Engineering xxx (xxxx) xxx

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Views and Comments

Higher Performance Seismic Structures for Advanced Cities and Societies

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1. Introduction

Tokyo, one of the largest cities in the world, is the capital of Japan, a heavily earthquake-prone country. The Japanese population and much of its functionality are highly concentrated in Tokyo. The estimated damage to Tokyo as a result of future large earthquakes with a magnitude greater than the Japanese scale 7 is extremely high. The number of casualties could exceed 20 000 due to both the shaking itself and post-earthquake fires. The number of stranded workers, students, and others unable to return home due to failures in long-distance commuting lines would be as high as 8 million. The number of buildings likely to collapse or burn is estimated at 610 000. The economic loss, including the effect of the decrease in productivity and services, could be as high as 95 trillion yen, which is nearly equivalent to the Japanese annual general account budget [1,2].

Like Tokyo, many large cities and other societies exist in the world that are vulnerable to catastrophic damage from large earthquakes. Advanced modern cities and societies must be more sustainable and resilient in order to reduce earthquake damage, which may be comparable to that described above for Tokyo. To achieve this goal, structures must be more reliable.

Structures can be subjected to strong shaking during major earthquakes, although such earthquakes are very rare. This shaking can cause structural components to become detached from each other, and the structure can break apart. Consequently, the structure could lose vertical load-carrying capacity and collapse. The fall of heavy disintegrated structural components can cause the death of residents and neighbors. Such phenomena have been observed in several types of building structures in past large earthquakes—typically in old wooden, reinforced concrete (RC), and masonry buildings that collapsed in Kumamoto, Japan (2016), Haiti (2010), Gorkha, Nepal (2015), Sichuan, China (2008), L'Aquila, Italy (2009), Amatrice, Italy (2016), and Puebla, Mexica (2017). The collapse of these brittle structures directly caused the injury and death of many people. Although the United States has not experienced a large earthquake since Northridge (1994), a significant number of brittle structures still exist, and risk of their collapse remains. Even moderate earthquakes can be devastating in regions where the earthquake risk is considered to be relatively low and there is inadequate awareness of earthquake risk. Therefore, efforts to improve the structural performance of such brittle structures are continuously needed.

Scientists and engineers have developed seismic design technologies to reduce structural collapse. First, structures have been designed to maintain their integrity in large earthquakes. These technologies include the connections in wooden houses, the wooden frames in masonry structures, hoops in RC columns, strong-column weak-beam design theory, and the prevention of connection failure in steel structures. Second, a ductile structural design approach has been adopted. Plastic deformation of structures in large earthquakes can absorb seismic energy and prevent structural collapse. The application of this seismic design philosophy has significantly integrated structural components and prevented structural collapse, which has saved human lives. In fact, the number of buildings that have collapsed in large earthquakes in Japan has been dramatically reduced in buildings designed after the enforcement of seismic design regulations that require an evaluation of structural ductility. However, many well-designed buildings that experienced excessive plastic deformations in large earthquakes have had to be demolished because they sustained damage in their primary (gravity-load-resisting) structural elements such as columns, beams, and joints. Residents do not usually realize that damage is expected in the structural design of a building after an earthquake, and do not want to continue living in damaged buildings. Therefore, there is a need for a new structural design approach in which damage in the primary structure is avoided by separating it from the seismic structure that will carry earthquake lateral loads and absorb the seismic energy. Passively controlled structures and seismically isolated structures are effective for this purpose and should be more commonly used.

2. Brittle structures

Most of the critical damage and structural collapse from earthquakes have been observed in brittle structures, which have limited ductile deformation capacity against lateral forces. With no appreciable ductile deformation capacity, a brittle failure in an element or connection can trigger failures in other elements or connections. This chain of brittle failure can lead to overall structural failure or collapse.

https://doi.org/10.1016/j.eng.2018.11.023

Structures are often constructed in a brittle manner due to a lack of knowledge or awareness of earthquake risk, and/or due to budget constraints. Fig. 1 shows an unreinforced masonry building that failed in the Gorkha earthquake in Nepal in 2015. Bricks became detached in unusual directions under strong shaking during this major earthquake, causing the building to fall apart. Similar damage has been observed in many other earthquakes including those in L'Aquila (Fig. 2), Haiti, Sichuan, Amatrice (Fig. 3), and Puebla. Masonry structures have been widely adopted in many regions in order to take advantage of their ease of construction, which allows bricks to be laid without the use of large construction machines. However, the strength of the connections between the bricks is typically insufficient to resist strong shaking during major earthquakes. Possible countermeasures include installing wooden frames or reinforcement (Fig. 4) and strengthening the mortar cement. Many of these buildings are non-engineered and have been constructed without the proper involvement of structural engineers. Although the seismic strength of such masonry buildings varies widely, and its assessment is difficult, greater involvement of structural engineers is needed.

Fig. 5 shows masonry buildings that were damaged by the Great Kanto Earthquake in Japan in 1923. Since the end of the 19th century, Japan had imported many technologies in various scientific and engineering fields from Western countries. Using this imported technology, new masonry buildings were constructed. However, the Great Kanto Earthquake revealed the weakness of these masonry structures against earthquakes, because the technology had been initially developed in less earthquake-prone countries.

Fig. 1. Unreinforced masonry building damaged in the Gorkha earthquake in 2015 [3].

Fig. 2. Collapsed masonry buildings in the L'Aquila earthquake in 2009 [4].

Fig. 3. Collapsed masonry buildings in the Amatrice earthquake in 2016.

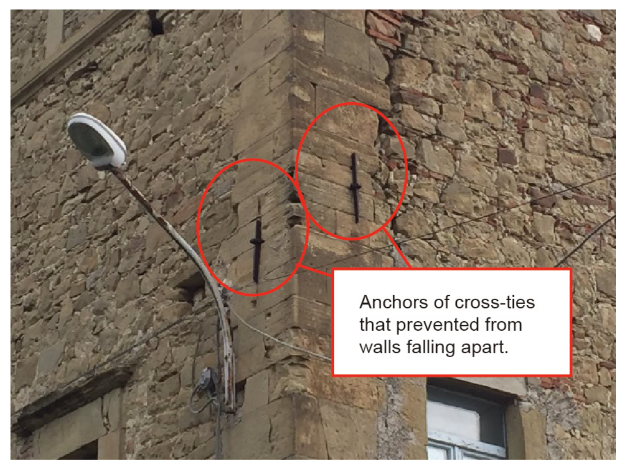

Fig. 4. Surviving masonry building with cross-tie reinforcement in the Amatrice earthquake.

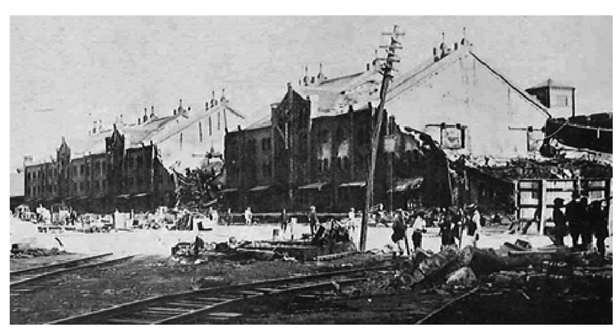

Fig. 5. Masonry buildings damaged in the Great Kanto Earthquake in 1923 [5].

Since masonry buildings were found to have suffered significant damage during the earthquake, RC structures without brick infill walls became more popular. Their high level of fire resistance was welcomed after experiencing the post-earthquake fire that had burned down broad areas of Tokyo. Although RC structures tend to be less brittle, it was revealed in the Great Hanshin Earthquake (1995) that they could still fail in a highly brittle manner.

Fig. 6 shows RC columns that lost their vertical load-carrying capacity after loss of confinement of the core concrete due to insufficient hoop spacing and end hooks. Before the Great Hanshin Earthquake, design provisions on the hoop spacing had been revised to 100 mm or less; however, buildings constructed before the revision were damaged in the manner shown in Fig. 6.

Steel is a type of ductile construction material and steel structures can be ductile; however, inadequate detailing or construction may cause such structures to experience brittle failure under large earthquakes. Fig. 7 shows brittle failure in steel structures that occurred in the Great Hanshin Earthquake. The welding at beam-to-column connections had failed and anchor bolts had ruptured. Connection detail requirements were revised after this earthquake.

Most houses in Japan are wooden, and many of these old wooden houses are non-engineered. Fig. 8 shows a failure of connections between columns and beams. The collapse of wooden houses caused more than 90% of the casualties in the Great Hanshin Earthquake. More than 20 years later, the Kumamoto earthquake occurred in 2016. Fig. 9(a) shows a failure between a wooden column and the sill. As Figs. 8 and 9(a) show, certain aspects have not been improved over the last 20 years in the field of structural engineering. Connection failures still lead to the collapse of houses (Fig. 9(b)).

In order to avoid brittle failure, which may directly cause injury and death, structures are designed to maintain their integrity during large earthquakes. In brittle failure modes, structural components become physically detached, which is associated with an immediate loss of connecting strength in earthquakes. Therefore, it is necessary to either make the components ductile or allow alternative ductile components to fail. Improvements have been made in the details of connections in wooden houses, wooden framing in masonry structures, hoops in RC columns, strong-column weak-beam design theory, and the prevention of connection failure in steel structures. The fragmentation and falling of heavy structural components can directly cause casualties. Structures must therefore be able to resist gravity loading, even after experiencing strong shaking during large earthquakes.

Fig. 8. Connection failure of a wooden house in the Great Hanshin Earthquake in 1995 [8].

Professor Yoshikatsu Tsuboi (1907–1990), a leading space structural engineering researcher, expressed his impression in a conference on the structural damage of the earthquake that occurred near Izu-Oshima in 1978:

Seismic engineering research has been developing all over the world, and most of it focuses on the magnitude of lateral forces

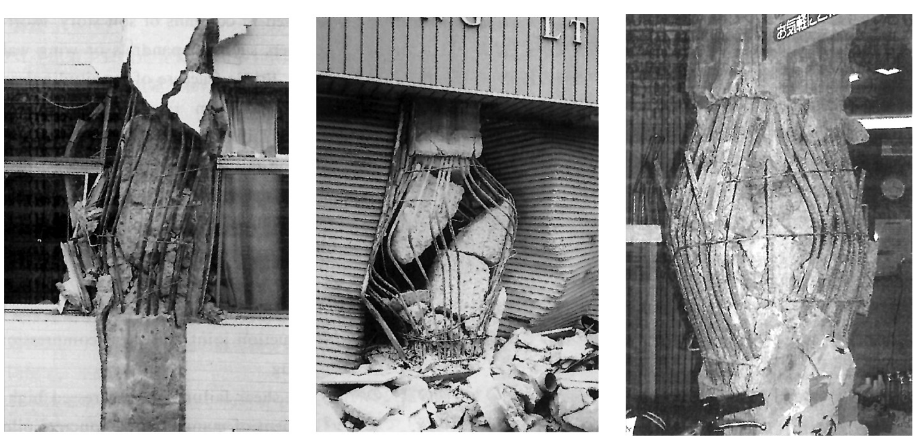

Fig. 6. Failure of RC columns in the Great Hanshin Earthquake in 1995 [6].

Fig. 7. Failure of steel structures in the Great Hanshin Earthquake [7].

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Fig. 9. Wooden houses in the Kumamoto earthquake in 2016. (a) Connection failure; (b) collapsed houses.

and displacements in structures by earthquakes. However, people may be injured or die directly because the structure collapses or the components fall by gravity, which is the permanently working force on the structures. It is essential that structural components such as columns, beams, slabs and walls are to be designed not to fall after earthquakes. If a large earthquake had hit a space station, where only negligible gravity exists, it would have tilted but would never have fallen nor hurt the residents.

3. Ductile structures

Seismic design provisions in Japan were revised in 1981. In this revision, a two-step design methodology was introduced for larger structures. According to this methodology, structures should remain elastic in moderate earthquakes, and should allow inelastic ductile deformation in large earthquakes without collapsing. The failure mechanisms and ultimate lateral strengths of structures should be evaluated. Depending on the ductile deformation capacities of the structures, the required ultimate lateral strengths are defined. The goal of this revision was to protect human lives from large earthquakes by allowing lateral displacements associated with damage but preventing collapse. Thus, building damage was considered to be a trade-off for saving lives. "Ductility is damage." These words were presented by Professor Vitelmo V. Bertero (1923–2016) more than 20 years ago, and succinctly express this fact.

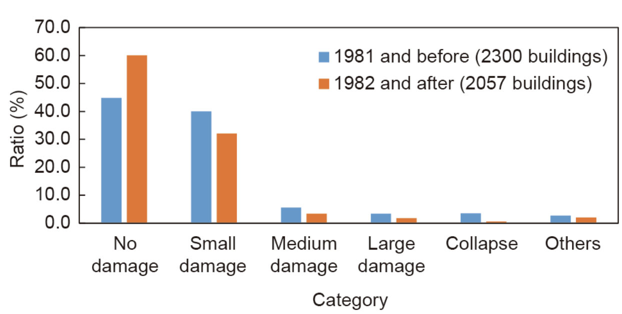

Fig. 10. Percentages of damaged buildings in the Great Hanshin Earthquake [6].

The application of this seismic design philosophy significantly improves the safety of residents in structures. In fact, the number of severely damaged or collapsed buildings in large earthquakes in Japan decreased dramatically for buildings designed after enforcement of the revised seismic design regulations. Fig. 10 shows the percentages of damaged RC buildings, as investigated near the epicenter of the Great Hanshin Earthquake [6]. It is notable that the total percentage of buildings constructed after the 1981 revision that experienced moderate to large damage or collapse was 5.8%, whereas the total percentage for buildings constructed before the revision was more than double, at 12.5%.

However, many well-designed buildings that experienced plastic deformation had to be demolished. Fig. 11(a) shows an RC residential building that was designed and constructed in compliance with the 1981 revision. This building was significantly damaged by the Great Hanshin Earthquake. As shown in the figure, major flexural cracks were observed in many beams near the column connections. This damage had been expected in the design; as designed, the plastic deformation dissipated the earthquake energy and saved human lives.

In this sense, the building was successfully designed; however, the building was eventually demolished rather than being repaired (Fig. 11(b)), as residents would not have wanted to remain in the building once they saw the damage. Even though the flexural cracks were expected and were not considered critical by specialists, the residents would consider them to be signs of severe damage. Fig. 12 also shows a damaged building that did not collapse in the Amatrice earthquake (2016). Structural engineers would have expected this damage and considered the design successful;

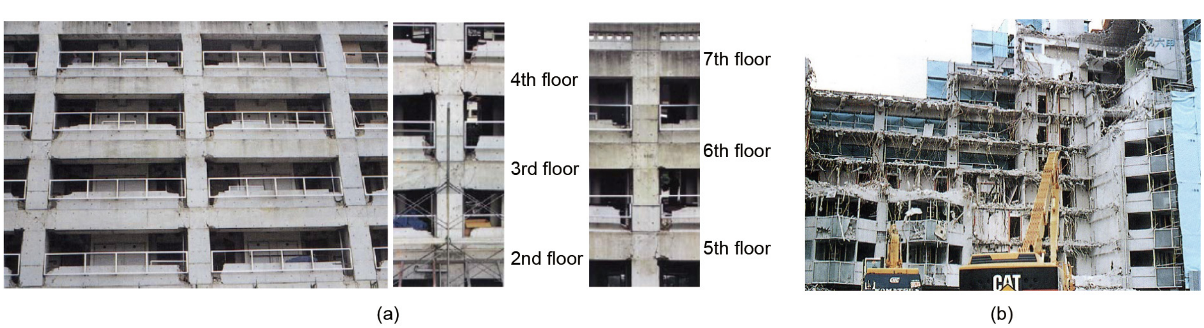

Fig. 11. Damaged and demolished residential buildings in the Great Hanshin Earthquake. (a) Flexural cracks of beams; (b) demolished building.

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Fig. 12. A damaged building that did not collapse but remained unused after the Amatrice earthquake of 2016.

however, the building was not used again and remained empty after the earthquake.

Although only two buildings completely collapsed in the Christchurch Earthquake in New Zealand in 2011, approximately 1700 out of 2400 buildings were demolished due to cracking or tilting. Fig. 13 illustrates the locations of the repaired and demolished buildings. It is notable that more buildings were demolished than repaired.

These two examples of the response to non-critical structural damage challenge the adequacy of the ductility design approach, which has been widely accepted by structural engineers around the world.

4. More reliable structures

The Japanese two-step elastic and inelastic design methodology was introduced more than 35 years ago. In the last 35 years, technologies have developed significantly and societies have dramatically changed. Social demand for resistance to natural disasters has also changed. Life safety used to be the main goal; now, the continuous use of buildings and houses is also required in mature, modern societies.

A business continuity plan after a large earthquake is important, not only for large companies but also for medium and small companies. Interruptions to business operations make the recovery from earthquake damage difficult. Business networks have become complex, and the interruption of operations in small companies can affect the entire network. Furthermore, the continuous use of houses may be even more important. Houses are essential for human activity and should be operational as shelters for residents in the case of disasters. If houses are damaged and cannot be used, residents must move to and stay in temporary evacuation shelters for a long period of time. It is crucial that hospitals, firefighting facilities, and other important buildings remain operational after large earthquakes. Similarly, bridges, tunnels, and other essential structural features must remain operational.

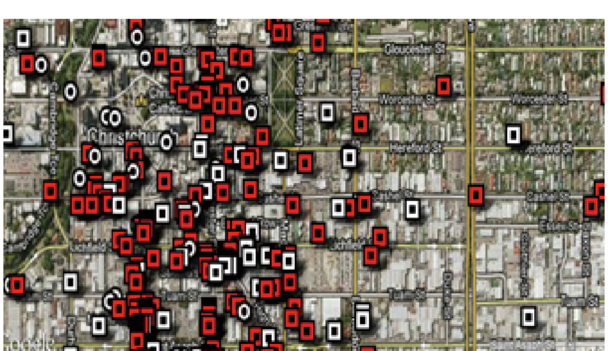

Fig. 13. Damaged buildings in the Christchurch earthquake of 2011; white and red squares indicate repaired and demolished buildings, respectively.

In order to make buildings more resistant to large earthquakes, an alternative approach to ductility design is needed. In this alternative design approach, damage is not allowed in the primary structure; rather, replaceable components are installed for seismic energy dissipation. To meet this goal, seismically isolated structures and passively controlled structures are effective. The primary structure, which carries the gravity load, should be designed to remain intact in large earthquakes. Furthermore, the seismic behavior and performance of such structures should be properly explained to building owners and to broader society. Structures that are designed using this approach should be able to be used continuously after a large earthquake, and decision-makers should not easily consider demolishing them.

Fig. 14 illustrates the concept of a structural system with seismic members and a primary structure. Buckling restrained braces (BRBs) act as the seismic members, which are separated from the primary structure. Fig. 15 schematically shows the seismic isolation system [9].

Fig. 16 shows the cumulative number of seismically isolated and passively controlled buildings constructed in Japan after

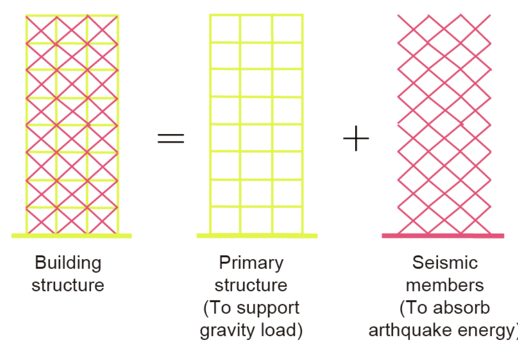

Fig. 14. Separation of primary and seismic members in an alternative approach to ductility design.

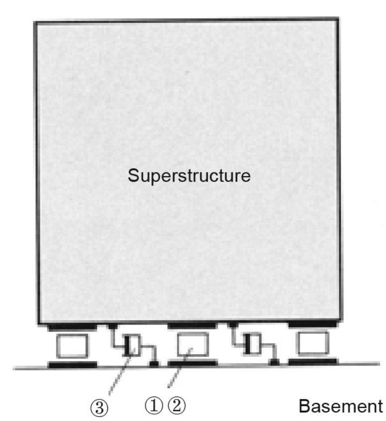

Fig. 15. Schematic diagram of a seismically isolated structure. The superstructure is flexibly connected to the foundations by mechanisms ①, ②, and ③, where mechanism ① supports the superstructure in the vertical direction, mechanism ② exhibits a restoring force in the horizontal direction, and mechanism ③ absorbs energy in the relative displacement between the superstructure and the foundations [9].

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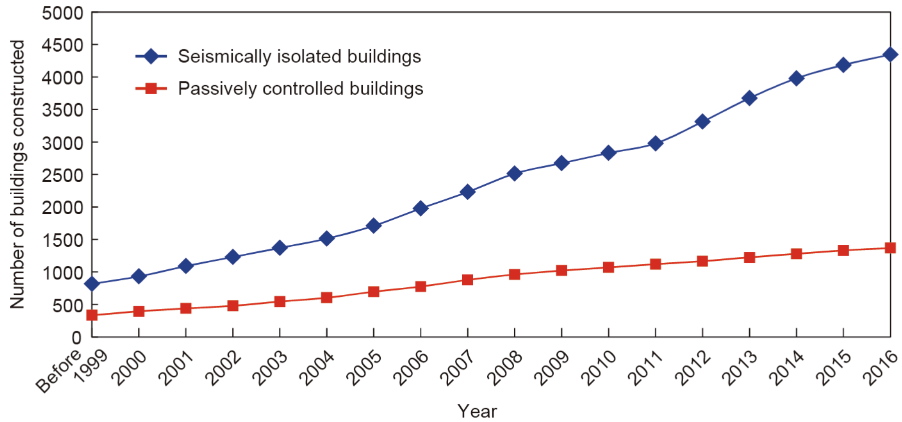

Fig. 16. Statistics of seismically isolated and passively controlled buildings in Japan.

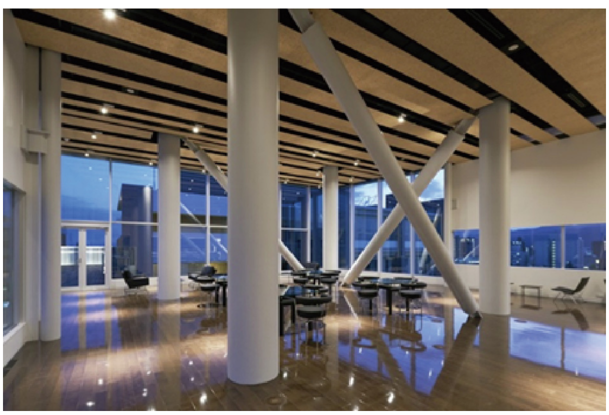

Fig. 17. A passively controlled building using BRBs (the Kyoto University of Foreign Studies).

1999. Seismically isolated structures have been used to a greater degree for major buildings such as hospitals, large warehouses, and high-rise residential buildings. The number of seismically isolated structures constructed until 2016 is more than 4000. Passively controlled systems have been installed in many high-rise buildings, and in most of the recent ones. This trend shows that people are increasingly recognizing the performance and effectiveness of these buildings against earthquakes: Fewer buildings were damaged in recent major earthquakes in one of the most earthquake-prone countries in the world.

The data in Fig. 16 include only large-scale buildings; therefore, the real number of seismically isolated and passively controlled buildings must be much greater. This is especially true for passively controlled buildings, which can now be designed within a regular building approval procedure without peer reviews by specialists, if the buildings are not very large. As an example, Fig. 17 shows an interior view of a six-story university building in which BRBs are used and exposed in the community space. There are many relatively small seismically isolated and passively controlled buildings in Japan; these are not included in the statistics in Fig. 16.

5. Conclusions

Ductile structural design is effective in terms of saving lives; however, many well-designed buildings that have experienced excessive plastic deformations in large earthquakes have had to be demolished because they sustained damage to their primary structural elements. This fact implies a need for a new structural design approach in which damage in the primary structure is avoided by separating it from the seismic structure that will carry earthquake lateral loads. For this purpose, passively controlled structures and seismically isolated structures are effective and should be more commonly used.

Acknowledgements

The essence of this paper comes from 30 years of discussion with Professor Stephen Mahin at the University of California Berkeley and Professor Jerome J. Connor at the Massachusetts Institute of Technology, who are greatly acknowledged. Professor Vitelmo V. Bertero at the University of California Berkeley, Professor Yoshikatsu Tsuboi at the University of Tokyo, and Professor Emeritus Tsuneyoshi Nakamura at Kyoto University are also acknowledged. The authors would like to thank Nagahide Kani, executive advisor of the Japan Society of Seismic Isolation, and Won K. Lee for their support.

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