EARTHQUAKE RESPONSE CHARACTERISTICS OF A SEISMICALLY-ISOLATED BUILDING WITH IRREGULARITY

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Abstract

Seismic isolation systems for building structures are effective to decrease the acceleration responses of the superstructures under strong ground motions during severe earthquakes. Earthquake response observations on seismically-isolated buildings are generally carried out to verify the performance of the systems.

In this paper, the vibration characteristics of a seismically-isolated building with irregularity is discussed using response records observed during earthquakes including the Great East Japan Earthquake occurred on 11 March 2011 (hereafter "3.11 earthquake"). Non-linear response analyses are carried out to recognize the seismic performance of the building during severe earthquakes.

The structural system of the superstructure is rahmen with bracing, and composed of concrete-filling-steel-tube for columns, steel for beams and braces. Two parts of the building with different heights are connected as L-shaped in the floor plan. One part of the building has 7 stories, and the other 14 stories. The center of the high-rise part of the building, from the 2nd up to the 7th stories, is opened like a huge gate. The building has irregularity in both of the floor plan and the elevation. The high-rise part has a length of 100m in the longitudinal direction.

The investigated building is located on the site of soft soil condition with 385km from the epicenter of "3.11 earthquake". The maximum acceleration observed on the ground at the building site is 2.0m/s^2 approximately. It is confirmed that the base isolation system of the building reached plastic stage by strong ground motion during "3.11 earthquake".

In the analysis of the earthquake response observation records, the predominant periods in the longitudinal direction at the end of the low-rise part of the building are identified in two different period bands. One is a short period band due to the predominant period of the low-rise part, and the other is a long period band affected by the high-rise part connected to the low-rise part of the building.

Since the high-rise part of the building has a length of 100m in the floor plan, response analyses using accelerogram with the difference in arrival time to the building foundation tend to simulate the results of earthquake response observation better. In particular, the influence of seismic waves with the time lag appears remarkably in the response in the transversal direction at the end parts of the L-shaped floor plan.

Keywords: seismic isolation; building structure; irregularity; earthquake response observation, response analysis

1. Introduction

Seismic isolation systems for building structures are effective to decrease the acceleration responses of the superstructures under strong ground motions during severe earthquakes. Earthquake response observations on seismically-isolated buildings are generally carried out to verify the performance of the systems. It is very important that the response characteristics of the building structures are simulated to verify the seismic performances. Seismically-isolated building structures can be constructed even if the building is long and the superstructure is irregular in both the plan and the elevation, but it is important to understand the seismic response characteristics.

Using response records observed during the Great East Japan Earthquake occurred on 11 March 2011 (hereafter "3.11 Earthquake"), response characteristics of a seismically-isolated large building structure with irregularity and the analytical results are described in this paper.

2. Investigated Building Structure

The investigated building structure is located at the coast of Tokyo bay, Japan, and seismically-isolated at the basement; i.e. the structure is constructed with base isolation system on the site of soft soil condition. The base isolation system is composed with laminated rubber bearing with/without U-shaped steel damper units, sliding bearing units, and lead damper units. The outline of the structure is shown in Table 1, and the location of isolation units is shown in Fig.1. The part in the light gray in this figure is not investigated in this paper.

The structural system of the superstructure is rahmen with bracing, and composed of concrete-filling-steel-tube for columns, steel for beams and braces. The floor plan of the building is in L-shape with 7stories on one side and 14 stories on the other. The low-rise part is shown inside the dotted light gray line in Fig.1. The center of the high-rise part of the building, up to the 7th story, is open like a huge gate. The low-rise part has an atrium with a part of the 3rd to 7th floor removed. Thus, the building structure has irregularity in both the plan and the elevation. The high-rise part has a length of 100m in the longitudinal direction. The isolation system units are placed so that the center of rigidity of the isolation layer is close to the center of mass of the superstructure.

Table 1 – Outline of the Investigated Building

Number of Stories	14F (partially 7F), B1F, PH1F
Eaves Height [m]	High-rise Part : GL+67.32, Low-rise Part : GL+31.20
Building Area [m^2]	6,434.27
Total Floor Area [m^2]	51,685.96
Structural System	Superstructure : Rahmen with Bracing System Column : CFT (partially Steel), Beam : Steel, Brace : Steel Substructure : Base Isolation System Laminated Rubber Bearing with/without Steel Damper Sliding Bearing, Lead Damper Foundation : Steel Pipe Pile

3. Earthquake Response Observation

3.1 Outline of Observation System

The earthquake response observation system has been carried out on the investigated building since March 2010. The layout of the sensors for earthquake response observation of the structure is shown in Fig.2. 3-axis accelerometers are installed with 2-axis in horizontal and one in vertical directions. The rotation and elevation angles and horizontal 2-axis displacement transducers, and scratch plate devices for relative displacement are also set as shown at the isolation layer. The observation system for the substructure starts to record, when any of the three components of accelerometer No.004 observed over 4mm/s^2, and the system for the superstructure starts over 5mm/s^2 for accelerometer No.101. Data sampling time is 0.01s for both the observation systems.

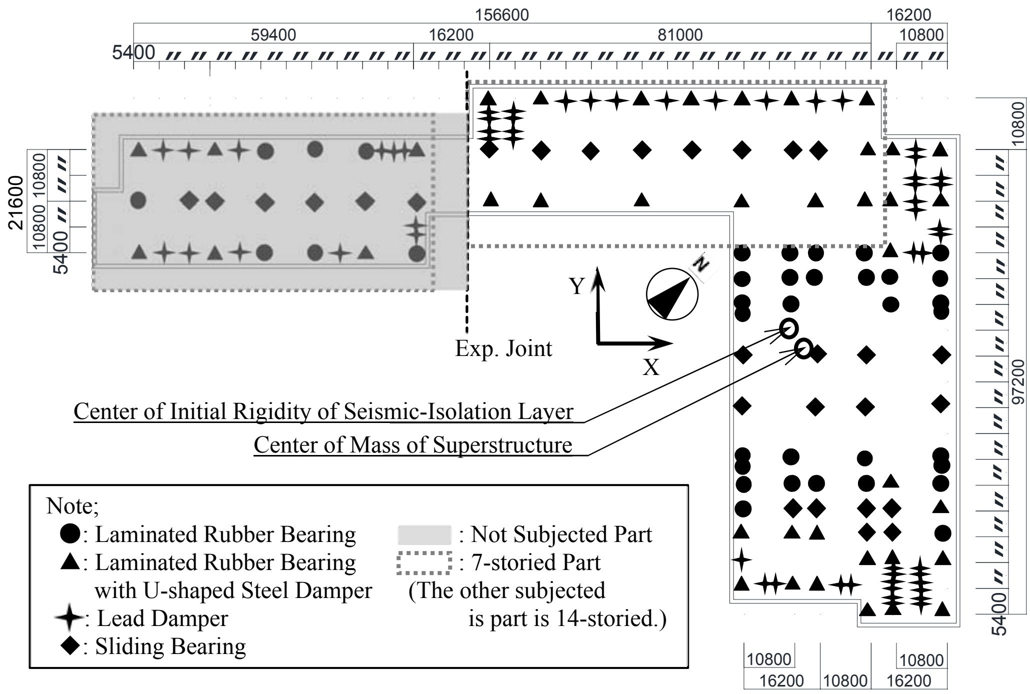


Fig. 1 – Location of Base Isolation Units

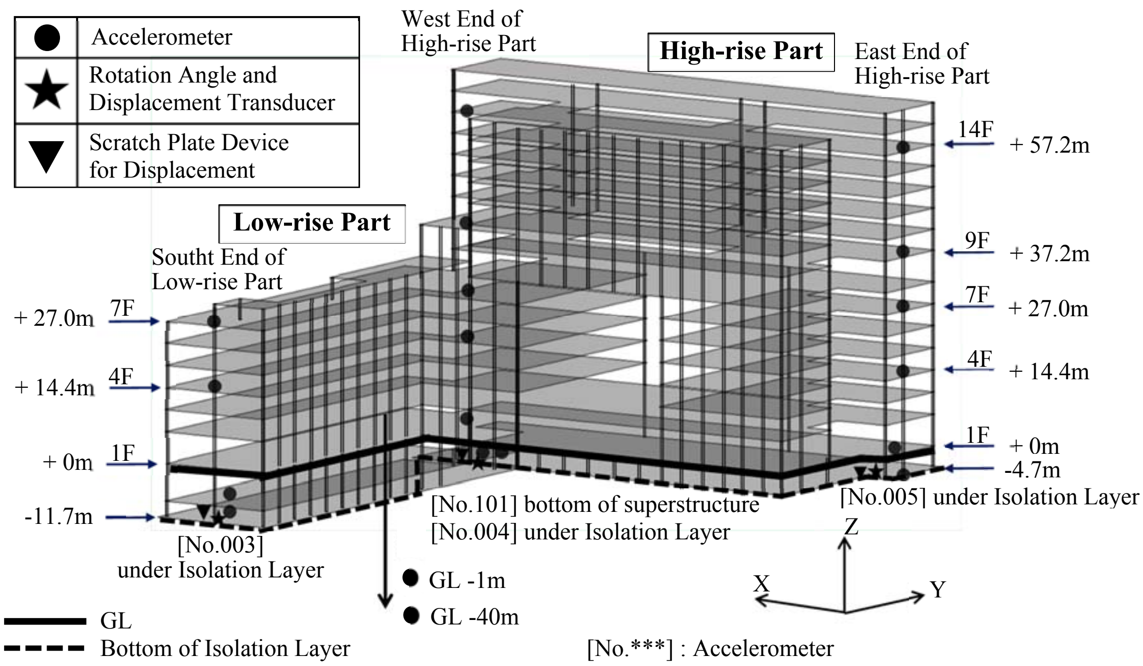


Fig. 2 – Layout of Sensors for Earthquake Response Observation

The distance from the accelerometer No.004 to No.005 at the east end of high-rise part of the building is approximately 100m, and the distance to No.003 at the south end of low-rise part is approximately 80m. These accelerograms are used for the simulation of the response of the investigated building due to "3.11 Earthquake".

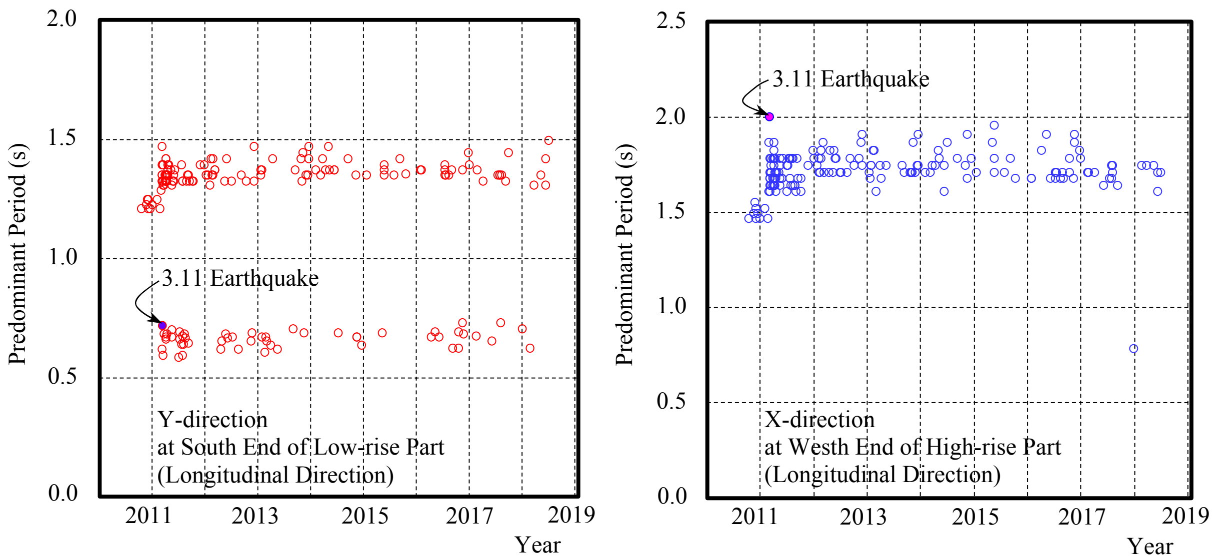
3.2 Response Characteristics of Investigated Building

The response of the investigated building to the seismic motion recorded from October 2010 to November 2018 using the observation system was analyzed. 180 waves with the JMA (Japan Meteorological Agency) instrumental seismic intensity 1.5 or more (II or more with the JMA seismic intensity) were used for the analysis. These seismic intensities correspond to a maximum ground acceleration of about 2.5cm/s^2 or more.

The Fourier analyses of earthquake response observation records were carried out, and the predominant periods of the structure were identified in the basis of the Fourier's spectrum ratios of RF/BS. 'RF' and 'BS' mean the roof floor level and the bottom of the superstructure, respectively. Changes of predominant periods in the longitudinal direction of the high-rise and low-rise parts of the structure are shown in Fig.3. The periods after "3.11 Earthquake" are slightly elongated in comparison with the periods before the earthquake, although the number of the data before the earthquake may not be sufficient.

It was confirmed that some non-structural members were damaged by the "3.11 earthquake" and the seismic isolation members exceeded the elastic range. This property can be confirmed in the transition of the dominant period shown in Fig.3. There is no significant change in the predominant period due to earthquakes after the "3.11 earthquake".

Predominant periods in the longitudinal direction at the south end of the low-rise part appeared in two different bands, i.e. a long period around 1.4s and a short period around 0.7s. Predominant period is generally in proportion to the eaves height of the building. It is considered that the low-rise part has a long-period band because the low-rise part is attached to the high-rise part of the building. It is presumed that the predominant period in the longitudinal direction at the south end of the low-rise part appears to the band of the short period.



a) South End of Low-rise Part b) West End of High-rise Part

"3.11 Earthquake" means the Great East Japan Earthquake occurred on 11 March 2011

Fig. 3 – Changes of Predominant Periods during Earthquakes

3.3 Observed Results during the Great East Japan Earthquake

Observed acceleration records at the west end of high-rise part of the building during the "3.11 earthquake" are shown in Fig.4. Since the observation record up to 117 seconds has been lost, the response analysis to the two-directional horizontal input using the record of 117 to 420 seconds is conducted. Response analyses are performed for the case considering difference in arrival time of ground motion input and for the case without the time lag.

"3.11 Earthquake" had a moment magnitude of 9.0, and the JMA (Japan Meteorological Agency) seismic intensity VII was recorded in the devastated area in the east part of Japan. The seismic intensity VII was the most serious category with severe damages in the JMA scale. Pseudo response spectra at GL-40m on the site during "3.11 Earthquake" are shown in Fig.5. Response spectra for seismic design to earthquake motion defined as "rarely occurs" and "occurs extremely rarely" by the Ministry of Construction Notification No.1461 (2000) in Japan are also drawn in this figure.

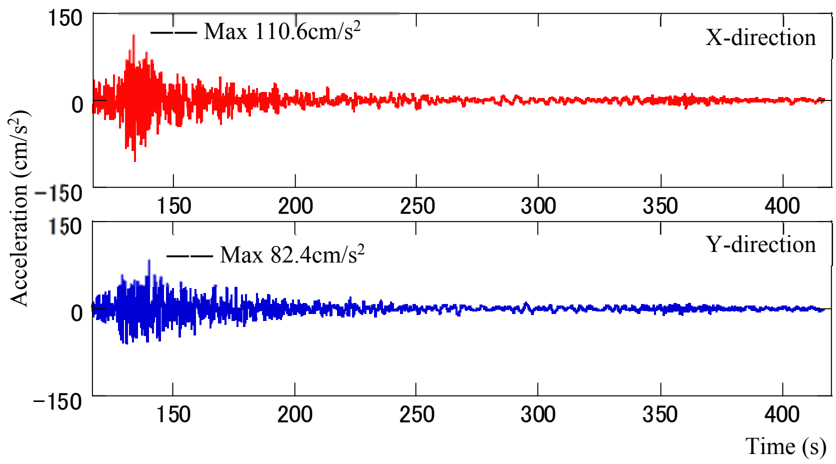


Fig.4 – Recorded Acceleration under Isolation Layer at West End of High-rise Part during "3.11 Earthquake" [No.004]

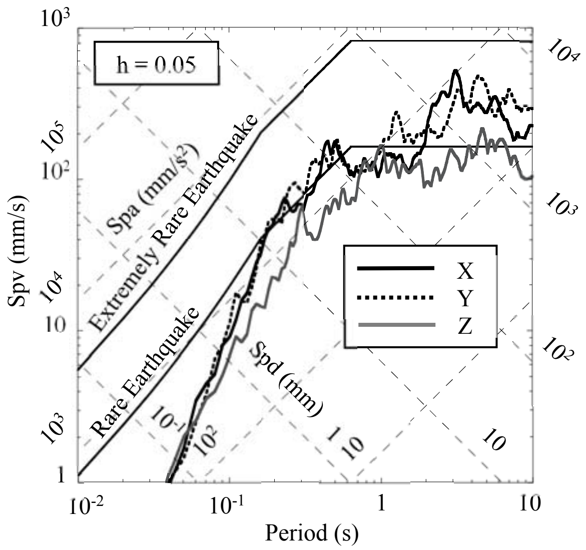


Fig.5 – Pseudo Response Spectra of "3.11 Earthquake" at GL-40m

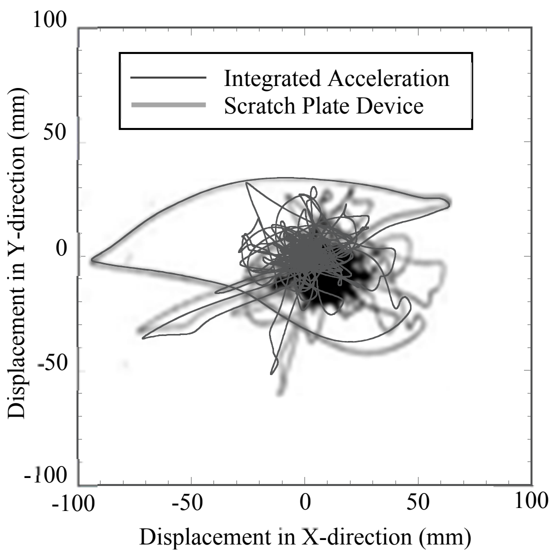


Fig.6 – Horizontal Orbit of Relative Displacement at Isolation Layer during "3.11 Earthquake"

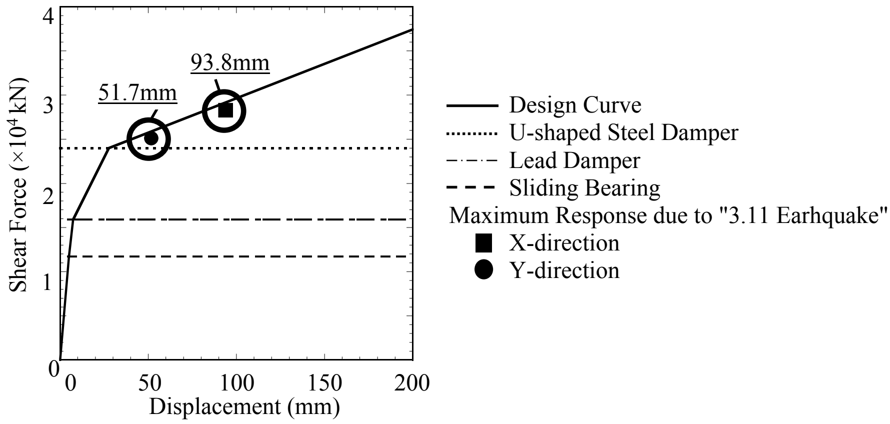


Fig.7 – Shear Force vs. Displacement at Isolation Layer

Allowable deformation at the isolation layer is 490mm in the seismic design for rare earthquakes, and the allowable shear strain of laminated rubber bearings is approximately 250%. The allowable deformation is 690mm for extremely rare earthquakes, and the allowable shear strain approximately 350%. Horizontal clearance between the isolated structure and the underground retaining wall is 850mm in the structural design.

Horizontal orbits of response relative displacement at the isolation layer during "3.11 Earthquake" are shown in Fig.6. The response displacement based on integrated acceleration resembles the building movement provided by the scratch plate device. It is confirmed that the maximum displacement of the isolation layer is less than 1/5 of the allowable value in the design; 490mm.

The relationship between shear force and displacement at the isolation layer is shown in Fig.7. A relationship between shear force and displacement drawn in the figure shows the design model for the isolation layer. It is proven that all of the isolation units yielded and the deformation reached the plastic zone according to "3.11 Earthquake".

4. Earthquake Response Analyses

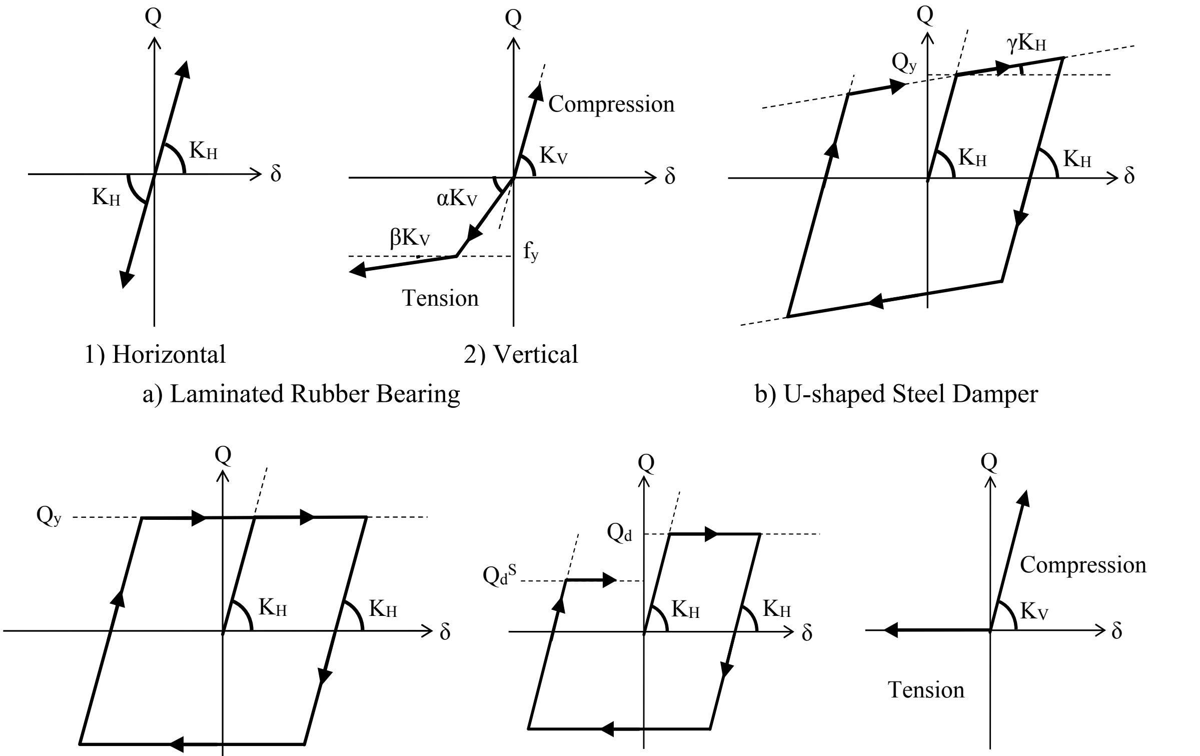
4.1 Analytical Model

Response analyses according to the three-dimensional frame model considering the nonlinearity of seismic isolation units were carried out by using SNAP [ver.7] produced by Kozo System Co., Ltd., Japan. An elastic model is assumed for the superstructure. Hysteretic rules for isolation units are shown in Fig.8, and the characteristics for the nonlinearity are based on the designed values. The superstructure was modeled as elasticity. Columns, beams and braces were replaced with wire rods, and bracing system was substituted for deck plates for floors of the superstructure. The building weight was given at the nodes as concentrated masses.

The damping for the superstructure was given in the stiffness proportional, and the damping factor was made to be 2% for the first vibration mode. Damping characteristics for isolation units was given as hysteresis.

4.2 Input Ground Motion

If the building structure is long in the floor plan, the difference in arrival time of a seismic wave to the foundation will affect the response of the building due to the input ground motion. The time lag of the input ground motion will reduce the uniformity of seismic motion input to the building, decrease the translational response and increase the torsional response of the building.



1) Horizontal 2) Vertical
a) Laminated Rubber Bearing
b) U-shaped Steel Damper
1) Horizontal 2) Vertical
c) Lead Damper
d) Sliding Bearing

α, β, γ : Degradation Coefficient (α=0.1, β=0.001, γ=0.017) Degraded Sliding Resistant Force ($Q_d^S=0.268\times Q_d$)

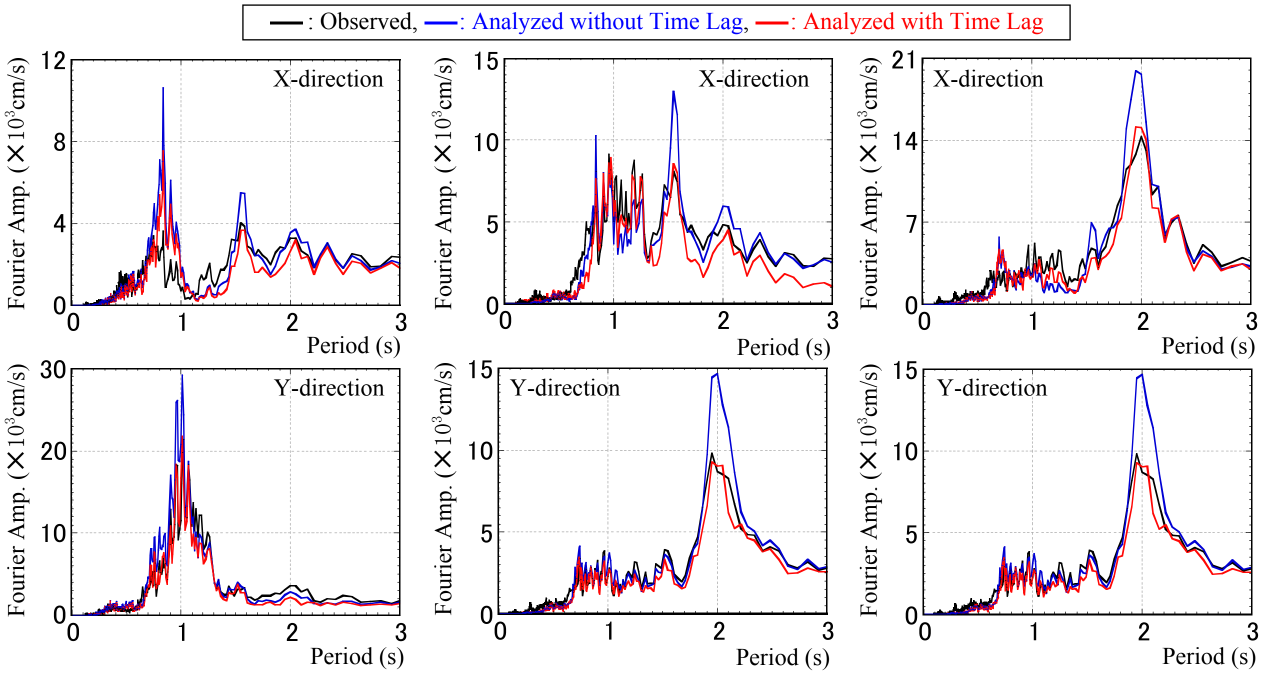
Fig.8 – Hysteretic Rules of Seismic Isolation Units

Earthquake response analyses will be performed using the acceleration records observed during the "3.11 earthquake". Since the observed record up to 117 seconds has been lost, the two-directional horizontal accelerogram from 117 to 420 seconds were used for the analyses. The response analyses are performed by inputting ground motion using the time lag as a parameter.

The seismic motion input to each position of the isolation units under the isolation layer of the building is obtained using the accelerogram recorded at the observation points of Nos.003 to 005 shown in Fig.2. In the case without the time lag, the acceleration recorded under the isolation layer at the west end of high-rise part (No.004) is input to the foundation of the building. In the case considering the time lag, the acceleration recorded under the isolation layer at the east and west ends of the high-rise part and the south end of the low-rise part (Nos.003-005) are used for the response analysis. The acceleration input to the bottom of the isolation units is calculated by linearly interpolating these acceleration records according to the position of each unit. The earthquake response of the building is analyzed by inputting these ground accelerogram simultaneously to the bottom of each isolation unit.

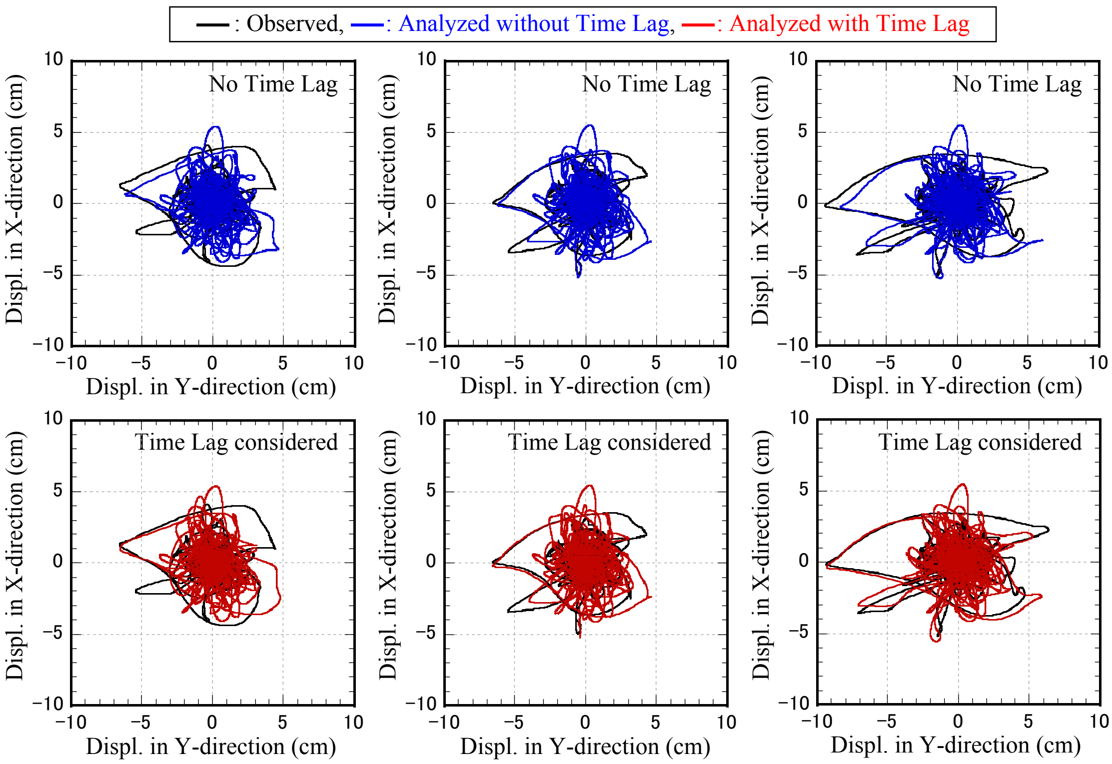
5. Response Analyses due to the Great East Japan Earthquake

Comparisons of the Fourier amplitude spectra of the response acceleration measured on the top floor of the ends of the high-/low-rise parts of the building are shown in Fig.9. The observation results can be simulated by considering the time lag in the ground motion input. In the transversal direction of the building, the analytical results based on the ground motion input without the time lag were significantly different from the observational results.



a) South End of Low-rise Part b) West End of High-rise Part c) East End of High-rise Part

Fig.9 – Fourier Amplitude Spectra of Acceleration on Top Floor



a) South End of Low-rise Part b) West End of High-rise Part c) East End of High-rise Part

Fig.10 – Horizontal Orbits of Relative Displacement at Isolation Layer during "3.11 Earthquake"

Comparisons of horizontal orbits of relative displacement at the isolation layer are shown in Fig.10. The characteristic shape of the orbits can be reproduced by considering the time lag. At the west end of the high-rise part of the building, there is no significant difference depending upon whether there is a time lag in ground motion input. On the other hand, the difference between the south end of the low-rise part and the east end of the high-rise part of the building is remarkable. At these ends of high-/low-rise parts, the results showed that the maximum relative displacement at the isolation layer was almost the same by considering the time lag.

6. Concluding Remarks

Vibration characteristics of a seismically-isolated building with irregularity in both the floor plan and the elevation was analyzed based on earthquake observation records. The investigated building was damaged on non-structural members during the Great East Japan Earthquake occurred on 11 March 2011, and the seismic isolation units exceeded the elastic range. Elongation of the predominant periods during the earthquake was confirmed by analyzing the response observation records.

The dominant periods in the longitudinal direction at the end of the low-rise part of the building was identified in two different period bands. One is a long-period band caused by connection of the low-rise part to the high-rise part, and the other is a short-period band that appears in the longitudinal direction at the south end of the low-rise part.

As a result of consideration of the differences in arrival time of a seismic wave to the building foundation, the analytical response values at the end parts of the L-shaped floor plan correspond with the observed values well. The influence of the time lag of seismic waves becomes remarkable in the response in the transversal direction at the end parts of the L-shaped floor plan.

However, the design values are used as the characteristics of the seismic isolation units in this study. The variation of the characteristic values and the change due to environmental conditions are not considered in the analytical model. It is necessary to verify the results of earthquake response observation in consideration of these effects.

7. Acknowledgments

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8. References

[1] Takeru SHIMIZU, Hikaru SATO and Fumitoshi KUMAZAWA (2019): Vibration Characteristics of a Seismically-isolated School Building with Irregularity. Part 1: Analysis of Transfer Characteristics Based on Microtremor Measurement and Earthquake Observation Records, Part 2: Response Analyses using Observed Ground Motion during the 2011 Tohoku Earthquake considering Phase Difference, *Summaries of Technical Papers of Annual Meeting*, Architectural Institute of Japan, Vol.B-2, pp.273-276 (in Japanese).

[2] KUMAZAWA Fumitoshi, TATSUMI Kazuki and YAMASHITA Soushi (2015): Earthquake Response Characteristics of a Seismically-Isolated Building with Irregularity, *Proceedings of The Third Conference on Smart Monitoring, Assessment and Rehabilitation of Structures*, No.105, Antalya, Turkey.

