# DEVELOPMENT OF SEISMIC RESPONSE CONTROL RACK FOR AUTOMATIC WAREHOUSE

**Hidetaka Funaki, Fumitoshi Kumazawa, Kenji Kabayama**

**Graduate School of Engineering and Science, Shibaura Institute of Technology**

**na15502@shibaura-it.ac.jp**

**ABSTRACT**

The earthquake that struck near the Pacific coast of the Tohoku region on March 11, 2011, inflicted tremendous damage to logistics systems. Automated storage and retrieval systems are logistic facilities capable of both storing and managing merchandise. The racks of automated storage and retrieval systems may be as tall as 30 m. Earthquakes, therefore, can cause stored products or goods to fall down from the racks so that the fallen items suffer damage, obstruct crane movement and impair logistic services.

The authors have developed a system for controlling the seismic response of storage racks by using roller bearings and viscous dampers. The newly developed seismic response control rack system consists of a pair of rack units, a movable rack equipped with base dampers and a fixed rack, and the two racks are connected together at their tops.

## 1. INTRODUCTION

Figure 1 shows a typical rack system. As shown, a pair of rack units are placed face-to-face on both sides of the space in which an automatic stacker crane moves around. Pallets are placed on the support beams connected to the rack columns. If, therefore, the racks are shaken in the event of an earthquake, pallets may slide back and forth and fall down. In the 2011 earthquake, many storage racks were shaken in the rack opening direction, and palletized goods fell down into the stacker crane zones. The authors, therefore, have developed a seismic response control technology for storage racks in order to control the seismic response of automated storage and retrieval racks in the direction of rack openings through which palletized items are deposited and retrieved.

Figure 2 compares structural models of a typical conventional storage rack system[1] and the seismic response control rack system. The conventional rack system is an earthquake-resistant structure, and the bottoms of its columns are fixed to the floor. The newly developed seismic response control rack system consists of a pair of rack units whose tops are connected together and seismic response control devices provided at the base of one of the two rack units. The seismic response control system uses roller bearings that allow smooth sliding only in one direction in conjunction with viscous dampers.

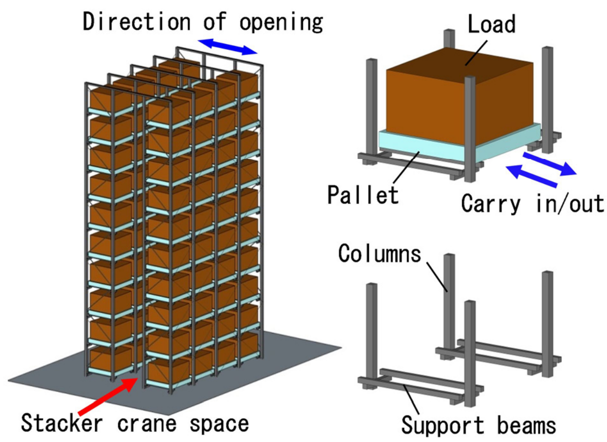



Fig.1 Typical rack structure

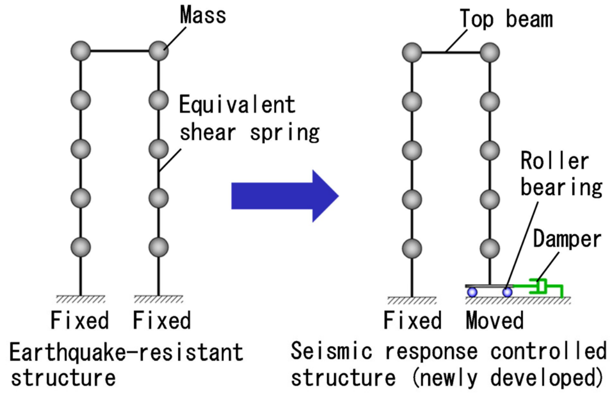



Fig.2 Concept of seismic response control rack

## 2. EXPERIMENT

The seismic response control devices used in the shaking table experiments are shown in Photo 1. When an earthquake occurs, the lower end of each of the columns of the movable rack provided with the roller bearings slides horizontally, and the viscous dampers reduce horizontal oscillation. The horizontal stiffness of the rack system makes the restoring force to bring the bottoms of the columns of the movable rack back to their original positions after the earthquake. By installing these seismic response control devices, the predominant period of vibration of the pair of racks can be made longer. The addition of efficient damping capability reduces the earthquake-induced oscillation of the structural frame.

To verify the effectiveness of the seismic response control devices used as part of the rack structure, a series of shaking-table experiments was conducted by using a test rack structure. Figure 3 shows the test rack structure used, and Table 1 lists its structural members. The test rack structure, built with materials similar to ones used in conventional racks, consists of a pair of 10-level-high, 4-space-wide rack units located on both sides of a load handling space. The test rack structure can be used for seismic response control testing because one of the pair of racks is provided with seismic response control devices under the columns. The test rack structure can be used for earthquake resistance testing, too, because the roller bearings can be made immovable to prevent sliding. Testing under the roller-bearing-only condition is also possible because the viscous dampers built into the seismic response control devices can be removed. In the shaking-table experiments, a 100-kilogram steel plate was placed in each of the 80 storage spaces (shelves) of the test rack structure.

Figure 4 shows the response spectra of the shaking table input motions. A total of three earthquake motions were used as inputs: two earthquake motions obtained through strong earthquake observation run by the Japan Meteorological Agency (JMA) and the National Research Institute for Earth Science and Disaster Prevention (earthquake motion observed in Shirakawa City, Fukushima Prefecture, during the 2011 earthquake off the Pacific coast of the Tohoku region and the earthquake motion observed in Kobe City during the 1995 Hyogoken Nanbu Earthquake) and the 1940 El Centro earthquake motion, which is a widely used earthquake motion record. To check the vibration characteristics of the test rack structure, random motion excitation (0.2 Hz to 50 Hz) was also carried out. The direction of shaking table excitation was only one, the direction of rack opening, because that is the direction of concern in connection with the seismic safety measures under consideration in this study. Figure 5 shows the transfer function for the shaking table input (random motion, 200 cm/s$^2$) with respect to the acceleration response at the 10th level of the rack structure. These results show that the predominant period of the motion of the earthquake-resistant rack structure whose columns

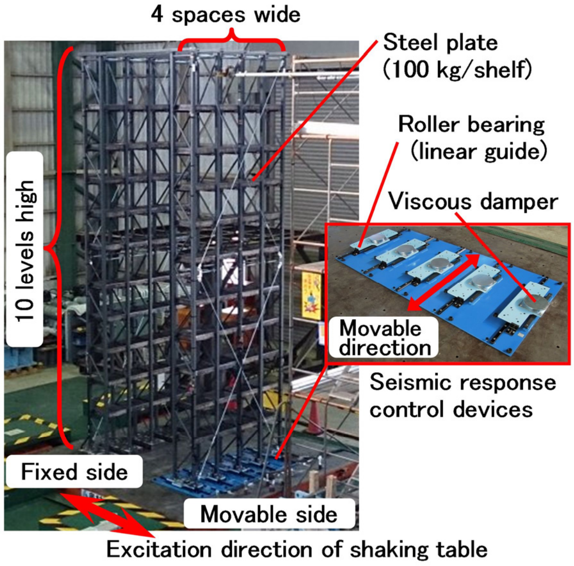



Photo 1 Shaking table experiment

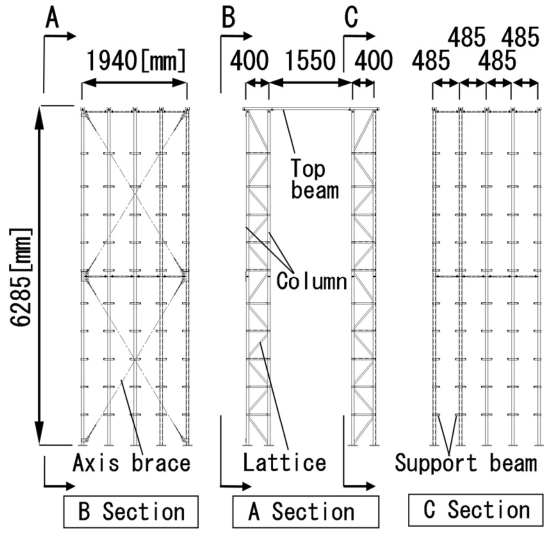



Fig.3 Test structure (rack)

Table 1 Structural member list

| Member | Size | Material |
|---|---|---|
| Column | □-50×50×2.3 | STKR400 |
| Support beam | L-30×30×3 | SS400 |
| Top beam | C-75×45×15×2.3 | SSC400 |
| Lattice | $\phi$-27.2×2.3 | STKR400 |
| Axis brace | M10 | SS400 |

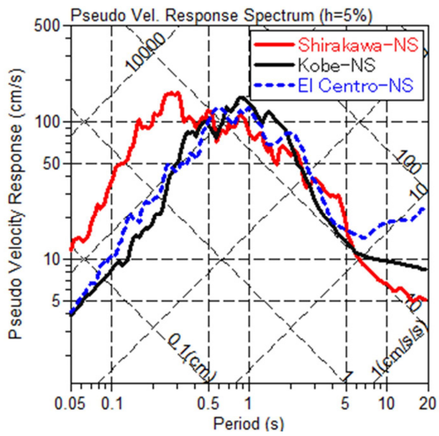



Fig.4 Response spectrum of table input motion

are fixed to the floor is 0.39 s, while that of the motion of the seismic response control rack structure that includes one rack unit with sliding columns is 0.94 s. These results show that by allowing the columns of the movable rack unit to smoothly slide horizontally, the first-mode natural period of a two-unit rack structure can be made longer by a factor of 2 or more. Those results also show that the viscous dampers are effective in reducing the acceleration response at the predominant period.

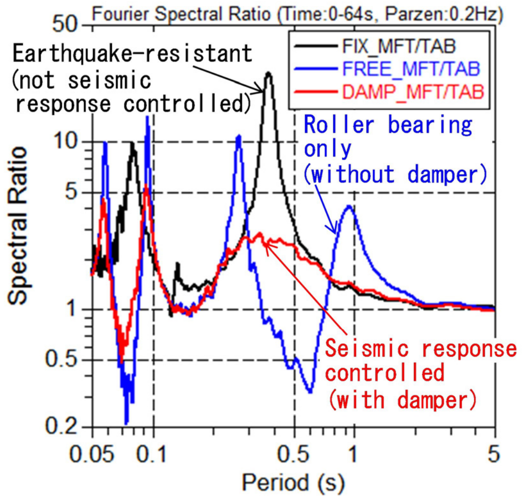



Fig.5 Transfer function for random motion

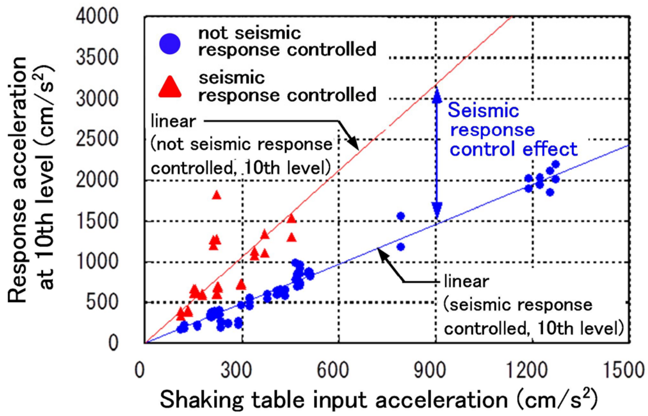



Fig.6 Comparison of maximum response acceleration

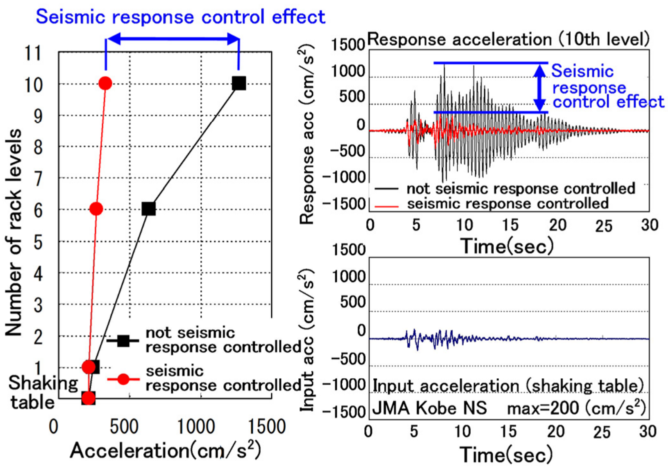



Fig.7 Examples of experiment results (JMA Kobe NS motion, 200 cm/s$^2$)

Figure 6 shows the maximum response acceleration distributions obtained from excitation experiments conducted by varying the shaking table input level of the three representative observed earthquake motions in steps. Examination of the maximum response acceleration at the 10th level of the seismic response control rack structure reveals that the rack structure reduces oscillation approximately by half, compared with the earthquake-resistant rack structure, regardless of the type and input level of earthquake motion. As an example of a comparison of measured seismic response control effects, Figure 7 shows the time history waveforms in the case where the earthquake motion observed in Kobe City during the 1995 Hyogoken Nanbu Earthquake was normalized to a maximum acceleration of 200 cm/s$^2$ is input. Comparison of the response accelerations at the 1st, 6th and 10th levels of the rack structure reveals that the response acceleration of the rack structure has been reduced to up to about a quarter of the original response acceleration. Thus, it has been demonstrated that the newly developed seismic response control technology is effective in preventing stored items from falling down from rack shelves.

## 3. ANALYSIS

The accuracy of the seismic response control rack experiments was evaluated through simulation analysis. Figure 8 illustrates the analysis models used, and Table 2 shows rack frame details. As the first step, a 3D frame model was constructed, and the horizontal characteristics of the frame were identified by giving forced displacement to the top of the frame. As the next step, it was assumed that an steel plate having a mass of 100 kg is placed on each rack shelf, and the frame with those masses plus the mass of the frame itself was modeled as an equivalent shear spring with 11 lumped masses located at the pallet locations. It is generally known that since, in most cases, pallets are simply put on the frame members, the displacement of pallets and palletized items helps reduce earthquake-induced loads[2]. Since the purpose of the analysis was a simulation analysis of the seismic response control effect, it was assumed that, as in the shaking table experiments, the steel plates are

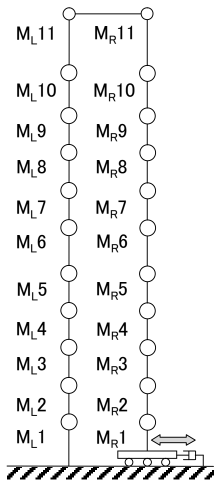


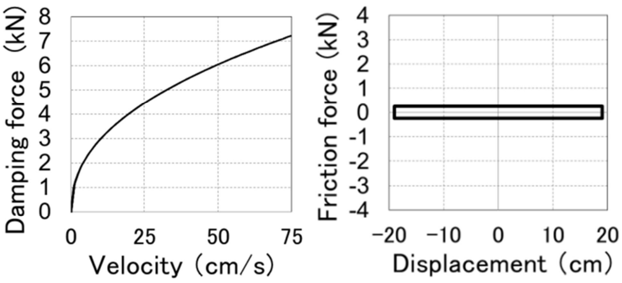

Fig.8 Analysis model

Table 2 Analysis model details (per rack unit)

| Mass point | Height [cm] | Mass [kg] | Equivalent stiffness [kgf/cm] |
|---|---|---|---|
| 11 | 624.0 | 47.0 | 2428.5 |
| 10 | 544.0 | 435.1 | 3237.9 |
| 9 | 482.5 | 430.3 | 4032.9 |
| 8 | 431.0 | 428.3 | 4245.7 |
| 7 | 379.5 | 428.3 | 4538.4 |
| 6 | 328.0 | 443.2 | 4158.6 |
| 5 | 266.0 | 428.2 | 5810.2 |
| 4 | 214.5 | 428.3 | 6958.3 |
| 3 | 163.0 | 428.3 | 8905.4 |
| 2 | 111.5 | 428.3 | 13016.6 |
| 1 | 60.0 | 447.0 | 25253.8 |

fixed to the frame. The frame with the built-in seismic response control devices has roller mechanisms and dampers under the columns of only one side of the two-unit rack structure. The characteristics of the roller bearings and dampers were modeled as shown in Figure 9. It was assumed that a friction force of 0.25 kN occurs when the roller bearings slide and that the damping force of the viscous dampers is dependent on velocity. Characteristics of the seismic response control devices identified through component testing were reflected in modeling.

As an example, Figure 10 compares the results obtained from time history response analysis with measured values. In the case shown in Figure 10, the earthquake motion observed in Kobe City during the 1995 Hyogoken Nanbu Earthquake was normalized to a maximum acceleration of 500 cm/s$^2$ for use as an input motion. As shown, the measured values of frame response acceleration and the response displacement of the seismic response control devices show close agreement with the simulation analysis results.




Characteristics of damper     Characteristics of roller bearing

Fig.9 Modeling of seismic response control devices

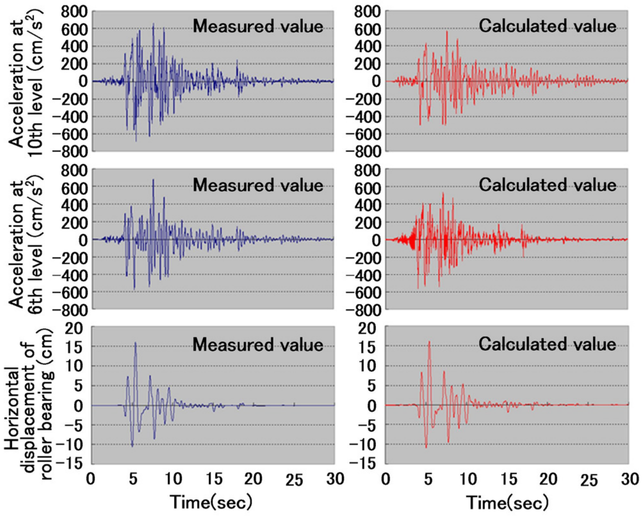



Fig. 10 Comparison of measured values and calculated values (JMA Kobe NS motion, 500 cm/s$^2$)

## 4. CONCLUSION

In this study, shaking table experiments and earthquake response analyses to simulate their results were conducted concerning a newly developed seismic response control technology applicable to storage racks used as part of automated storage and retrieval systems, and comparisons were made of response-reducing effects under different conditions. As a result, the study has shown that racks equipped with the newly developed seismic response control devices are significantly more effective than typical conventional earthquake-resistant racks in reducing earthquake-induced oscillation. Simulation analyses were also conducted by using a model that allows for the dynamic friction force of roller bearings and the damping force of viscous dampers. The results of earthquake response analyses performed by using an equivalent shear spring model having lumped masses at pallet locations agreed well with the shaking table experiment results, confirming the validity of the analysis model. Thus, it has become possible to analytically evaluate the effectiveness of the newly developed seismic response control system applied to various newly built or existing racks in controlling their seismic response.

## REFERENCES


[1] The Japan Society of Industrial Machinery Manufacturers: Research Report on Ways to Ensure Seismic Safety of Automated Storage and Retrieval Systems (in Japanese), June 1981.

[2] Ogawa, N.: "Seismic response of frame structures with movable loads" (in Japanese), AIJ Journal of Structural and Construction Engineering, No. 370, pp. 28–39, December 1986.



**Hidetaka Funaki** received the B.E. (1993) degree in architecture from Shibaura Institute of Technology. He is currently a doctor course student at Graduate School of Engineering and Science, Shibaura Institute of Technology. His current interest is passively-controlled buildings.



**Fumitoshi Kumazawa** received the D.E. (1996) degree in structural engineering from the University of Tokyo. He is a professor, Department of Architecture and Building Engineering, Shibaura Institute of Technology, Japan. His current interest is earthquake response characteristics of building structures especially with irregularity.



**Kenji Kabayama** received the D.E. (1996) degree in structural engineering from Tokyo University. He is a Professor, Department of Architecture and Building Engineering, Shibaura Institute of Technology. His current interesting fields are upgrade of seismic safety evaluation, damping property of building structure, seismic performance of aging deteriorated building.