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Scientific paper

Application of High Performance Fiber Reinforced Cementitious Composites for Damage Mitigation of Building Structures

Case study on Damage Mitigation of RC Buildings with Soft First Story

Hiroshi Fukuyama[1]

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Abstract

It is essential to introduce performance-based design systems and develop new technologies for meeting the social requirements of building structures. This paper begins by discussing the need for damage mitigation for building structures under performance-based design. Based on this concept, the application of a High Performance Fiber Reinforced Cementitious composite (HPFRCC) device is introduced. This device is a HPFRCC short column reinforced with steel bars that has very high strength, stiffness and ductility compared with conventional RC columns with the same configuration and bar arrangement. An analytical study on the seismic response of a soft first story building with and without such HPFRCC devices was performed as a case study to investigate the feasibility of the proposed technique for damage mitigation against large earthquakes. The results indicate that HPFRCC devices can reduce the drift angle of the soft first story from 2% to 0.5% in the case of seismic input with maximum velocity normalized at 50 cm/s. Since a drift angle of 0.5% means an elastic response of the structure, HPFRCC devices are confirmed to have significant potential as a new structural technology for damage mitigation.

1. Introduction

Performance-based design is a sophisticated design system that allows building owners to set freely the level of structural performance. Under this system, the structural designer creates the building structure based on the required structural performance, evaluates whether it is satisfied, and the evaluated performance is stated.

When structural performances are evaluated and the results are disclosed, clients will be able to regard building structures as market products whose performance level and total cost can be compared just like automobiles and computers (**Fig. 1**). Clients will then be able to request an appropriate level of performance, which is not necessarily the minimum level requirement stated in the present code.

The social requirements for infrastructure and building structures have been ever changing along with social and economic development. As peoples' lifestyles and social activities have diversified in recent years, the performance items and levels that people require of infrastructure and building structures too have become more diversified. This tendency will continue in the future as long as society keeps on maturing. Technical development in the 21 century should aim to adequately meet such changing requirements of an evolving society. Therefore, the development of new technology and materials to realize high performance that adequate meets social requirements will be expected.

In this paper, damage mitigation technology, which can prevent or control damage to building structures, is focused on as a new social requirement for the maintenance of safety and serviceability. When a building is damaged, its performance in terms of safety, serviceability, durability and so on suffers. The aim of damage mitigation is to prevent or minimize the deterioration in performance of buildings in order to recover easily the original level of building performance during restoration.

The need for damage mitigation for building structures is discussed in this paper, and a seismic displacement control element using High Performance Fiber Reinforced Cementitious composites (HPFRCC), which exhibits strain-hardening and multiple cracking properties in tension, is introduced as a new structural technology for damage mitigation. The characteristics of HPFRCC are defined and classified by RILEM (1996) and JCI (2004). **Figure 2** shows the super ductile property of a HPFRCC plate without any steel bars as reinforcement

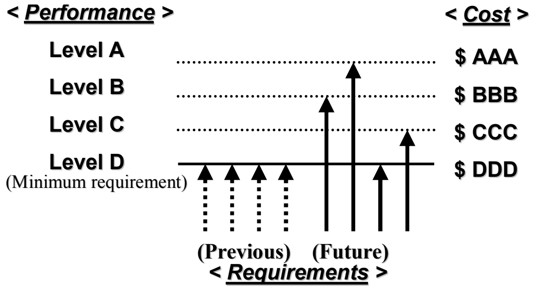

Fig. 1 Performance menu (comparison between performance level and cost).

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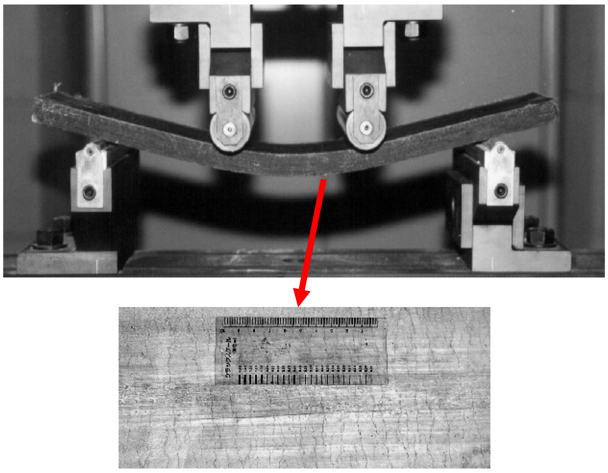
[1] Chief Researcher, Dept. of Structural Engineering, Building Research Institute, Tsukuba, Japan
E-mail: fukuyama@kenken.go.jp



Multiple fine cracks observed at the bottom surface

Fig. 2 Ultra ductile properties of High Performance Fiber Reinforced Cement Composite (HPFRCC).

under bending obtained thanks to the multiple cracking property of HPFRCC.

2. The need for damage mitigation

2.1. Global environment

Buildings in Japan typically have a short life span due to the prevalence of scrap-and-build in this country. This may be caused by the small living space, the difficulty of replacing equipment, and the lack of seismic capacity of old buildings constructed just after the World War II. Yet from the viewpoint of the global environment, including the conservation of energy and the reduction of waste products, extending the service-life of buildings is an urgent task.

Requirements that are often pointed out for the realization of long-lived buildings include easy maintenance and renewal of building facilities and improvement of the durability of building structures. However, it is very important, in addition, to also develop new structural technology that secures a building's long-term service even in the event of disturbances including large earthquakes during its service life. Appropriate prevention and/or control of damage and deterioration would be expected to allow maintenance or recovery of the original level of performance of a building with no or little restoration.

2.2 Lessons from the 1995 Kobe earthquake

Requirements for the prevention and/or control of damage to buildings in earthquakes emerged after the 1995 Kobe Earthquake. BRI (1995) reported that not a few buildings were demolished and reconstructed because of the high repair cost, although most of these buildings showed fairly good performance of a level sufficient for saving human lives per code requirements, as shown in **Fig. 3**. In this case, the total repair cost is higher than the cost of constructing a new building, indicating the need to consider the life cycle cost. Maintenance of the necessary building functions is essential for ensuring the continuity of daily social and economic activities following a large earthquake, and quick recovery of building functions lost through damage is also required for disaster resilience.

(a) View of RC frame-structure building

(b) Shear failure of columns

(c) Damage of beam ends and beam-column joints

Fig. 3 Collapse prevented but severe damage building designed according to the current Japanese seismic code, following the 1995 Kobe Earthquake.

These requirements suggest the importance of evaluating repairability in addition to general performance parameters such as structural safety and serviceability.

2.3 Seismic retrofit target

Seismic retrofit is applied to many Japanese buildings designed according to old seismic codes predating the major seismic code revision of 1981. The primary aim of seismic retrofit is to protect human lives. Since seismic retrofit does not directly aim to prevent damage to buildings, retrofitted buildings are likely to suffer damage to a certain extent the next time a major earthquake occurs. The damaged buildings may require extensive repair at high cost before they can again be considered safe for occupation.

In order to control structural damage, a higher level of target performance for seismic retrofit, as shown in **Fig. 1**, should be applied to buildings that may require a huge cost of repair or need to be demolished and reconstructed because of excessive repair cost.

2.4 Problems of existing building stock

A large number of buildings were constructed during the high-economic-growth period of the 1960s and 1970s due to the severe lack of housing after World War II. Now this building stock is facing reconstruction due to poor seismic safety and building serviceability, rather than durability issues. The average lifetime of these Japanese residential building is only approximately 30 years. Thus development of structural technology for damage mitigation that can upgrade the existing building stock into a long-lived building stock in order to reduce the cost of reconstruction, energy expenditures and waste products, is an urgent task. There is great demand for structures that not only will not collapse, for public safety purposes, but also will not be damaged, for structural survivability purposes, upon the occurrence of disasters. However, the newly developed structural technology to meet these demands is still too expensive to be distributed widely.

2.5 Global economic losses caused by earthquake disasters in the world

Global economic losses and casualties caused by earthquake disasters are shown in **Fig. 4**. This data is from the Emergency Disasters Data Base of CRED (Center for Research on the Epidemiology of Disasters) (http://www.em-dat.net/). According to this data, the number of casualties caused by earthquakes has been decreasing, but the total number of casualties per decade is still approximately 100,000, underlining the fact that the most important goal remains securing public safety.

On the other hand, economic losses have been increasing as societies and economies across the world have matured in recent years. Damage to building structures accounts for a certain ratio of total economic loss. Therefore, on a global basis, potential demand for damage mitigation technology is considered to be very large.

3. Application of HPFRCC for damage mitigation

3.1 Current damage mitigation technology

Whether current damage mitigation technology can satisfy social requirements is examined in this section.

(Source: CRED EM-DAT, http://www.em-dat.net/)

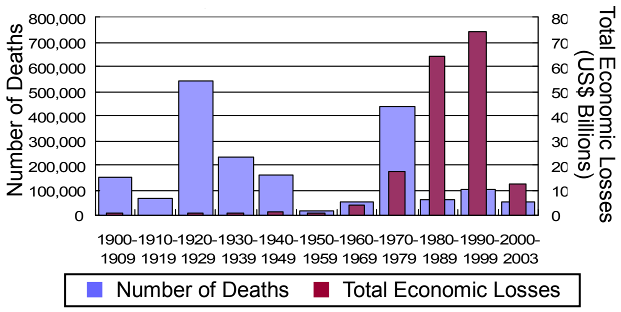


Figure 4 Economic Losses and Causalities caused by Earthquake Disasters in the World.

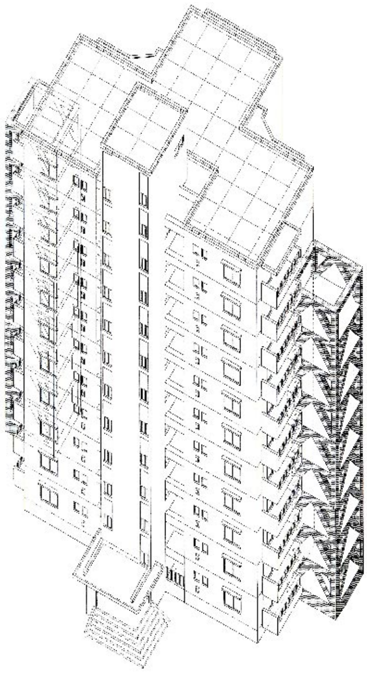


Fig. 5 Prototype residential building used for cost study. (This figure shows the case with exterior RC frames for strengthening.)

A cost study of the seismic retrofit of an 11-story concrete residential building with 33 units as shown in **Fig. 5** was performed by Fukuyama (2005) to evaluate performance level and technical cost. The total cost of construction was calculated as 40 million yen (US$ 333,000), or 1.2 million yen (US$ 10,000) per unit, employing conventional structural strengthening technology, including the use of infill shear walls, the installation of RC exterior frames, and the strengthening by FRP wrapping, and with the seismic retrofit goal of meeting the minimum seismic requirements based on the current seismic code.

On the other hand, the total cost ranges from 170 million to 320 million yen (US$ 1.4 million to 2.7 million), or 5.2 million to 11.2 million yen (US$ from 45,000 to 98,000) per unit, when seismic isolation devices at the base or top of the first story columns, or energy dissipation dampers for response control, oil dampers or visco-elastic dampers, are employed to meet damage mitigation requirements.

While total cost depends on various conditions, at present, the cost of damage mitigation technology is several times higher than that of conventional technologies for the protection of human lives.

Damage mitigation technology is not widely accepted as a structural strengthening technology for residential buildings, although it is considered suitable for strengthening important buildings such as disaster preparedness centers and hospitals. For general consumers, strengthening one’s house ranks on a par with living expenses such as dining out or shopping for clothes and automobiles. Therefore, development of inviting structural technology with good cost performance is essential to their satisfaction.

3.2 Damage mitigation using HPFRCC devices

"Engineering" is defined as a technological activity to meet the requirements of a diversified and sophisticated society such as a new kind of or a higher level of performance requirement. Therefore, it is not necessary to stick to the conventional technologies.

Damage mitigation technology for RC structures is technology that maintains the original performance level of structures with no or little repair. It may also be defined as technology that reduces damage while maintaining the same safety level. Aiming for such a goal, it is natural to employ new materials for structural engineering.

Li (1993), Fukuyama *et al.* (1999), Fukuyama *et al.* (2000), Parra-Montesinos and Wight (2000), Fischer *et al.* (2002), Fischer and Li (2002), Kesner and Billington (2002), Fischer and Li (2003), Fukuyama and Suwada (2003), Li (2003), Canbolat *et al.* (2005) and Parra-Montesinos (2005) introduced the use of HPFRCC to attain a higher level of performance or new performance factors not found in conventional RC structures.

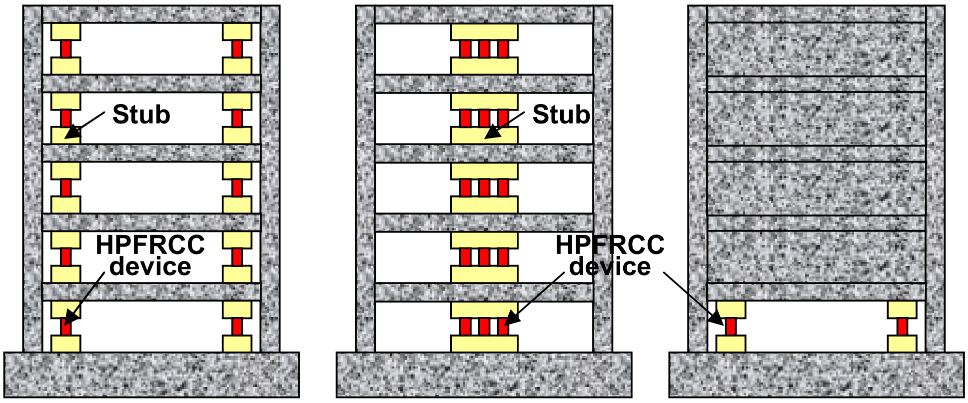
If the use of HPFRCC meets social requirements including cost reduction while maintaining the same performance level, it can be one of the useful structural technologies for performance-based design. The targeted HPFRCC applications are both existing and new buildings.

There are two methods to apply HPFRCC for damage mitigation. One method is to apply HPFRCC to structural members instead of concrete. This method can improve the structural performance of the targeted members as well as reduce damage due to multiple cracking. With this method, damage is mitigated by increasing the shear strength and bond splitting strength through the strain hardening characteristics and by minimizing the width of cracks so as to require no repair through multiple cracking, whereby the number of fine cracks increases. In the latter case, the width of each crack is 0.1 mm and less.

The other method to apply HPFRCC for damage mitigation is to mitigate damage to existing RC buildings by reducing seismic displacement through response control elements. Small response control elements work as large RC elements and can be obtained using HPFRCC. Cheaper cost is also an advantage compared with conventional strengthening methods, which include installing walls, installing steel framed braces, or installing energy dissipation dampers. This method is discussed in greater detail in the following chapters.

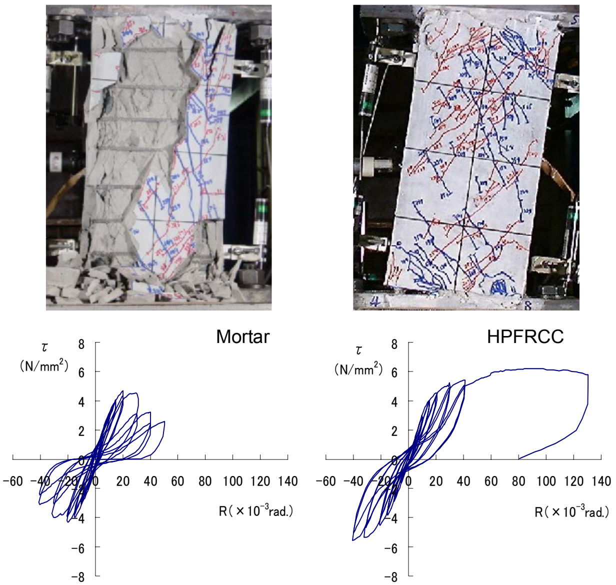
4 Applications to the response control elements

Fukuyama *et al.* (2003) introduced short span column members used as response control elements, as shown in **Fig. 6**, which can reduce the seismic displacement of building structures and mitigate damage to structural members of buildings. These structural elements have high stiffness, strength and ductility capacity. They are suitable for the response control of concrete structures that have relatively higher stiffness compared to steel structures, because they can bear high stress from the small deformation stage and implement effective response control. High stiffness and strength (horizontal capacity) can be achieved by using short span elements. In this case, the response control elements of short columns are supported by stubs. The roles of stubs are to adjust the span of the response control elements, anchor the longitudinal reinforcement and connect elements to the frame. If the response control elements are applied to existing RC buildings, the stabs can be connected through grouted mortar with lap-spliced steel bars fastened to the stabs and to existing RC beams using



(a) HPFRCC devices at end of the span (b) Plural HPFRCC devices at center of the span (c) HPFRCC devices on the soft first story

Fig. 6 Applications of HPFRCC devices as response control elements.



(a) In case of mortar matrix (Severe damage without ductility)

(b) In case of HPFRCC (More than 13% rad. ductility)

Fig. 7 Lateral-loading-test results of HPFRCC device compared with mortar device.

post-installed anchors. This is a common connection method used for seismic strengthening by installing RC walls or steel framed braces. In general, any types of connection are available if they have enough capacity to transfer shear and axial forces acting in the connection.

The stiffness and strength of the elements can be altered by varying the configuration, bar arrangement and the type of HPFRCC materials. Further, these cementitious materials have good formability. Therefore, response control elements optimized for the characteristics and the shape of each structure can be obtained.

The structural performance of response control elements was examined using the static loading test. The results are shown in **Fig. 7**. Conventional mortar materials were badly damaged and eventually fractured due to the large shear force and compressive force, thus preventing the targeted deformation capacity from being obtained. On the other hand, large deformation capacity of over 13% rad. under the very high average shear stress of 6 N/mm^2 and damage reduction effect were observed in the case of the HPFRCC device.

For building structures, application of response control elements to the location of nonstructural members that are ignored in structural design will improve performance without any effect on floor planning. Greater cost reduction can be expected compared to existing seismic dampers using low-yield-point strength steel, as well as greater friction, viscoelasticity and fluid viscosity, because the cost of the cementitious material is low even with mixing fiber material.

The large energy absorption of HPFRCC response control elements is the result of the excellent energy dissipation capacity of longitudinal reinforcement. HPFRCC materials are not expected to be capable of energy absorption. However, HPFRCC plays a very important role in terms of assisting the work of longitudinal reinforcement by assuring the unification of HPFRCC and steel bars in order to effectively obtain maximum energy absorption capacity and stress bearing capacity of the response control elements until very large deformation. This prevents brittle failure including shear failure, bond splitting failure and anchorage failure even after bar yielding.

The large rotation at the end of the element occurs as shown in **Fig. 7 (b)** due to the dominant flexural deformation at the end of the HPFRCC devices. Large compressive forces will occur in the device since any axial elongation resulting from the rotation of the HPFRCC device is restrained by the surrounding structures. Therefore, HPFRCC is also expected to prevent brittle compressive failure.

5. Damage control of existing buildings with soft-first story

This chapter discusses the concept of damage control and its possible application for soft-first-story buildings, as shown in **Fig. 6(c)**, are discussed.

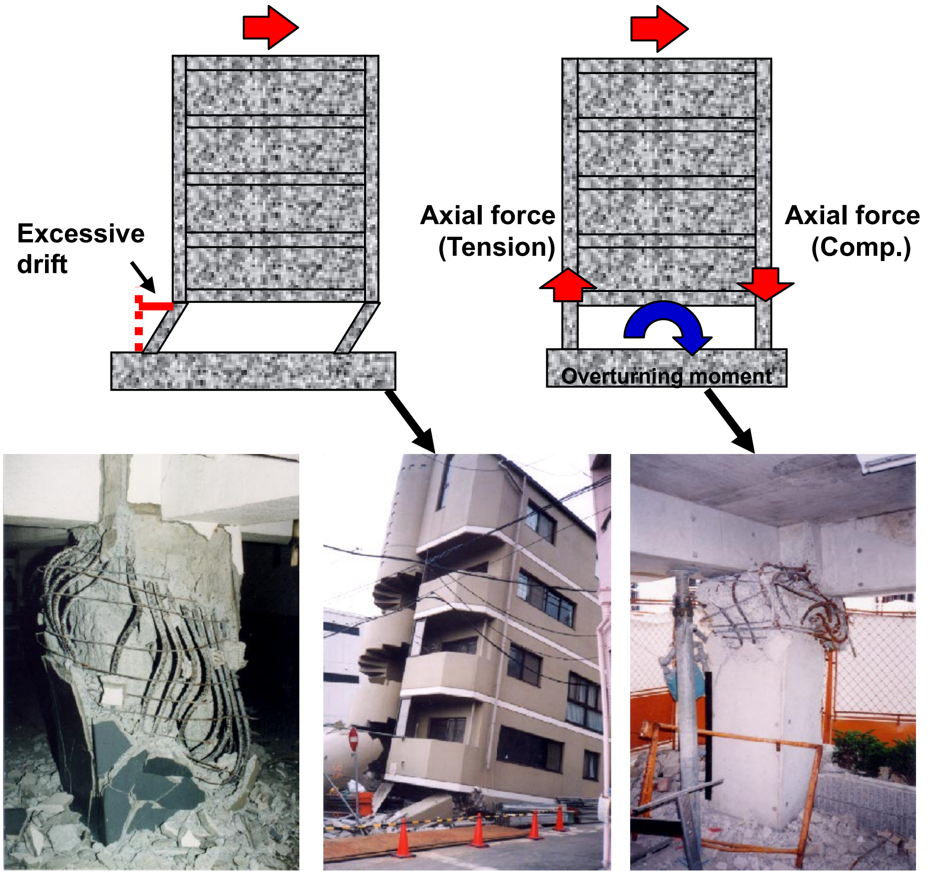
5.1 Collapse pattern of soft-first-story buildings

Typical examples of damage to a building with a soft first story are shown in **Fig. 8**. **Figure 8 (a)** shows a first story collapse caused by the shear failure of a column, a case frequently observed in past earthquakes. This type of damage can be prevented in buildings with a soft first story that were designed according to the current code. Other types of damage observed in buildings with a soft first story after the 1995 Kobe Earthquake are shown in **Figs. 8 (b)** and **8(c)**. **Figure 8 (b)** shows a first story collapse caused by excessive drift due to lack of horizontal capacity and energy concentration into the first floor. **Figure 8 (c)** shows the failure of a column on the first story which was acted on by major varying axial force resulting from overturning moment. The buckling of the longitudinal reinforcement in **Fig. 8 (c)** is caused by major compressive axial force after yielding of the longitudinal reinforcement under tension stress. Rupture of the longitudinal reinforcement may be expected if another major tensile axial force acts on the columns after the buckling.

Accordingly, for the security of soft-first-story buildings, it is essential to prevent the shear failure of columns and minimize seismic displacement in the first story. It is also important to minimize axial force on the columns as much as possible.

5.2 Conventional method to strengthen soft-story buildings

The method for reducing the response of the soft first story of a building is to impose most of the horizontal force on the multi-story shear wall. In this case, the wall



(a) Shear failure of columns

(b) Excessive drift at soft first story

(c) Axial collapse of columns due to huge cyclic axial force caused by large overturning moment

Figure 8 Collapse pattern of soft-first-story buildings.

should be the bearing wall set in the crosswise direction on the soft first story. However, the soft first story is originally designed to utilize the wide space of lower floors for parking lots or shops. Therefore, setting bearing walls decreases the amount of open space of the soft first story.

When the bearing walls are allowed to be set from the viewpoint of structural function, such response control methods are structurally reliable and their use is preferable. However, if a wide open space on the soft first story is required, it is impossible to use not only the bearing walls but occupying braces and seismic devices as well.

5.3 New response control method of existing soft-story buildings

The damage is likely to be concentrated on the first floor in a building with a soft first story. If the response and damage on the soft first story can be controlled effectively, damage control of the whole building is easily realized and the soft-first-story buildings are considered to be good for damage control. However, more should be done than simply strengthening the soft first story, because damage control of the first story should not cause a shift of the most heavily damaged floor to a higher story.

Additional columns are introduced as response control elements (HPFRCC devices) that can reduce the seismic displacement of the soft-first-story building and damage to the whole building (**Fig. 6 (c)**). The functions of this additional column are to hugely improve the stiffness and the strength of the soft first story with relatively small elements, and to bear the axial force. Additionally, because of the bearing walls on the upper floor, the response control elements can perform effectively without any reinforcement to prevent the early yielding of the beam in case of a beam-column rigid frame. In brief, the additional column can work effectively for both collapse patterns of the soft-first-story buildings shown in **Figs. 8 (b)** and **8(c)**.

5.4 Effect of response control

This section discusses the feasibility of damage mitigation of soft-first-story buildings based on the results of the parametric response analysis conducted by Fukuyama (2004) using HPFRCC devices adjacent to the existing column.

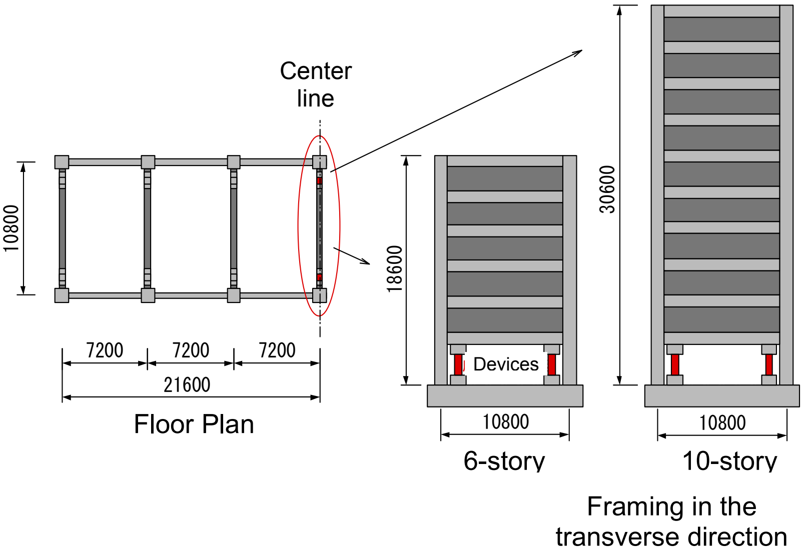


Fig. 9 Target buildings.

(1) Outline of analysis

The buildings analyzed in this study were six-story and ten-story residential buildings with 7.2 m x 6 m spans in the longitudinal direction and 10.8 m x 1 m spans in the transverse direction. **Figure 9** shows their floor plan and framing in the transverse direction. Both buildings were designed based on the design standard that was in use before the 1995 Kobe Earthquake. The base shear coefficient, the shear force at the base of the building divided by the weight of the building without HPFRCC devices, is 0.51 for the six-story building and 0.48 for the ten-story building. In this study, only one span in the transverse direction is analyzed by time history seismic response analysis.

In the analysis, columns are modeled as linear members with elasto-plastic springs at the top and bottom and a vertical spring in the middle. Three linear members model the shear walls; in the center of the wall there is an elasto-plastic spring and on both sides of the wall there are springs in the axial direction that are pinned at the top and bottom. The axial stiffness of the springs at the two ends of the shear walls is equivalent to that of the side columns of the shear walls. The central member is modeled as an elasto-plastic spring with axial, flexural, and shearing stiffness equivalent to those of the wall panel. The central member column is modeled with a hinge only at its base.

The restoring force models used for each member are: a TAKEDA model (Takeda *et al.* 1970) for a flexural spring, an Axial stiffness model for a spring in the axial direction, and an Origin-oriented model for a shear spring (Aoyama 1990).

The HPFRCC devices can be modeled in a similar way as the column members. First, the devices are modeled as linear members, and then modeled with an elasto-plastic spring at the end of each member. The stub part is treated as a rigid zone. The devices are assumed to have properties similar to normal reinforced concrete columns that undergo large bending deformations. Therefore, as in the case of the RC columns, a TAKEDA model is used as the restoring force model for the spring at the end of members.

Iwabuchi *et al.* (2003) confirmed the reliability of this analysis by conducting a substructure pseudo dynamic test of a soft-first-story building with HPFRCC devices.

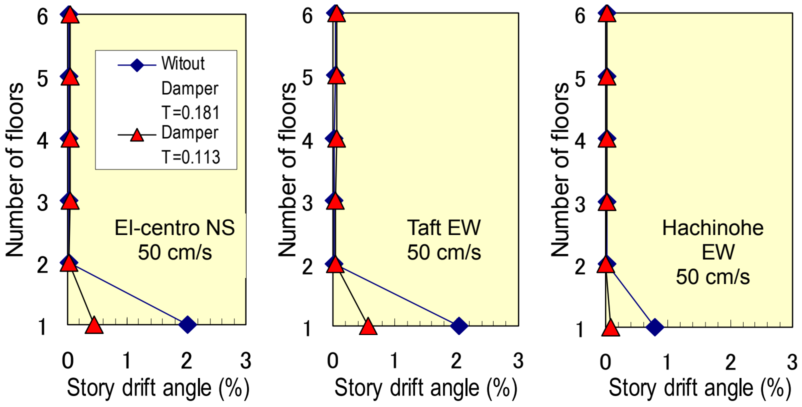
The input seismic waves used in the analyses are the El-Centro NS, Taft EW and Hachinohe NS normalized to a maximum velocity of 50 cm/s and the El-Centro NS normalized to a maximum velocity of 75 cm/s.

The HPFRCC devices are designed to be half the size (1/4 the sectional area) of the existing columns on the soft first floor. Their length being 1/2 the existing column, their volume is thus 1/8. The total amount of longitudinal reinforcement is adjusted in order to set the shear strength associated with the flexural yielding at both ends to 1/2 that of the existing columns.

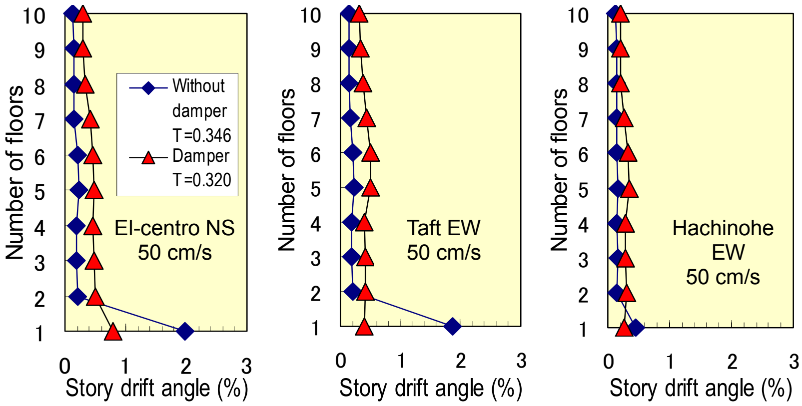
(2) Results of response analyses

Figure 10 shows the distribution of maximum story drift angles obtained by the analysis. Both in the six-story and the ten-story buildings, the first story drift angle in the case without HPFRCC devices is a maximum of 2%. It is reduced to about 0.5% when HPFRCC devices are installed. The existing columns remain within the elastic zone and damage requiring repair can be prevented when in the case of severe earthquake which is taken into account by the usual design.

The axial force of the HPFRCC devices accounts for 30% of the axial compressive capacity. The axial load of the existing columns is reduced by co-operation of the HPFRCC devices. For example, when the El Centro NS wave is used for the ten-story buildings, the maximum axial force ratio, ratio of acting axial force to the compressive capacity of existing columns, changed from 0.36

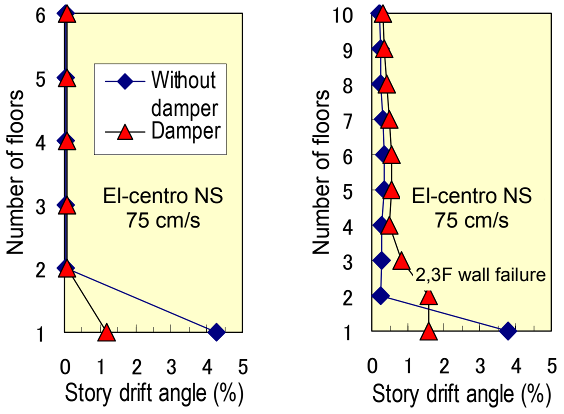


(a) 6-story building.



(b) 10-story building.

Fig. 10 Distribution of maximum story drift angles in case of seismic input with maximum velocity normalized at 50 cm/s.



6-story building **10-story building**

Fig. 11 Distribution of maximum story drift angles in case of seismic input with normalized at 75 cm/s in maximum velocity.

(in case without HPFRCC devices) to 0.24.

In order to confirm the response properties in the case of an extra-large earthquake, the El-Centro NS wave was used as input. **Figure 11** shows the response when the input excitation is normalized to have a maximum velocity of 75 cm/s. The drift concentration on the first floor was larger for the six-story building than for the ten-story building and the HPFRCC devices showed remarkable performance as well when the maximum velocity of the input motion was 50 cm/s. The first story drift angle without HPFRCC devices was approximately 4.3%. It was drastically reduced to 1.2%. For the ten-story building, the drift angle of the first story without HPFRCC devices was 3.8%. It was reduced to approximately 1.5%, but in this case, shear failure of the walls on the second and higher floors occurred. Here, reduction of the seismic displacement is aimed for by improving the strength of the first story, but too much improvement would cause damage on the second and higher floors. Thus it is recommended that the strength of the first story with devices be strong enough to control response deflection within the design criteria but less than that of the second story.

In any case, when HPFRCC devices are installed and the seismic displacement of the soft first story building remains within the elastic zone, it is possible to prevent damage in a severe earthquake which is taken into account by the usual design. It is expected that no residual deformation occurs since the main building structure is within the elastic range. Thus no post-earthquake repair is required.

6. Conclusions

This paper discusses damage mitigation of building structures as a new social requirement for the maintenance of safety and serviceability. Demand for damage mitigation is predicted to increase based on a number of points, including global environments, the lessons from the 1995 Kobe Earthquake, the seismic retrofit target, the problems of the existing building stock, and economical losses caused by earthquake disasters around the world. However, meeting a high level of performance such as damage mitigation against large earthquakes with appropriate cheaper costs is still difficult using existing conventional technologies.

Against such a background, the application of HPFRCC is introduced as an example of cost effective and advanced technology for the purpose of damage mitigation.

As a case study, the application of HPFRCC devices as seismic response control elements to soft-first-story building is proposed. The feasibility of damage mitigation with this technique is confirmed through time history seismic response analyses. This approach can conserve wide spaces on the first story while reducing response drift by increasing the shear capacity of the first story. The large axial force acting on conventional columns can also be reduced through co-operative support by the HPFRCC devices. As a result, compressive failure of existing column can be prevented successfully.

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