Proceedings of the 15th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2007
October 21-26, 2007, Miami, Florida, USA

EXPERIMENTAL STUDIES OF FREE-STANDING SPENT FUEL STORAGE CASK SUBJECTED TO STRONG EARTHQUAKE

K. Shirai
CRIEPI, 1646, Abiko, Abiko-shi, Chiba-ken, 270-1194, Japan

M. Wataru
CRIEPI, 1646, Abiko, Abiko-shi, Chiba-ken, 270-1194, Japan

T. Saegusa
CRIEPI, 1646, Abiko, Abiko-shi, Chiba-ken, 270-1194, Japan

ABSTRACT

Concrete cask spent fuel storage system is considered to essentially have an economical advantage and becoming widely used. For vertically free-standing concrete cask on the floor pad in the cask storage facility, its tip-over and sliding behavior and the integrity of the spent fuel during strong seismic motions are still the technical key issues to guarantee its safe performance. In this paper, the experimental studies are reported by performing the seismic excitation test with a full-scale model concrete cask including 21 PWR simulated fuel assemblies, using 3D full-scale earthquake testing facility, operated by the National Research Institute for Earth science and Disaster prevention. As a result, it is found that the tip-over of the full-scale cask did not occur and, the maximum response deformation of the fuel remains under the elastic region by the interaction effect due to the existence of the gap between the canister and cask body, and the gap between the fuel and basket.

INTRODUCTION

In Japan, the first ISFSI outside of Nuclear Power Plant (NPP) site in use of dual-purpose metal cask is being planned to start its commercial operation in around 2010 in Mutsu city, Aomori prefecture. Recently, due to the economical reason, the concrete modular storage technology, such as concrete cask, concrete silo, is also becoming world-widely used. Fig.1 shows the schematic view of storage house with the concrete cask. On safety technical requirements for spent fuel interim storage facility using dry cask, Japanese competent authority, NISA/METI (Nuclear and Industrial Safety Agency, Ministry of Economy and Trade Industry) issued the technical requirements on interim spent fuel storage facility (ISF) using dry metal cask and concrete cask on April 2006[1], [2]. According to this guideline, the cask oriented vertically in the freestanding condition should be protected from the tipping-over or interfering neighbor casks, and the integrity of the spent fuel also be intact during the strong earthquake motions.

In parallel with those regulatory and promoting activities on ISF, CRIEPI has been performed supportive research studies for the regulation and early realization of ISF. Key issues of these studies include safety requirements in operation and maintenance during spent fuel storage and unloading/loading for transportation, long-term integrity of metal canister and concrete materials, and so on. CRIEPI completed the research program of the demonstrative concrete cask performance tests for interim storage of spent fuel to reflect in the technical requirements issued by NISA, which includes heat removal tests, drop test and seismic tests with the full-scale cask. Up to now, to evaluate the tipping-over phenomena under strong earthquake motion, the excitation tests were performed with a one-third scale model concrete cask using two-dimensional shaking table test [3]. However, as the concrete cask has multiple gap structures, such as the annulus space for cooling air between the canister and concrete container and the gap between the spent fuel and basket, seismic response of the spent fuel may be complicated and their integrity should be investigated under the interactive reaction force with the basket subjected to the strong seismic motion to prevent the systematic failure of the spent fuel which might be possibly degraded (such as by hydride re-orientation) during long-term storage. The purpose of the investigations in this paper is to study the seismic response of the concrete cask and the integrity of the spent fuel under strong earthquake motion considering the horizontal and gravitational direction excitations by performing the excitation tests with a full-scale concrete cask using three-dimensional shaking table test devices.

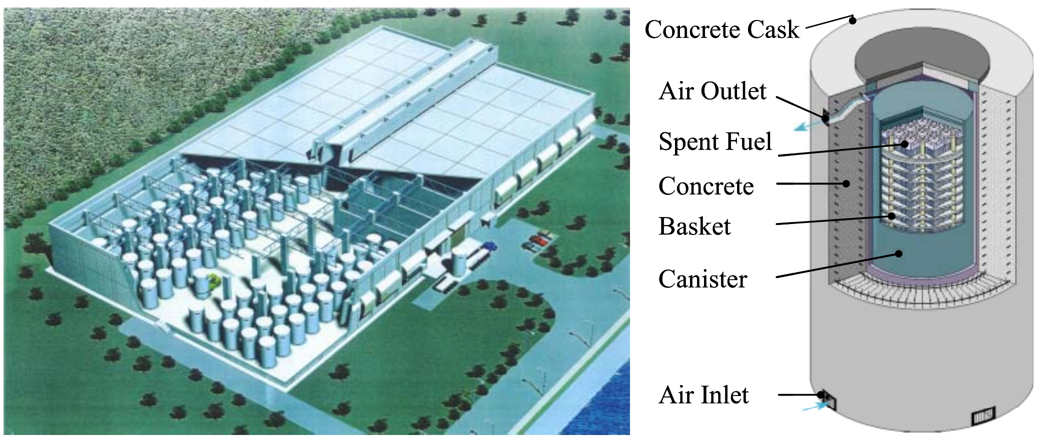

Figure 1. Schematic View of Storage House and the Concrete Cask in Japan

SEISMIC TEST DESCRIPTION

Seismic tests for the full-scale concrete cask and storage house floor were executed using a three-dimensional shaking table in 3-D full-scale earthquake testing facility "E-Defense " designed and constructed by National Research Institute for Earth science and Disaster prevention as shown in Figure 2 [4].

Fabrication of Full-Scale Concrete Cask and Floor Model

Specifications of the full-scale concrete cask are shown in Table 1. The concrete cask was assumed to be for indoor use, especially considering long-term integrity of concrete materials, the restraint of cracking due to thermal stress and the improvement shielding ability [5]. The concrete cask for the seismic test basically consists of the storage container and the canister. Moreover, the storage container is divided to the hollow body made of the reinforced concrete and the detachable bottom circular plate, which is made of the reinforced concrete structure or the concrete filled steel structure to evaluate the friction effect of the bottom material. The cask lid is the hollow structure to lead the sensor cables out of the inside and the counter weights are considered on the top of the cask instead of the lid weight. The air inlet and outlet ducts are neglected to simplify the test cask configuration. A 80cm thick and 8m wide reinforced concrete slab (weight 125ton) was used as the storage house floor model and set on the shaking table (Table size 20mx15m, Payload 12MN).

The test canister (external diameter 1.64m, height 4.45m, empty weight 13ton), which can store 21 PWR spent fuels, is a structure in which the basket is the assembly of rectangular hollow block made of aluminum alloy, and is made from stainless steel and combines with the storage container. To simplify the seismic test procedure, only one lid made of carbon steel with the bolted joint structure is applied to the test canister as shown in Fig.3.

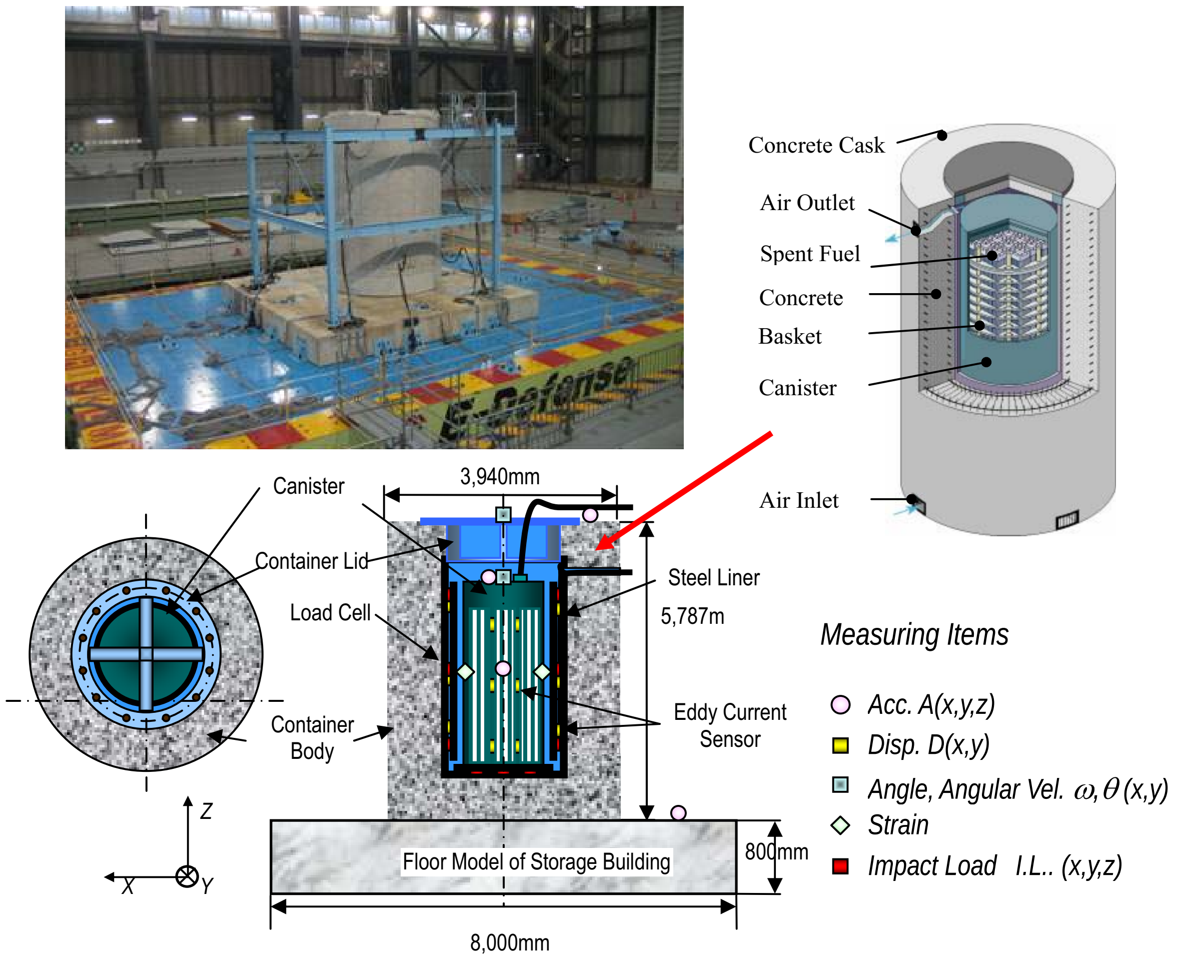

Figure 2. 3D Earthquake Testing with Full-Scale Concrete Cask and Concrete Floor

Table 1. Specification of Concrete Cask for Seismic Test

Part		Specification	
Cask Body	Hollow Body	External Diameter	3.9 m
		Internal Diameter	1.8 m
		Height	5.3 m
	Bottom Circular Plate	External Diameter	3.9 m
		Height	0.5 m
	Total Weight		145 ton
	Design Concrete Strength		24 MPa
Canister		External Diameter	1.64 m
		Height	4.45 m
		Mass	27 ton (with spent fuel)

Figure 3. Outline of the Test Canister and the Basket

As for spent fuel structures, one full-scale PWR fuel (17x17) and 20 dummy PWR fuel structures, which modal deformation was equivalent to the full-scale one, were fabricated. To simulate the UO_2 pellet, the equivalent material (lead-antimony pellet) was applied. Considering the loss of the hold force between the spent fuel rods and the degraded grid cells after the discharge from the reactor, the hold force between the fuel rods and the grid cells of the full-scale PWR test fuel was mitigated by the resize of the grid cell configuration. The modal frequency of this PWR test fuel is as shown in Fig.4.

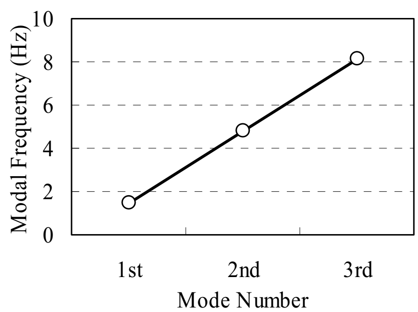

Figure 4. Modal Frequency of the PWR Test Fuel

Figure 5. Eddy Current Displacement Sensor inside the Basket

<u>Measuring Items</u>

The measuring items during the seismic excitation test are also shown in Fig.2. The angle $\theta(x)$, $\theta(y)$, angular velocity $\omega(x)$, $\omega(y)$, acceleration $A(x)$, $A(y)$, $A(z)$, displacement $D(x)$, $D(y)$, $D(z)$ of the cask body and the canister were measured. Moreover, the constraint $\varepsilon(\theta)$, $\varepsilon(z)$, acceleration $A(x)$, $A(y)$, $A(z)$, and the displacement $D_{gap}(x)$, $D_{gap}(y)$ of the canister and the simulated PWR fuel structures were also measured as shown in Fig.5. Data recording total time and the sampling frequency were set to 196 seconds and 2kHz, respectively.

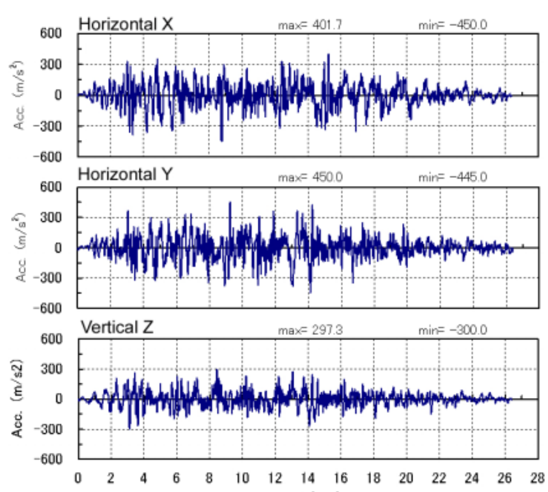

Figure 6. Time Histories of the Artificial Wave

Test Condition

For input of the seismic excitation test, two recorded waves during typical natural earthquake waves (El Centro : Imperial Valley Earthquake, 1940, JMA Kobe : Hyogo-ken Nanbu Earthquake, 1995) and one artificial seismic wave were employed. Artificial seismic wave was determined by referring the Earthquake ground motion whose source not to be identified, issued by NSC [6]. Fig.6 shows the time histories of the artificial wave. In the excitation test, the acceleration levels were varied according to the test conditions. Test condition includes the cases considering horizontal and vertical motions simultaneously. Moreover, the essential rocking response of the free-standing test canister and the effect of the friction between the cask bottom and the concrete floor on the overall response were also investigated.

Table 2. Test Conditions

Test Case	Existence Gap*			Number of Fuel	Input Wave		
	Fu-Ba	Can-Con	Con-Fl		Type	Direction	Level
#1 PWR Fuel	○	---	---	1	Random** Sinusoidal Observed Artificial***	X X+Y X+Y+Z	1/2 2/3 1/1 7/5
#2 Friction	---	---	○	---	Sinusoidal	Y	---
#3 Canister	○	○	---	21	Random, Sinusoidal Observed Artificial***	X X+Y X+Y+Z	1/2 2/3 1/1
Concrete Cask**** #4 CFS Bottom Plate #5 RC Bottom Plate	○	○	○				

* Fu : Fuel, Ba: Basket, Can : Canister, Con : Container, Fl : Floor

** 0.2-30Hz (Duration : 40 seconds)

*** Earthquake ground motion whose source not to be identified, issued by NSC[6]

**** CFS : Concrete Filled Steel, RC : Reinforced Concrete

SEISMIC TEST RESULTS

Kinetic Coefficient Friction

To obtain the kinetic coefficient friction between the surface of the bottom plate and the concrete surface of the floor model, the sinusoidal wave excitation tests (Test Case #2) using two types of the bottom circular plates were performed as shown in Fig.7. The kinetic coefficient friction value is defined by the ratio of the maximum acceleration measured on the bottom plate to the maximum acceleration value of the input wave.

Figure 7 Sinusoidal Wave Excitation Test with the Bottom Circular Plate

Fig.8 shows the example of the measured time history of the coefficient friction value during the sinusoidal wave excitation test in case of frequency 3Hz. As there was no significant difference between the static coefficient and the kinetic one, the friction coefficient between CFS/RC plates and the floor model can be assumed to be constant and set to about 0.5 and 0.7.

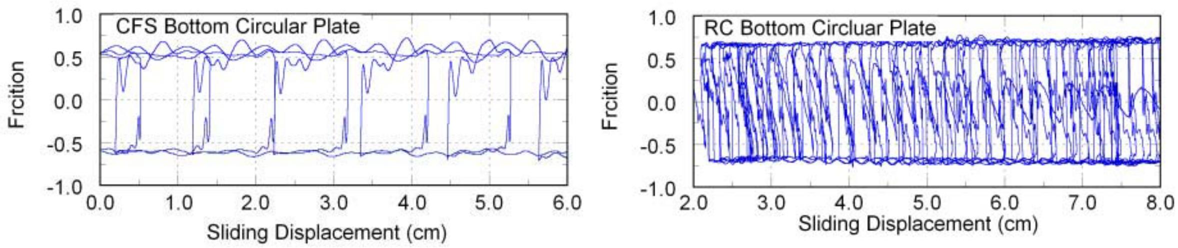

Figure 8 Measured Time History of the Coefficient Friction Value

<u>Seismic Response of the Canister</u>

To obtain the uplifting or tipping-over limit and the rocking response of the cylindrical structure under the strong earthquake motions, the wave excitation tests using the full-scale canister and the floor model (Test Case #3) were performed as shown in Fig.9.

Figure 9 Wave Excitation Test with the Full-Scale Canister

Fig.10 shows the summary of the seismic response of the full-scale canister. The rapid increase of the response angle beyond the up-lifting limit level (about 250gal) was observed. In case of the artificial wave excitation, the increase of maximum response angle by the effect of the vertical motion was not so remarkable. During seismic response of the canister, three-dimensional behavior like top-spinning was observed as shown in Fig.11. As the power of the JMA Kobe wave was bigger than the other waves in low frequency region, the response for JMA Kobe wave excitation was much bigger than the one for the other wave excitations. Maximum rotational response angle for the three direction excitation with JMA Kobe wave was about 0.09 rad. However, the residual sliding displacements were very small.

<u>Seismic Response of the Storage Container</u>

To obtain the rocking and sliding response of the storage container under the strong earthquake motions, the wave excitation tests using the full-scale cask and the floor model (Test Case #4, 5) were performed as shown in Fig.2.

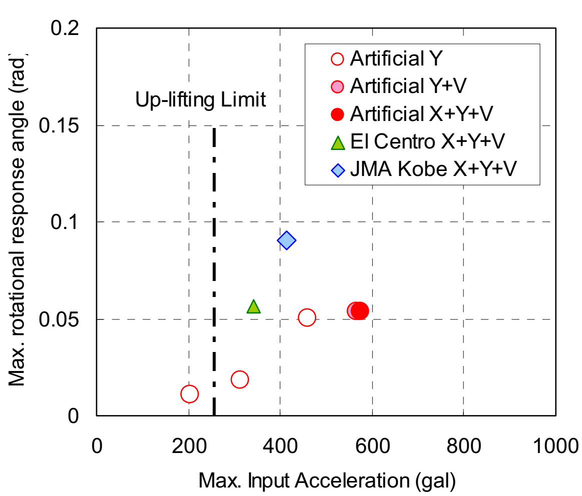

Figure 10 Summary of the Seismic Response of the Full-Scale Canister

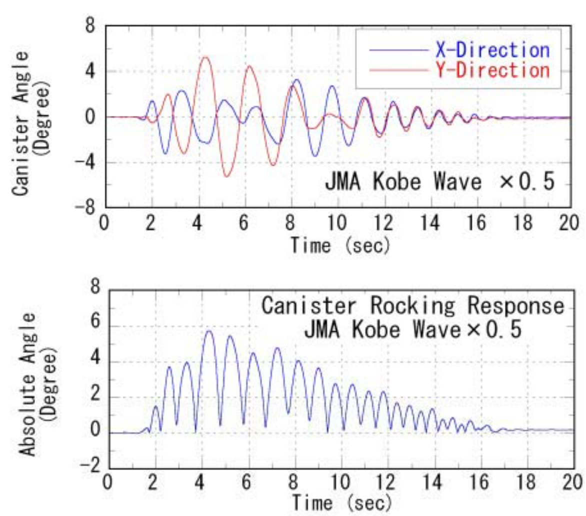

Figure 11 Canister Rocking Response for Multi Direction Excitation

Fig.12 shows the summary of the seismic response of the full-scale concrete cask. The rapid increase of the response angle beyond the up-lifting limit level (about 650gal) was observed, especially in case of the RC bottom plate. For Hyogo-ken Nanbu earthquake 1995 wave (Max. acceleration level 818gal), the maximum rotational response angle was about 0.028rad, and the maximum sliding displacement was estimated to be over 80cm. In case of the artificial wave excitation, the increase of maximum response angle by the effect of the vertical motion was not so remarkable. It is found that the tip-over of the full-scale cask was not occurred at the acceleration level which exceeds the input level one-and-a-half times as strong as the uplifting limit level, but the special attention should be paid for the sliding or jumping behavior of the cask under the strong earthquake motion, even if the friction coefficient is still large.

<u>Seismic Response of the Fuel</u>

Fig.13 shows the measured time history of the deformation of the fuel rod loaded in the center of the canister. The max tensile strain about 20μm/m is occurred by the release of the static gravity force, therefore as the max compressive is about 60μm/m, the maximum gravitational acceleration is assumed to be 3G. Fig.14 shows the summary of the seismic response of the simulated PWR fuel which was loaded in the center of the canister. Although the impact velocity of the fuel exceeds 300mm/s, the corresponding max deformation is reached to 250μm/m, and the spent fuel structures still seems to be existed in the elastic region under the strong seismic motion. Therefore, it seems that the integrity of spent fuel might be maintained under the Japanese typical design seismic loads.

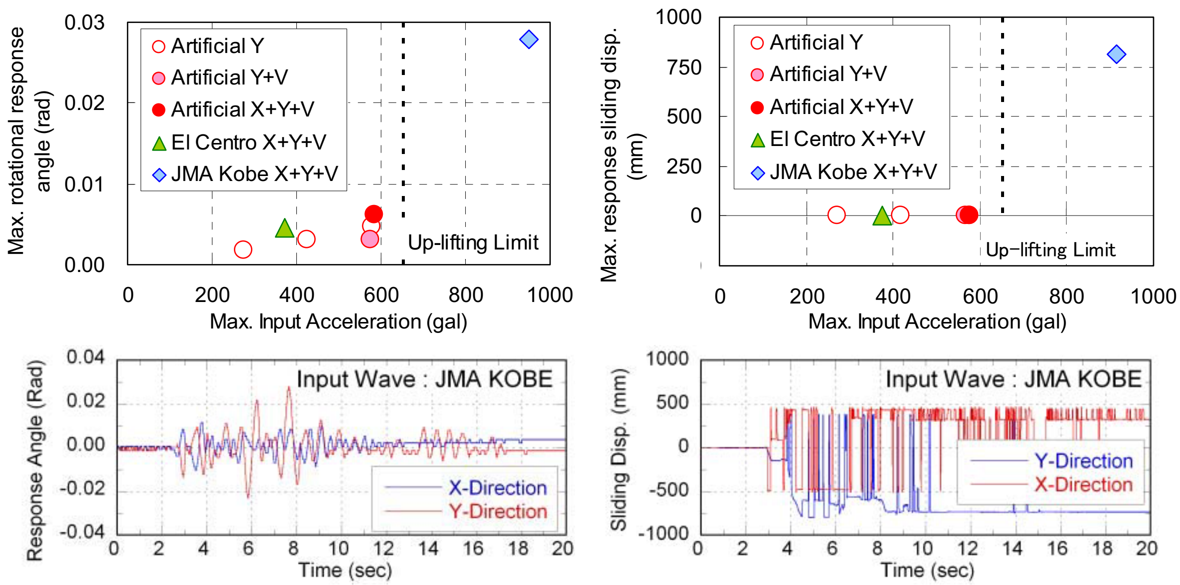

Figure 12 Summary of the Seismic Response of the Concrete Cask in Test Case #5 (In Use of the RC Bottom Circular Plate)

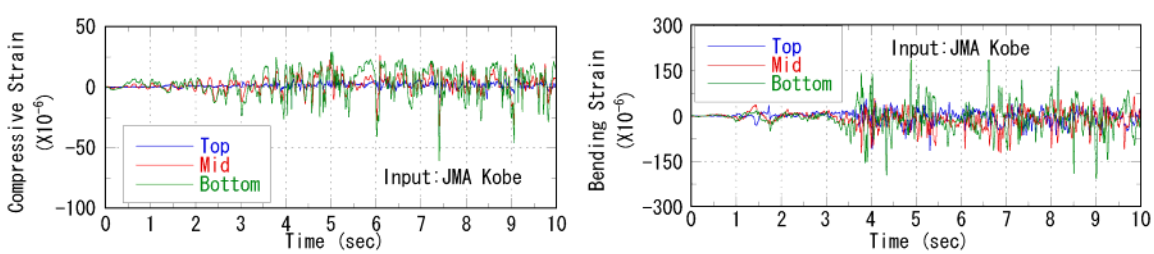

Figure 13 Measured Time History of the Deformation of the Fuel Rod

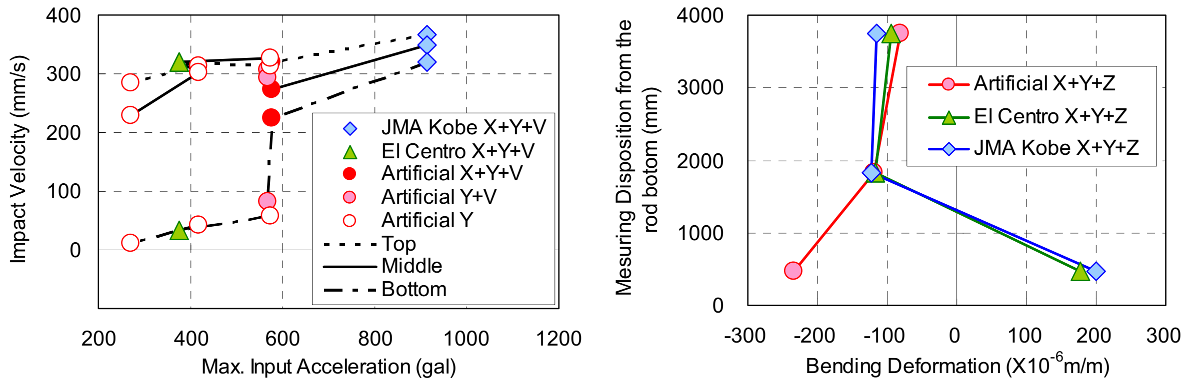

Figure 14 Summary of the Seismic Response of the Simulated PWR Fuel

CONCLUSIONS

For vertically free-standing concrete cask on the floor pad in the cask storage facility, its tip-over and sliding behavior and the integrity of the spent fuel during strong seismic motions are still the technical key issues to guarantee its safe performance. By performing the seismic excitation test with a full-scale concrete cask including 21 PWR simulated fuel assemblies, using 3D full-scale earthquake testing facility, it is found that the tip-over of the full-scale cask did not occur and, the maximum response deformation of the fuel remains under the elastic region by the interaction effect due to the existence of the gap between the canister and cask body, and the gap between the fuel and basket, but the special attention should be paid for the sliding or jumping behavior of the cask under the strong earthquake motion.

ACKNOWLEDGMENTS

These works have been carried out under the contract from NISA/METI.

REFERENCES

[1] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, “Technical Requirements on Interim Spent Fuel Storage Facility Using Dry Metal Cask”, NISA-314c-06-02, (in Japanese), (2006).

[2] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, “Technical Requirements on Interim Spent Fuel Storage Facility Using Dry Concrete Cask” NISA-314c-06-01, (in Japanese), (2006).

[3] SHIRAI, K., et al., Experimental studies of free-standing spent fuel storage cask subjected to strong earthquake, SMiRT17, K470, Prague, Czech, Republic, Aug., (2003).

[4] NATIONAL RESEARCH INSTITUTE FOR EARTH SCIENCE AND DISASTER PREVENTION (NIED), Hyogo Earthquake Engineering Research Center, http://www.bosai.go.jp/hyogo/ehyogo/

[5] SHIRAI, K., et al., Demonstration Tests Program Using Full-Scale Metal Cask and Concrete Cask, IAEA-CN-144-33, International Conference on Management of Spent Fuel from Nuclear Power Reactors, IAEA, Vienna, Austria, June, (2006).

[6] NUCLEAR SAFETY COMMISSION, “Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities”, Sep., (2006).