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Seismic Isolation and Response Control of Buildings in Japan

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Abstract An overview of seismic isolation and structural control in Japan is presented. The paper includes a mention of the history of aseismic technology and the earthquake threat in Japan, summarizes the merits of seismic isolation and response control, and discusses the types of devices used and some recent project examples. The projects presented are mostly examples of response control used for high-rise buildings. These types of buildings are not amendable to seismic isolation, and are a challenge to applying damping devices, as their high aspect ratio means that their dominant deformation mode is bending. Japanese engineers have developed a range of unique techniques to apply response control to these types of structures. Concluding remarks discuss some of the current challenges to expanding the use of seismic isolation and response control technologies.

Keywords Earthquake, Seismic isolation, Response control, Device, Society

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1. Introduction

Japan is faced with many natural hazard threats ranging from heavy rains, strong winds and typhoons to severe earthquakes. In particular, earthquakes represent the most serious threat, not only to structures but to entire cities and society as a whole. Research and technology development in Japan to counter the earthquake threat have taken place over more than one hundred years and many important achievements have been attained. Some of the original pioneering research was performed by Professor Toshikata Sano who, after detailed reconnaissance following the 1906 San Francisco earthquake, described earthquake forces as a percentage of gravity, and published his findings in 1916 (T. Sano 1916). The earliest study in the world that to attempt a detailed description of earthquake forces was that of M. Panetti after the 1908 Messina earthquake (S. Otani, 2003). Following Sano's work, in 1922 Professor Tanaka Naito published a study of shear walls to resist horizontal earthquake forces (T. Naito, 1922). This is considered to be the first description of the design of seismic structural members. A devastating earthquake hit Tokyo and the surrounding Kanto region in 1923, causing a huge amount of destruction to buildings. In the aftermath and recovery following the earthquake technologies to protect structures were desperately needed and the development of structural systems based on Sano and Naito's research was rigorously pursued.

Even for a structure designed for seismic loads, severe earthquake shaking beyond the design level will cause structural damage and, in some cases, even collapse. The idea to use eccentrically braced frame as designated "sacrificial members" and to concentrate damage in these members to protect essential, gravity-load carrying members was first proposed by Professors Fujimoto and Wada, et al. (M. Fujimoto, 1972). This approach was later given the name "damage control design" and the concept has gradually evolved into what is now referred to as response control using dampers.

Economic growth has led to the construction of buildings and infrastructure, including the increased construction of high-rise buildings, nuclear power plants and other critical structures and advanced structural engineering technologies have advanced extensively from the 1970s to the 1990s. Seismic isolation and response control technologies attracted significant attention starting



Figure 1. Residential house in Yachiyodai: The first seismically isolated building. (Courtesy of Tokyo Kenchiku SE Inc.)

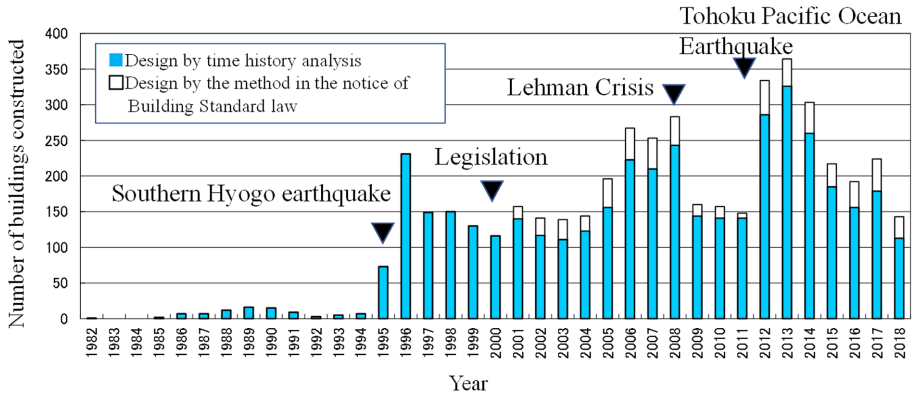


Figure 2. Progress of seismic isolation in Japan, by year.

in 1980s and the first seismically-isolated building in Japan, a single-family detached house, was constructed in 1982 (Fig. 1) (M. Sugiura, 1993). The house was supported on six rubber bearings and included a type of friction damper as part of the isolation system. Research on seismic isolation and response control increased and the technologies were slowly applied. However, the country had to experience the enormous damage of the 1995 Kobe earthquake to rapidly increase the rate of adoption.

Fig. 2 Progress of seismic isolation in Japan, by year.

The WEST building, or West Postal Saving Computer Center, a seismically isolated data center near Kobe, performed very well in the earthquake, being one of the few positive results amongst the many lessons of that disaster (K. Kawada, 1995). The good performance of substantially increased the awareness of seismic isolation in Japan and the number of buildings using isolation increased significantly in the years following the earthquake. The progress of seismically isolated building construction in Japan is shown in Fig. 2 with data compiled by the Japan Society of Seismic Isolation (JSSI hereafter) from its member companies. The 2011 Great Tohoku Earthquake also had a big impact on the adoption of isolation in Japan due to the many seismically isolated building that performed well in the earthquake.

Since its establishment in 1993, the JSSI has been active in exchanging information amongst its members and encouraging the use of seismic isolation and response control technologies and has contributed to Japan being one of the countries in the world with the largest number of seismic isolation and response control technology applications. Further, many Japanese structural engineers now understand that large and important buildings should utilize isolation or some form of response control technology for their seismic protection.

2. Earthquakes in Japan

Japan sits on the Eurasia, Amur and Okhotsk plates and is close to the Pacific and Philippine Sea plate subduction zones at the Japan Trench and Nankai Trough (A. Taira,

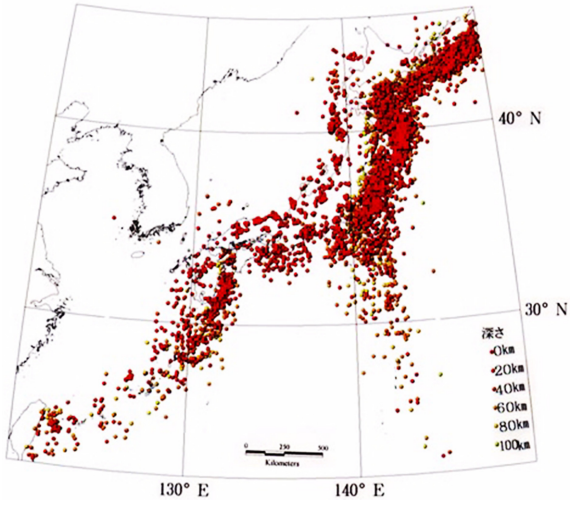


Figure 3. Earthquake epicenters around Japan, 1977-present.

2001). The epicenters of earthquakes recorded since 1977 are plotted in Fig. 3. It is seen that the area is dense with earthquake activity, being one of the most earthquake prone regions in the world. Earthquakes in Japan are caused both by intraplate faults and plate boundary movement in subduction zones.

In Japan the geology around intraplate faults is often dominated by deep soil sediments and these can result in significant amplifications of seismic shaking. Plate boundary subduction can cause very large earthquakes of very long duration, as was seen in the M9.0 Great Tohoku Earthquake. Although near-field effects associated with intraplate faults is not as severe in Japan as in California, nonetheless, Japanese structures must resist a wide range of different shaking and have robust structural systems to maintain safety.

3. Benefits of Seismic Isolation and Response Control

Japanese structures need to withstand various types of earthquake events. Structural systems that resist earthquake

forces by their strength and deformation (ductility) were studied and in 1980 code provisions were strengthened to ensure that structures would have sufficient strength to protect life safety. However, large earthquakes demonstrated that, even if human life is protected, there are many other issues associated with the large amount of structural damage that occurs. Building functionality was not maintained, building contents were not protected, and in many cases, buildings had to be demolished due to the severity of damage to their structural systems.

The seismic structural design approach called “damage control design” using eccentric braces?represented a new vision of seismic design whereby damage of structural elements was limited to specifically designated locations in the structural system. The original concept of damage-controlled design was based upon the plasticity of beams and girders, and the idea subsequently evolved into the concept of response control using dampers that replaced some of the braces and thus could avoid damage in columns and primary beams dramatically. Seismic isolation represents the highest level of seismic performance that can be achieved, by using isolation devices to entirely support the structure and decouple it from ground shaking. In the case of isolation introduced at the mid-height of a structure, the superstructure response above the isolation level is reduced, and in that part of the structure below the isolation level there may also be a moderate reduction of seismic forces.

The main benefits of seismic isolation system are to:

1. Reduce superstructure accelerations
   Seismic isolation utilizes isolation devices – the two main types being rubber bearings and sliding bearings – to support structures and to lengthen the horizontal natural period of the structure sufficiently to move it away from the highest earthquake spectral range, allowing the structure to avoid resonance and limiting the acceleration response.
2. Reduce superstructure story drifts
   The stiffness of the superstructure above the isolation level should be high relative to that of the isolation system itself. Preferably, the first natural period of the superstructure should be less than half that of the isolation system. This period separation ensures that design reduces the superstructure story drifts are sufficiently small to keep structural member forces within a good margin of their capacity. By limiting story drifts the deformations of non-structural members are also reduced along with damage to these elements.
3. Protect building contents and property
   Reducing acceleration responses substantially increases the protection of non-structural elements, building contents and property, by limiting overturning forces and reducing movement. This ensures that sensitive and expensive equipment in important buildings such as hospitals are protected against damage from seismic shaking.
4. Maintain building functionality
   Building functionality is achieved by the three benefits above.
5. Increase architectural design freedom
   By limiting the accelerations and story drifts in the superstructure, structural members can be made smaller compared to a conventional structure, and thus more freedom and opportunity can be achieved for architectural design.

One aspect to be considered in introducing seismic isolation is the need for a movement gap between the isolated building and the surrounding ground. If the necessary space for an isolation gap is not available, an alternative design approach is to use response control using dampers in the building superstructure. For this, and other reasons, most of the recent high-rise building construction in Japan has utilized response control. Although the performance of a response controlled structure is not be as high as that of an isolated structure, the use of dampers still has the following valuable benefit:

3.1. Reduce structure accelerations and story drifts

By including dampers in the structural system the overall structure damping is increased, which in turn better absorbs the seismic energy and reduces the level of structural response, both in terms of acceleration and deformation.

4. Main Types of Devices

The main types of devices used for seismic isolation are shown in Fig. 4 and those for response control in Fig. 5. Most seismic isolation bearings used in Japan are rubber bearings, but the use of sliding type bearings has increased in recent years. Hysteretic dampers are the most common type of damping devices for both seismic isolation and response control, and the use of oil dampers is increasing. The usage of the different types of devices for both technologies are shown in Fig. 6.

5. Recent High-rise and Retrofit Applications

The technologies of seismic isolation and response control are primarily intended for increasing the seismic performance of low- to medium-rise buildings. For higher height aspect ratio structures, however, different application techniques for the technologies are required because the structural deformations are dominated by flexural rather than shear behavior. The following project examples illustrate unique structural engineering solutions and, in many cases, also involved creative construction techniques. All of the buildings described received JSSI awards for design and construction using seismic isolation or response control technologies.

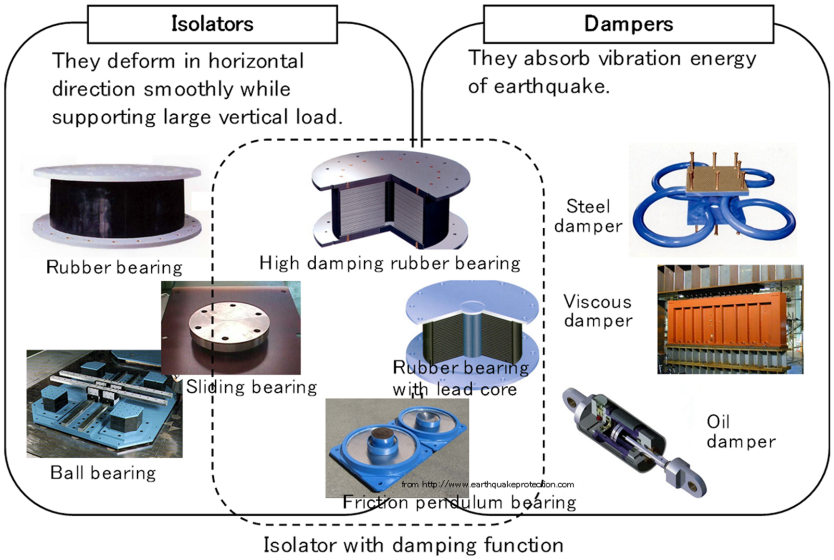


Figure 4. Types of seismic isolation devices used in Japan.

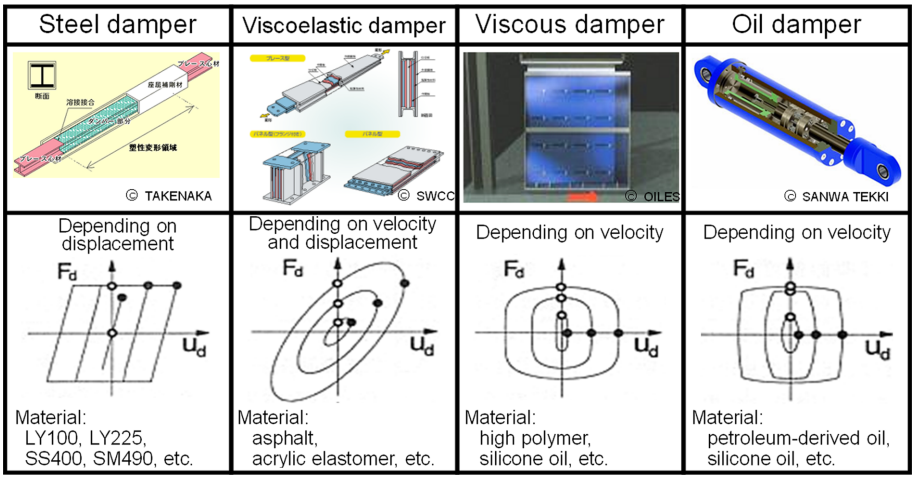


Figure 5. Types of response control devices used in Japan.

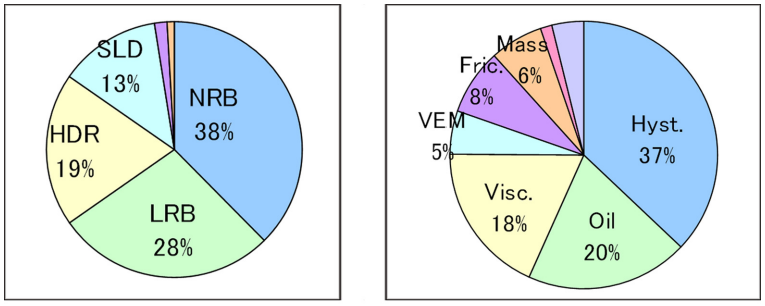


Figure 6. Device usage in seismic isolation and response control.

5.1. Nakanoshima Festival Tower

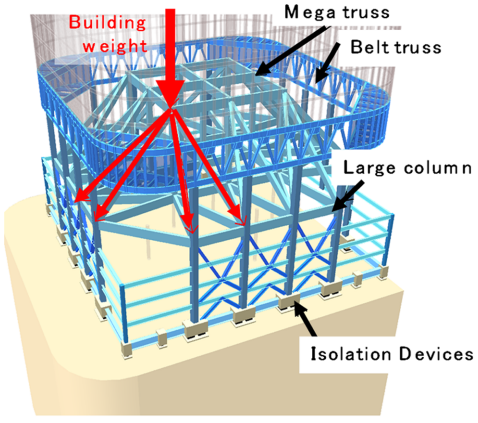
This building was designed by Nikken Sekkei and constructed by Takenaka Corporation Osaka in 2012 (Fig. 7). The building complex that incorporates a concert hall, offices, restaurants and medical facilities vertical arranged, with the overall name of "Festival Tower". The concert hall is located at the lowest level to maximize functionality. This layout, however, presented a significant challenge for the structural design since the concert hall represented a large volume in the center at the base of the structure requiring that the weight of the upper levels be transferred entirely to perimeter columns surrounding the concert hall. An added challenge was that the building had larger mass at the higher levels due to the density occupancy configuration. The designers chose to use mid-story seismic isolation to minimize the earthquake loads on the building. There was no available additional space around the building to allow for isolation and the associated movement clearance at ground level. The use of seismic isolation is one way to minimize bending deformations in of high-aspect ratio buildings. Implementing isolation at the ground or basement level will achieve the largest seismic performance benefit, but when not possible, mid-story isolation can still achieve significant benefits, by reducing shear forces in the lower level columns, and at the same time minimizing accelerations in the upper stories of the structure.

5.2. Ginza Itoya Building

This building was completed in Ginza, Tokyo in 2015. The project involved the complete replacement of an historic stationary store. Ginza is a traditional shopping area in Tokyo, with the buildings located on deep sites and with narrow street frontages. As is seen in Fig. 8, the building has narrow facade with a large height-to-width aspect ratio of 7. A rigid central pillar, or spine, was



Design: Nikken Sekkei
Construction: Takenaka
Building height: 199m

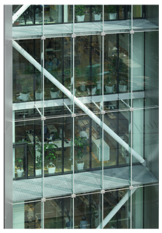


Devices: Rubber bearings

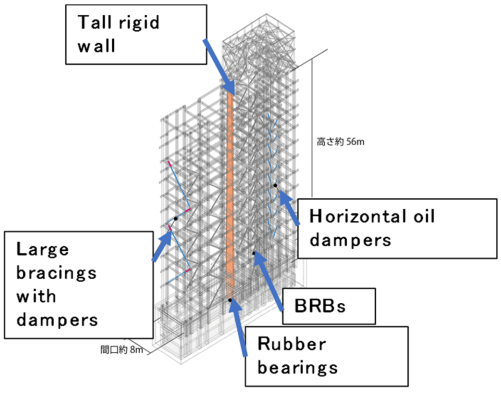
Figure 7. Nakanoshima Festival Tower.



Design: Taisei
Construction: Taisei
Building height: 56m



Exterior view of large bracings with dampers



Devices: Oil dampers, BRBs, Rubber bearings

Figure 8. Ginza Itoya Building.

introduced to minimize inter story drifts and to avoid concentrations of story deformation. Rubber bearings were also used for the connection between the central pillar and the foundation to minimize the stresses acting at the bottom of the pillar. Slender braces with oil dampers were integrated in the transparent, street-facing facade. Finally, a large mass foundation was utilized to minimize rocking in the transverse direction.

5.3. Shinjuku Sumitomo Building

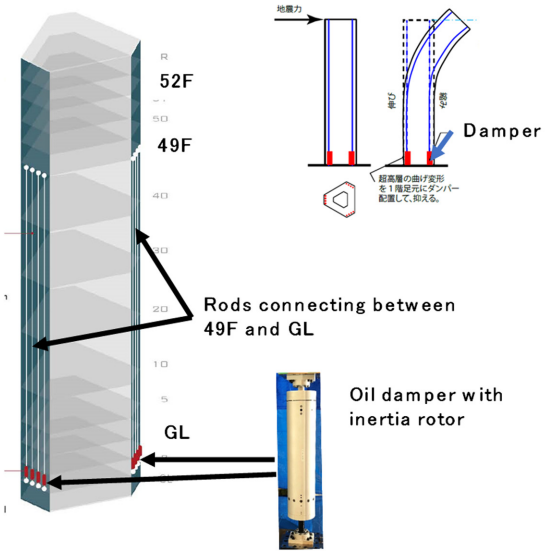
This building was originally completed in 1974 in the Shinjuku area of Tokyo (Fig. 9). It has 54 floors above ground and a height of 211 m. The structure was designed using dynamic analysis which was a state-of-the-art technology at the time. Recent seismological studies indicated that stronger earthquake shaking than the original design assumptions are expected, and the decision was made to retrofit the building. An innovative approach involving connecting the basement directly to the 49th floor level with 170m rods incorporating inertial rotors oil dampers was adopted increase the damping of the building and to reduce its flexural deformations. The building has a unique triangular plan with small maintenance areas at each corner, and the vertical rods are accommodated in these areas. The retrofit construction was completed in 2020.

5.4. Shinjuku Mitsui Building

Another unique method to enhance the seismic performance of existing very tall buildings is to use tuned mass



Original design: Nikken Sekkei
Retrofit design: Nikken Sekkei
Original construction: Kajima, Takenaka, Sumitomo



Devices: Oil damper includes inertia rotor

Figure 9. Shinjuku Sumitomo Building.



Original design: Nihon Sekkei
Retrofit design: Kajima
Original construction: Kajima, Mitsui
Retrofit construction: Kajima
Building height: 225m



Mass weight: 300ton x 6 = 1800ton (total)
Restoring system: Pendulum
Devices: Oil damper

Figure 10. Shinjuku Mitsui Building.

dampers, (TMDs), located at high level of the building. Tuned mass dampers are usually used to reduce vibrations induced by wind excitation but were utilized to improve the seismic performance of the Shinjuku Mitsui Building (Fig. 10). This building was originally constructed in 1974 and the need to retrofit to withstand strong and long-period earthquake shaking was recently identified. Six 300 ton masses were suspended on 8 m long cables each allowing two directional horizontal movement. Each mass was also connected to the building with four 2 m stroke oil dampers. The six pendulums were designed with their natural period equal to that of first mode of the building. The total weight of 1800 tons, being 3% of the total weight of the building was large enough to control the building response under earthquake excitations. By using a sufficiently large mass, the TMDs are able to control earthquake induced vibrations. The TMDs can control the response of the building, regardless of whether it is dominated by flexural or shear behavior, since they are installed at the top of building, where the movement is largest. The TMDs were located at the roof level and the retrofit construction was undertaken without requiring any relocation of the building occupants during the work. The retrofit construction was completed in 2015.

5.5. Kagawa Prefectural Office East Building

This building, designed by Kenzo Tange and completed in 1958 (Fig. 11), is regarded as one of his architectural masterpieces and was designated as Japanese National Important Property in 2021. The east building is 43 m high. The building has been well maintained, and the original architectural aesthetics are nicely preserved. Fortunately, the region has experienced no large earthquakes since the time of the building's construction. A seismic assessment in 1997 concluded that the building was seismically inadequate, and the prefectural office undertook a comprehensive evaluation of strengthening options, with special consideration of how to preserve the architectural aesthetics and maintain the building's function to the community. Seismic isolation was selected as the most appropriate upgrade scheme in 2014, and the retrofit construction work was completed in 2019. The seismic isolation devices were installed under the building, and this required ground improvement and the installation of steel piles under existing footings to avoid stress concentrations or damage to the superstructure during the construction. A large mat slab was introduced at the bottom of the excavation to integrate and strengthen both the high-rise and low-rise portions of the building complex together. The two buildings are now connected by new foundation beams to ensure that they move together above the isolation devices.

6. Discussion

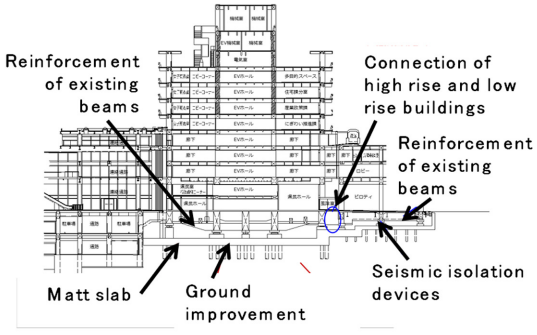
An overview of the state of the art of seismic isolation and response control technologies in Japan has been presented. These technologies have become widely understood and used in Japan. However, the number of buildings with seismic isolation is still only 5%, by means of total floor area of buildings constructed by 2023. Seismic isolation and response control technologies offer the highest levels of seismic performance to protect human life, building structures and their contents, property, and to maintain societal function, and should be used more widely. The following are some of the ongoing challenges faced to expand the use of these technologies:

1. The number of engineers experienced with seismic isolation and response control and who can design, construct, and maintain these types of structures needs to be increased.
2. Improve design methods for seismically isolated and response controlled structures.

   The design of seismically isolated and response



Original design: Kenzo Tange, Yoshikatu Tuboi
Retrofit design: Obayashi, Matsuda Hirata
Original construction: Obayashi
Retrofit construction: Obayashi, Suga
Building height: 43m



Devices: Rubber bearings, Sliding bearings

Figure 11. Kagawa Prefectural Office Building.

controlled buildings is generally performed using nonlinear time-history analysis methods, which while sophisticated are time-consuming and expensive. Simplified design methods, which are easier for more engineers, and also less expensive and time-consuming require further development and acceptance.

3. Increase awareness of the merits of seismic isolation among architects.
   Seismic isolation and response control are widely accepted as "good aseismic design approaches" to achieve a high level of seismic protection for structures. When structures utilize these concepts, architectural freedom is increased, and more creative architectural designs are possible even in earthquake prone regions. To realize this benefit, better awareness of these technologies by architects is needed.
4. Expand the use of the technologies to smaller cities.
   By addressing challenges 1 to 3 above, the use of seismic isolation and response control can grow beyond large cities and across the country.
5. Increase international collaboration.
   Japan is one of the countries in the world that has most extensively applied seismic isolation and response control technologies. These technologies need to be used more worldwide and Better international collaboration to share and exchange information is needed.
6. Maintain high quality in the design, manufacturing, and project delivery process.
   As the number of projects using seismic isolation and response control grew in Japan, quality issues arose in some areas. In particular, some device manufacturers could not properly handle the large demand and short-cuts were taken in manufacturing and testing that sacrificed quality. Engineers and authorities are still working to address and eliminate these issues. As the use of the technologies expands worldwide, countries should be vigilant in ensuring similar problems do not re-occur.

Seismic isolation and response control technologies are widely understood to be the best methods to minimize the seismic effects on structures. Engineers around the world should be encouraged to adopt these technologies with full awareness of these implementation challenges.

7. Conclusions

Seismic isolation and response control technologies have evolved significantly over recent decades and are now mature and well understood for widespread application to many types of structures. These technologies are currently the best methods to achieve the highest level of seismic structural protection nonetheless, even wider knowledge of design, construction and long term maintenance is required to ensure effective and safe application.

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