Proceedings of International Structural Engineering and Construction, 8(1), 2021
Interdisciplinary Civil and Construction Engineering Projects
Edited by El Baradei, S., Abodonya, A., Singh, A., and Yazdani, S.

ISSN: 2644-108X
www.doi.org/10.14455/ISEC.2021.8(1).STR-56

TREND OF SEISMIC RESPONSES OF EXISTING HIGH-RISE RC BUILDINGS

YUSUKE MAIDA[1], TOMOFUSA AKITA[2], and NOBUYUKI IZUMI[3]

[1]*Dept of Architecture and Building Engineering, Tokyo Institute of Technology, Meguro, Japan*
[2]*Dept of Architectural Design and Engineering, Yamaguchi University, Ube, Japan*
[3]*Graduate School of Engineering, Chiba University, Chiba, Japan*

This report presents studies on the seismic response of high-rise RC buildings in Japan. Data concerning the seismic response of approximately 600 high-rise RC buildings constructed from 1972 to 2015 were collected. Seismic response characteristics were analyzed by focusing on differences in seismic resistant structures, seismic response control structures, and seismic isolation structures. The results indicated that the maximum story drift ratio response under the level 1 study seismic ground motion (R_1) and the level 2 study seismic ground motion (R_2) criteria is smaller for seismic isolation structures than that of the seismic resistant structure and seismic response control structures. In addition, focusing on the R_2- R_1 relationship, the correlation is low in the seismic resistant and seismic response control structures, but is almost linear in the seismic isolation structure. This is because the seismic isolation structure is designed such that the superstructure does not become plastic even with level 2 seismic ground motion.

Keywords: Seismic resistant structures, Seismic response control, Seismic isolation, Seismic performance.

1 INTRODUCTION

In Japan, the first high-rise reinforced concrete (RC) building was built in 1972. Currently, more than 600 high-rise RC buildings are constructed. In high-rise RC buildings since the 2000s, structures using technologies such as seismic response control and seismic isolation have become mainstream. More high-rise and free-form high-rise RC structures can be realized by increasing the strength of concrete and reinforcement, and by developing seismic response control and seismic isolation technology.

The authors analyzed the structural characteristics according to the progress of the RC structural technology, divided into three design phases (the 1st phase: 1972-1989, the 2nd phase: 1990-1999, and the 3rd phase: 2000-) based on the data presented in the performance evaluation sheet (The Building Center of Japan 1972-2015), and reported mainly the seismic resistant structure in the data before 2006 (Izumi *et al.* 2009). In a previous report (Maida *et al.* 2018), data on approximately 600 high-rise RC buildings published from 1972 to 2015, in addition to the data generated since 2007, were classified as seismic resistant, seismic response control, and seismic isolation structures, and the structural characteristics were analyzed.

The purpose of this report is to grasp the tendency of seismic response for the data at the time of design of approximately 600 buildings presented from 1972 to 2015 in Japan. The data are classified as seismic resistant, seismic response control, and base isolation structures, and the tendency of seismic response such as base shear coefficient and response value by seismic response analysis is compared and analyzed.

The transition of the number of existing high-rise RC structures by seismic resistance, seismic response control, and seismic isolation structure is shown in Figure 1. The 1st to 3rd phases shown in the figure were defined as follows. The 1st phase (1972-1989) was when Japan's first high-rise RC building was constructed and its design and construction technology was established. In the 2nd phase (1990-1999), the development of high-strength RC structures was promoted through the "New RC Project" (Murota *et al.* 1994), and the application of seismic response control and seismic isolation structures to high-rise RC structures began in earnest. The 3rd phase (2000-2015) was when the demand for residential high-rise RC buildings increased in urban areas, and construction increased rapidly.

In the 3rd phase, more than half are seismic response control or seismic isolation structures. In the next chapter, the seismic responses will be compared and analyzed, focusing on the differences in seismic resistance, seismic response control, and seismic isolation structure. In this case, in order to exclude the influence of the difference in the number of construction buildings and the age of the design, only the data of the 3rd phase is used in the comparison by structure.

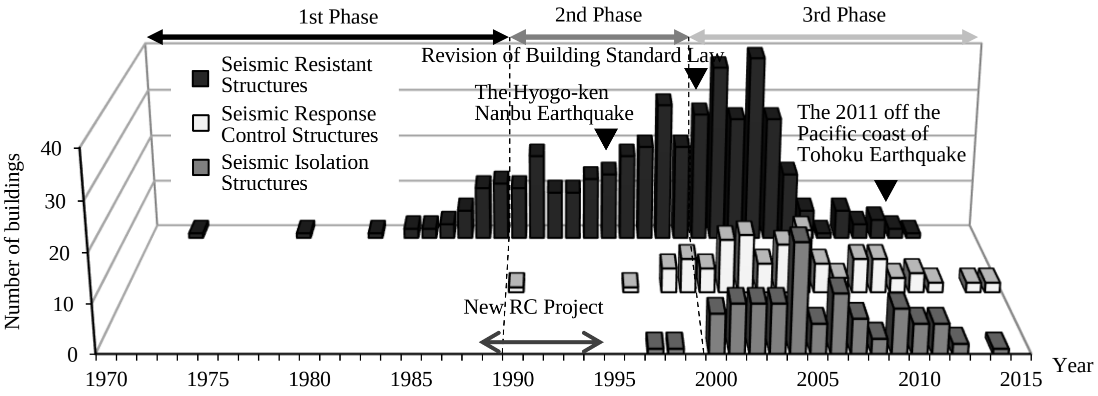


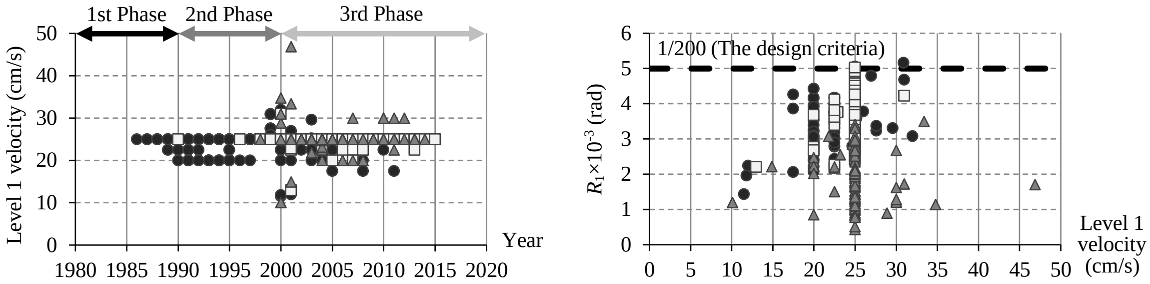
Figure 1. Transition of number of seismic resistant, seismic response control, and seismic isolation structures.

2 RESPONSE DURING THE DESIGN OF EXISTING HIGH-RISE RC BUILDINGS

In the seismic design of high-rise RC buildings, seismic response analysis is generally carried out for two-level seismic ground motion. There are two levels, level 1, which is a "rare earthquake," and level 2, which is an "extremely rare earthquake". In this chapter, the magnitude of the seismic ground motion for each level (maximum velocity) and response deformation are discussed.

2.1 Maximum Velocity and Maximum Story Drift Ratio of Level 1

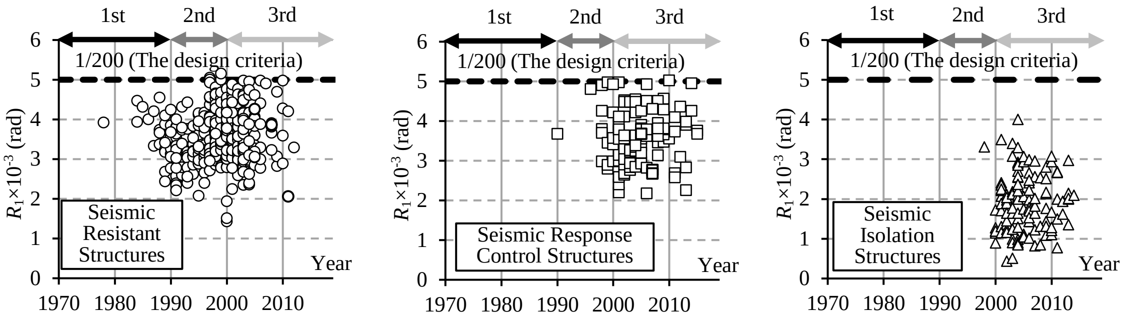
Figure 2 (a) shows the transition of the maximum velocity of the seismic ground motion used in the level 1 study (Level 1 velocity). Figure 2 (b) shows the maximum response story drift ratio for the level 1 study seismic ground motion (R_1) and Level 1 velocity relationship.



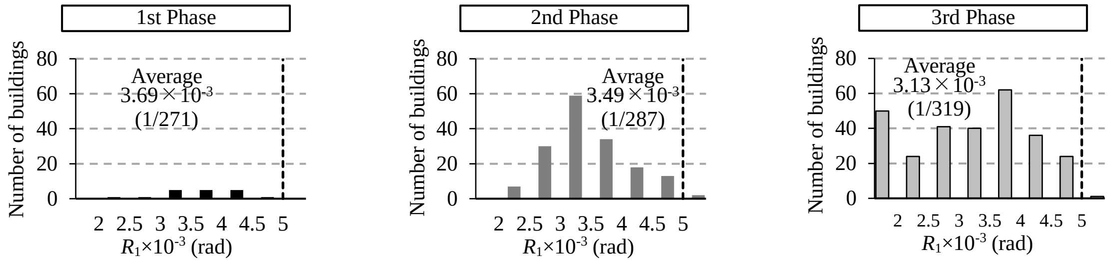
(a) Transition of Level 1 velocity.

(b) R_1- Level 1 velocity relationship.

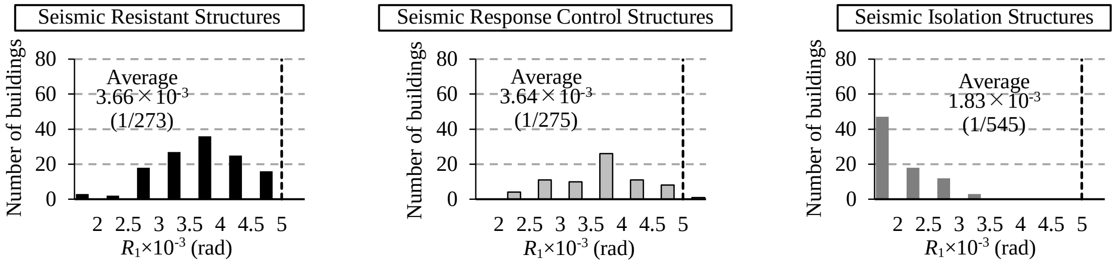
Figure 2. Transition of Level 1 velocity and R_1- Level 1 velocity relationships.



(a) Transition of R_1.



(b) Number of buildings and average value (each phase).



(c) Number of buildings and average value in 3rd phase (each structure).

Figure 3. Maximum response story drift ratio for level 1 study seismic ground motion.

In the 1st and 2nd phases (before 1999), 20-25 cm/s was used in many cases, but in the 3rd phase (after 2000), the Level 1 velocity showed variations. For the above reason, in the 1st and 2nd phases, the ground motions that were created by amplifying the actual observed seismic waveforms were used as the ground motions for the study. However, due to the revision of the Building Standards Law in 2000, the input seismic motion that should be considered in the design of high-rise buildings, etc., was stipulated by a notification by the Ministry of Construction. It can be seen that the seismic isolation structure uses a slightly higher velocity than the seismic resistant and seismic response control structures. From the R_1-Level 1 velocity relationship, in the seismic resistant and seismic response control structure, R_1 tends to increase with increasing velocity. On the other hand, in the seismic isolation structure, R_1 is suppressed to be small even if the Level 1 velocity increases.

Figure 3 (a) shows the transition of R_1 due to the difference in seismic resistance, seismic response control, and seismic isolation structure. Further, Figure 3 (b) shows the number of buildings and the average value by design age, and Figure 3 (c) shows the number of buildings and the average value by structure. In the figure, the broken lines indicate 1/200 rad, which is a general design criterion for Level 1 seismic ground motion.

In the case of the seismic resistant and seismic response control structures, R_1 is 1/500 to 1/200 rad in the majority of buildings regardless of the design age, but some buildings exceed 1/200 rad. In the case of the seismic isolation structure, R_1 is less than 1/250 rad. Comparing the average values of R_1, there is not much difference by the design age. The 1st phase is 1/271 rad, the 2nd phase is 1/287 rad, and the 3rd phase is 1/319 rad. It tends to decrease slightly as age increases. This is because the construction ratio of the seismic isolation structure increased as the age progressed. Comparing R_1 by structure, the seismic resistance and seismic response control structure is approximately 1/270 rad, and the seismic isolation structure is approximately 1/545 rad.

2.2 Maximum Velocity and Maximum Story Drift Ratio of Level 2

Figure 4 (a) shows the transition of the maximum velocity of the seismic ground motion used in the level 2 study (Level 2 velocity), and Figure 4 (b) shows the maximum response story drift ratio for the level 2 study seismic ground motion (R_2) and Level 2 velocity relationship.

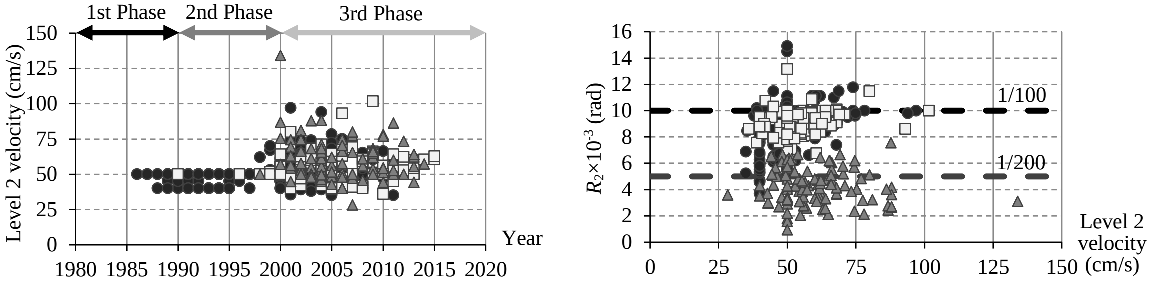
Before 1999, there were many cases in which 40 to 50 cm/s was used for Level 2 velocity. After 2000, a maximum velocity larger than 40 to 50 cm/s was used for the same reason as level 1 velocity. From the R_2-Level 2 velocity relationship, in the case of seismic resistant and seismic response control structures, R_2 tends to increase as the maximum velocity increases. There is no clear tendency in the seismic isolation structure.

Figure 5 (a) shows the transition of R_2 due to the difference in seismic resistance, seismic response control, and seismic isolation structure. Further, Figure 5 (b) shows the number of buildings and the average value by design age, and Figure 5 (c) shows the number of buildings and the average value by structure. The broken line in the figure shows general design criteria (Architectural Institute of Japan 2009).

In the seismic resistant and seismic response control structures, the design criterion for level 2 seismic ground motion is often the maximum story drift ratio of 1/100 rad, but in some cases R_2 exceeds that. In the seismic isolation structure, the design criterion for level 2 seismic ground motion is often the maximum story drift ratio of 1/200 rad, but in some cases, R_2 exceeds 1/200 rad. On comparing the average values of R_2, the difference by design age was found to be insignificant. When comparing R_2 by structure, the seismic resistance and seismic response control structure is approximately 1/110 rad, and the seismic isolation structure is approximately 1/234 rad. The percentage of cases that exceeded the general design criteria of R_2 was approximately 9% for seismic resistant and seismic response control structures and approximately 28% for seismic isolation structures.

2.3 Maximum Story Drift Ratio of Level 1 and Level 2 Seismic Ground Motions

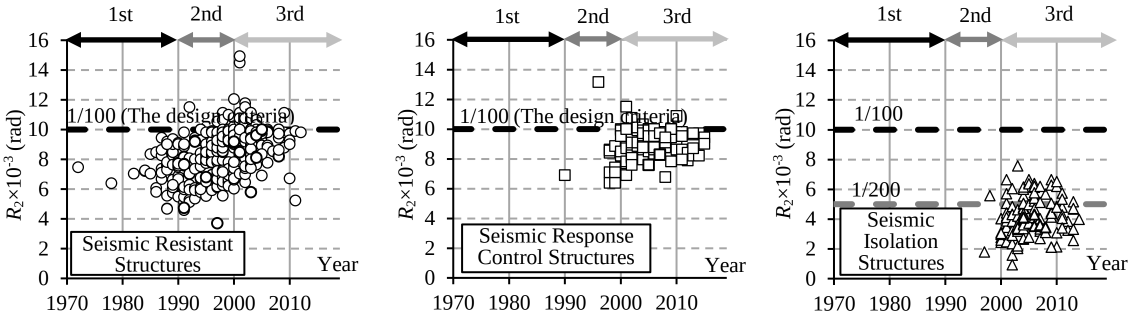
Figure 6 shows the R_2- R_1 relationship, which is classified based on seismic resistant, seismic response control, and seismic isolation structures. In the case of the seismic resistant and seismic response



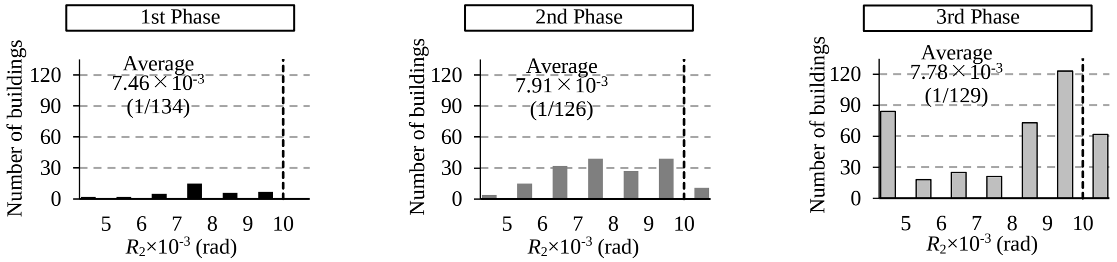
(a) Transition of Level 2 velocity.

(b) R_2- Level 2 velocity relationship.

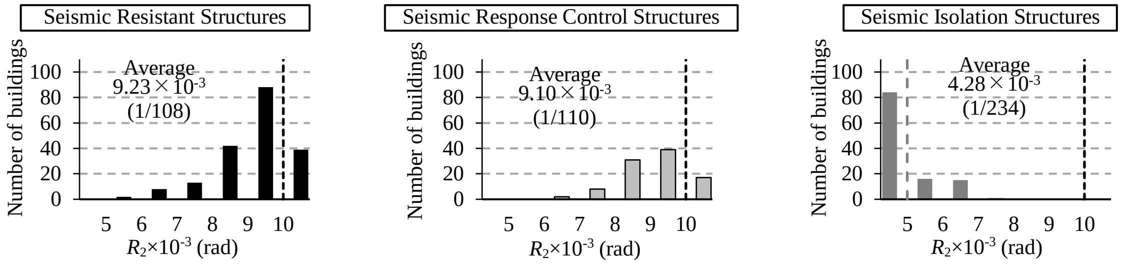
Figure 4. Transition of Level 2 velocity and R_2- Level 2 velocity relationships.



(a) Transition of R_2.



(b) Number of buildings and average value (each phase).



(c) Number of buildings and average value in 3rd phase (each structure).

Figure 5. Maximum response story drift ratio for level 2 study seismic ground motion.

control structures, the R_2- R_1 relationship is not a clear linear relationship. This is because there are many cases of R_2 of approximately 1/100 rad. On the other hand, in the seismic isolation structure, the R_2- R_1 relationship is almost linear. It is believed that the seismic isolation structure is designed to maintain the superstructure in the elastic range even for level 2 seismic ground motion. However, since there are many cases where R_2 exceeds 1/200 rad, it can be seen that the target deformation of the design is large in seismic isolation structure of RC high-rise building.

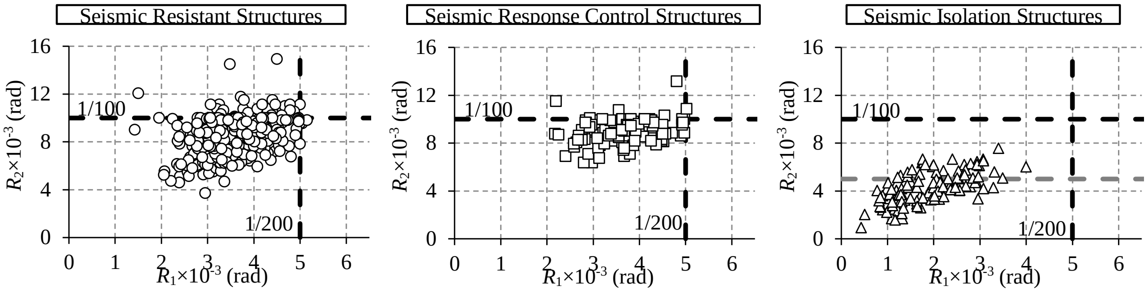


Figure 6. R_2- R_1 relationship.

3 SUMMARY

The data on approximately 600 existing high-rise RC buildings, published from 1972 to 2015, were classified as seismic resistant, seismic response control, and seismic isolation structures, and seismic response trends were compared and analyzed. Results obtained are summarized below.

(1) The average value of the maximum story drift ratio for level 1 seismic ground motion was approximately 1/270 rad for seismic resistant and seismic response control structures, and approximately 1/545 rad for seismic isolation structures.

(2) The average value of the maximum story drift ratio for level 2 seismic ground motion was approximately 1/110 rad for seismic resistant and seismic response control structures, and approximately 1/234 rad for seismic isolation structures. The percentage of cases that exceed the general design criteria of R_2 for seismic resistant and seismic response control structures (1/100 rad) is approximately 9%. The percentage of cases that exceed the general design criteria of R_2 for seismic isolation structures (1/200 rad) is approximately 28%, and the target design deformation is large.

(3) Focusing on the R_2- R_1 relationship, the correlation is low in the seismic resistant and seismic response control structures but is almost linear in the seismic isolation structure. This is because the seismic isolation structure is designed such that the superstructure does not become plastic even with level 2 seismic ground motion.

References

Architectural Institute of Japan, *State-of-the-Art Report on High-Strength Concrete*, 386-388, October, 2009.

Izumi, N., Kimura, H., and Ishikawa, Y., *Structural Characteristics of High-Rise RC Buildings in Japan*, Journal of Structural Engineering, Architectural Institute of Japan, 55B, 351-360, March, 2009.

Maida, Y., Makita, S., Nishina, T., and Izumi, N., *Structural Characteristics of Existing High-rise RC Buildings Classified as Seismic Resistant, Seismic Response Control, and Seismic Isolation Structure*, AIJ Journal of Technology and Design, 24(56), 171-176, February, 2018.

Murota, T., Aoyama, H., and Hiraishi, H., *History and Summary of New RC Project*, Concrete Journal, 32(10), 6-10, October, 1994.

The Building Center of Japan, *Building Letter*, 1-525, 1972-2015.