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Recent earthquakes and the need for a new philosophy for earthquake-resistant design

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ABSTRACT

Modern seismic design and construction technologies have undergone significant developments over the last 100 years. In order to prevent collapse of buildings under large earthquakes while maintaining reasonable construction costs, structures are allowed to undergo ductile plastic deformations under current design and detailing methods. This implies that large numbers of buildings may be significantly damaged and not only individual buildings but also entire cities may lose their function following extreme earthquake events. In recent large earthquakes, it has been observed that many properly designed and constructed buildings, which did not collapse, were no longer functional and were later demolished rather than being repaired. Considering such situations, the earthquake-resistant design philosophy developed in the previous century should now be revised to meet modern social and economic requirements and Sustainable Development Goals ("SDGs"). The seismic design philosophy for building and infrastructure should be changed from life-saving to business continuity for modern and resilient societies. Structures should be designed to be quickly restored to full operation with minimal disruption and cost following a large earthquake.

1. Introduction

Development of seismic engineering technologies will never eliminate earthquake disasters. Humans will never be able to conquer nature and can only live in it with a better relationship. Seismic engineering specialists have achieved only a limited understanding of global crustal behavior. While predicting the magnitude, epicenter, and precise time of large earthquakes is very difficult and beyond our scientific knowledge, earthquakes are certain to occur within a long enough time period. The currently existing seismic design methods allow structures to undergo plastic deformations under large earthquakes, while remaining elastic under small or moderate earthquakes. The plastic deformation dissipates earthquake energy and is intended to prevent structural collapse. While this design method is highly effective for protecting human lives, it does not fully account for people's lives after the earthquakes. People may be unable to return to their damaged houses and may be forced to stay inconveniently in evacuation shelters for a long recovery term. They may be unable to work and consequently may fall in financial difficulties. In this recent matured and complex society, people's demand for building structures has increased and many people expect buildings to remain fully operational after large earthquakes. Corresponding to such societal demands, a new seismic design approach to generate resilient building structures against large earthquakes is needed [1–4]. Special structures, serving important functions, such as hospitals, fire-fighting stations and power plants, are normally designed to remain fully operational even after large earthquakes. This structural design approach shall be expanded to more general structures. Such structural design philosophy is required for modern and resilient societies. In order to achieve this, increase of the initial construction cost is the issue; however, the disruption cost can overcome the initial cost to improve the structural performance. Although quantitative cost evaluation with respect to the structural performance or the seismic risk is not within the scope of this paper, the fact that the additional initial cost can provide structural sustainability and business continuity shall be certainly recognized. The structural design approach toward more reliable structures shall be more commonly accepted (Fig. 1).

2. Damage by recent earthquakes

The number of deaths and missing people caused by natural disasters in Japan was fewer than 1000 per year for the 34 years before 1995, when the Great Hanshin (Kobe) earthquake occurred [5]. In 1995, people noticed that the relatively few number of deaths and

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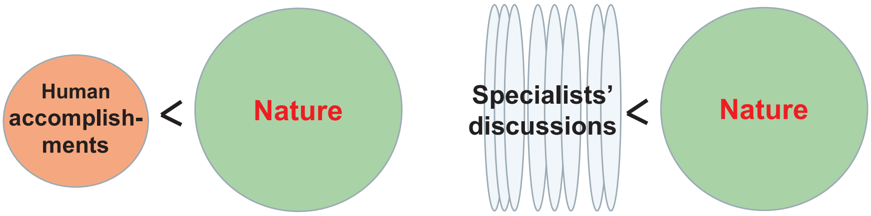


Fig. 1. Relationships between human achievements and nature.

(a) Flexural cracks of beams

(b) Demolished building

Fig. 2. Damaged and demolished residential building in 1995 the Great Hanshin earthquake.

missing people that lasted for a period of time was not a proof that seismic engineering technology had overcome earthquakes.

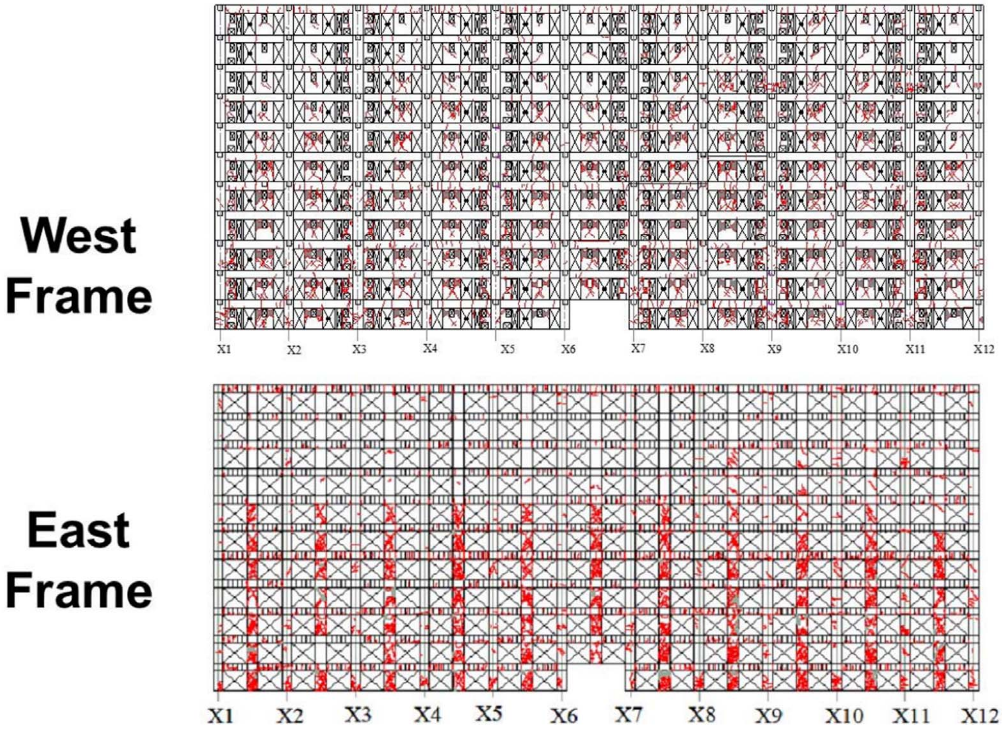
Seismic design provisions in Japan were revised in 1981. In this revision, evaluations of failure mechanisms and ultimate lateral strengths became required for larger buildings. Plastic deformations are allowed for large earthquakes under the assumption of ductile behavior in reinforced concrete and steel members. The goal of this revision was to protect economically human lives against large earthquakes by allowing building damage. Therefore, building damage was considered as the trade-off saving lives.

Fig. 2a shows a reinforced concrete residential building designed and constructed to comply with the 1981 revision. It was significantly damaged by the Great Hanshin earthquake in 1995. 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. 2b).

Fig. 3 shows a residential building damaged by the Great East Japan earthquake in 2011. The columns, beams and non-structural reinforced concrete walls were damaged. The damage in the non-structural walls was particularly severe and they failed in shear. This type of damage is not critical for building stability. In this sense, this damage had been expected and the structure behaved as predicted in the design. The damaged walls had absorbed the seismic energy; however, the walls were no longer functional as the building's exterior. While the structural designer or seismic engineering specialist may consider the design to have been successful, lay people, including the residents, may not have agreed. The building was red tagged in the emergency evaluation and the residents were prohibited from returning to their homes. The building was later demolished.

Although repairing the damaged building may have been less expensive than demolishing it and reconstructing a new building,

(a) Non-structural walls failed in shear



(b) Damaged frames

Fig. 3. Damaged and demolished residential building in the Great East Japan earthquake.

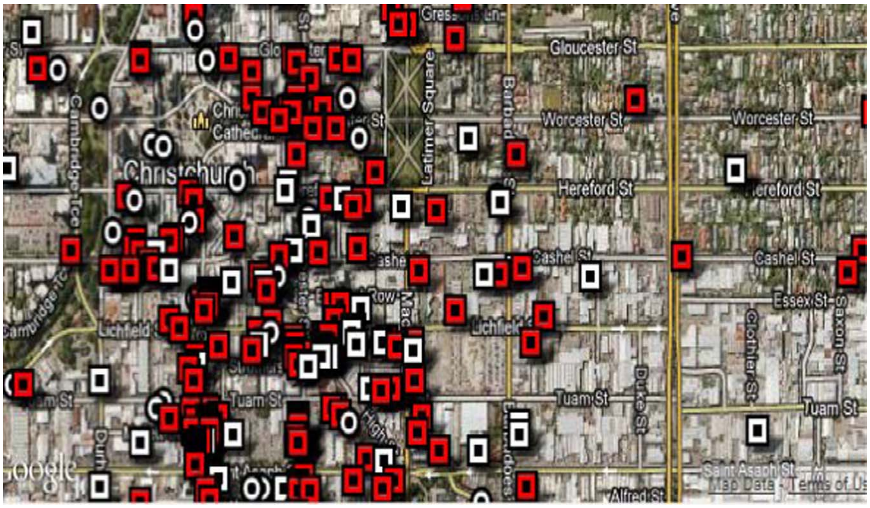


Fig. 4. Damaged buildings in 2011 Christchurch earthquake.

(a) Collapsed wooden houses

(b) Minor cracks on columns

(c)Fallen equipment

(d) Empty room with patients evacuated

(e) Seismically isolated hospital building

(f) Maximum displacement of 450 mm

Fig. 5. Damages by the 2016 Kumamoto earthquake.

demolition was nonetheless chosen. During the earthquake, residents likely experienced significant shaking, heard components breaking or fracturing, and may have imagined that the building might collapse. The reason that demolition was selected may have been to prevent the future possibility of residents having a similar experience in the event of a later large earthquake if the building was brought back to its original condition by simply repairing the damage. Other possible reasons may have been that the Japanese government provided financial support for demolition or that neighbors requested that the damaged building be removed.

While only two buildings had 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. 4 illustrates the repaired and demolished buildings. The white and red squares indicate the repaired and demolished buildings, respectively. Note that more buildings were demolished than repaired.

In the 2016 Kumamoto earthquake, the vulnerability of old wooden houses, which is well known in the engineering community, was again observed (Fig. 5a). In a reinforced concrete hospital building of conventional design, the equipment fell due to the large acceleration.

Table 1
Fundamental goals of seismic design against large earthquakes.

	Current seismic design approach	New seismic design approach
H	Human lives likely to be saved	Human lives surely to be saved
B	No certainty of future building use with repair	Building to be used with some repair
C	No continuous operation after earthquake	Continuous use even after earthquake

Minor cracks were observed in the columns and walls (Fig. 5b, c). Although these types of damage do not affect the seismic performance of the structure, people in the building, including 300 patients and doctors, had to be moved to other hospitals (Fig. 5d) and the hospital was not used for rescue activities.

Another seismically isolated hospital building (Fig. 5e) experienced large movement, with a maximum amplitude of 900 mm (i.e. a maximum displacement of 450 mm) (Fig. 5f). This is the largest displacement ever recorded in past earthquakes. Despite experiencing this large displacement, the superstructure was almost intact and the building was fully active after the earthquake and was able to accommodate the Disaster Medical Assistance Team (DMAT). Many structures designed by new technology have not fully experienced severe earthquakes nor proved their performance; however, there are certainly some structures like this hospital had experienced and no damage.

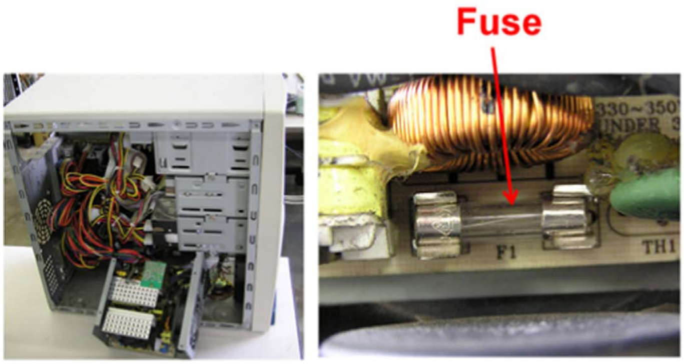
Reviewing the facts described above, we understand that there is some room to improve the current seismic design practice. People do not stay in buildings that are red tagged in post-earthquake evaluations. Most structural engineers understand the rationale behind a seismic design approach in which plastic deformation of beams, columns and walls is expected; however, the ductility based on this deformability is equivalent to the damage of a structure. This damage is easily recognized by people after large earthquakes, while the seismic performance is hardly evaluated, even by specialists. Damage should therefore be more strictly controlled during large earthquakes.

3. New seismic design philosophy

Table 1 compares the fundamental goals of the current and newly proposed seismic design approaches. These goals are described from three points of view, "H", "B", and "C", which refer to "Human lives", "Building future use" and "Continuous operation", respectively. It is seen that the current design approach may be insufficient to support modern sustainable and resilient societies without pursuing the continuous use of buildings after earthquakes. On the other hand, buildings designed under the new approach would achieve these goals easily for small and moderate earthquakes and likely even for large earthquakes.

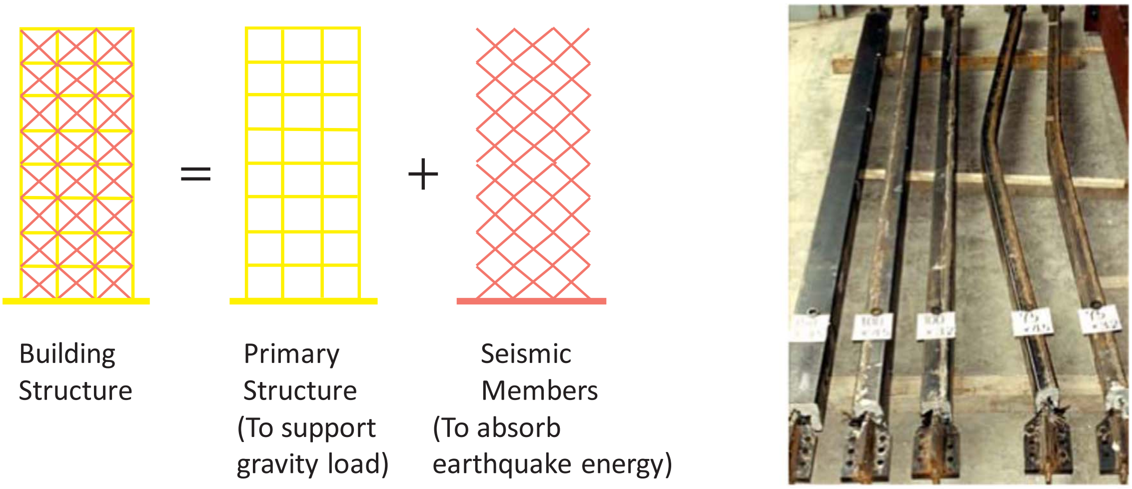
In order to achieve the goals of the new seismic design approach shown in Table 1, an effective method of design would allow structural components play separate roles. The primary structure supports the gravity load and the seismic members mainly resist earthquake loads. Therefore, the seismic members protect the primary members against large earthquakes. Similar systems to protect the main body are often found in nature and industrial products. Collarbones are broken to ease forces on the human body (Fig. 6a). Bumpers in cars are obviously components to protect the main body (Fig. 6b). Fuses in computers are buffers to protect the main system against excessive electric currents (Fig. 6c).

(a) Collarbone (b) Bumper



(c) Fuse

Fig. 6. Buffers in nature and industrial products.



(a) Separation of primary and seismic members

(b) Experiments of BRBs

(c) Application of BRBs

Fig. 7. Buckling restrained braces (BRBs).

Fig. 7a illustrates the concept of a structural system with seismic members and a primary structure. Buckling Restrained Braces (BRBs) represent the seismic members, which are separated from the primary structure. The ductile BRBs will yield and absorb the earthquake energy to the buildings (Fig. 7b, c). They protect the primary structure, which remains elastic, and the goals of H, B and C for the new seismic design approach in Table 1 can be satisfied.

Fig. 8 schematically shows the seismic isolation system [6]. The superstructure is flexibly connected to the foundations by mechanisms (1), (2), and (3).

where,

(1) the mechanism for supporting the superstructure in the vertical direction
(2) the mechanism for exhibiting a restoring force in the horizontal direction
(3) the mechanism for absorption of energy in the relative displacement between the superstructure and the foundations

Fig. 9 shows seismically isolated buildings at the Tokyo Institute of Technology (TITech) designed under the new seismic design approach shown in Table 1. The structure has 20 stories and is 91.35 m in height. Columns of the superstructure consist of concrete-filled square tube (CFT) columns, and all beams are made of steel wide flange sections. The seismic lateral forces are significantly reduced by the effect of seismic isolation and the number of the CFT columns is 16, which is fewer than that in ordinary structural systems. The seismic isolation

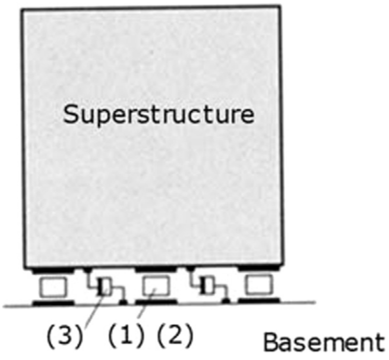
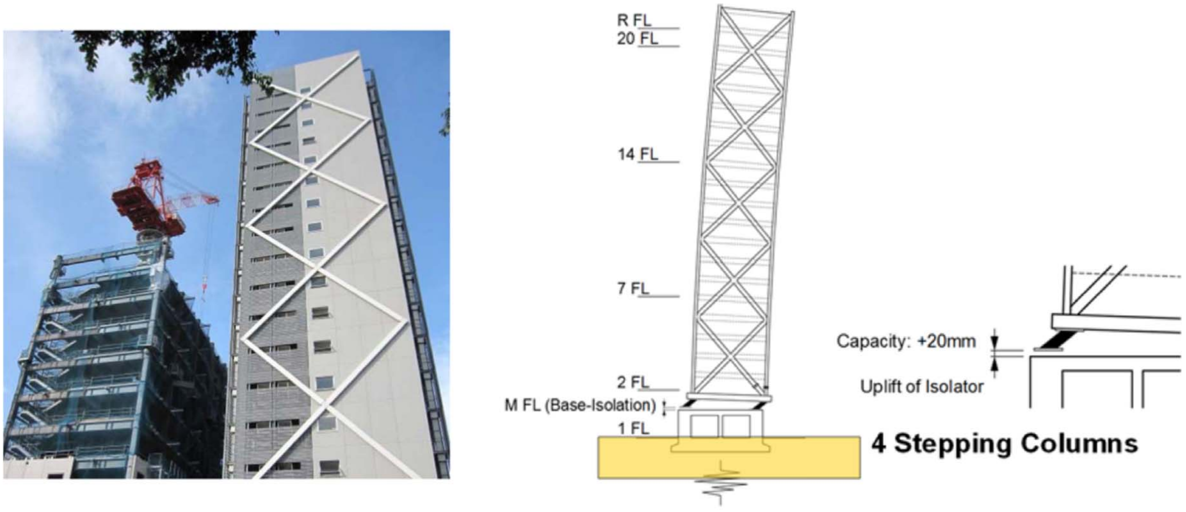
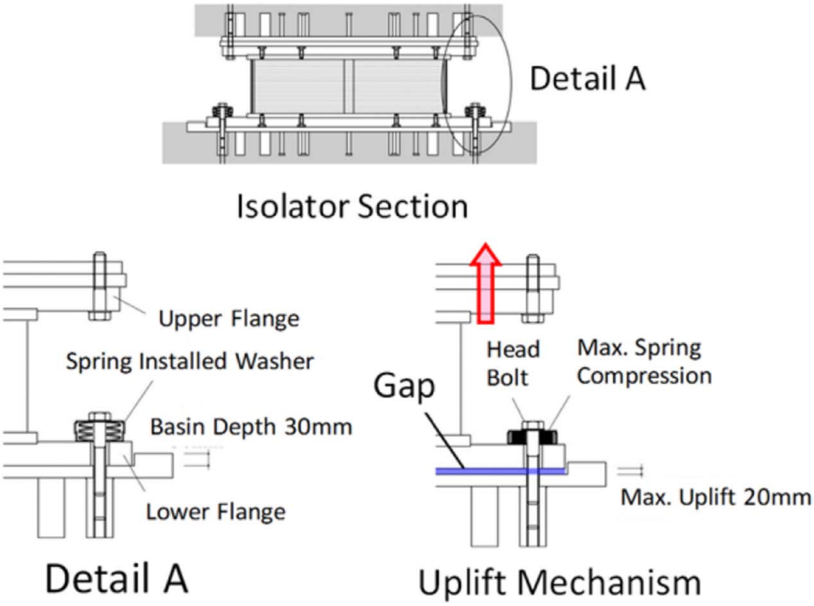


Fig. 8. Schematic diagram of a seismically isolated structure.



(a) Exterior frame (b) Structural scheme



(c) Uplift mechanism of isolators at corners

Fig. 9. Seismic isolated building in TITech.

system consists of 16 rubber bearing isolators, 14 steel dampers, and 2 oil dampers. The braces are placed in the outer frames to resist earthquakes in the transverse direction. The inner frames are moment frames and most of the lateral forces in the transverse direction are carried by the two outer frames. Due to the concentration of the lateral forces and the large aspect ratio, the overturning moment of the outer frames is large. Therefore, the isolators are required to work even under the uplift forces. The isolators at the 4 corners in the outer frames (i.e. isolators shown in Fig. 9b) are connected by the anchor-bolts through the conical spring washers, and the bottom plate of each isolator sits on a circular hole made in the base-plate (Fig. 9c). Accordingly, the uplift forces against the devices are relieved by this mechanism. The outer frames are securely connected to the adjacent inner frames with strong beams in the longitudinal direction and the uplift of the columns does not exceed more than 20 mm in large earthquakes (Fig. 9b). The construction cost is lower than that of an alternative design with ductile frames satisfying the strong-column-weak-beam conditions.

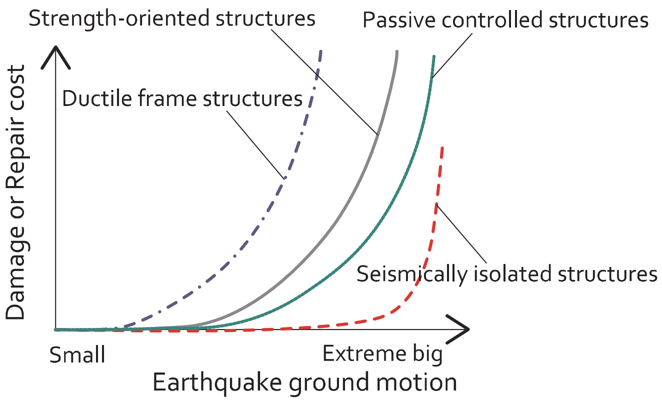
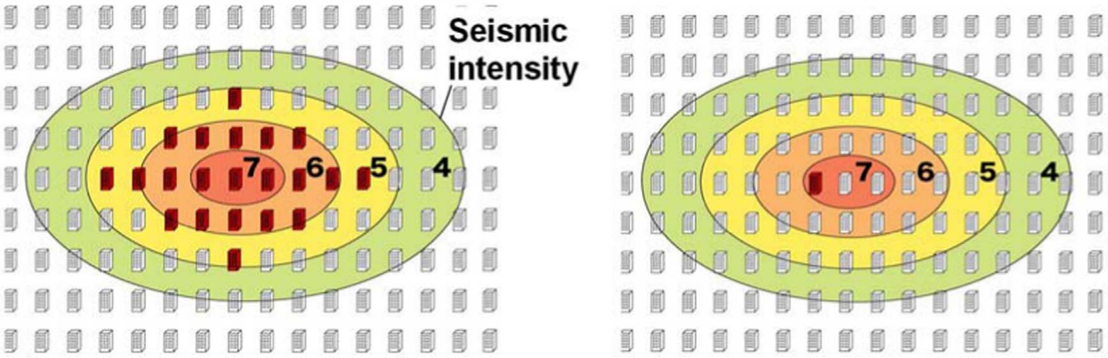


Fig. 10. Relationships between earthquake ground motion and damage or repair cost.

(a) Damage of a single vehicle [7]

(b) Simultaneous damage not happening in vehicles but happening in buildings under large earthquakes

Fig. 11. Safety design of vehicles and buildings.



(a) Many ductile frame buildings damaged

(b) Limited seismically isolated buildings damaged

Fig. 12. Desired seismic design of buildings in big cities.

The possibility of unstable modes of failure cannot be completely eliminated even in new construction practices and new technological devices. Therefore, varied and comprehensive discussions and preparations of countermeasures for cases that exceed certain performance limits are necessary. In this building, the spring washers in Fig. 9b were installed as stoppers for exceedance of the vertical uplift of more than 20 mm.

Fig. 10 shows conceptual relationships between earthquake ground motion and the damage or repair cost for different structural systems, which are: ductile frame structures, strength-oriented structures, passive controlled structures and seismically isolated structures; where, the passively controlled structures are those equipped with energy dissipating devices such as BRBs or oil dampers, and the strength oriented structures are conventional structures primarily relying on elastic lateral strength to resist seismic forces. The damage or repair cost is the lowest in the seismically isolated structures, followed the passive controlled structures, strength-oriented structures and ductile frame structures. Since the ductile frame structures dissipate seismic energy through damage of the main structure, the repair cost is consequently high. Although quantitative discussions on this issue are difficult, resilient structures such as seismically isolated structures or passive controlled structures are effective for the SDGs and continuous use of the buildings, described as the goals of the new seismic design approach in Table 1.

Fig. 11 illustrates the difference in safety design between vehicles and buildings. The design philosophy of protecting the lives of drivers and passengers by sacrificing the engine or main body of the vehicle is desired for major traffic accidents (Fig. 11a) [7]. These traffic accidents are generally local events and do not happen simultaneously in multiple places. Therefore, the damage is limited to a single or a limited number of vehicles. On the other hand, if most buildings would be designed with the same approach against large earthquakes, many non-functional buildings would be generated simultaneously near the epicenter of the large earthquakes (Fig. 12a). This is the situation similar to what occurred following the Christchurch earthquake in 2011 (Fig. 4). If this were to occur in a big city, the entire city would lose its functionality and recovery activities would be highly restrained. Evacuation shelters would not be sufficiently provided. Such a situation is not acceptable for modern resilient societies. The design approach for buildings should be different from that for vehicles. New design philosophy for buildings with minimal damage against large earthquakes shall be accepted especially for big cities (Fig. 12b).

4. Conclusions

The existing seismic design approach has been developed to allow for ductility of building structures to resist large earthquakes economically. While structures are designed to remain elastic in small or moderate earthquakes, they are allowed to experience plastic deformations in large earthquakes to prevent their collapse and save human lives. This design approach has been effective in terms of protecting people; however, it may not be sufficient for modern, complex societies. In past large earthquakes, many buildings that were damaged but did not collapse were eventually demolished rather than being repaired. It should be noted that there is a large gap between structural safety levels that specialists consider acceptable and the expectations of lay people for buildings against large earthquakes. If most buildings in large cities are designed under this design approach they would be badly damaged in future large earthquakes, and the cities would have difficulties in recovery activities and could experience catastrophic loss of function. Corresponding to people's expectations from buildings, the goals of a modern seismic design philosophy should be changed from solely life-safety to also ensuring post-earthquake use and operation. For this goal, it would be effective to design building structures in which the structural components play separate roles. The primary structure will support the gravity load and the seismic members will mainly resist earthquakes. Damage in the primary structure should be minimized during large earthquakes for modern, sustainable and resilient societies. Over the last 100 years, seismic engineering technologies have undergone significant development. More importantly, buildings with higher seismic performance can be constructed less expensively than before. The seismically isolated building at TITech is an example realizing significantly higher seismic performance with lower construction cost compared with an alternative conventional design. In the future, there must be more opportunities to apply these developed technologies to buildings. The ultimate goal of the development of seismic engineering technologies by researchers and engineers is to provide better structures to our society. These specialists should not merely develop new technologies, but more spontaneously act to have such technologies implemented.

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