



SYNTHETIC SEISMIC DESIGN STRATEGY FOR BUILDING STRUCTURES IN URBAN AREAS

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Abstract

Cities are syntheses of many individual buildings and infrastructures that support the function of the built environment. Current seismic design strategies focus on individual buildings, including the safety of their occupants, operation of the business they host, and the economic loss they may bring about to their owners if they are damaged during earthquakes. In such strategies, life safety is always the most important performance target than other concerns such as continuous operation and economic loss. This makes people tend to underestimate or even overlook the importance of the latter performance requirements. In big cities, earthquake damage to so many of the buildings at the same time may cause disasters for people who live in the cities, even if the extent of damage to each building is acceptable per the current seismic design codes for buildings. Seismic design of buildings in urban areas should not focus only on individual buildings themselves. Instead, the seismic performance target of individual buildings should conform to the performance target of the city. In this paper, the shortcoming of ductility-based seismic design strategy is first discussed from the viewpoint of demolition of damaged buildings. The important differences between individual buildings and cities are summarized in terms of their spatial scales and life spans. It is because of the huge spatial scales of modern cities that the discontinuity of their functions may make the cities unsuitable for people to live after major earthquakes, even if not a single building collapsed and caused direct fatality. Therefore, seismic damage control for functionality becomes a critical concern for the sake of cities, especially if the cities are too big to fail, such as Tokyo, Beijing and Los Angeles. It is because of the long life spans of cities that major earthquakes would sooner or later strike the city during its life span. Its buildings should therefore be seismically designed to remain functional under very rare earthquakes, which is compatible to the life span of the city rather than the buildings themselves. Several techniques among many others for seismic damage control are recommended at the end of the paper. These techniques have proved to be effective in protecting not only the safety, but also the functionality of buildings under major earthquakes.

Keywords: resilience; urban community; damage control; ductility; base-isolation;



1. Introduction

Building collapse is a primary source of deaths and injuries in major earthquakes. Since the early 20th century, the earthquake engineering community has recognized the benefit of structural ductility in protecting buildings from collapse without significantly increasing the construction cost. Various strength reduction factors have been stipulated in major seismic codes in the world to lower the strength requirement depending on the level of structural ductility, which is guaranteed by specific detailing of structural members based on capacity design methodology. For example, the ultimate strength requirement for very rare earthquake (approximately 10% in 50 years exceedance probability) in Japan is 0.25~0.4 for steel frames, 0.3~0.45 for reinforced concrete frames and 0.4~0.55 for reinforced concrete shear wall structures. Such a ductility-based approach leads to very different strength requirements for structures of the same material and on the same site. For example, the strength of well detailed RC frames can be 30% lower than ordinary RC frames. Ductility is considered as an equivalent to strength for collapse prevention. Under moderate earthquakes, however, the well-detailed structures of high ductility but low strength are likely to sustain much severer damage than those of high strength but low ductility. The relationships of seismic damage (or repair cost) and earthquake intensity of such structures are illustrated in Figure 1.

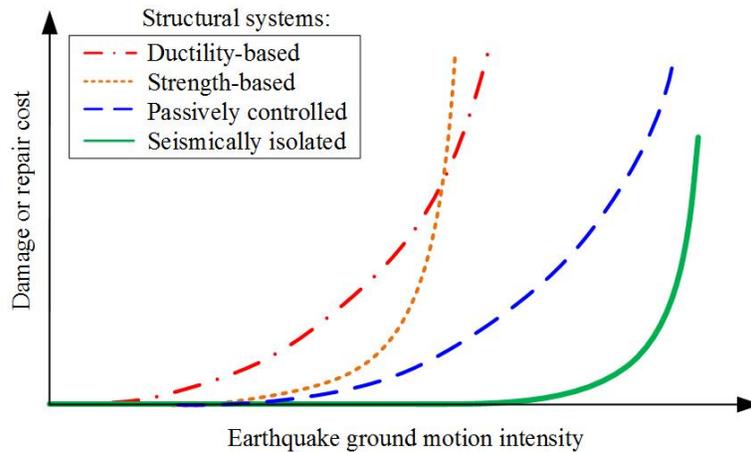


Fig 1 – Seismic damage or repair cost of buildings with various earthquake-resistant systems

In the 1990s, the earthquake engineering community witnessed the fast development and widespread applications of passive control and base-isolation techniques in Japan and other seismic regions, especially after the major earthquakes such as the 1995 Kobe earthquake. Both passively controlled and seismically isolated structures are expected to exhibit high energy dissipation capacity. Different from conventional ductility-based structures, they are equipped with specifically designed energy dissipating devices to concentrate possible damage so that the rest of the structural system is protected from considerable damage. In the ‘damage tolerant structure’ proposed in 1992 by Wada et al ^[1], the whole structural system is divided into an energy dissipating secondary system for lateral earthquake actions and a primary system for gravity load. Seismic damage are concentrated in the secondary system, which can accommodate large inelastic deformation without significant damage, and can be easily replaced in case they are badly damaged. Although the strength of either passively controlled or seismically isolated structures are not necessarily higher, their damage during major earthquakes are expected to be much less than conventional earthquake-resistant structures (Figure 1).

2. Demolition of buildings

Several issues may discourage the use of ductility-based structures, among which the great effort and cost related to the demolition of damaged buildings after major earthquakes have become a major concern. In Nepal, people used to live in stone masonry houses which were insufficient in both strength and ductility. From the 1990s, RC frames have gained surprisingly high popularity in not only urban, but also rural areas in Nepal. During the

reconnaissance after the 2015 Gorkha earthquake in Nepal, owner-built RC frames could be seen even in very remote and mountainous villages. Many of such owner-built frames were damaged to various extents or even collapsed. Most of the damaged frames were difficult to repair. The owners would have to pay to demolish their damaged homes and flatten their lands before they could possibly rebuild their homes.

Demolition of RC buildings is usually time consuming and expensive, especially when the buildings are tall. Several RC buildings collapsed during the 2016 Tainan earthquake. [Figure 2](#) shows the site of demolishing a collapsed multistory RC building. A large soil slope was piled besides the building to send the excavators and other machines to top of the building.



Fig. 2 – Temporarily piled slope for excavators to demolish a collapsed frame building in Tainan earthquake

The ground shaking of the 2011 Tohoku earthquake did not cause widespread collapse of buildings. However, the buildings whose seismic damage were not well controlled were very likely to be demolished even if the damage to the structural components were only moderate. [Figure 3](#) provides an example. The 12-story RC residence sustained severe damage to the nonstructural walls while the structural components in the superstructure were almost intact. However, the buildings were demolished after the earthquake primarily for the high repair cost.



Fig. 3 – A 12-story steel reinforced concrete apartment in Sendai after 2011 Tohoku earthquake and was later demolished (Courtesy of Professor Y. Sanada at Osaka University)

Similar examples can be found in the aftermath of most major earthquakes in recent decades. [Miranda and Ramirez \(2012\)](#) ^[2] demonstrated through a case study of loss estimation that the total loss may be increased by 45% by including the loss due to demolition in the estimation for ductile structures. The influence of demolition related cost for strength-based structures are not as significant.

3. Urban communities versus buildings

Although the loss due to demolition maybe huge for owners of individual buildings, several other issues of the damage behavior of ductile structures may become even more important when urban communities are of concern. Urban communities are substantially different from individual buildings at least in the spatial scales and life spans. These differences make the seismic risk of urban communities very different from that of individual buildings.

3.1 Spatial scale

As a symbol of modern civilization, automobiles are carefully designed to protect the driver and passengers' life safety in car accidents. For example, the engine room in front of a car is intended to crush to buffer the impact and dissipate energy in a car accident ([Figure 4](#)). This is very similar to the idea of protecting life safety in buildings by means of structural ductility. After a car accident, the cars are often so badly damaged that they cannot be used or repaired anymore. In most cases the insurance companies will pay for the loss of such unfortunate accidents. Such a system runs very well around the world. For buildings and houses, however, the likelihood of major devastating earthquakes in a city is much lower than deadly car accidents; once it happens, the consequence is usually considerably worse than car accidents in terms of the city. Much lower hazard and much higher consequences place a practical difficulty in promoting earthquake insurance for buildings.



Fig. 4 – Vehicle crash test where engine room is sacrificed (Source: <http://www.fxxw.net/article/show.asp?id=114712>)

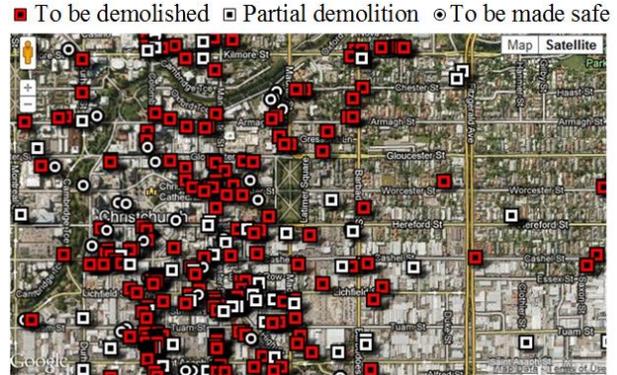


Fig. 5 – Distribution of damaged houses in downtown Christchurch after 2010-2011 earthquake sequence in New Zealand (Courtesy of Professor MacRae Gregory at University of Canterbury)

The consequence of major earthquakes is not limited to a single or several buildings like in a car accident. Urban communities are composed of many individual houses and buildings. It also contains many cars. The difference is that it is extremely rare that tens of thousands of cars are broken by car accidents at the same time in a city, but it is very common for tens of thousands of buildings in the city to be damaged or even collapse during a single earthquake, like what has happened in Christchurch after the earthquakes in 2010 and 2011 ([Figure 5](#)).

This is especially true if the city is full of buildings that were seismically designed based on a conventional idea of ductility. At a city-wide scale, different areas may suffer from ground motions of different intensities. Take JMA intensity in Japan for example. Ductility-based buildings are likely to become red-labeled (deemed unsafe to occupy) when the JMA intensity is 5 or higher ([Figure 6a](#)). On the other hand, strength-based buildings may sustain worse damage in high intensity areas whereas in lower intensity areas such as Intensity 5,



the damage can be quite limited because of their higher strength (Figure 6b). If the same city is full of strength-based buildings, the malfunctioned area could be expected to be smaller. This may not be significant for individual buildings, but the rescue and emergent relief can become easier because a larger portion of the city remains functional.

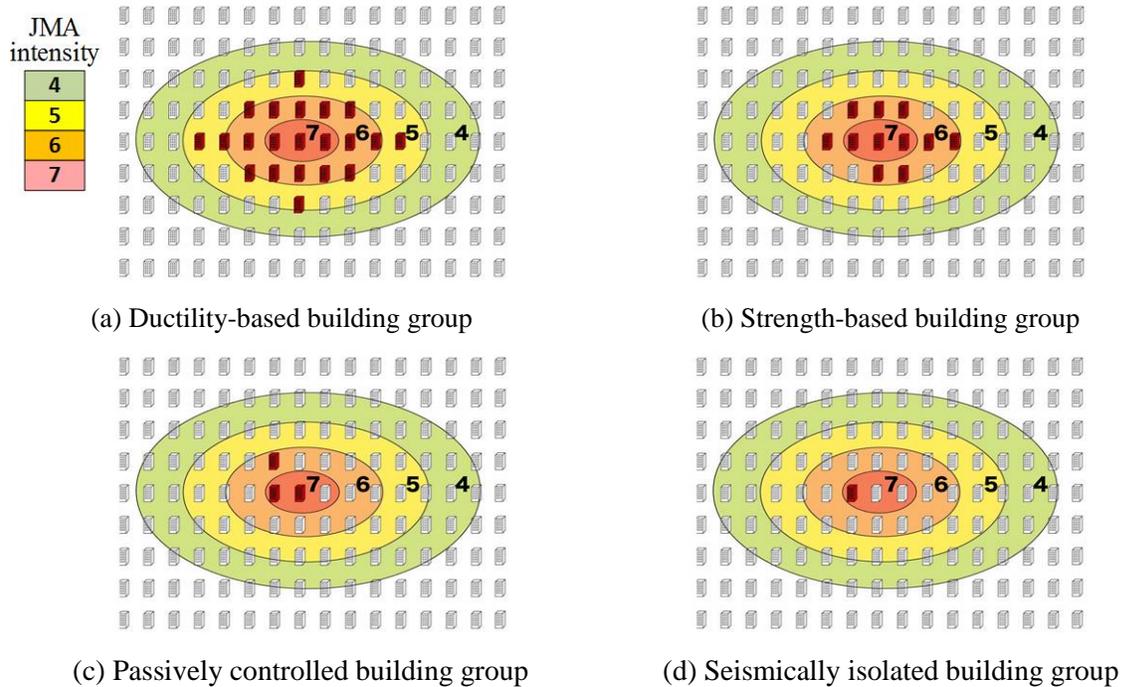


Fig. 6 – Spread of seismic damage to urban areas of different types of buildings under major earthquakes

By incorporating a damage control methodology, such as the passive control or seismic isolation techniques, the number of red-labeled buildings can be significantly reduced (Figure 6c and 6d). If only a few buildings in a metropolis are badly damaged and all the others can be continuously occupied, the influence of the earthquake will be like a car accident: the spread and extent of influence will be very limited. In such cases, the city will be able to recover quickly by its own resources.

3.2 Life span

As far as an individual building is concerned, its probability of being attacked by major earthquakes during its service life is very low. The shorter its service life is, the lower the probability will be. Based on this idea, it is usually allowed to design temporary structures for a lower seismic hazard level. In countries like Japan and China, the actual service lives of buildings are often only 20~30 years, although they are designed to have a 50-year service life. Many of the buildings will not be influenced by major earthquakes before they are demolished and new buildings are constructed on the same sites. For cities in seismic areas, however, a very rare earthquake is almost sure to take place within the city's life span, which can be several thousand years. When most of its buildings and houses are seismically designed not to collapse for very rare earthquakes, the city's normal operation may sustain substantial loss because of the extensive damage of its buildings, even if they do not collapse. For individual buildings, such extensive damage is expected by the engineers and is allowed by the code and the law. For the sake of the city, however, such damage that disrupt the function or even occupancy of so many buildings will result in a substantial loss of the city (Figure 7a). The city will become a place where people cannot live. It will not be able to recover in the near future unless adequate resource from outside can be dispatched in a short time. In such cases, the city is hardly considered as a resilient community. For higher resilience, buildings in urban areas should be seismically designed to remain functional or at least safe to occupy under very rare earthquakes, which is compatible to the life span of cities rather than the buildings.

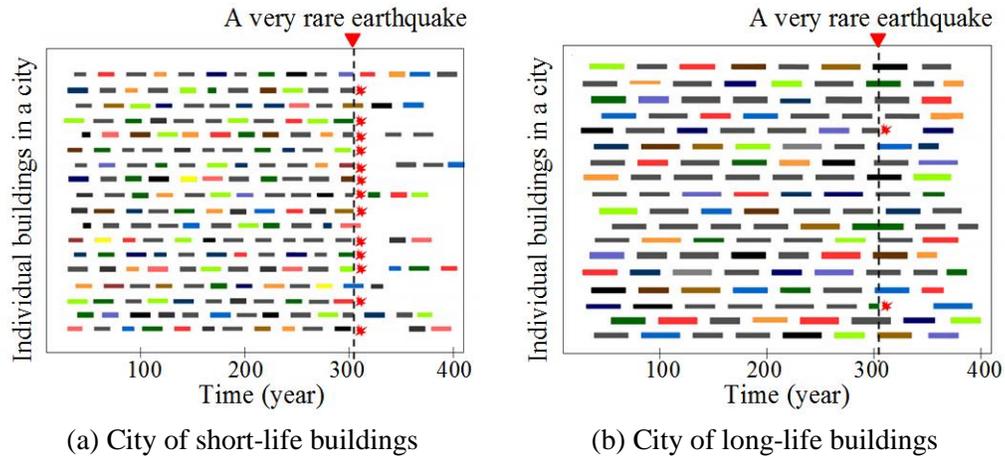


Fig. 7 – Sustainability of cities in earthquake-prone regions

The seismic resilience of an urban community can be significantly enhanced by increasing the seismic performance of its individual buildings. Higher seismic performance is not limited to higher anti-collapse capacity. It should at least also involve seismic damage control under various levels of ground motions. By reducing the earthquake-related loss in the full life cycle of buildings, their life spans can be extended. When a city of such long-life buildings is hit by a very rare earthquake, which is certain to come considering the city’s life span, only a marginal portion of its buildings lost their functions. The normal operation of the city will not be much affected.

4. Advanced technologies for seismic protection

Passive control and seismic isolation are effective techniques to control the seismic damage of building structures. In the 2016 Kumamoto earthquake in Japan, the many base-isolated buildings in Kumamoto prefecture survived the strong shaking. In particular, as confirmed by the nurses in the Kumamoto University Hospital, the 13-story base-isolated building was fully operational immediately after the earthquake (Figure 8a), although the maximum displacement at the isolation layer reached as large as $\pm 300\text{mm}$. The M7.3 main shock on April 16 was first initiated close to the Kumamoto city and the rupture propagated towards the northwest (Figure 8b), where another base-isolated hospital, the Aso Medical Center (Figure 8c), was located.

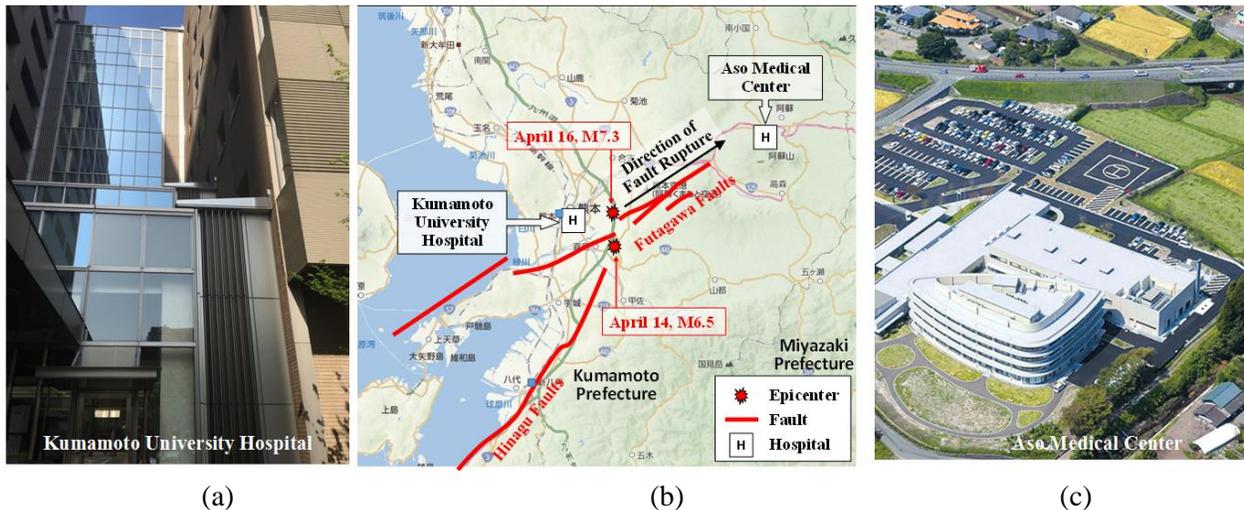


Fig.8 – Seismically isolated hospitals in Kumamoto earthquake: (a) Intact curtain wall of 13-story Kumamoto University Hospital; (b) locations of hospitals and faults (prepared on Yahoo Map) and (c) aerial view of Aso Medical Center (Source: <http://lets.kumanichi.com/kangoshi/p003.php>).

Because of the directivity effect of near-fault rupture propagation, the Aso Medical Center building was very likely to have suffered from near-fault pulse-like ground motion, which is especially deadly for long-period base-isolated structures. The record of the scratch board installed at the base level of the building showed that the maximum displacement of the isolation layer was approximately ± 450 mm. This is the largest displacement ever recorded in base-isolated buildings in Japan. Even though, the building only sustain marginal damage, including a squeezed cladding board at an expansion joint.

In recent years, rocking mechanism is receiving increasing attentions for seismic protection of buildings. More than a thousand years ago, ancient Japanese has utilized rocking mechanism as a means of seismic isolation. The Shosoin (royal warehouse) in Nara as depicted in Figure 9(a) was built more than 1300 years ago. The superstructure was supported by a dense array of stout wooden columns, which rest on the stone bases on the ground (Figure 9b). When the building moves laterally during earthquakes, the stout columns lean and uplift the superstructure. The gravity of the superstructure then automatically provide a restoring force that pulls the columns back to their original positions. The applications of similar mechanisms are being explored in various forms to mitigate the seismic damage of modern buildings [3][4].

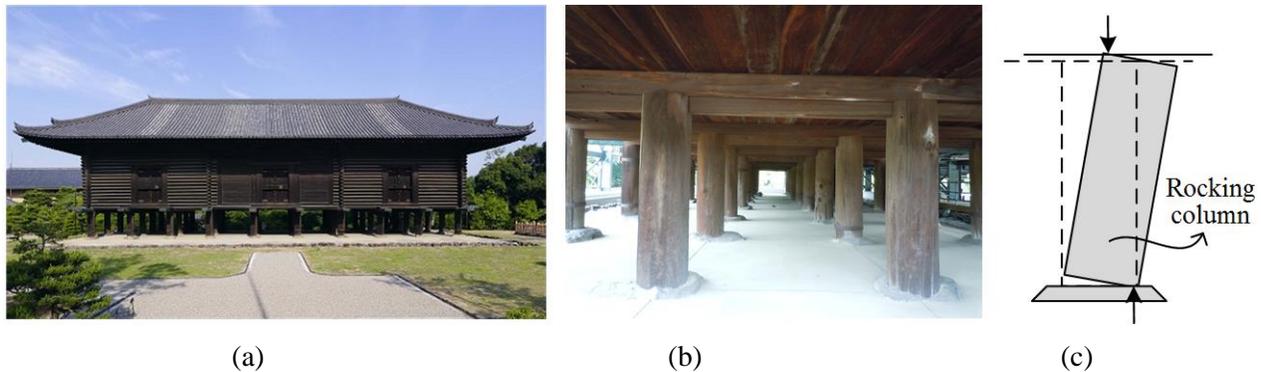


Fig. 9 – Shosoin in Nara that was built more than 1300 years ago: (a) Front view; (b) wood columns in bottom story and (c) mechanism of a rocking column.

In controlling the seismic damage of buildings, the control of the global deformation pattern of the structural system is essentially important. The nature of seismic isolation is to concentrate most lateral drift to the isolation layer at the bottom of buildings, which exhibits low lateral stiffness and superior energy dissipating capacity. An opposite but still effective idea is to distribute the lateral drift among the structural system as evenly as possible, so that the structure does not collapse in a weak story pattern. The seismic retrofit of the G3 Building on the Suzukakedai campus of Tokyo Tech is a comprehensive demonstration of this idea. The substandard steel reinforced concrete frame was retrofitted by six pin-supported walls around its perimeter, and shear-type steel dampers were installed between the added walls and the existing frame columns along the height of the building (Figure 10a). According to a seismic inspection in 2008, the existing frame was highly vulnerable to weak story collapse at its bottom story and the 9th story (Figure 10b). The added walls for retrofitting are expected to work as coordinators among the stories. They are flexible in lateral drift because the bottom bending restraint is released by mechanical pins at the bottom. They are post-tensioned to increase the stiffness, which is important for them to distribute lateral drift among stories (Figure 10c). Seismic damage is expected to concentrate in the steel dampers, which are detailed to be replaceable so that the structure can be quickly repaired in case the dampers are badly damaged. More details of the project are referred to [5] and [6].

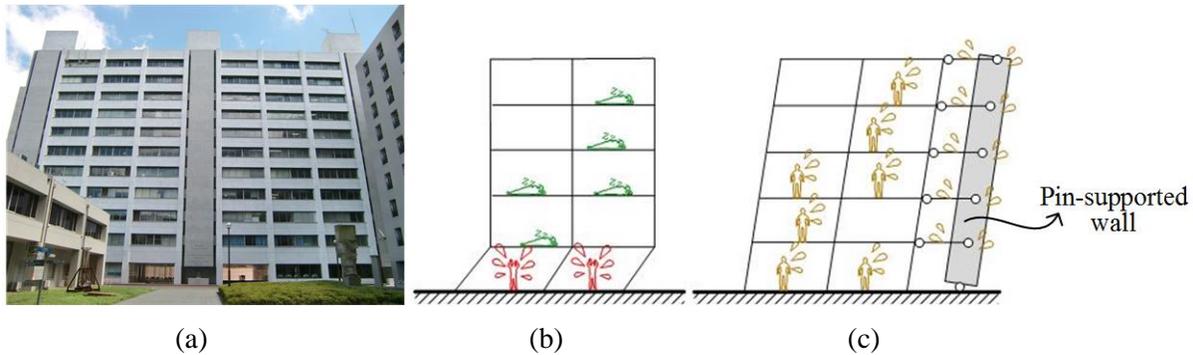


Fig. 10 – G3 Building in Tokyo Tech seismically retrofitted by pin-supported walls: (a) Front view; (b) weak story mechanism and (c) glocal mechanism with pin-supported walls.

5. Conclusions

The safety of individual buildings cannot always guarantee the safety of big cities under very rare earthquakes. On one hand, problems of cities take place in a much larger spatial scale than individual buildings. When a major earthquake strikes, a large number of buildings in a city are affected at the same time. Excessive seismic damage in the buildings may lead to the failure of a city's normal operation, even if the buildings do not collapse. On the other hand, although there is only a small possibility that a very rare earthquake would strike a building in its service life, it is almost certain for a city in a seismic area to suffer from a major earthquake, because its life span is much longer than individual buildings. If each building is designed for only preventing collapse under major earthquakes, the city will sooner or later become a place where people cannot live when a major earthquake strikes, and the recovery will be slow and painstaking.

Therefore, when selecting the seismic performance of buildings in large cities, it is important to set the performance targets conforming to the spatial scale and life span of cities rather than those of individual buildings. This requirement lays the foundation of a synthetic seismic design strategy for building in urban areas, which emphasizes the effective control of seismic damage and targets at the function continuity or immediate occupancy of buildings under very rare earthquakes.

Conventional ductility-based seismic design cannot meet this requirement without significantly increasing the construction cost, whereas the building owners are not obliged to pay such additional cost for the sake of the city, the common welfare or the welfare of future generations. Modern techniques, such as seismic isolation, controlled rocking mechanisms and pin-supported walls with dampers, provide a variety of solutions for more effective seismic damage control, which in some cases do not increase the cost or only increase the cost by a small fraction.

6. Acknowledgement

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