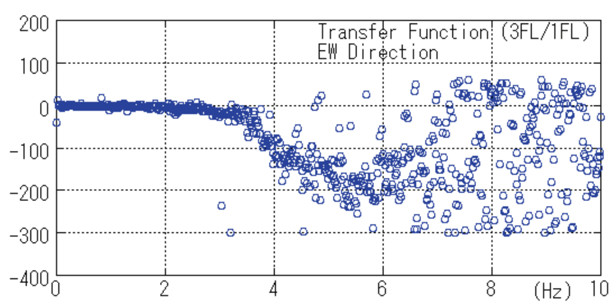


Figure 26 Phase transfer function of the 3rd FL from Ground FL (EW)

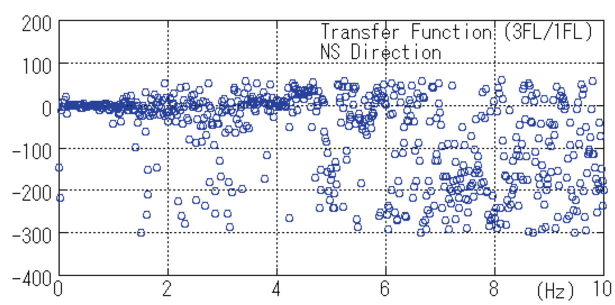


Figure 27 Phase transfer function of the 3rd FL from Ground FL (NS)

Data of the event on April 16 in 2011

One of the many events after March 11 is picked up and shown in Figure 28 and Figure 29. The epicentre of this event is 36.4N 140.0E and is 300km away from the facility on the university campus. The Acceleration spectrum and Velocity response spectrum are shown in Figure 30 to Figure 31. The magnitude of the event is M 5.9 and the intensity in the vicinity area is 4 according to JMA scale. It is quite interesting that the response spectrum in EW direction is relatively smaller than the counterpart in NS direction. These phenomena are commonly observed in most cases. We must admit this is not a particular characteristic of the event but a general tendency associated with the system dynamics. As a result we must admit that this phenomenon is associated with the structure dynamics rather than earthquake characteristics.

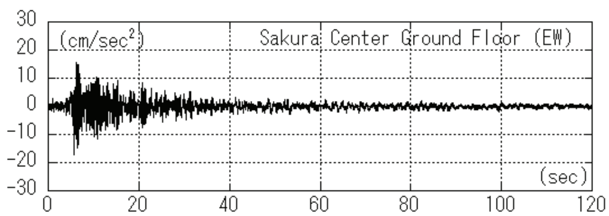


Figure 28 Observed Acc. on the Ground FL (EW)

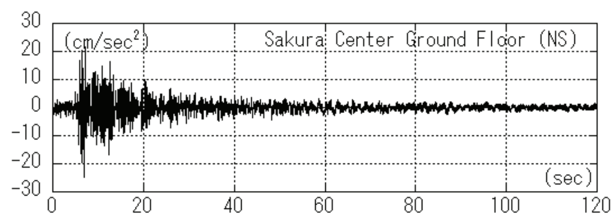


Figure 29 Observed Acc. on the Ground FL (NS)

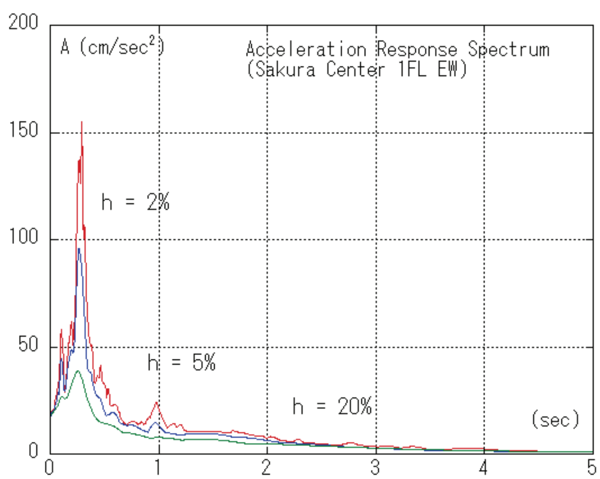


Figure 30 Acceleration Response Spectrum (EW)

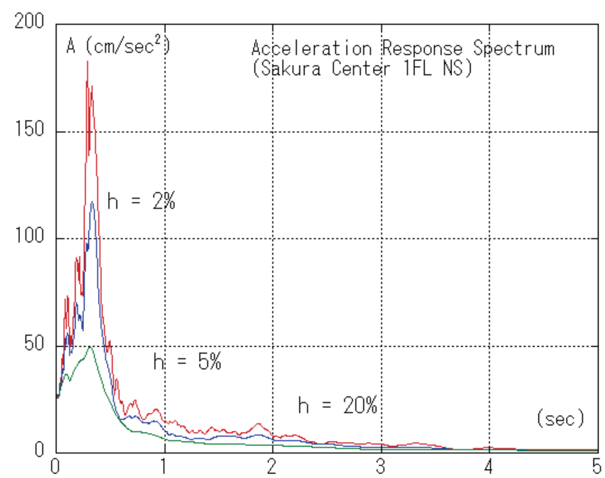


Figure 31 Acceleration Response Spectrum (NS)

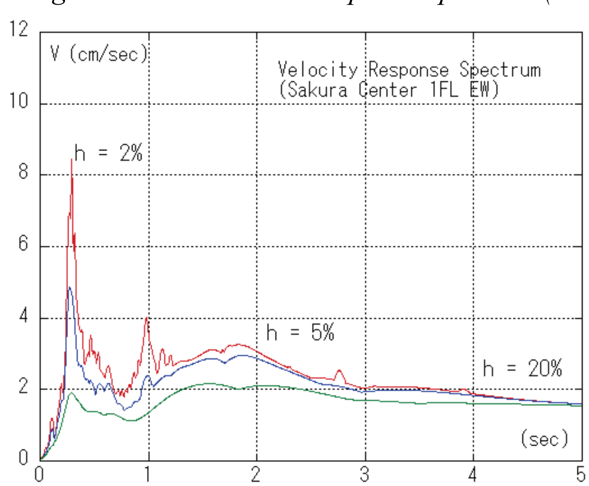


Figure 32 Velocity Response Spectrum (EW)

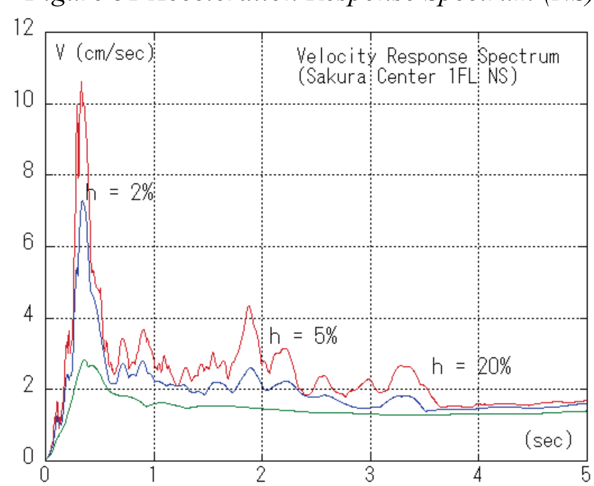


Figure 33 Velocity Response Spectrum (NS)

Response of the structure on April 16 in 2011

The acceleration responses on the third floor in EW direction and NS direction are shown in Figure 34 and Figure 35, respectively. The transfer function of floor response from ground motion is shown in Figure 36 and Figure 37, while the phase transfer functions are shown in Figure 38 and Figure 39. Judging from the transfer functions we concluded that the natural frequency is about 3.9Hz and the damping factor is about 7%. The damping factor seems to be a little less than the value in the major event, and the natural frequency is a little higher than in March 11. This observation result suggests that the optimum damping coefficient of the devices will be smaller than the specified values of the actual devices. Long term monitoring approves that the damping augmentation from the following equation shows a good agreement with the observed damping performance. Referring to Figure 2 we came to understand that the optimum frequency ω_{opt} is at least 23.9 r/s and η_{eq} is not less than 0.09. This means that β is not less than 0.5, which means ω_l is smaller than 21.4 r/s or 3.4 Hz.

$$\eta_{eq} = \frac{\beta}{2+\beta}\sqrt{\frac{1}{2(2+\beta)}} \qquad \beta = \frac{{\omega_\infty}^2 - {\omega_o}^2}{{\omega_o}^2} = \frac{k_d}{k} \qquad where \qquad \omega_{opt} = \sqrt{\frac{{\omega_o}^2 + {\omega_\infty}^2}{2}} \tag{1}$$

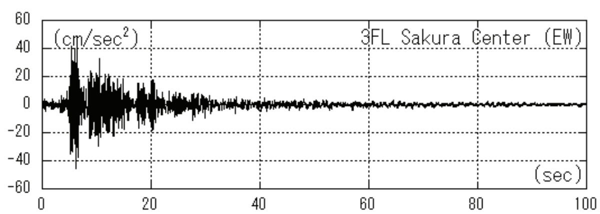


Figure 34 Observed Acc. on the 3rd FL (EW)

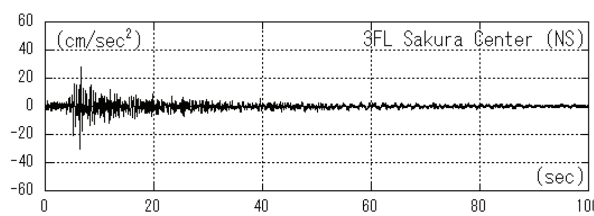


Figure 35 Observed Acc. on the 3rd FL (NS)

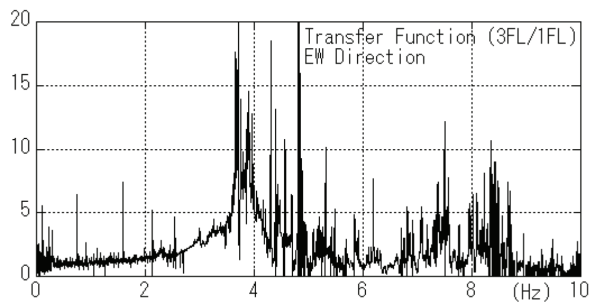


Figure 36 Amplitude Transfer function of 3rd FL/GL (EW)

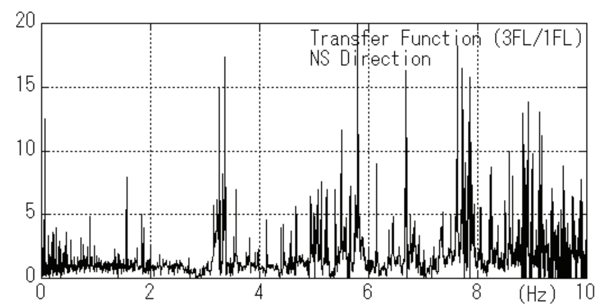


Figure 37 Amplitude Transfer function of 3rd FL/GL (NS)

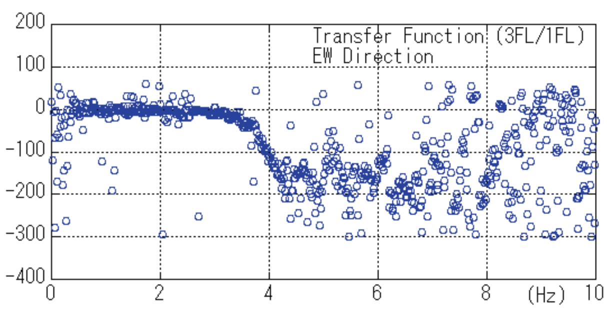


Figure 38 Phase transfer function of 3rd FL/GL (EW)

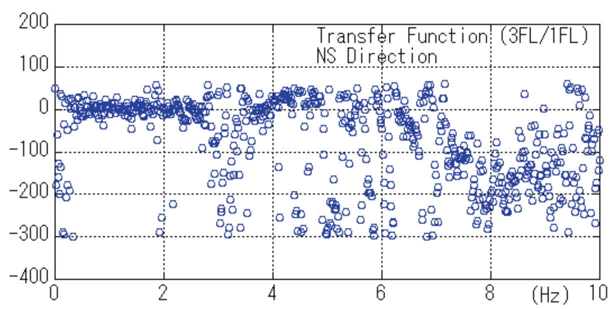


Figure 39 Phase transfer function of 3rd FL/GL (NS)

Comparison between EW ground motion and NS ground motion

The acceleration transfer function in EW direction is smaller than the counterpart in NS direction. There are many observation data after March 11 in 2011, but there is no exception for this phenomenon. The author believes that the damping augmentation of the structure system dynamics in EW direction attenuated the ground motion in the same direction. If this assumption is true, the damping device installation not only reduces the structure response but also attenuates the input disturbances. Further study is necessary for qualitative conclusion, but long term observation can only reveal the unexpected effect of the damping augmentation of superstructure on the soil condition.

Conclusions

The nonlinear compressive damping devices was invented and applied to a complex building structure, which is used as a student dining hall and gymnasium. The structure health monitoring system or network sensor system was implemented with the facility and successfully recorded the structure response vibrations on occasion of earthquake events since 2005. The author's laboratory identified the system dynamics of the structure prior to the major event of earthquake in March 11 in 2011. The health monitoring system succeeded in recording the response vibration on the third floor level and ground floor level during the event. We compared those data obtained before the major event and after the event and came to conclusion that the installed damping devices worked as much as expected and kept the structure intact in case of a major earthquake with intensity 5 according to JMS. This whole project took about 7 years starting from design in 2004 to post analysis in 2012. Although the installation of compressive damping devices has been proved effective as much as ordinary linear dampers and the stiffness associated with damper installation rather than damper connection stiffness is of more importance, yet it still is difficult to evaluate the attenuation effect of structural damping factor on the reduction of ground motion in case of major earthquake. The author wishes to share this valuable data and experiences with other engineers in the same field of science to mitigate the earthquake disasters.

Acknowledgements

The author expresses gratitude to many under graduate and graduate students involved in this project while they were enrolled in the department of architecture of Tokyo City University. The author also expresses appreciation to those engineers in Hitachi Corporation, which manufactured the compressive damping devices according to the specification provided by the author's laboratory. The specification was determined by the FEM analysis conducted by Mr. Katayanagi and Mr. Segawa, who were former graduate students of the Department of Architecture, the Tokyo City University.

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