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HPFRCC DEVICE FOR SEISMIC RESPONSE CONTROL

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SUMMARY

High performance fiber reinforced cementitious composite (HPFRCC) is characterized by tensile strain hardening and multiple cracking. One proposed application of HPFRCCs is in devices for controlling the deformation due to seismic response of buildings so as to mitigate structural damage of buildings for continuous use. In order to verify the effectiveness of HPFRCC response control devices, shaking table tests are performed on a 1 x 2 span 3-story steel frame which incorporate these elements in each story. The test results show that HPFRCC devices are able to significantly reduce response deformation of the steel frame.

INTRODUCTION

As High performance fiber reinforced cementitious composites (HPFRCCs) are highly ductile and can help prevent damage spontaneously by spreading fine cracks, Fukuyama [1], Suwada [2], they are ideal for use in improving the safety, reparability and durability of concrete structures. By adding short fibers into the mortar matrix at about 1 to 2 % by volume, HPFRCCs show a strain hardening property with strain capacity of 1 to 2 % even after cracking has initiated under tensile stress. In addition, HPFRCCs exhibit a multiple cracking behavior.

Figure 1 shows a photograph of a bending test of a thin HPFRCC plate. The photograph shows that the HPFRCC specimen is able to mitigate the "tensile fragility" that has plagued conventional cement materials. What's more, mixing high-stiffness fibers with excellent bond characteristics can ameliorate the decline in stress that occurs after the maximum compressive strength - a characteristic similar to that shown by concrete confined by lateral reinforcement.

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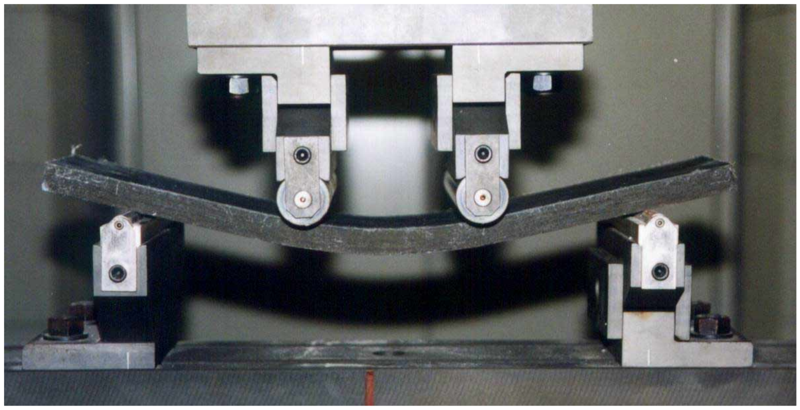


Figure 1 Ductile property of HPFRCC plate

Because of these advantageous properties, it would appear that the use of HPFRCCs in place of concrete can lead to better control of the failure mechanism, deformation capacity, hysteresis characteristics and degree of damage of reinforced concrete members. Furthermore, since HPFRCCs are cement-based, their shapes can be easily molded as desired to control their rigidities, strengths, and other properties. Therefore, it is not surprising that many types of applications have been considered for HPFRCCs. The application considered in the present study is their use as response control elements for damage mitigation of multi-story buildings.

Compared to steel frame structures, reinforced concrete structures have very high rigidity. Because of this, it has not been easy to effectively minimize response deformation from minor level in deformation with conventional hysteresis dampers that rely on energy absorption through its relatively large deformations. However, HPFRCCs make it possible to create high-rigidity dampers that can be applied to such structures. Furthermore, the use of cement-based materials in HPFRCCs makes it easier, cheaper, and more efficient than conventional vibration control elements to control the response deformation of a building.

In the following sections, the response control concepts of HPFRCCs are discussed followed by a presentation of results of shaking table tests that were conducted with a large steel frame to investigate feasibility of application of HPFRCCs as response control elements.

DEMAND FOR DAMAGE CONTROL

The routine construction and demolition of short-lived buildings in Japan has become a major problem in terms of building life, energy conservation, and waste, and is thus in need of urgent resolution. To increase the lifespan of buildings, fundamental improvements must be made to the durability of these structures. At the same time, demands are rising to develop techniques for controlling and preventing structural damage and aging during building lifetime caused by external forces such as earthquakes and for ensuring that buildings can be used for a long time after the occurrence of earthquakes while limiting the scope of repairs that have to be made.

The impetus for these demands for limiting and preventing damage from a major earthquake sprang from the 1995 Kobe Earthquake, in which human losses were minimized due to the buildings designed in accordance with the current seismic code, but the cost for repairing the damage was so high that many buildings have demolished and reconstructed, underscoring the need to consider the concept of life cycle costs. This means that in addition to the normal functions of safety, serviceability, etc., it is also, necessary to evaluate reparability.

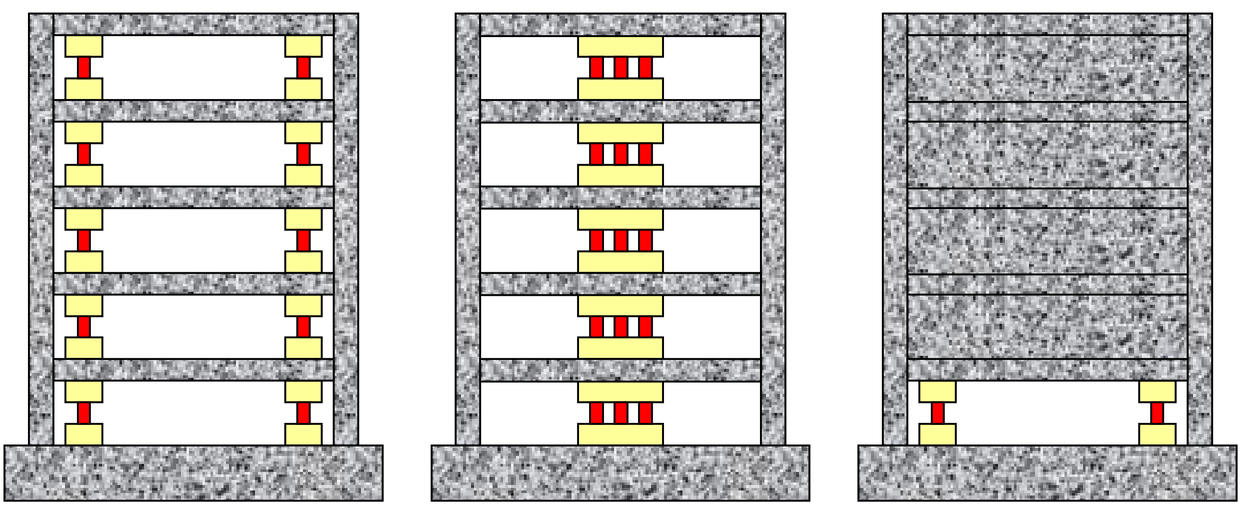
Today, structures throughout Japan are being seismically strengthened, but the direct rationale for this work is to save human lives rather than to minimize damage. Therefore, it can be expected that in the near future, huge costs associated with repairing buildings damaged by major earthquakes will most likely become a public issue. At the same time, the tremendous number of buildings constructed during the period of high economic growth in Japan, '60s and '70s, will soon be discussed on its replacement, so it is imperative that technology be developed that can extend the lifespan and reduce the costs and residuals associated with rebuilding.

All the above indicates that there is in Japan a strong demand for buildings that not only secure the structural safety by preventing any failure or collapse but, also, continue to maintain the building function for continuous use by preventing structural damage of the building from the view of easiness of repair, appropriately, Fukuyama [3].

SEISMIC RESPONSE CONTROL DEVICES FOR DAMAGE REDUCTION

Figure 2 shows the short span column members that are considered to be elements that can suppress damage to the structural elements by reducing the response displacement of the entire structure. These response control members have high rigidity, strength, and ductility that enable them to resist for high stress from minor deformations and efficiently absorb energy. As a result, they can be used to suppress response deformation of concrete structures that have relatively higher rigidity than steel frame structures.

Furthermore, since these members are freely moldable their strengths and rigidities can easily be changed by altering the shape, reinforcement arrangement, and material design of the cement composites, and therefore they can be used as suitable response control elements in buildings having a wide variety of shapes and characteristics. Figure 2 shows response control elements as dark-gray part, with stabs as light-gray part, that provide high rigidity and lateral resistance capacity even when used in relatively small sizes. By installing these response control elements in locations that are overlooked in the structural design as non-structural walls, the building performance can be improved without impacting the floor plan. With the introduction of HFPRCCs all these can be achieved at much lesser cost than with conventional energy dissipation devices.



a) Application to column-side devices for frame structure

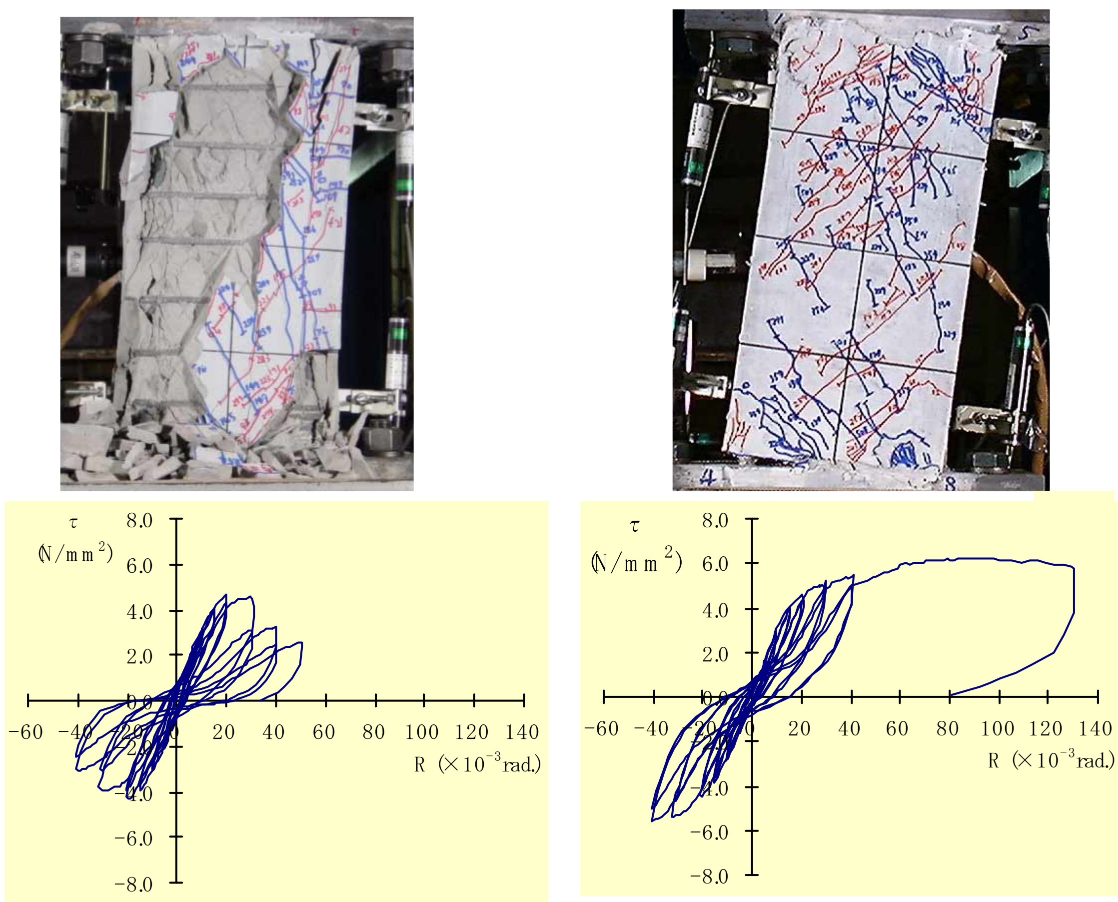
b) Application to integrated mid-span devices for frame structure

c) Application to column-side devices for soft-first story

Figure 2 Application examples of response control elements

The energy absorption of the response control elements is mainly expected to those of steel reinforcement in the concrete, not to the energy absorption of the HPFRCCs themselves. For the latter to be realized the composite materials has to maintain the identification of the matrix and steel reinforcement so that the response control elements can manifest an efficient energy absorption ability and high load-bearing capacity even under large deformations. Specifically, this entails preventing brittle failures such as shear failure, bond splitting failure, anchoring failure, etc., even after the reinforcement has yielded. In addition, a tremendous amount of compressive force acts on the members whenever the response control elements inside the frame structure undergo rotational deformation, so these members are, also, expected to prevent compressive brittle failure of members.

The structural performance of conventional and HPFRCCs response control elements is first investigated in static loading tests. As seen in Figure 3, there is massive amount of damage in conventional mortar, 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 13% radian or more, Fukuyama [4].



a) In case of mortar matrix
(Severe damage and small deformation capacity are shown.)

b) In case of HPFRCC matrix
(Large deformation capacity without failure until deformation of over 13% rad. can be seen.)

Figure 3 Results of the static loading tests of response control elements
(Damage properties and average shear stress (τ) - deflection angle (R) relationships)

Table 1 Dimensions of the test frame

Story height	1.8 m
Total height	5.4 m
Plane dimension	3 m×4 m
Column section	H148×100×6/9 (SM490)
Beam section (perpendicular to shaking direction)	H148×100×6/9 (SM490)
Beam section (shaking direction, both ends)	H150×150×7/10 (SM490)
Beam section (shaking direction, center)	H300×150×6.5/9 (SM490)
Floor weight for each floor	4000 kg

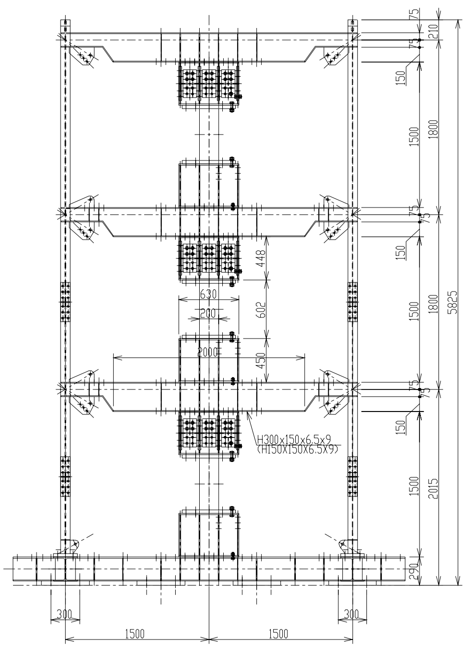


Figure 4 Central plane of structure of test assembly

Figure 5 Test assembly on shaking table

LARGE SHAKING TABLE TESTS

This section gives an overview of the large shaking table tests of a steel frame conducted to investigate the effectiveness of HPFRCC response control elements.

Test Specimen

Table 1 lists the dimensions of the steel frame used in the test. The frame consists of three 1.8 m-high stories and each story had 3 m x 1 span in the direction of shaking, and 2 m x 2 spans in the transverse direction. Fig. 4 shows the central plane of the structure where response control elements were installed at each story. Fig. 5 shows a photograph of the entire test specimen.

Fig. 6 shows the cross-section and views of the response control elements. The elements have a cross-section of 100 x 200 mm, height of 530 mm and are reinforced by four 13 mm diameter deformed bars. The shear reinforcement is of 6 mm diameter deformed bars with interval of 50 mm. The HPFRCC mortar contains polyethylene and steel cord fibers which are each mixed in at a volume ratio of 1 %, giving it a compressive strength of 55 N/mm^2. Screw-ribs bars are used for the longitudinal reinforcement and these reinforcements are bolted into the steel frame plate at the end using relief joints and high-tensile strength bolts. As the relief joint was somewhere within 65 mm from the end of the HPFRCC specimen, the location of hypothetical yielding of longitudinal reinforcement would be 65 mm from the end.

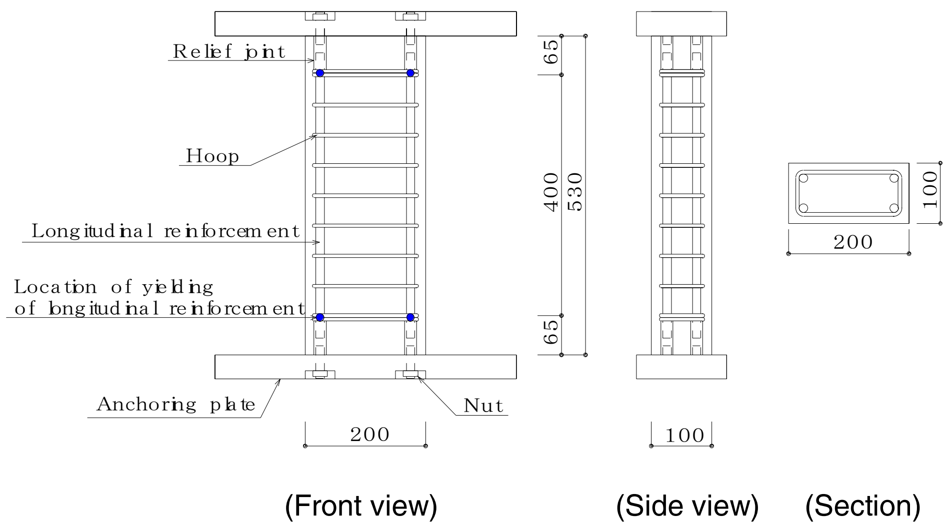


Figure 6 Schematic drawing of a response control element

Input to Shaking Table and Measurements

The input seismic waves are based on the 1940 El Centro NS waves, which were gradually made more intense by increasing the normalized velocity from 5 to 10, 15, 30, 40, 50, and finally 60 cm/sec. The shear force, axial force and lateral displacement acting on the HPFRCC response control elements are measured by placing accelerograms in the central part of each layer, strain gauges in the steel frame, and displacement transducers in the frame and response control elements. All measurements were sampled at 2,000 Hz. The axial force on the HPFRCC response control element is calculated as the difference between the axial forces on the compression and tension sides columns of the steel frame that are measured with the strain gauge.

Response Analysis

In order to determine the response of the steel frame with the HFPRCC response control elements a tri-linear model is created from the load-deformation relationship of the story levels derived from the push over analysis. The mass model in Figure 7, equivalent shear-spring model, was used to carry out time history seismic response analysis.

Figure 8 shows three Q - δ curves from measurements taken at the first floor for maximum velocities of 5 cm/s to 60 cm/s for the steel frame with response control elements, the response control elements indicated as ‘device’, and the steel frame by itself. The maximum velocity of the input motion associated with each data point is indicated in the figure. In the case of the response control elements the displacement δ is taken as the story drift and not relative displacement of the two ends of the control elements.

Results of Shaking Table Tests

Figure 9 shows the hysteresis behavior of the shear force-story drift (Q - δ) relationship of the first floor with input motion as the El Centro normalized to maximum velocities of 50 cm/s and 60 cm/s. There are three curves in each of the figures. The top curve is the Q - δ curve for the entire system (frame + device) obtained by multiplying the acceleration data of each story by the mass; the bottom curve is for the steel frame calculated by considering the P - δ effect based on the column members of the steel frame and the middle curve is the Q - δ curve of the response control elements. The shear force acting on the response control elements is taken as the value that the shear force on the frame subtracted from the shear force on the entire test assembly. As for the displacement, the measurements obtained from the displacement transducer installed on the frame are used.

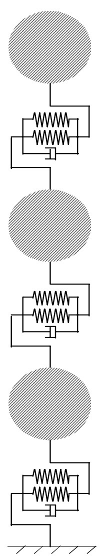


Figure 7
Analytical model

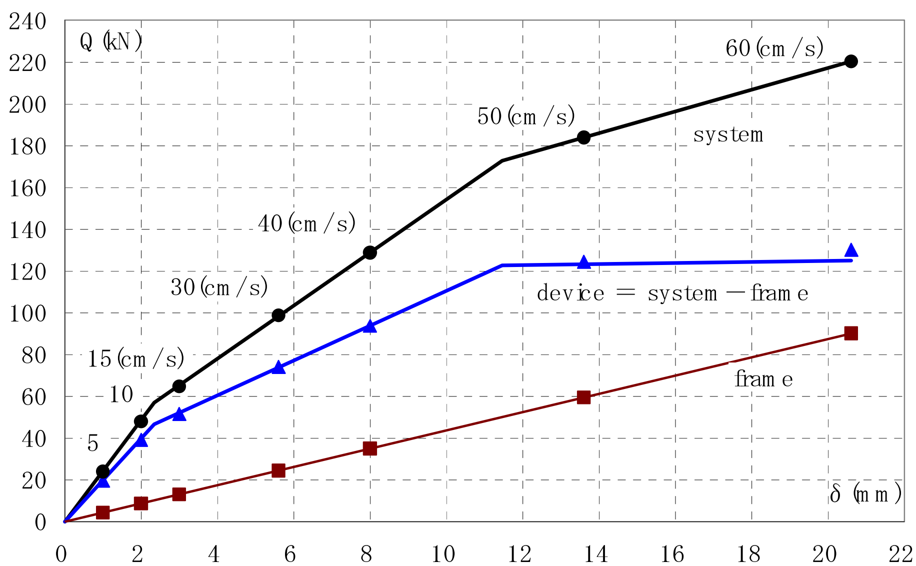


Figure 8 Results of response analysis

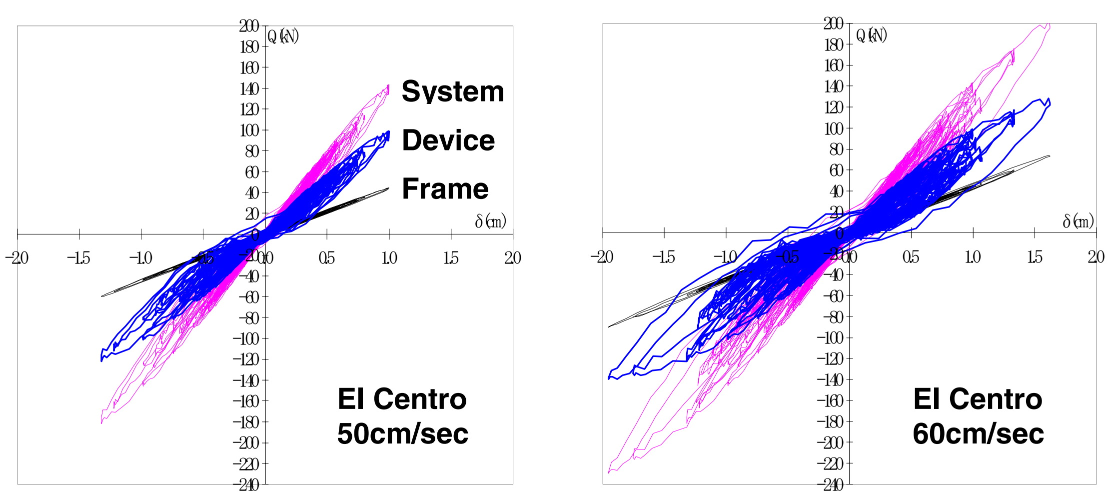
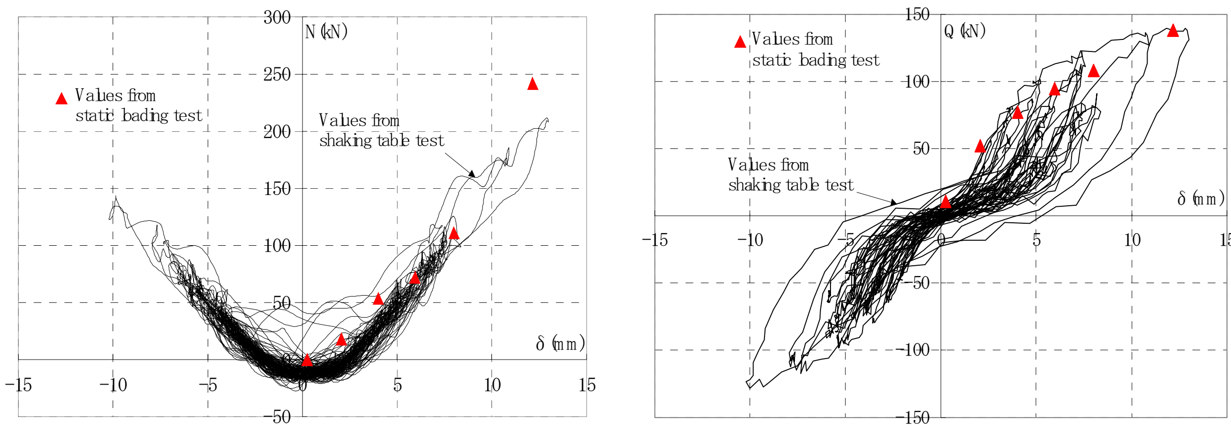


Figure 9 Relationship between shear force and story drift of the first floor



a) N - δ relationships (max speed of 60 cm/s in shaking table tests)

b) Q - δ relationships (all of the test results obtained in the shaking table tests)

Figure 10 Comparison between static loading and shaking table tests

In the experiment, cracks appeared in the response control elements when the El Centro normalized to a velocity of 10 cm/sec is entered, and at 30 cm/sec the longitudinal reinforcement yielded and the rigidity declined. At 60 cm/s there is no observable excessive cracking, crashing, peeling of mortar matrix, etc. in the response control elements, and, as can be seen from the Q - δ curves the shear force Q did not decline even as the deformation was progressing, indicating that the response control elements functioned satisfactorily.

Figure 10a shows the axial force – story drift (N - δ) relationship of the response control elements on the first floor for the El Centro wave with normalized speed of 60 cm/s. This figure also shows values obtained from static loading tests of a response control element, represented by triangles. Figure 10b shows all of the Q - δ relations of response control elements on the first floor as well as the values obtained from static loading tests of a response control element, represented by triangles. One thing to note is that in the static loading tests, the elongation in the axial direction due to rotational deformation of the response control elements is completely confined.

From these results, it can be seen that in both the dynamic and static tests the axial force acting on the response control elements becomes larger as lateral displacement proceeds, which in turn causes lateral resistance (Q) to increase as deformation increases. This type of behavior is believed to arise from confinement of the elongations in the axial direction due to rotational deformations of the response control elements that causes confining axial forces to act on the response control elements and because of these axial forces the shear resistance force increases. Therefore, in order to quantify the restoring force characteristics of the HPFRCC response control elements it is necessary to evaluate the strength considering the influence of the confining axial force.

Figure 11 compares the analytical and experimental Q - δ relations of the first floor of the steel frame with the response control elements. A good correspondence is seen between the two curves though the shear force of the analytical skeleton curve slightly exceeds the experimental one near the first inflection point of the curve. This difference is believed to be the result of not accounting for the effect of cracking and the degrading of rigidity leading to yielding of the longitudinal reinforcement in the analytical formulation of the Q - δ relation of the response control elements. As seen in the figure, the experimental values are slightly larger at 30 cm/s and 40 cm/s than the corresponding analytical values. This could have happened because there is a slight difference between the analytical and experimental values of rigidity that indicates the maximum point, and the skeleton curve near the first inflection point showed a slightly higher value in the analysis than in the experiment.

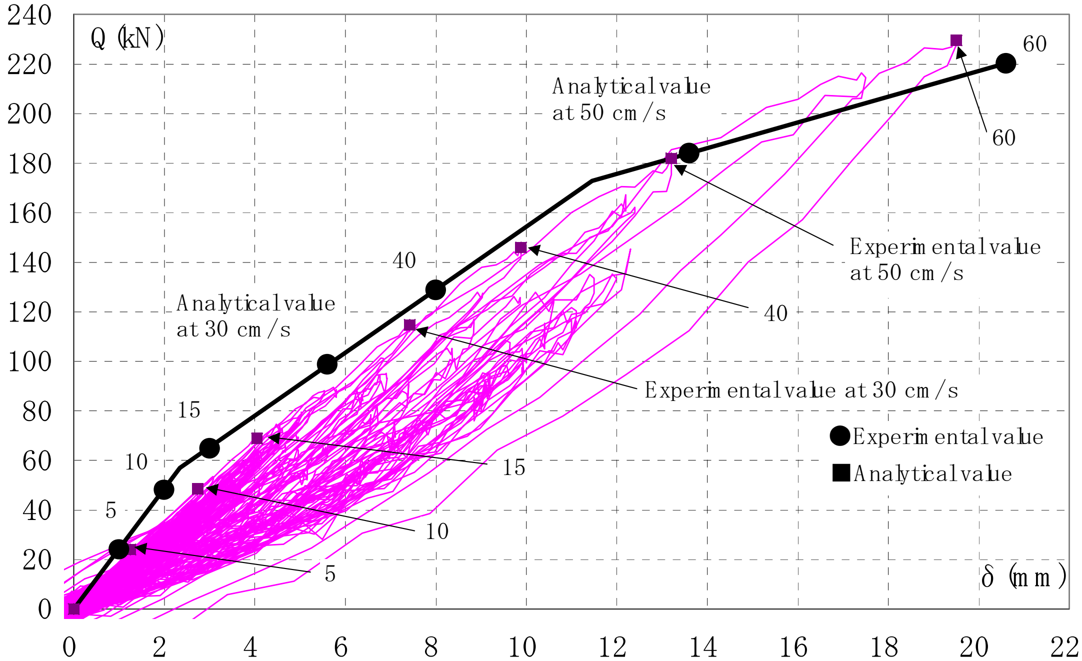


Figure 11 Analytical and experimental Q - δ relations of first floor

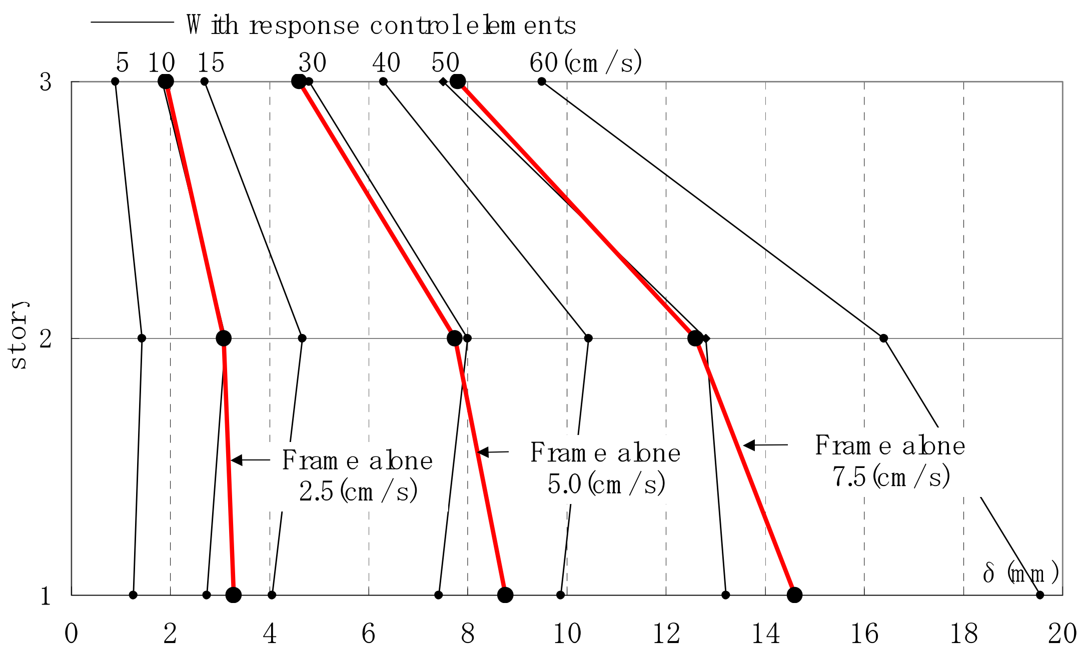


Figure 12 Comparison of maximum story drift of steel frame with and without response control elements

Figure 12 shows the response values of story drift for each input level of input motion. The vertical axis represents the floor number, the horizontal axis depicts story drift, and the numbers at the top of the graph are the input seismic level indicated as maximum velocity. The thin lines show distribution of the maximum story drift for each floor when the HPFRCC response control elements are incorporated and the bold line shows the same for the steel frame without the response control elements. In the shaking table tests, the steel frame by itself could be shaken only up to 7.5 cm/s of El Centro NS 1940 as above that, the elasticity of the frame could no longer be maintained. In the figure, the response of the frame alone at 7.5 cm/s is equivalent to the response of the frame with response control elements at 50 cm/s, clearly showing that the HPFRCC response control elements were able to significantly reduce response displacement. In addition, the response of the frame alone at 2.5 cm/s is equivalent to the response of frame with response control elements at 10 cm/s, demonstrating that there is a reduction in the response deflection even at low levels of input.

CONCLUDING REMARKS

After the 1995 Kobe Earthquake, there is strong demand for damage mitigation of buildings from a view of reparability. On the other hand, HPFRCCs which exhibit multiple cracking and strain-hardening properties have been developed in this decade. Because of these advantageous properties, it would appear that the use of HPFRCCs in place of concrete can lead to better control of the failure mechanism, deformation capacity, hysteresis characteristics and degree of damage of RC members. One proposed application of HPFRCCs is in devices for controlling the response deformation of buildings so as to mitigate structural damage of buildings for continuous use.

This paper describes the concept and characteristics of seismic damage reduction of buildings using HPFRCC response control elements. The applicability of the response control elements is investigated based on the results of large-scale shaking table tests. The test results show that HPFRCC devices are able to significantly reduce the response deformation of the steel frame.

This technology involves passive control and while it does not have the aura of active control. Nevertheless, in the development and application of Auto adaptive technologies, humans program an optimal control by estimating the state of the structure. This process is similar to designing device properties by assuming structural conditions in passive control. The difference lies in whether or not properties can be changed; the goal of response control is the same. However, what is more important than changing properties for response control is whether public demands for buildings, including cost, can be satisfied. The new technology is able to satisfy public demands for controlling response of buildings at a reasonable cost. From this perspective, this technology meets the requirements of a smart structural system, and thus should find wide acceptance for use in buildings from the perspective of performance-based design.

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