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Structural Health Monitoring (SHM) of a Base-Isolated High-Rise Building

Part I : System Identification (SI) Result of 2011 Tohoku Earthquake

構造—振動

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Base-isolated high-rise building, System identification
Structural health monitoring, 2011 Tohoku earthquake

1. Introduction

In these years, the application of structural health monitoring (SHM) has been growing at a high speed all around the world and played a critical role whether a structure is under construction, in service, or facing nature disaster like earthquakes or Tsunamis. In Japan, an earthquake prone country, SHM has been utilized since 1950s, and more than 850 buildings have been installed SHM systems since 2021 [1]. Besides, since Yachiyo-dai-house, the first seismic isolated building in Japan, was constructed in 1982, the number of seismic isolated buildings is gradually increasing in Japan, especially for high-rise buildings [2]. However, the research on SHM of seismic isolated buildings has limitation in the case of strong ground motion.

In 2005, there was a base-isolated high-rise building, called J2 building, constructed in Institute of Science Tokyo. After the 2011 Tohoku earthquake, an M_w 9.0 major earthquake, research has shown the estimation of the mode parameters of J2 building in the cases of the entire building and superstructure by system identification (SI) [3]. However, the behavior of isolation layer when encountering major earthquakes has rarely been analyzed. In this study, SI is conducted to isolation layer individually to discuss its effect during the 2011 Tohoku earthquake.

2. Monitoring system in J2 building

J2 building [4], a 20-floor base-isolated building with a height of 91.4m, has been constructed in Institute of Science Tokyo (the former Tokyo Institute of Technology), Suzukakedai Campus in 2005 (the left building in Fig.1). Besides, another building, J3 building (the right building in Fig.1), was built in 2012 and then connected to J2 building. In order to focus on the dynamic behavior of J2 building only, the monitoring records before the year 2012 are used in this paper.

In J2 building, the isolation layer is located between the 1st and the 2nd floors, the foundation and the 1st floor are

constructed in reinforced concrete structure, while the other floors are hybrid with steel beams and concrete filled steel tube (CFT) columns. Fig.2 illustrates the elevations of J2 building from two different sides. Besides, Mega-Braces (ϕ -



Fig.1 Photo of J2-3 building
(Left: J2 building; Right: J3 building)

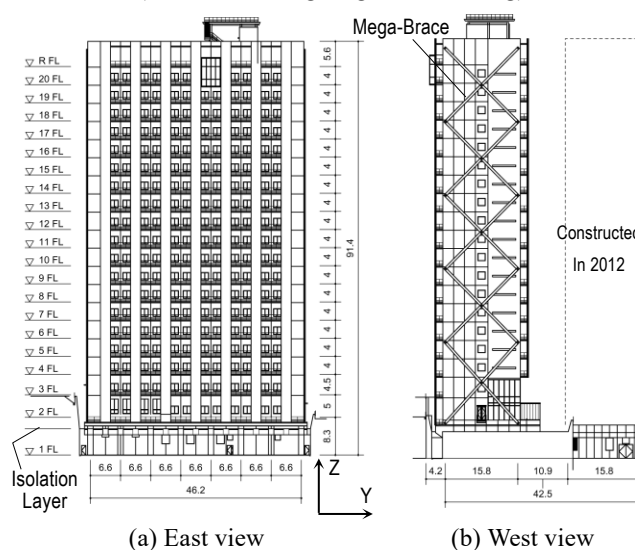


Fig.2 Elevation of J2 building

500mm×160mm×19 to 32mm) are equipped on both sides of J2 building (see Fig.2(b)), to enhance the horizontal stiffness of the superstructure.

On the isolation layer, several types of dampers are installed. In Fig.3, position A are the $\phi 1200$ mm rubber bearings with conical spring, position B are steel dampers, two different shapes of $\phi 1100$ mm rubber bearings with steel dampers are in position C and D, while the 1000 kN oil dampers are installed in position E.

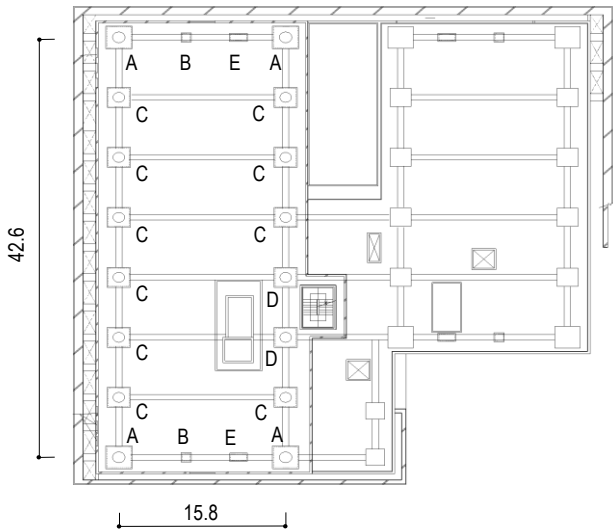


Fig.3 Layout of the isolation layer

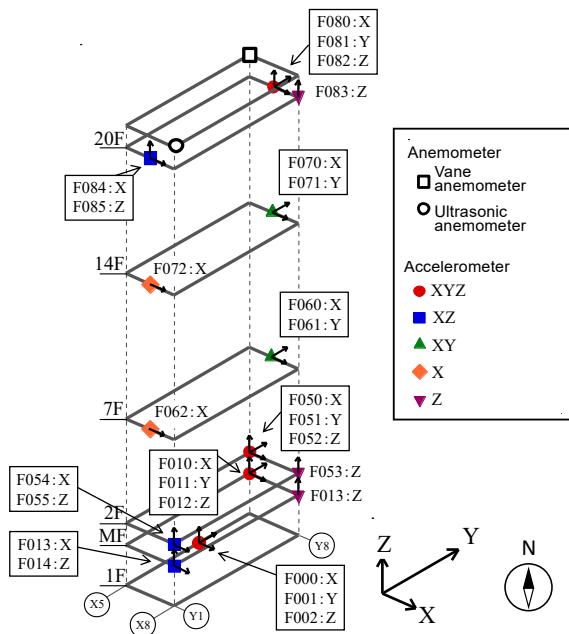


Fig.4 Locations of accelerometers

What's more, a long-term dense SHM system has been installed in J2 building on the 1st, 2nd, 7th, 14th, 20th floors and isolation layer, and the locations of accelerometers are shown

in Fig.4. The arrows in the figure indicate the respective directions in which acceleration data are recorded. For instance, the accelerometer denoted by a red dot on the 1st floor captures accelerations in the X, Y, and Z directions through channel numbers F000, F001, and F002, respectively.

3. Monitoring results of 2011 Tohoku earthquake

The 2011 Tohoku earthquake, also known as Great east Japan earthquake, has been considered as the strongest earthquake ever recorded in Japan. The M_w 9.0 mainshock occurred on March 11, 2011, at 14:46 JST in the Pacific Ocean, 72 km east of the Oshika Peninsula of Tohoku region, Japan. About 20 minutes after the mainshock, the Pacific coast in the north-eastern of Japan was inundated by a tsunami up to 40.5 m height.

J2 building is located on the south-west of the epicenter of 2011 Tohoku earthquake, with a linear distance of 404.16 km, as shown in Fig.5. Based on the response data recorded by the accelerometers with channel numbers F080 and F081 during this seismic event, the absolute peak top floor acceleration (PTA) in the X and Y directions are 88.58 cm/s^2 and 115.44 cm/s^2 , respectively. Similarly, the absolute peak ground acceleration (PGA) in the X and Y directions, obtained from accelerometers with channel numbers F000 and F001, were 50.15 cm/s^2 and 67.26 cm/s^2 , respectively. Besides, the acceleration time histories at various positions and directions throughout the building are presented in Fig.6. Additionally, the velocity and displacement time history would be calculated from the acceleration time history. As a result, the maximum acceleration and displacement responses of different floors can be summarized as Fig.7, offering an insight into the overall seismic performance of J2 building.

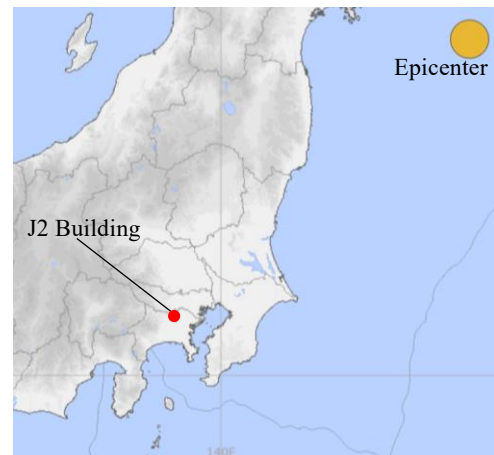


Fig.5 The location of J2 building and the epicenter of Tohoku earthquake

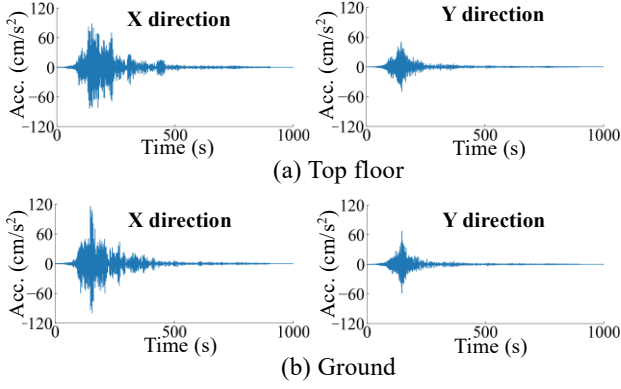


Fig.6 Acceleration time history during 2011 Tohoku earthquake

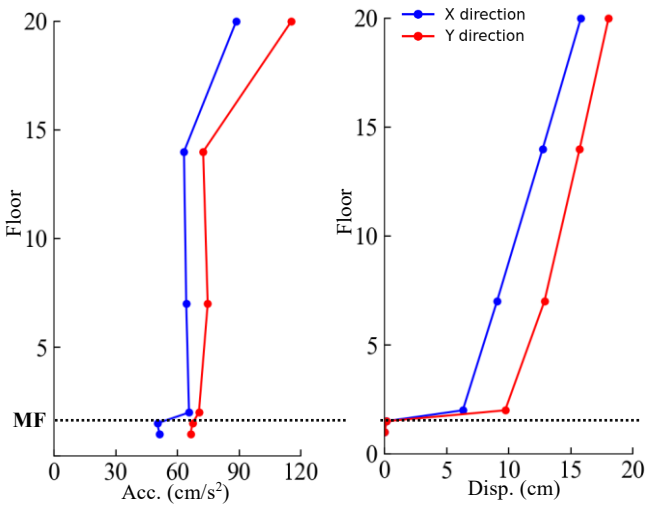


Fig.7 The maximum responses of 2011 Tohoku earthquake

4. System Identification (SI)

By utilizing the response data of J2 building during 2011 Tohoku earthquake, we conduct SI to analyze the dynamic characteristics of a base-isolated high-rise building during a major earthquake. Specifically, the natural frequency and damping ratio are estimated from transfer function, which serves as a fundamental concept determining the relationship of input and output of a system. In this paper, transfer function is calculated by the following equations.

$$|H(f)| = \left| \frac{F_{out}(f)}{F_{in}(f)} \right| \quad (1)$$

$$\theta = \phi_{out} - \phi_{in} \quad (2)$$

where f is the frequency, $|H(f)|$ is the amplitude transfer function, θ is the phase transfer function, $F_{in}(f)$ and ϕ_{in} are the Fourier spectrum of the input data and its phase angle, and $F_{out}(f)$ and ϕ_{out} are the Fourier spectrum of the output data

and its phase angle.

In this paper, three scenarios are considered when choosing different input and output floors. The case of the entire building means that the input floor is the isolation layer (named as MF), and the output floor is the top floor. The case of superstructure utilized the input data from the 2nd floor and output data from the top floor. What's more, the case of isolation layer is to consider the input data from MF and output data from the 2nd floor. The calculation principles of these three scenarios are shown in Fig.8.

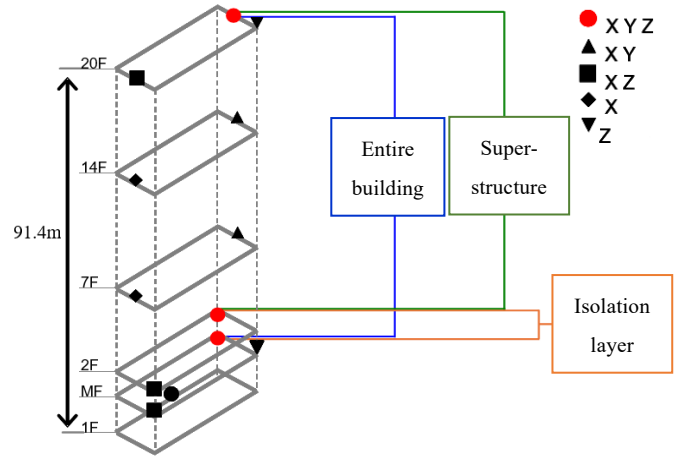


Fig.8 Calculation principles of transfer function

After calculating the transfer function, the result is conducted curve fitting by the following equations to obtain the natural frequency and damping ratio.

$$H' = \sum_{s=1}^3 \beta_s \{ \varphi_{s,j} \} \left[\frac{1 + 2\xi_s \left(\frac{f}{\omega_s} \right) i}{1 + \left(\frac{f}{\omega_s} \right)^2 + 2\xi_s \left(\frac{f}{\omega_s} \right) i} \right] + \frac{1}{z} \quad (3)$$

where

$$\frac{1}{z} + \sum_{s=1}^3 \beta_s \{ \varphi_{s,j} \} = 1 \quad (4)$$

$$f_s = \frac{\omega_s}{2\pi} \quad (5)$$

where H' is the transfer function calculated by curve fitting, s is the mode number, j is the floor number, f_s and ω_s is the natural frequency and natural circular frequency of the s -th mode, ξ_s is the damping ratio of the s -th mode, $\{ \varphi_{s,j} \}$ is the participation factor of the j -th floor and s -th mode, f is the frequency, i is the imaginary unit, and $\frac{1}{z}$ is the remaining rigidity. As an example, the calculated results by (1) and (2)

and the curve fitting results of the three scenarios in X direction are shown in Fig.9.

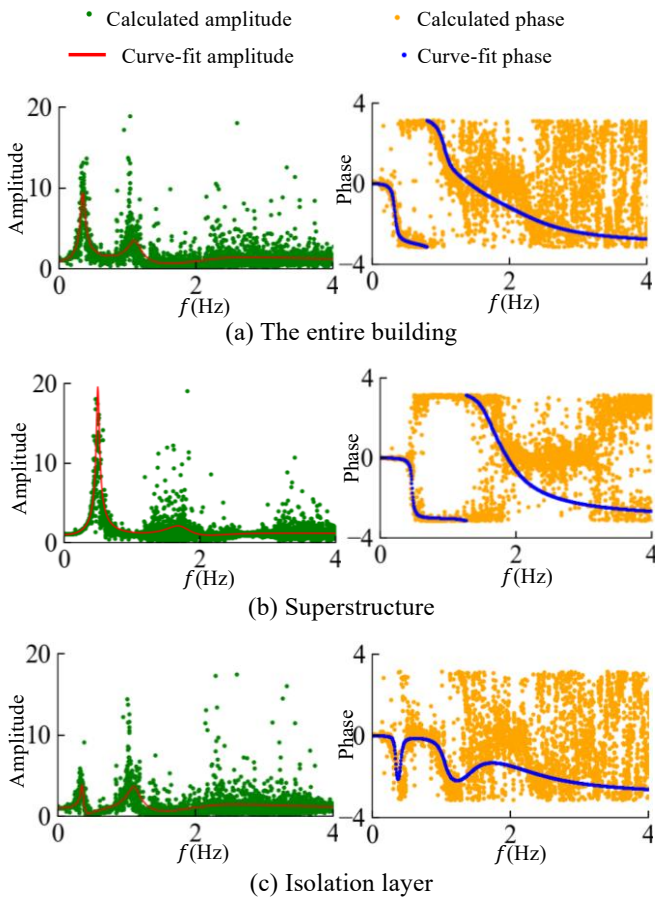


Fig.9 Transfer function during the 2011 Tohoku earthquake in X direction

By conducting SI for J2 building, with the comparisons among the entire building, superstructure, and isolation layer presented in Fig.10.

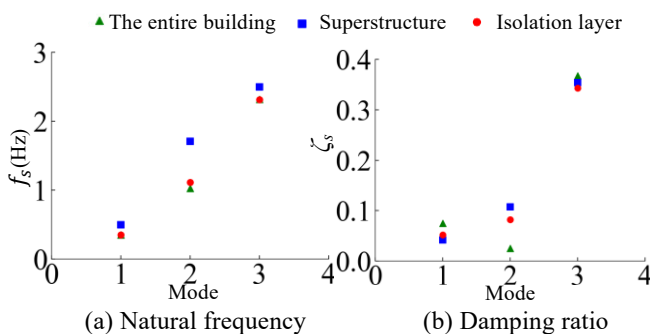


Fig.10 The SI results of J2 building

As shown in Fig.10(a), the natural frequencies in the first three modes for the entire building and isolation layer are

almost the same and lower than those of the superstructure. However, in Fig.10(b), the damping ratio does not exhibit any discernible trend across within the first three modes.

5. Conclusion

This paper provides an overview of J2 building, a base-isolated high-rise building located in Institute of Science Tokyo, detailing the structure of its isolation layer, and the long-term structural health monitoring (SHM) system. Using the response acceleration recorded during the 2011 Tohoku earthquake, system identification (SI) was performed to determine the natural frequency and damping ratio of this building in three scenarios, which are the entire building, the superstructure, and the isolation layer.

The SI results show that the natural frequency of the entire building is nearly identical to that of the isolation layer and significantly lower than that of the superstructure, but the damping ratio of each case doesn't exhibit a specific relationship with the others.

6. Acknowledgement

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