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

PartⅡ: Recovery Effect after 2011 Tohoku Earthquake

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

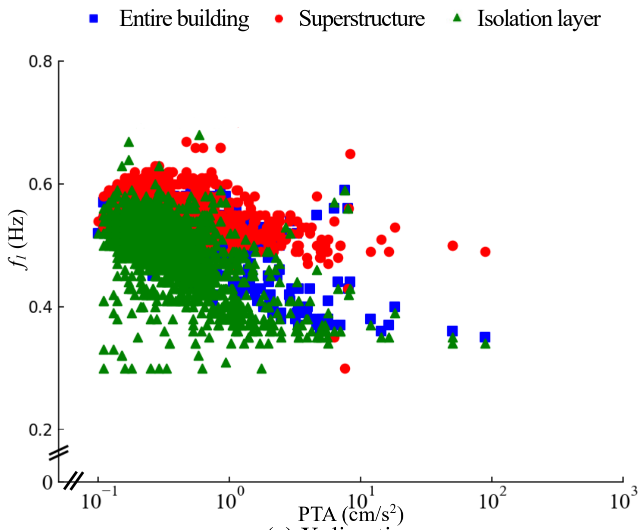
1. Introduction

In part I of this research, short-term structural health monitoring (SHM) has been conducted to J2 building, a base-isolated high-rise building, during the mainshock of 2011 Tohoku earthquake. Moreover, long-term SHM plays a critical role after nature disaster to estimate structural damage. Research has proved that the natural frequency of structures has been found to present a rapid decrease after an excitation, whose magnitude is positively correlated with the reduced value of natural frequency [1,2].

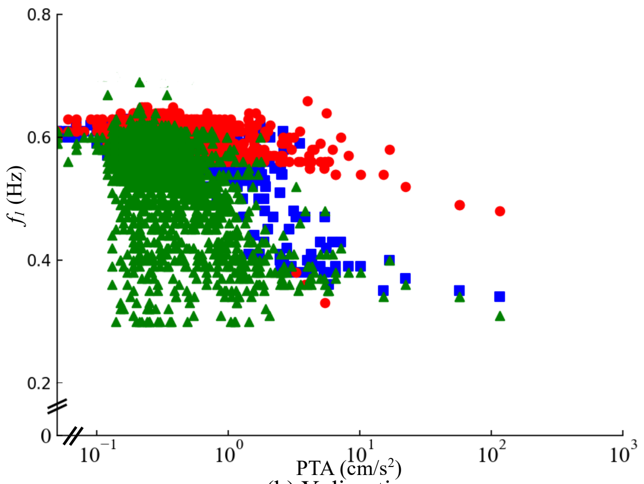
For fixed-base buildings, the natural frequency presents a full recovery after decreasing under weak motion, but with about 17% of permanent reduction under strong motion [3,4]. Some previous research on the SHM records around 2011 Tohoku earthquake in Japan have also confirmed that the natural frequency of fixed-base buildings couldn't be fully recovered [5,6]. In other hand, the long-term SHM results of seismically isolated buildings have rarely been mentioned. About this, Siringoringo and Fujino [7] reported that the 1st mode natural frequency of a base-isolated building could fully recover to its original level after 2011 Tohoku earthquake in about five months. However, their result was only obtained from one specific building. In this paper, the SHM records around 2011 Tohoku earthquake from another base-isolated building, J2 building, are used to analyze the recovery effect.

2. Monitoring records around 2011 Tohoku earthquake

As part I, the same system identification (SI) processes are conducted to 2808 earthquake response records of J2 building from February 17, 2009, to September 27, 2011, and the results of X and Y direction are summarized in Fig.1. In both figures, the horizontal axis means the absolute peak top floor acceleration (PTA), while the vertical axis means the 1st mode natural frequency. In Fig.1, the same conclusion can be obtained as that of part I, which is the 1st mode natural frequency of the entire building almost coincides with the isolation layer, and below that of the superstructure. Meanwhile, in all the three scenarios, the 1st mode natural frequency decreases when the PTA increases, and the slope of the decreasing tendency of the entire building is close to that of isolation layer, which is larger than that of the



(a) X direction



(b) Y direction

Fig.1 Summary of the 1st mode natural frequency superstructure. Overall, it may be said that the dependence on acceleration (PTA) of the entire building is close to that of isolation layer, and much higher than that of superstructure.

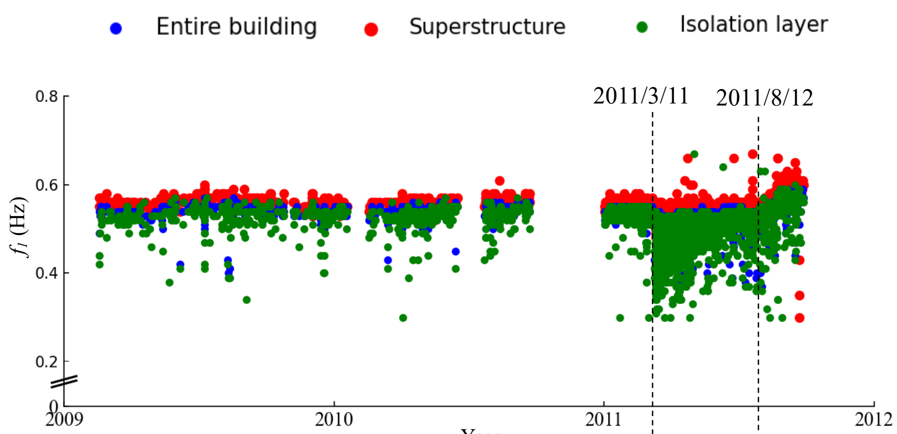
3. Elastic behavior of base isolated buildings

3.1. Variation of the natural frequency over time

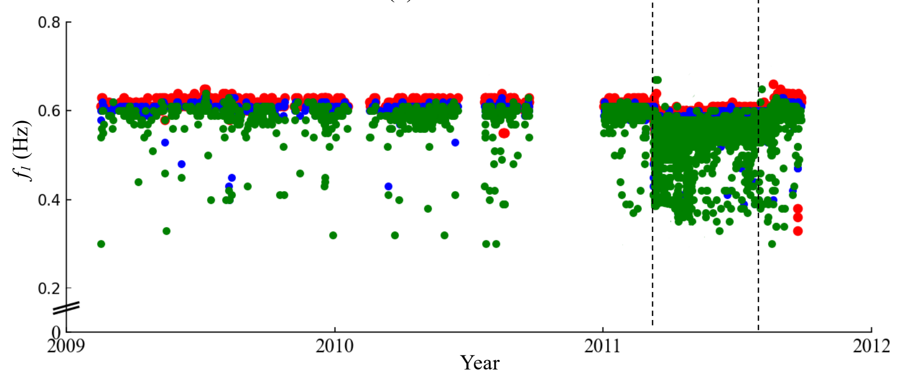
In Fig.2, the chronological variation of the 1st mode natural frequency of the J2 building in both the X and Y directions is presented. The time axis can be clearly divided into three distinct periods.

- The first period refers to the time before March 11, 2011, during which the 1st mode natural frequency remains essentially stable with minimal fluctuations. This period represents the pre-earthquake condition of the building, where the structural response was unaffected by any major earthquake.
- The second period begins on the date of the 2011 Tohoku earthquake, an Mw 9.0 major earthquake. During this period, which spans from March 11, 2011, to August 12, 2011, the 1st mode natural frequency shows a sudden and significant decrease. This drop reflects the immediate dynamic response of structure due to the strong ground motion. Notably, following this drop, the 1st mode natural frequency maintains a relatively stable level for approximately five months.
- The third period, starting after August 12, 2011, marks the phase of recovery. During this time, the 1st mode natural frequency exhibits a gradual increase, eventually returning to its original pre-earthquake value. This recovery highlights the adaptive behavior of base isolated buildings, where the natural frequency progressively stabilizes, reflecting the ability to restore its dynamic performance over time.

This behavior of base-isolated buildings is notably different from that of fixed-base buildings [5,6], where the natural frequency can't be fully recovered, but there will be some loss. Moreover, in each period, the changes in the 1st mode natural frequency of the entire building, superstructure, and isolation layer consistently follow the same trend. However, the 1st mode natural frequency values of the entire building are nearly identical to those of the isolation layer, and both are significantly lower than those of the superstructure. This observation aligns with the conclusions presented in Part I.



(a) X direction



(b) Y direction

Fig.2 The 1st mode natural frequency of the entire building changes over time

3.2. The dependence of natural frequency on acceleration

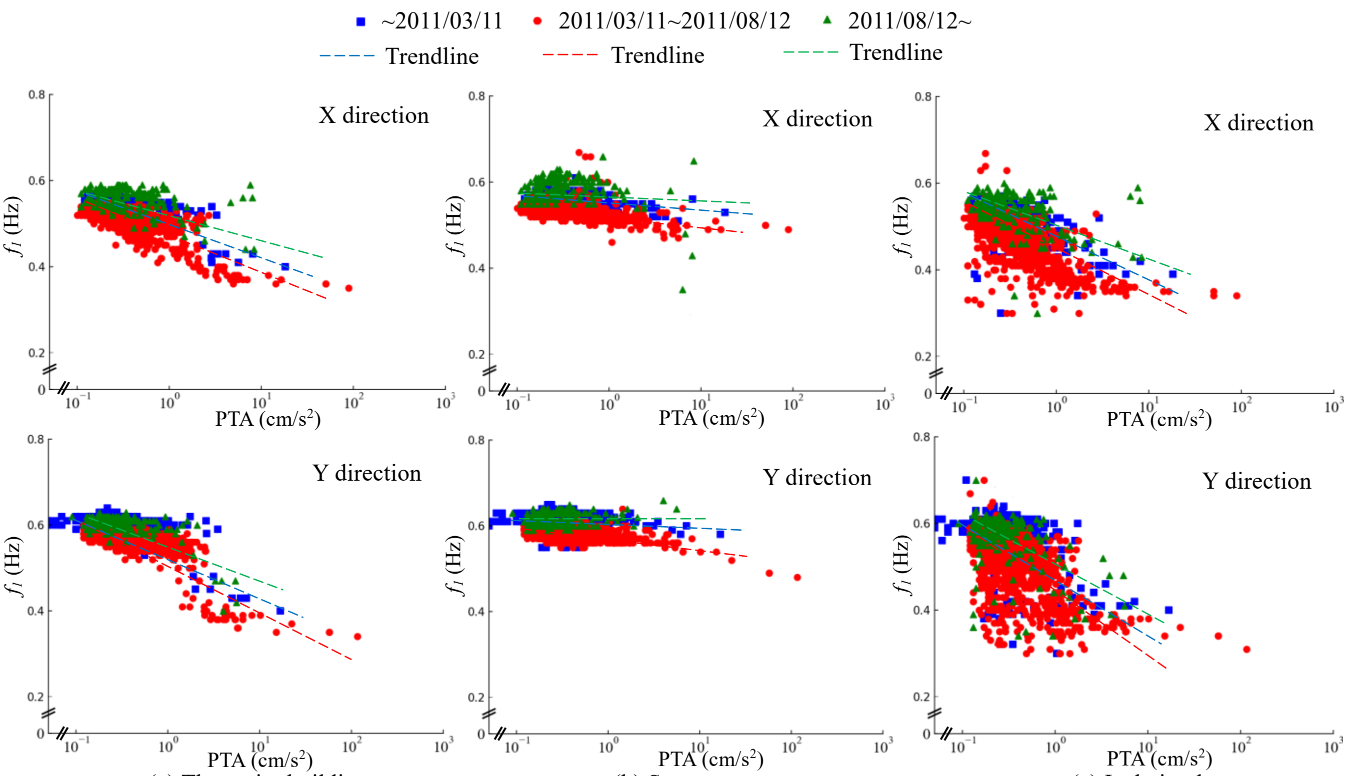
The variation in the 1st mode natural frequency across the three scenarios—the entire building, superstructure, and isolation layer—during different time periods is illustrated in Fig. 3. In each figure, the horizontal axis represents PTA, while the vertical axis denotes the corresponding 1st mode natural frequency. The plotted data provides a clear depiction of frequency-PTA relationship, which means how the 1st mode natural frequency depends on acceleration (PTA) during the various periods under study.

As shown in Fig. 3, the same conclusions as those presented in Chapter 3.1 can be drawn. After the 2011 Tohoku earthquake, the 1st mode natural frequency exhibits a sudden and significant decrease, indicating the immediate impact of the seismic event on the dynamic properties of the building. Within approximately five months, the 1st mode natural frequency demonstrates a full recovery, returning to its pre-earthquake levels. This recovery phase highlights the inherent resilience and adaptability of the base-isolated structure under severe seismic loading conditions.

In the case of the entire building, the behavior of the natural frequency provides additional insights into the dynamic response. During the 2nd period (immediately after the earthquake), the slope increases significantly from that of the 1st period (before the earthquake), indicating an elevated sensitivity to acceleration caused by the strong ground motion. This heightened sensitivity reflects the temporary decline in the dynamic performance of the building. Then, in the 3rd period (the recovery period), the slope decreases gradually, ultimately returning to a level beyond its original state before the earthquake. This trend illustrates that, while the building's dynamic characteristics were temporarily affected, they undergo a steady recovery over time, demonstrating the efficiency of the base isolation system in restoring performance.

A similar recovery process is observed for the isolation layer, which exhibits the dominant role of the isolation layer in governing the overall dynamic behavior of the base-isolated structure, highlighting its critical contribution to seismic resilience.

However, when focusing on the behavior of the superstructure in Fig.3, it is evident that the changes in the 1st mode natural frequency and acceleration dependence are significantly less pronounced compared to the entire building and the isolation layer. This observation can be attributed to the isolating effect of the isolation layer, which effectively decouples the superstructure from ground motion, drastically reducing the seismic forces transmitted to the upper levels of the building. Consequently, the dynamic response of the superstructure during and after the earthquake is less affected, resulting in smaller variations in its natural frequency and acceleration dependence.



(a) The entire building (b) Superstructure (c) Isolation layer

Fig.3 The 1st mode natural frequency in different time periods

This analysis highlights the critical role of the isolation layer in safeguarding the structural integrity and dynamic stability of the building. By absorbing and dissipating seismic energy, the isolation layer ensures that the seismic impact on the superstructure is minimized, allowing it to maintain its dynamic performance with minimal disruption. Moreover, the ability of the base-isolated system to facilitate a predictable recovery process underscores its effectiveness as a seismic protection strategy for high-rise buildings subjected to major earthquakes.

Through this study, we gain critical insight into the recovery effect of base-isolated high-rise buildings, which sets them apart from fixed-base buildings, underscoring the effectiveness of seismic isolation in sustaining structural integrity and ensuring a recovery of dynamical characteristics after major earthquakes. This observation underscores the critical role of the isolation layer in ensuring that the superstructure experiences limited disruption, thereby safeguarding its performance and contributing to the overall resilience of base-isolated buildings.

4. Conclusion

This paper presented an analysis of the 1st mode natural frequency of J2 building using long-term structural health monitoring (SHM) and the system identification (SI) procedures, examining three scenarios: the entire building, the superstructure, and the isolation layer. The response acceleration data utilized in this paper was recorded before and after the 2011 Tohoku earthquake, allowing for an investigation of the time-dependent recovery behavior of a base-isolated high-rise building following a major earthquake. The key findings are summarized as follows:

1) As a long-term monitoring result, the 1st mode natural frequency of the entire building of a base-isolated high-rise building closely matches that of the isolation layer and is notably lower than that of the superstructure.

2) In response to a major earthquake, the 1st mode natural frequency of a base-isolated high-rise building undergoes an immediate decrease, subsequently recovering to its original level within approximately five months.

3) In the cases of both the entire building and the isolation layer, the slope of the frequency-PTA relationship, which represents the acceleration dependence, exhibits a sudden and significant increase immediately after a major earthquake. Then, this slope gradually recovers within about five months, aligning with the recovery trends observed in the 1st mode natural frequency, but slightly exceed its original level.

4) When considering the superstructure, the frequency-PTA relationship does not exhibit a similarly pronounced change as the entire building and isolation layer. The dynamic behavior of the superstructure remains relatively unaffected, with minimal variation in its acceleration dependence even during and after the earthquake.

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