Seismic Response Control by HPFRCC Device for RC Buildings with Soft-First Story

H. Fukuyama
Building Research Institute, Tsukuba, JAPAN

K. Iwabuchi
Kumagaigumi Co. Ltd., Tokyo, JAPAN

H. Suwada
National Institute for Land and Infrastructure Management, Tsukuba, JAPAN

ABSTRACT: Collapse or severe damage has been observed in many RC residential buildings with soft-first story at the previous earthquake disasters. This paper proposes a new technique for structural control of RC buildings with soft-first story by using HPFRCC devices, which are placed beside the existing columns in the first story. The advantage of the HPFRCC devices is selective structural performance by varying the configuration, bar arrangements and type of materials used. Also, since the HPFRCC devices can resist to the axial force, axial force acting in the existing columns due to overturning moment can be reduced. As the result of analysis, the seismic response of the buildings was successfully controlled to meet high level of structural performance requirements by using HPFRCC devices.

Keywords: damage, device, HPFRCC, RC building, response control, soft story,

1 INTRODUCTION

When the 1995 Kobe Earthquake hit the southern part of Hyogo Prefecture in Japan, the first floor of multi-story reinforced concrete (RC) residential buildings with independent columns on the first floor and shear walls on the second floor or above were heavily damaged.

The first floor of these types of buildings, commonly referred to as soft story buildings, has much lower yield strength and stiffness than the second and higher floors. When these buildings are subjected to lateral loads such as large-scale earthquake, most of the input energies are dissipated through plastic drifts on the first floor. Therefore, it is widely assumed that the seismic response can be reduced by increasing lateral capacity, ductility and damping of the first floor, so as to prevent the collapse of the first floor. Although infilling wall or installing response-control devices are useful upgrading methods for these purposes, wide space of the first floor is partitioned into small spaces.

This paper proposes and discusses on the response control elements using high performance fiber reinforced cement composite (hereinafter referred to as 'HPFRCC') applicable to soft story buildings.

2 LESSONS FROM THE 1995 KOBE EARTHQUAKE

2.1 *Damaged ratio of RC buildings with soft story*

The lessons from the disaster caused by the 1995 Kobe Earthquake on concrete buildings could be summarized as follows. (Fukuyama & Sugano, 2000)

- Most new buildings designed and constructed according to the present seismic codes showed fairly good performance from the view of preventing severe structural damage and/or collapse for life safety as a minimum requirement, even to such severe earthquake ground motions.
- The collapsed or seriously damaged ratio of RC building with soft story in the most affected areas, which reported seismic intensities "7" in JMA (Japan Meteorological Agency) scale, i.e. 17.0%, was much higher than that without soft story, i.e. 7.0 %.
- The damage to RC buildings was serious for those constructed before 1981, especially before 1971, because Japanese seismic design codes in 1950, which was basically same as the first Japanese seismic design codes for buildings in 1924, was revised in 1971 and

1981. The collapsed or seriously damaged ratios of buildings designed and constructed in accordance with the codes before 1971 revision, before 1981 revision and of current are, 8.1 %, 3.7 % and 1.1 % for buildings without soft first story, and 12.2 %, 11.7 % and 2.4 % for buildings with soft story, respectively.

Therefore, urgent needs of seismic performance evaluation to identify seismically vulnerable buildings, which have not experienced severe earthquake ground motion yet, and of seismic strengthening to upgrade their seismic performance have been strongly recognized, especially for the existing old RC residential buildings with soft-first story. However, it is very hard to strengthen the soft-first story of the RC buildings without partitioning the wide space in the first floor. An advanced technique to strengthen the soft story RC building with maintaining the wide space in the first floor is strongly required.

2.2 *Failure pattern of RC buildings with soft story*

Figure 1 shows typical failure patterns of the soft story of RC buildings. The left Figure 1 (a) shows shear failure of a column, which was observed frequently at the previous earthquakes in the RC buildings with soft story designed according to the previous code. This type of failure could be prevented in the buildings designed according to the current code in Japan. However, other types of failure of the soft story were observed in the disaster caused by the 1995 Kobe Earthquake. Those are collapse due to excessive drift of the soft story, mainly caused by the lack of story shear capacity, as shown in Figure 1 (b), and collapse caused by the reversed axial force due to large overturning moment as shown in Figure 1 (c). In case of Figure 1 (c), buckling of the longitudinal steel bars under the compressive axial force, which have yielded by the tensile axial force firstly, was observed. The bars may rupture if the large tension forces act after buckling. Thus not only shear failure of the columns but excessive story drift and/or excessive axial force of the columns should be prevented for meeting the structural safety requirement.

2.3 *Importance of damage minimization*

Many buildings that had protected human lives by successfully preventing collapse had to be demolished and reconstructed due to the large cost of extensive repair work necessitated by the severe seismic damage. This underscores the importance of the concept of life cycle cost whereby it is not enough just to consider general structural performance such as safety and serviceability, but it is also necessary to also take into consideration reparability of structures (Fukuyama 2002).

(a) Collapse due to shear failure of columns

(b) Collapse due to excessive drift of the soft-first story

(c) Collapse caused by the reversed axial force due to overturning moment

Figure 1 Collapse of the soft story building

3 DEVELOPMENT OF HPFRCC

Recently, many types of HPFRCC have been developed, which exhibit strain hardening and multiple cracking characteristics under the uniaxial tensile stress (JCI Task Committee on DFRCC, 2002).

Authors have also developed some types of HPFRCC that have high ductility while being capable of reducing damage through the formation and dispersion of micro cracks (Fukuyama et al. 1999, Suwada et al. 2001). HPFRCC with 1% to 2% of short fibers by volume mixed with a mortar matrix show a strain hardening property with strain capacity in excess of 1% in tension as well as a multiple micro-cracking property. Several HPFRCC have ductile properties in compression similar to concrete confined by lateral reinforcing bars, whereby their compressive stress gently decreases after reaching the maximum compressive strength.

These excellent properties of HPFRCC, combined with its flexible processing requirements and isotropic properties, signify a high potential for the improvement and development of multi-purpose performances, safety, reparability and durability of concrete building structures. Failure mechanism, ductility, hysteresis, and damage of RC members can be appropriately controlled by using HPFRCC instead of normal concrete (Fukuyama et al. 1999, Fukuyama et al. 2000). Moreover, stiffness and strength can be easily controlled by the configuration of members. It may therefore be possible to assemble dampers using HPFRCC (Fukuyama & Kuramoto 2001, Kesner & Billington 2002) such that they are more effective than conventional damping devices, e.g. metallic yielding devices, friction devices, fluid restoring force/damping devices, viscoelastic solid or fluid devices and viscous fluid devices, in controlling seismic response of RC buildings.

4 HPFRCC DEVICE FOR STRUCTURAL CONTROL OF SOFT STORY BUILDINGS

Figure 2 shows short-span HPFRCC column members used as devices for structural control through their strength, energy absorption and period changing characteristics, for reducing response displacement of an entire structure and thereby reducing damage to each component in the structure. The darker gray parts are HPFRCC dampers and the light gray "connectors" are concrete stubs for adjusting the clear height of the dampers, anchoring the longitudinal reinforcement of the dampers and connecting the dampers to the structural frame. Since short column members and/or wall members built of HPFRCC have high stiffness, high strength and ductility, they can efficiently absorb energy through small deformations. Thus they are suitable damper for RC structures with high stiffness.

Additionally, they have high compressive resistance capacity as a unique advantage. Then they are suitable damping device for RC soft story buildings, in which huge axial force occur at the soft story columns.

The stiffness and strength of a HPFRCC device can be easily changed by varying the configuration, bar arrangement, and type of materials used in composites. Moreover, these elements are built of cement materials that can be molded freely. Thus, it is possible to design the HPFRCC device whose properties and configurations are optimized for any given structure. Another advantage is that these elements are more cost effective than conventional energy absorption devices whose price ranges from 0.5 million yen to 3 million yen per unit in many cases. The price of HPFRCC devices will be much less than 0.5 million yen even though it contains relatively expensive short fibers, since the cost of cementitious materials is much cheaper than that of other types of materials used in conventional energy absorption devices.

Since most of the seismic energy is dissipated at the weak story in the soft story building, damage will concentrate to the soft story. Then if the response of the soft story can be appropriately controlled, it means damage of the soft story building can be minimized.

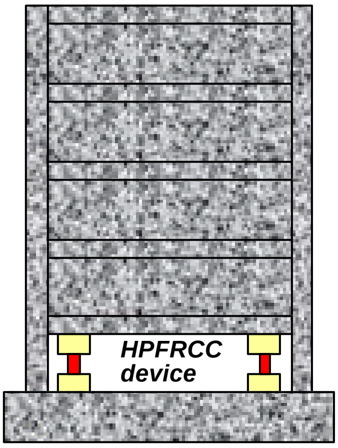


Figure 2 HPFRCC devices for structural control of RC buildings with soft-first story

In these devices, reinforcing bars are mainly expected to absorb energy by yielding at both ends. The introduction of HPFRCC will assist in securing a better integration of reinforcing bars in the matrix so that device will exhibit an enhanced, more effective energy absorption performance and at the same time be capable of undergoing large deformations. More specifically, HPFRCC prevent brittle failures, such as shear failure, bond-splitting failure, and anchorage failure, even after the reinforcing bars have yielded (Fukuyama et al. 2001). On many occasions HPFRCC device undergo rotational deformations within a frame. Thus large compressive forces will occur in the device since any axial elongation resulting from the rotation of the HPFRCC device is restrained. The use of HPFRCC is expected to prevent brittle compressive failure as well. Also since HPFRCC device can jointly support axial force with adjacent RC columns in case the device are used as column-side device as shown in Figure 2, the structural performance of RC columns can be upgraded by increasing the ductility of the device and preventing any damage due to a decrease in compressive axial forces acting on the columns. The support of axial force is a unique advantage of HPFRCC devices since this is a feature not offered by the conventional damping devices. Also HPFRCC device can function effectively without requiring any special strengthening on a beam due to presence of the shear walls in every upper floors of the soft story RC buildings.

The structural performance of HFPRCC device for response control elements is first investigated by static loading tests comparing a device made by mortar. As seen in Figure 3, there is massive amount of damage in mortar specimen, with large shear and compression ultimately leading to failure and a satisfactory deformation capacity is not realized. On the other hand, the HPFRCC member sustains much less damage and undergoes deformations as large as 1/10 radian or more (Fukuyama et al. 2003)

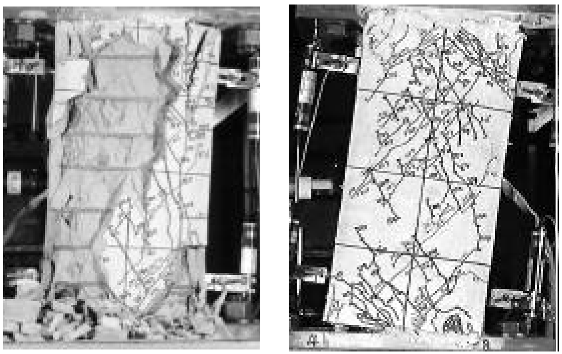
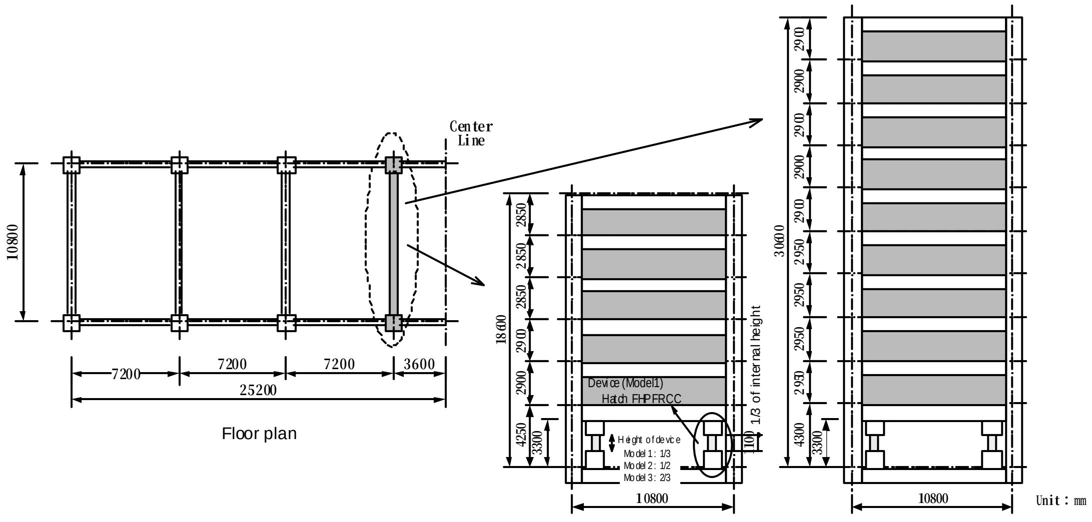

a) Mortar matrix b) HPFRCC matrix

Figure 3 Static loading tests on response control devices

5 TARGET BUILDING AND ANALYTICAL MODELS

5.1 *Target buildings*

The buildings analyzed in this study are six-storied and ten-storied residential buildings with 7.2 m x 7 spans in the longitudinal direction and 10.8 m x 1 span in the transverse direction. Figure 4 shows the floor plan and framing in the transverse direction.



Floor plan

Framing in the transverse direction

Figure 4 Target buildings

Table 1 List of sections and bar arrangements

Number of floors	Floors	Columns		Walls		Concrete (N/mm^2)	Reinforcement
		Section (mm)	Bar	Thickness (mm)	(vertical and horizontal)		
6	2F– 6F	800×700	X-direction 4-D25/ Y-direction 2-D25+2-D16	150	D10@150S	24	≧D19:SD345 ≦D16:SD295A
	1F	950×950	X-direction 8-D25/ Y-direction 6-D25 (Hoop:4-D13@100)				
10	6F–10F	900×800	X-direction 5-D29/ Y-direction 2-D29+3-D16	150	D10@150S	24	≧D19:SD345 ≦D16:SD295A
	5F	900×900	X-direction 9-D29/ Y-direction 2-D29+3-D16				
	3– 4F			180	D10@200D	27	
	2F					30	
	1F	1100×1100	X-direction 8-D25/ Y-direction 6-D25 (Hoop:4-D13@100)				D13:SD685

Both these buildings were designed based on the design standard that was in use before the 1995 Kobe Earthquake. Table 1 shows section and bar arrangements for the two buildings. The base shear coefficient without the HPFRCC devices is 0.51 for the six-storied building and 0.48 for the ten-storied building. In this study, only one span in the transverse direction is analyzed.

5.2 *Analytical model*

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 as shown in Figure 5; 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 the member. A stub part is treated as a rigid zone as shown in Figure 6 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. A skeleton curve is obtained based on initial stiffness, cracking strength, yield strength, and the equivalent stiffness of the yielding point, using conventional equations (AIJ 1999) for RC members used in the structural design. The stiffness after reaching the flexural yield point is set to be 0.001 times the initial stiffness.

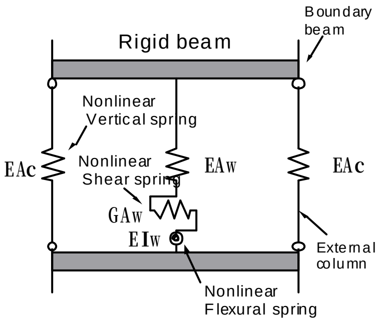


Figure 5 Analytical model for shear wall

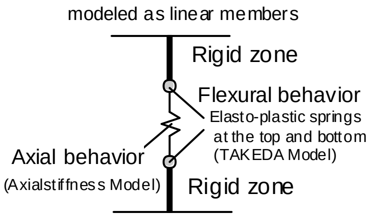


Figure 6 Analytical model for HPFRCC device

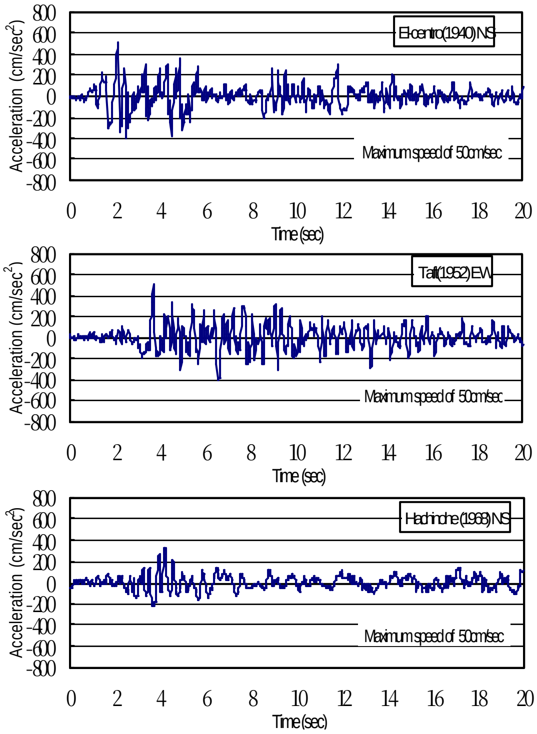


Figure 7 Acceleration record of input seismic waves

The input seismic waves used in the analyses are the El-Centro NS, Taft EW, and Hachinohe EW normalized to a maximum velocity of 50 cm/sec. Figure 7 shows the input seismic waves. Damping is modeled as an instantaneous stiffness proportional damping and the damping coefficient is set to 3 % at the natural period of the elastic model. The Newmark-ß method with ß= 0.25 is used for numerical integration to calculate the response of the buildings.

5.3 *Design method of the HPFRCC devices*

Three models of HPFRCC devices depend on its height and two cases of cross section depend on its moment capacity are assumed for the analysis. As shown in Figure 8, the height of the Model 1, Model 2 and Model 3 devices are equal to 1/3, 1/2, 2/3 of the column height, respectively. The moment capacity of the devices for case 1 and case 2 are set as 0.5 and 0.25 of that of column in the first story, respectively.

Table 2 lists the yield strength ratio (=V_{yd}/V_{yf}, where V_{yd} is the yield strength of the device and V_{yf} is the yield strength of the frame, both are indicated in shear force), and Figure 9 shows the shear strength-story drift curves of the frame and the device for Case 1 for the six-storied building.

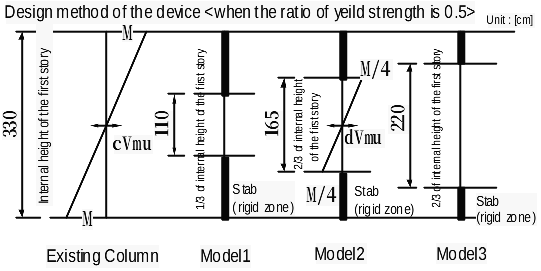


Figure 8 Design method of the HPFRCC devices

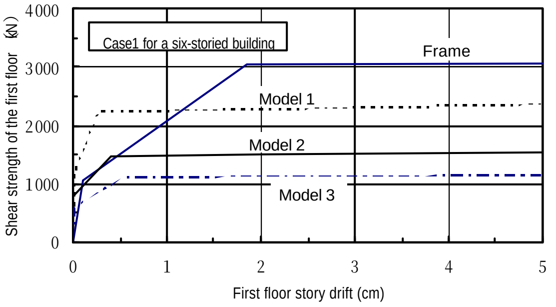


Figure 9 Relationships between load and drift

Table 2 Ratio of lateral force capacity at member yielding of device (V_{vd}) to that of column (V_{vf})

		Model1	Model2	Model3
		V_{yd}/V_{yf}	V_{yd}/V_{yf}	V_{yd}/V_{yf}
6-storied	Case 1	0.74	0.49	0.37
	Case 2	0.39	0.26	0.20
10-storied	Case 1	0.73	0.49	0.36
	Case 2	0.36	0.24	0.18

6 ANALYTICAL RESULTS AND DISCUSSION

6.1 *Results of response analysis*

Figure 10 shows the distribution of maximum story drift angles obtained by the analysis. In all cases the larger the yield strength ratio becomes (from Model 3 to 2 to 1), the smaller is the degree of concentration of drift on the first floor. In case of using Model l and Model 2 devices in the Case 1 analysis, it is possible to reduce the first story drift angle from 2% in case without the device to less than 0.5%, within the elastic zone. Then damage can be prevented so as not to require the repair after the event. On the other hand, it is hard to reduce the first story drift angle within the elastic zone in the Case 2 analysis. Then appropriate strength of the device is required for damage

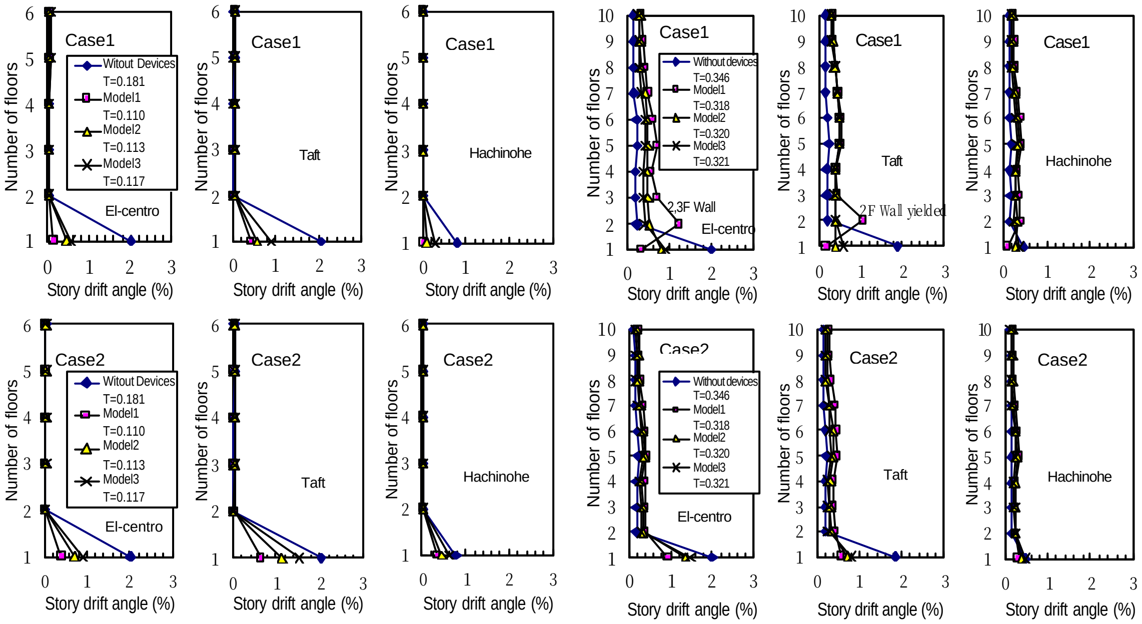


Figure 10 Distribution of maximum story drift angles in case of seismic inputs which have a maximum velocity of 50 cm/sec

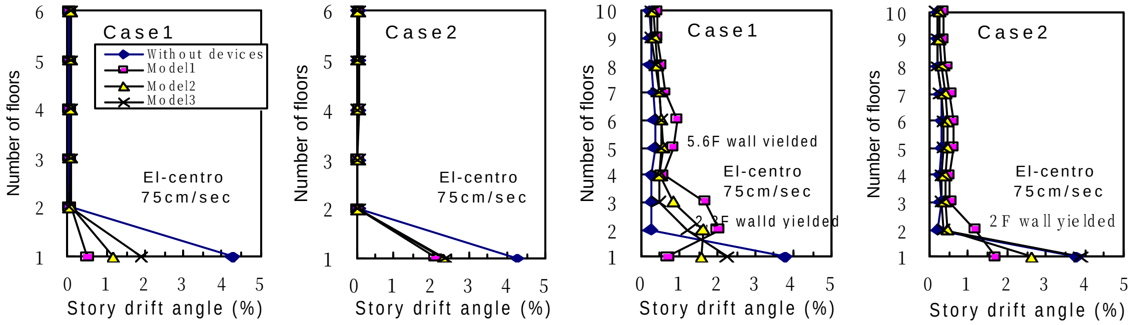


Figure 11 Distribution of maximum story drift angles in case of seismic input which has a maximum velocity of 75 cm/sec

prevention. However, in case the ten-storied building shear failure is likely to occur in the walls on the second floor or above. Thus story shear capacity should be less than that of upper stories with considering the seismic force distribution.

In order to confirm the response properties in a severe earthquake, the El-Centro NS wave is used as input. Figure 11 shows the response when the input excitation is normalized to have a maximum velocity of 75 cm/sec. The drift concentration on the first floor is larger for the six-storied building than for the ten-storied building and the device displays the same remarkable effect as in the earlier case when the maximum velocity of the input motion was 50 cm/sec. Therefore, it is possible to control the drift angle of the first floor from a value of about 4 % without the device to less than half to a value of 2 % with the device. In the case of the ten-storied building, more energy is absorbed by elastic drift of the second and higher floors. Accordingly, the degree of drift concentration on the first floor is smaller as compared to that for the six-storied building, and the overall impact of the device appears to be less. However, if the device is designed so as not to cause shear failure in the walls on the second floor, 4 % of the first story drift angle without the device can be reduced by 30 % to 40 % to 2.5 % radian. Thus, the use of the HPFRCC device makes it possible to control the response even in a severe earthquake.

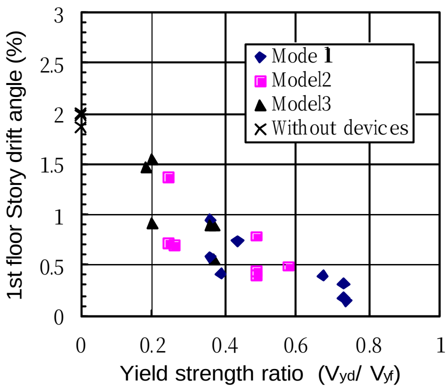


Figure 12 Relation between first floor story drift angles and yield strength ratio

6.2 *The device strength and the frame strength*

Figure 12 shows the relation between the device strength expressed in terms of the yield strength ratio (V_{yd}/V_{yf}) and the first floor story drift angle. In all three models tested, the first floor story drift angle reduces as the yield strength ratio increases. The yield strength ratio versus drift angle curve shows an inflection point at about 0.4 below ratio which the rate of increase of the drift angle with reduction in the yield strength increases. Judging from this, it is recommended that in order to make the device work effectively, the yield strength ratio should be 0.5 or above.

7 CONCLUSION

This paper discusses how HPFRCC devices installed beside columns of a soft story building can be effective in reducing the response. The analyses conducted in this study reveal the following:

The installation of a HPFRCC device beside the column of a soft story is effective in reducing the first story drift value without the device to less than half, thereby obtaining a high damping effect.

In the target buildings with the base shear coefficient of around 0.5, the response is effectively reduced by setting the yield strength ratio between the device and the frame to be 0.5 or above. In order to control even minor level story drifts the devices should have small shear span ratios as in Model 1. Moreover, the difference in strengths between the soft story and the upper floors should be as small as possible, within the range where the strength of the soft story does not exceed that of the upper floors.

It is essential that the device possess a steady hysteresis property for drifts that are fairly large, in order to confine the first floor story drift angle to lie within the elastic zone with input seismic wave of 50cm/sec.

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