Geoenvironmental Disasters

REVIEW Open Access

Review on seismic isolation and response control methods of buildings in Japan

Yutaka Nakamura[1*] and Keiichi Okada[2]

Abstract

This manuscript reviews seismic isolation and response control methods of buildings, which are able to make buildings resilient against earthquakes and have become popular during the last three decades in Japan. Seismic isolation is a method of protecting a building from major earthquakes by installing isolators and energy absorbing devices under the superstructure. The manuscript describes three types of laminated rubber bearings and three kinds of damping devices. Seismic isolation provides not only structural safety, but also safety and security for people and properties in the building. Seismic isolation is also used for the retrofit of historic buildings. Response control methods utilize various kinds of dampers that are installed into a building and absorb vibration energy. The manuscript explains three foremost response control dampers: the steel hysteretic damper, the viscoelastic damper and the viscous fluid damper. The effects of seismic isolation and response control methods were verified through shaking table tests, structural health monitoring and earthquake response analyses.

Keywords: Seismic isolation, Response control, Isolator, Laminated rubber bearing, Damper, Retrofit, Health monitoring

Introduction

The world earthquake map in Fig. 1 shows the tectonic plates and the epicenters of past earthquakes. Many earthquakes occur along the boundaries when the plates interact. The Great East Japan Earthquake occurred on March 11 in 2011. A magnitude-9 earthquake shook northeastern Japan, and the savage tsunami caused a lot of damage. About 20,000 people tragically lost their lives due to the earthquake. As shown in Fig. 2, we should protect people's lives, which is the fundamental principle without question. Next, we should protect people's property, their assets and belongings, not to mention houses, buildings, and infrastructures. Also, we should protect our economic activities. If our economic activities stop or collapse due to an earthquake, our daily lives become difficult, which is sure to disturb the post-earthquake rehabilitation.

Recently, 'Business Continuity Plan' (BCP) has become a buzzword in the field of disaster prevention. The modern society is connected and mutually dependent domestically and internationally. Information, logistics and currency go round the earth twenty-four-seven. So, if any supply chain is broken and the distribution stops functioning, our economy or business will suffer a great loss. BCP is a plan to continue business operations if the society is struck by disaster. In order to reduce the damage caused by a natural disaster and keep our business and life, we must create a 'Resilient Society', as shown in Fig. 3. Suppose that the ball is our society, and the hand is the natural environment that surrounds the society. Sometimes the natural environment attacks the society as a natural disaster. The hand can grasp the ball firmly and crush it. However, once the attack is over, the ball can return to its former shape immediately. This is the ideal performance of a 'Resilient Society'. We cannot prevent natural disasters, but we can design and build a 'Resilient Society' using technologies.

This manuscript reviews seismic isolation and so-called passive-type response control methods of buildings, which are able to make buildings resilient against earthquakes and have become popular during the last three decades in Japan. The mechanism and the devices of the two methods are described with the results of tests or analyses and the observed earthquake responses.

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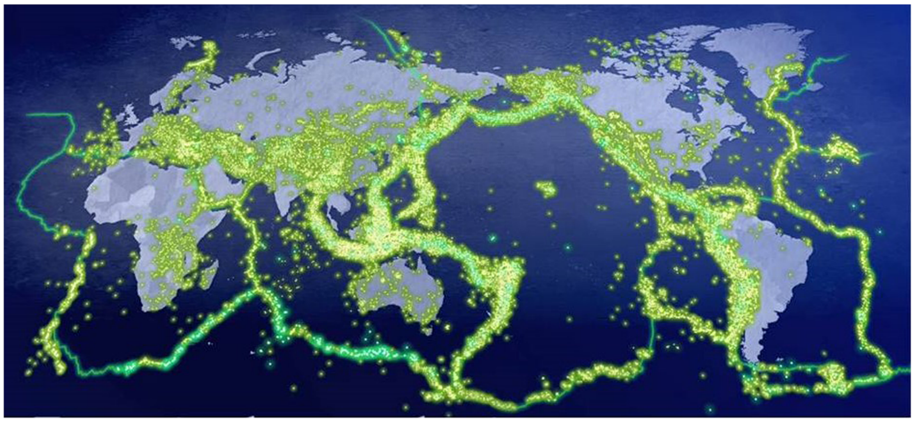

Fig. 1 World Earthquake Map

Seismic isolation method for buildings

Mechanism and seismic isolation devices

Seismic isolation is a method of protecting a building from major earthquakes by installing isolation devices under the building, as shown in Fig. 4. The seismic Isolation method has been studied and applied into buildings since the 1980's. For the conventional earthquake-resistant design, the columns and beams are designed to be strong and flexible enough to withstand earthquake motions. The vast majority of buildings are designed and built by this method. When a conventional building is subjected to a severe earthquake, the building can manage to avoid a collapse and save the occupants' lives. However, the furniture and equipment inside the building will most likely fall down and the structural elements may suffer severe damage (Fig. 4).

Isolation devices are installed under the building, and decouple the structure from the earthquake motions. Seismic isolation can reduce the shaking of the building dramatically. The seismic isolation method has become possible through the development of laminated rubber bearings. Figure 5 shows a cross-sectional view of a laminated rubber bearing. The rubber bearing consists of multiple layers of thin rubber sheets and reinforcing steel plates, and has very low horizontal stiffness. Figure 6 shows the widely-used seismic isolation devices. In the seismic isolation method, energy absorbing devices need to be installed together with laminated rubber bearings to decrease the deformation of the bearings during an earthquake. A lead-rubber bearing consists of layers of rubber and steel, around a core of solid lead plug in the center of the bearing. The lead plug serves as an energy absorbing device. A high damping rubber bearing uses special rubbers to supply significant damping to dissipate the energy caused by motion.

The seismic isolation methods can be divided into two types based on the location of the isolators (Fig. 7). One is called 'Base isolation' where isolators are installed at the base of the structure. The other is called 'Mid-story isolation' where isolators are installed at a level higher in the superstructure. Figure 8 shows a mid-story seismic isolated building (Nakamura et al. 2009). The building stands 80 m in length and 20 m in width, and the ground floor serves as an open space. One laminated rubber bearing is installed at each top of six big columns in the ground floor.

Fig. 2 Necessary protection against earthquakes

Effects and applications of seismic isolation method

Figure 9 shows the comparison of two furnished rooms set on a shaking table respond to an earthquake motion. One room is in a seismic isolated building. The other is in a conventional building. The image on the upper left shows the response of the room in a seismic isolated building. The image on the lower right shows the response of the room in a conventional building. In the conventional building, tableware in the cupboard fell down to the floor. On the contrary, little was damaged in the seismic isolated building, as the structure moved less forcibly. The seismic isolation method provides not

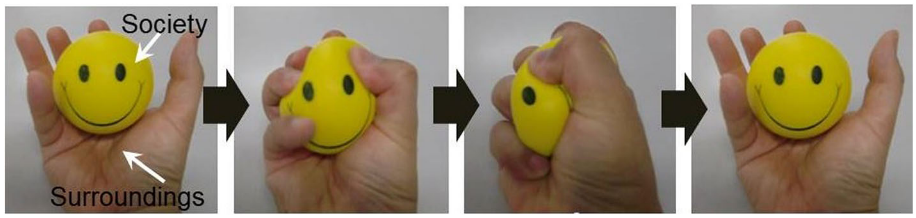

Fig. 3 Resilient Society: quick and fully recovery from natural disasters

only structural safety, but also safety and security for people and properties in the building.

Structural health monitoring is a technology for examining the health of buildings by using various kinds of sensors. It allows daily health examination and damage monitoring following earthquakes. Figure 10 shows the sensors that are installed in the mid-story seismic isolated building (Fig. 8) for the monitoring of the status (Okada et al. 2009).

When the Great East Japan Earthquake occurred on March 11, 2011, the sensors successfully recorded the isolator's behavior. The upper left figure in Fig. 11 shows the observed behavior of the rubber bearing, and the upper right figure shows the locus of the horizontal deformation of the rubber bearing. The maximum deformation of the rubber bearing was about 9 cm. The lower figure in Fig. 11 shows the observed acceleration waves on the ground and the second floor in the isolated structure. The maximum acceleration on the second floor was reduced to about half compared to that on the ground. These observed data clearly shows the effects of seismic isolation (Nakamura et al. 2011).

Figure 12 shows the number of seismic isolated buildings in Japan from 1982 to 2015 according to the survey by the Japan Society of Seismic Isolation (JSSI). The numbers includes seismic isolated hospitals, condominiums, and office buildings, but they do not include single-family houses. The application of seismic isolation increased dramatically in 1995. Obviously, the 1995 Kobe Earthquake triggered off the application. The blue line indicates the accumulating totals. At present, the number of seismic isolated buildings exceeds 4000.

Seismic isolation retrofit

Seismic isolation retrofit is a kind of earthquake-proof renovation where the isolators are installed into the basement of an existing building. Seismic isolation retrofit is an ideal way to preserve buildings of historical or cultural significance.

The National Museum of Western Art in Tokyo was originally designed by Le Corbusier, a great architect in the twentieth century, and constructed by Shimizu Corporation in 1958. This museum was renovated by using the seismic isolation retrofit in 1998 (Fig. 13). The National Museum of Western Art in Tokyo was the first building in Japan that used the seismic isolation retrofit (Saito et al. 2013). The lower left figure in Fig. 13 shows the sectional view of the original museum, and the lower right figure shows the one after the seismic isolation retrofit. The museum's seismic safety was upgraded a lot while maintaining its original design.

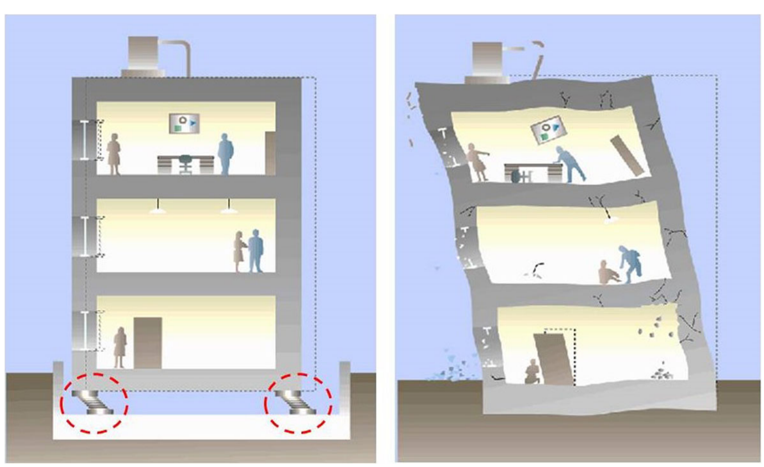

Fig. 4 Seismic isolated structure vs. conventional earthquake-resistant structure

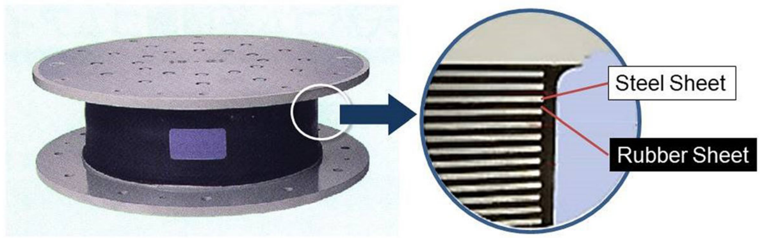

Fig. 5 Laminated rubber bearing

Figure 14 shows the construction process of seismic isolation retrofit. First, we excavate the foundation ground under the existing building and drive piles into the excavated places. These piles can support the weight of the building temporarily during the construction. Second, we excavate the remaining ground, and we cast concrete over a level surface in the excavated area. Third, we install seismic isolators beneath the footing of the building. Finally, we remove the piles. At this point, the building is fully supported on the isolators, and all of the retrofitting work is done.

Response control method for buildings

Configuration of response control method

The manuscript reviews so-called passive-type response control methods that utilize various dampers or energy-dissipation devices to make buildings resilient against earthquakes (Kasai et al. 2008, 2009). Figure 15 shows the configuration of response control dampers which are installed into a building and absorb vibration energy. Just like seismic Isolation, response control methods have been developed since early 1980’s. Response control methods are mostly applied to high-rise buildings in order to reduce earthquake responses.

Foremost response control dampers

Various kinds of response control dampers have been developed and applied into buildings, and new kind of damping devices are under study to improve the response control effects. The manuscript reviews three foremost response control dampers: steel hysteretic damper, viscoelastic damper and viscous fluid damper.

Figure 16 shows a steel hysteretic damper using low-yield strength steel. The steel hysteric damper consists of a low-yield strength steel plate inserted between a pair of steel channels that prevent the plate from buckling. Steel hysteric dampers are installed in a brace configuration as shown in Fig. 16.

Figure 17 shows a viscoelastic damper utilizing high-damping rubber (Nakamura et al. 2016). The high-damping rubber is inserted between steel plates. When the building is subjected to an earthquake, the inner high-damping rubber suffers shear deformation and can absorb vibration energy. The absorbed energy is converted into heat. Then, the temperature of the high-damping rubber goes up by a few degrees during the excitations.

Figure 18 shows a viscous fluid damper, or so-called oil damper. The viscous fluid damper is essentially made up of a cylinder filled with hydraulic fluid and a piston

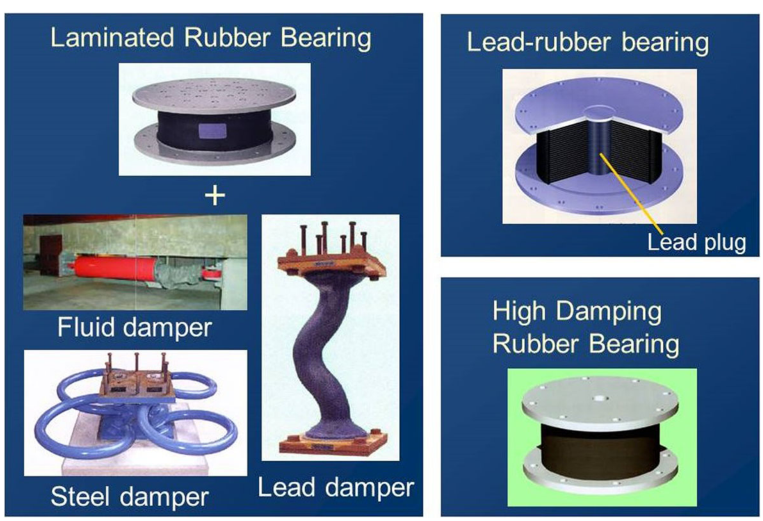

Fig. 6 Seismic isolation devices

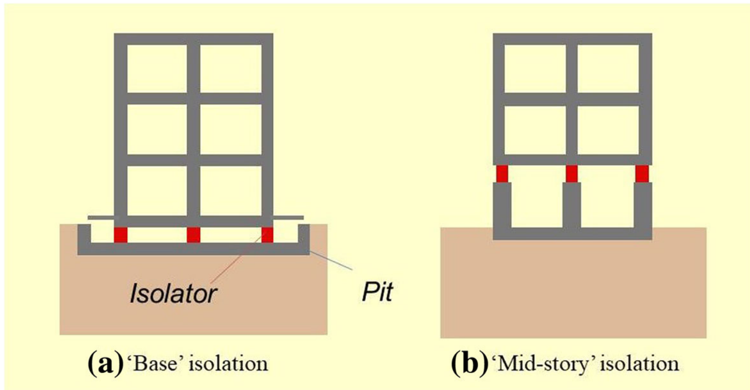

Fig. 7 Comparison of two furnished rooms set on a shaking table

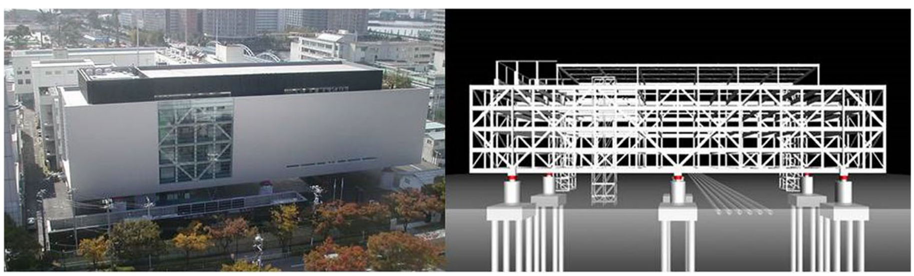

Fig. 8 Variations of seismic isolation method

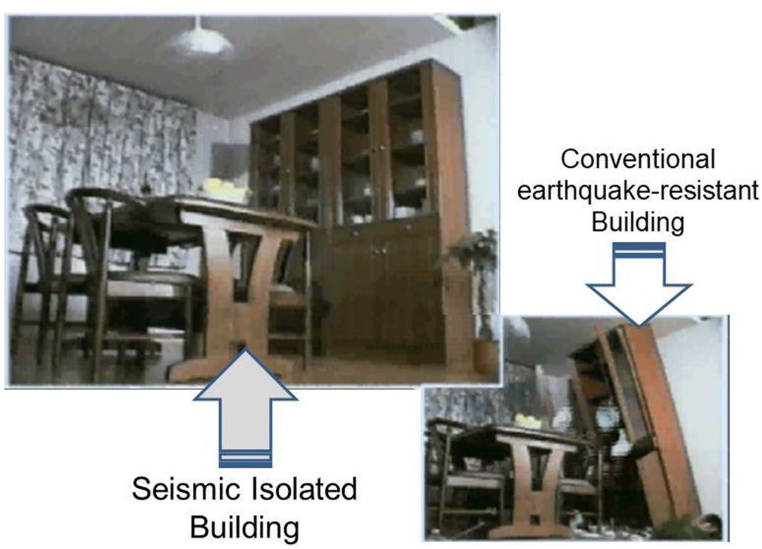

Fig. 9 Mid-story seismic isolated building (Main building of Shimizu Institute of Technology)

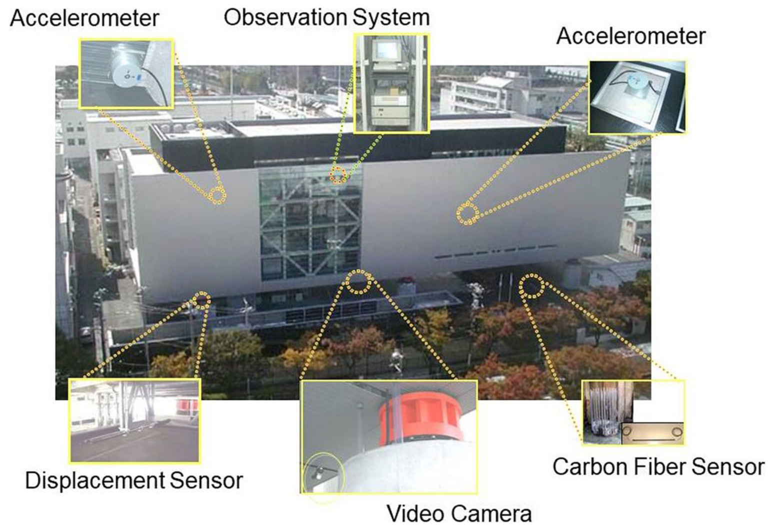

Fig. 10 Structure health monitoring

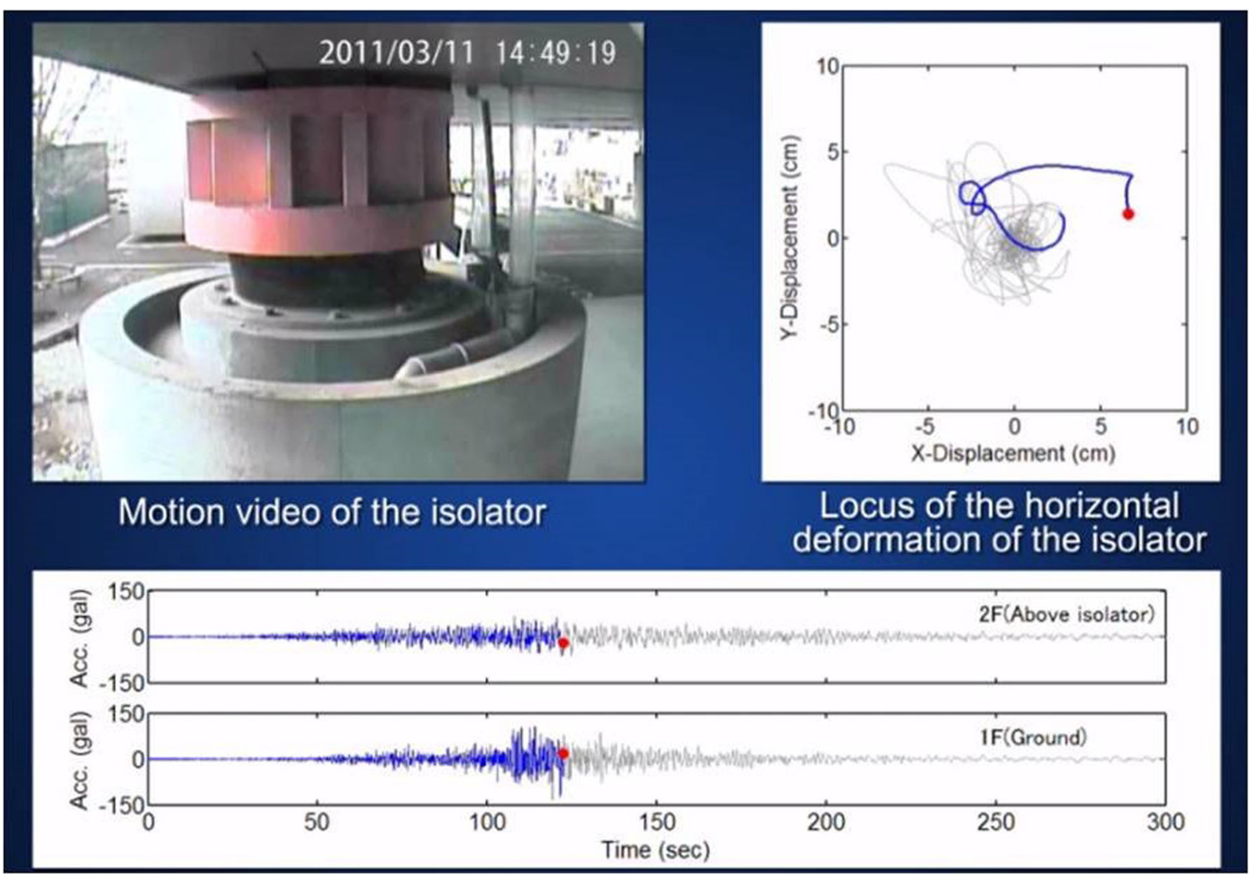

Fig. 11 Observational data from the 2011 Great East Japan Earthquake

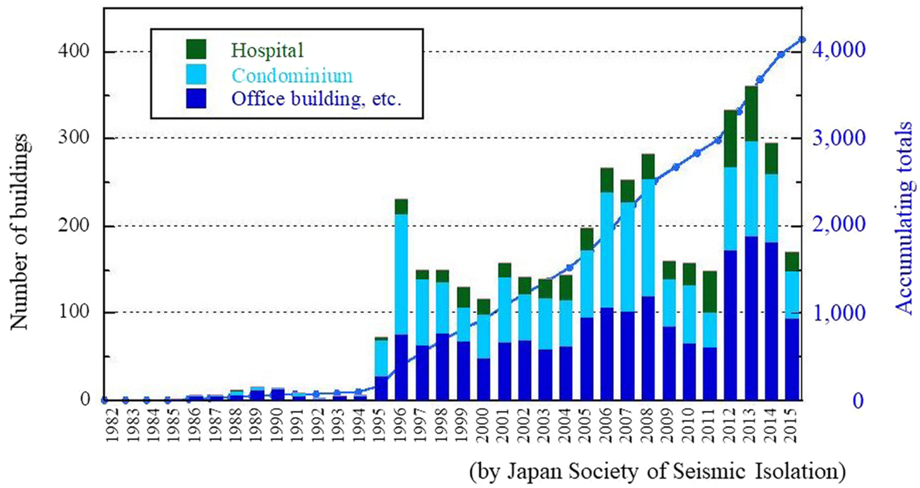

Fig. 12 Application of seismic isolation method in Japan

free to move in both directions. Hydraulic fluid flows from one chamber to the other through the valve by the motion of a piston. The flow of fluid through the valve causes energy dissipation.

Effects and applications of response control method

Figure 19 shows the results of earthquake simulation analysis of a 50-story high-rise building with and without viscoelastic dampers. The left is a 50-story building with dampers, and the right is one without dampers. When an earthquake motion shown below attacks the two buildings, the responses increase gradually. The response of the building without dampers becomes larger and larger, and eventually reaches the level where the furniture and equipment most likely fall down. Yellow and red color indicates the floor whose earthquake response reaches the dangerous level. Compared to the building without dampers, the response of the building with dampers is much smaller and remains under the safe level.

Figure 20 shows the number of response controlled buildings in Japan up to 2015 according to the survey by JSSI. Every year, around 50 to 100 response controlled buildings are constructed. The blue line indicates the accumulating totals. At present, the number of response controlled buildings exceeds 1300 in Japan.

Conclusions

Our society should protect not only people's lives, but also their property, houses, social infrastructure and economic activities against earthquakes. Seismic isolation

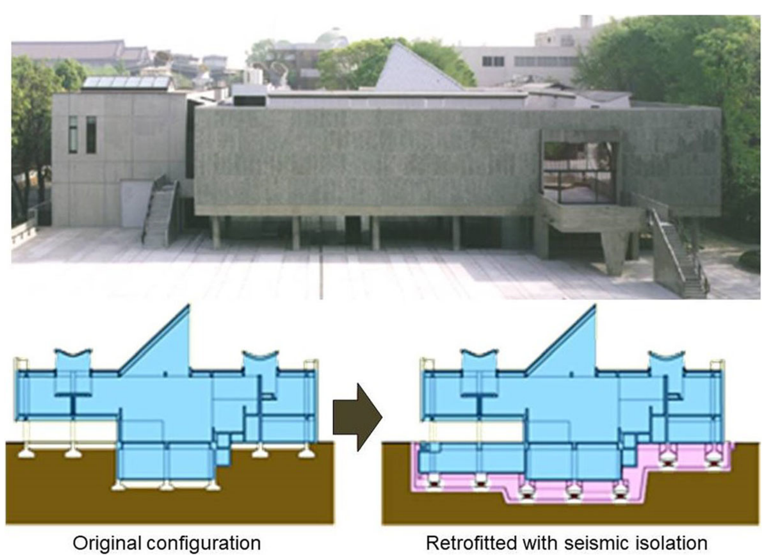

Fig. 13 Seismic isolation retrofit of the National Museum of Western Art

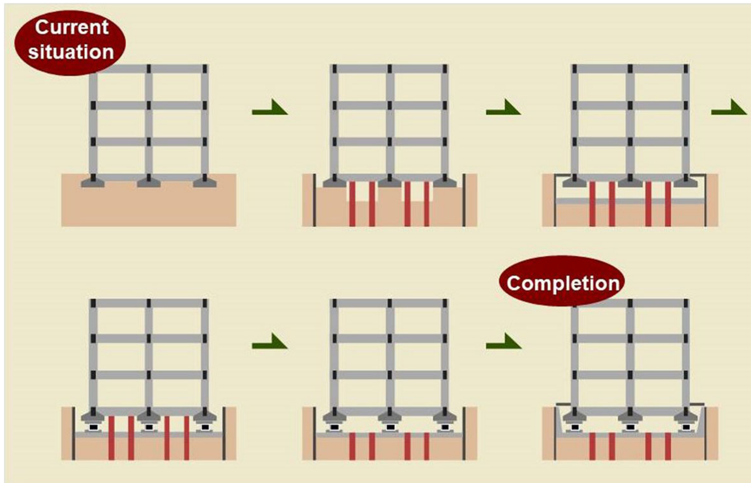

Fig. 14 Construction process of seismic isolation retrofit

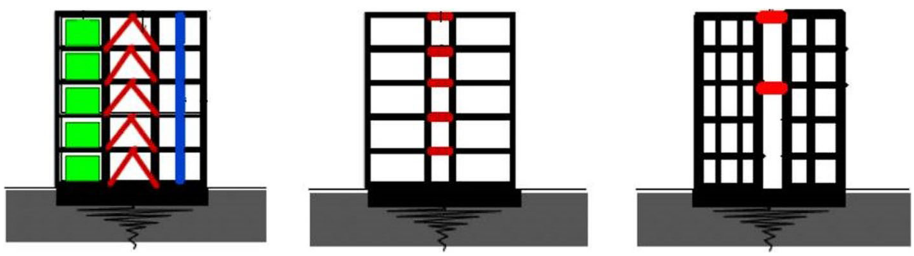

Fig. 15 Configurations of so-called passive-type response control method

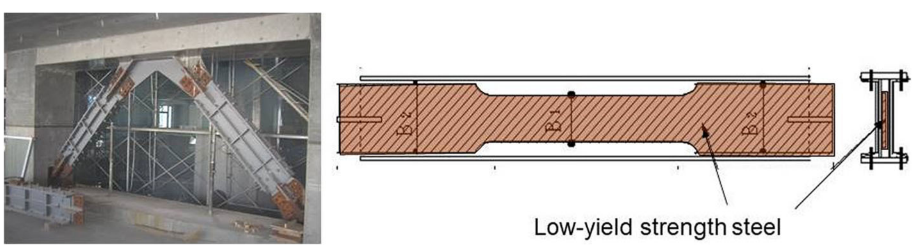

Fig. 16 Steel hysteretic damper using low-yield strength steel

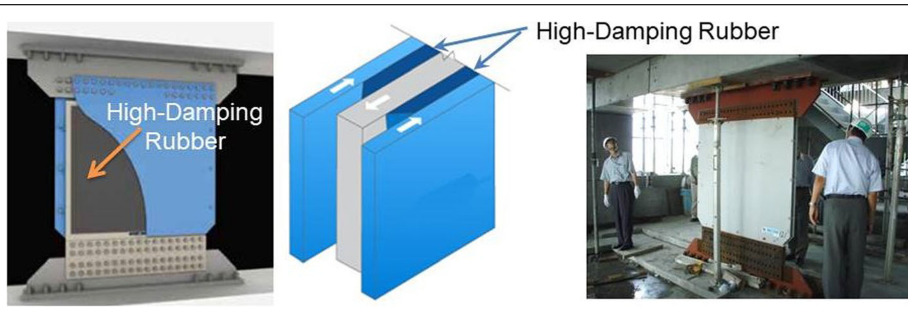

Fig. 17 Viscoelastic damper using high-damping rubber

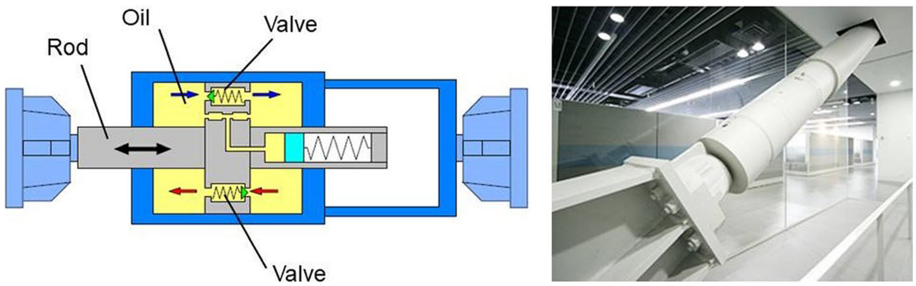

Fig. 18 Viscous fluid damper

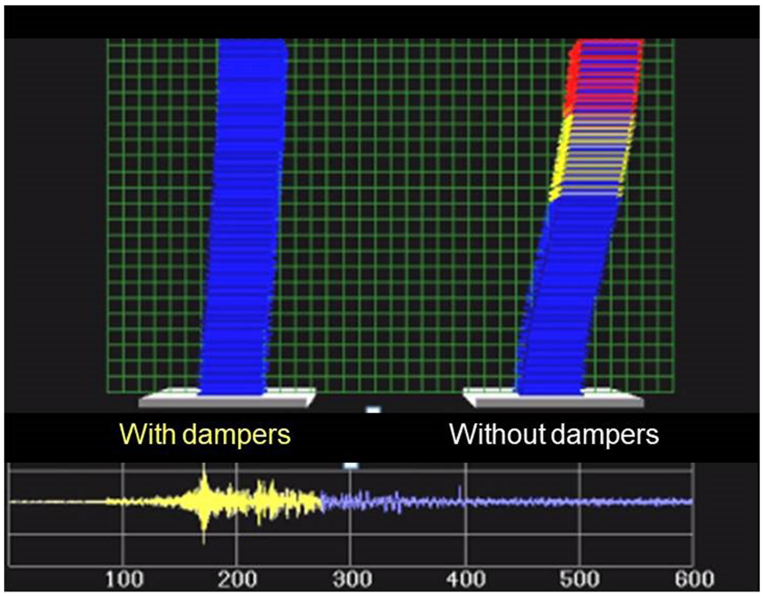

Fig. 19 Earthquake simulation analysis of a 50-story building with and without viscoelastic dampers

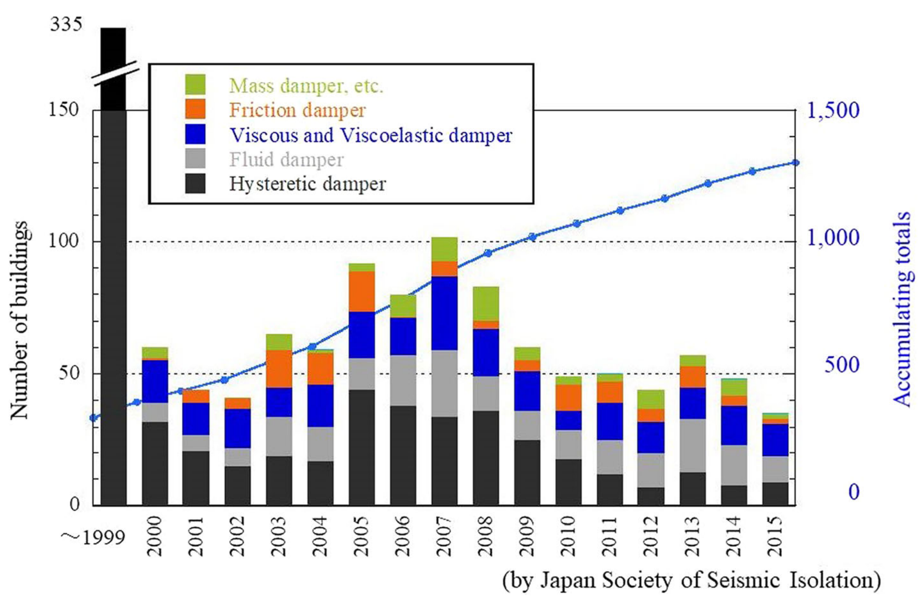

Fig. 20 Application of Response Control Methods in Japan

and response control methods of buildings have been studied and applied into buildings since the 1980's to make buildings resilient against earthquakes.

Seismic isolation is a method of providing structural safety and security for people and properties in the building against earthquakes by installing isolators and damping devices under the superstructure. The manuscript describes three types of laminated rubber bearings and three kinds of damping devices. Seismic isolation is also used for the retrofit of historic buildings. The National Museum of Western Art in Tokyo was the first building in Japan that used the seismic isolation retrofit.

Response control methods utilize various kinds of dampers that are installed into a building and absorb vibration energy. The manuscript explains three foremost response control dampers: the steel hysteretic damper, the viscoelastic damper and the viscous fluid damper. Response control methods are mostly applied to high-rise buildings in order to reduce earthquake responses.

The effects of seismic isolation and response control methods were verified through shaking table tests, structural health monitoring and earthquake response analyses. The number of seismic isolated buildings exceeds 4000, and the number of response controlled buildings exceeds 1300 in Japan. New technologies and methods are under study to improve the response reduction effects, and the application steadily increases.

Abbreviations
BCP: Business Continuity Plan; JSSI: The Japan Society of Seismic Isolation

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