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Development of transportable storage cask holder with high seismic resistance

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Abstract
Many spent fuel storage pools at nuclear power plants are now reaching their full capacity, and there is a growing need for interim storage of spent fuels in Japan. Dual purpose (transport and storage) dry metal casks are planned to satisfy the need, which can transport spent fuels to dry storage facilities and store them without removal or reloading.
In interim storage facilities in Japan, it is required to fix casks onto the floor in order to prevent them from falling over. MHI has developed the cask holder with high seismic resistance used in combination with a dual purpose cask in the interim storage facilities. The cask holder can keep a cask safely in a vertical position without any fixing connection. MHI carried out seismic tests on a 1/4 scaled model of the cask holder to examine the behavior of the cask holder and the cask.
This paper presents the outline of the cask holder and the seismic test results. Furthermore, a seismic design procedure for the cask holder is proposed.

1. Introduction
Dry casks to be stored in dry storage facilities in Japan are often designed to be fixed to a storage pad by means of four lower trunnions of a cask. If the design seismic condition is upwardly revised over the specifications of lower trunnions, it can be necessary to modify the cask design for replacement of existing casks.
As an effort to this issue, MHI has developed a cask holder with high seismic resistance for dual purpose (transport and storage) metal casks in dry storage facilities. Since the cask holder does not need to secure lower trunnions but holds a rigid bottom of a cask, no load acts on the lower trunnions during an earthquake. Therefore, there is no need to modify the design of casks in case that a more severe seismic condition is applied.
In this paper, the features of the cask holder are described, and seismic tests of the cask holder carried out by using a 1/4 scaled model are presented in detail. In addition, one of seismic design procedures for the cask holder focusing on a rocking behavior of an installed cask is proposed.

2. Features of Cask Holder

Figure 1 shows an overview of the cask holder. The cask holder consists of a base plate and a holding part having a recessed part. The inner diameter of the holding part is set slightly larger than the outer diameter at the bottom part of a cask installed. The cask holder can be fixed onto a floor of storage facilities with anchor bolts.

Each cask is installed onto a cask holder without fixing the cask holder and the lower trunnions of the cask. During an earthquake, a cask installed onto a cask holder can tilt or slide within the recessed part of the cask holder. The cask holder, however, can prevent the cask from falling over or colliding with another cask by holding the bottom part of the cask with the recessed part of the cask holder (see Figure 2).

The seismic condition in dry storage facilities is not reflected to the lower trunnions where no seismic force acts, but on the holding part of the cask holder especially by setting its width and height appropriately.

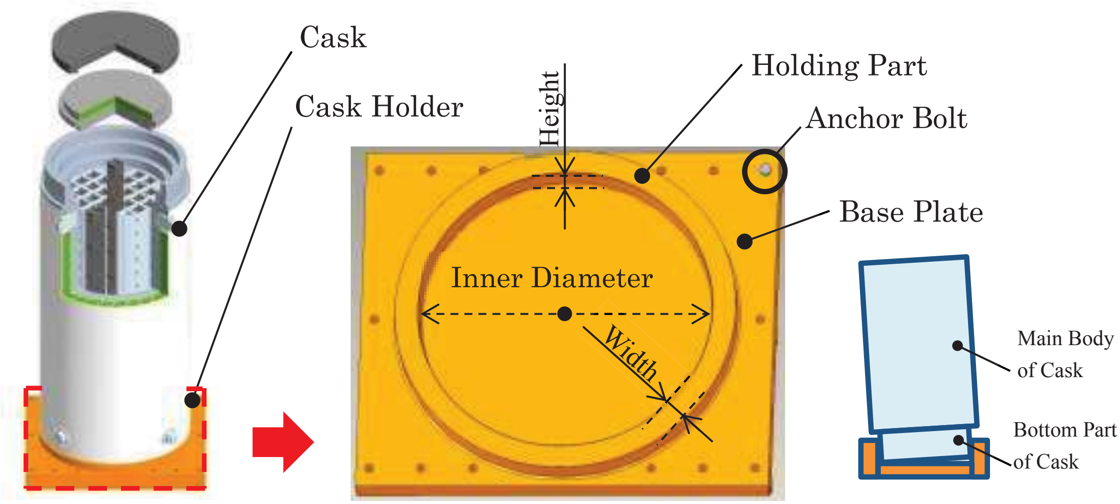


Figure 1 Configuration of Cask Holder

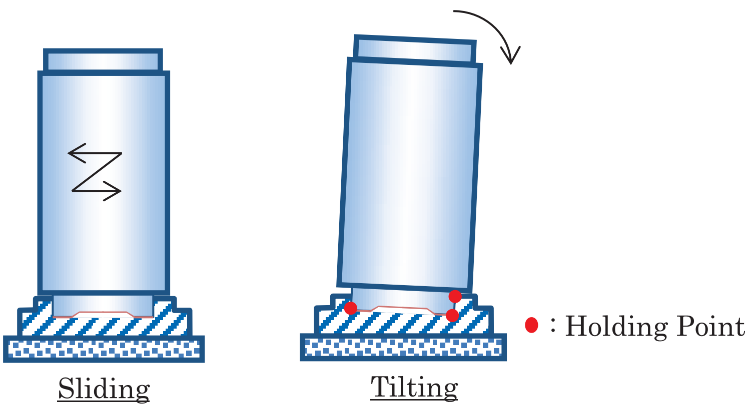


Figure 2 Behavior of Cask during Earthquake

3. Seismic Tests

Seismic tests were carried out using a 1/4 scaled cask holder model with a dummy cask model to examine the fundamental behavior of the cask holder and the cask.

3.1 Test Conditions

(1) Seismic test models

As shown in Figure 3, the 1/4 scaled cask holder model (0.54m I.D. / 0.06m depth / 0.8m length / 0.7m width / 0.1m height) was used in the seismic tests with the dummy cask model (0.54m O.D. / 1.28m length / 2000kg mass) which was also a basically 1/4 scaled model of MSF (Mitsubishi Spent Fuel) cask [1]. Table 1 shows the ratio of dummy cask model for the law of similarity. Though the shape of the dummy cask model was almost similar to that of the MSF cask, the moment of inertia was smaller than the general value based on the law of similarity, so that the dummy cask was easier to tip over than the original.

(2) Measurement

As shown in Figure 4, horizontal and vertical displacements as well as accelerations of the dummy cask model were measured to grasp its three-dimensional behavior. Laser displacement sensors were installed every 90 degrees at 2 kinds of elevations for horizontal displacements, and mounted on the outer surface of the dummy cask model every 90 degrees for vertical displacements. A tri-axial accelerometer was installed on the top of the dummy cask model to measure its response accelerations in two horizontal directions and in a vertical direction.

In addition, 44 biaxial strain gauges were arranged on the top surface of the holding part of the cask holder model in order to measure the strain caused by the collision of dummy cask model. They were attached in every 10 degrees, and especially in every 5 degrees near the directions of 0, 90, 180, and 270 degree, as shown in Figure 5.

(3) Seismic Wave

The time-history seismic waves shown in Figure 6 were applied in the seismic test, which were generated respectively for horizontal and vertical directions from the floor response spectra of PWR plants in Japan. The test model was excited simultaneously in 3 directions, applying the same horizontal seismic waves in two horizontal directions (X and Y directions) and the vertical seismic wave in a vertical direction (Z direction).

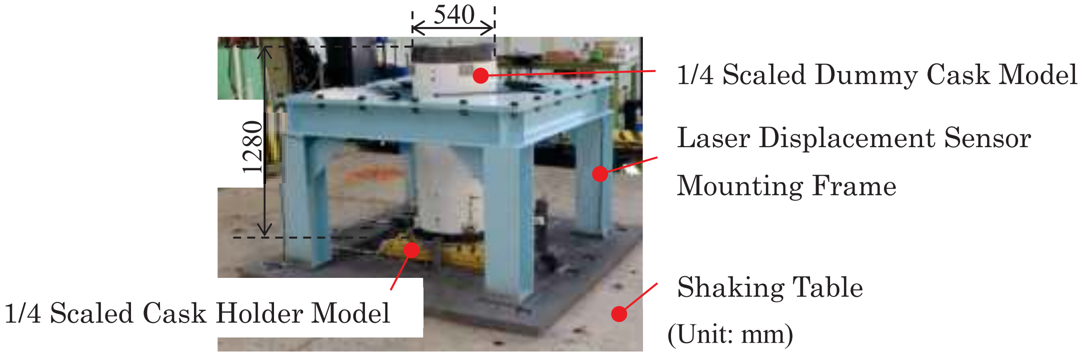


Figure 3 Test Models of Cask and Cask Holder

Table 1 Ratio of Test Model for the Law of Similarity

Quantity	Unit	Dimension	General Ratio for Scale Model		Ratio Employed in Test Model
Length	[m]	L	1/n	1/4	1/4
Acceleration	[m/s^2]	LT^{-2}	1	1	1
Mass	[kg]	M	$1/n^3$	1/64	1/64
Time	[s]	T	$1/n^{0.5}$	1/2	1/2
Inertia Moment	[$kg \cdot m^2$]	ML^2	$1/n^5$	1/1024	1/1600*1)
Load	[N]	MLT^{-2}	$1/n^3$	1/64	1/64

(Note)
*1) Approx. 36% Smaller than General Value for the Law of Similarity of 1/4 Scale Model.

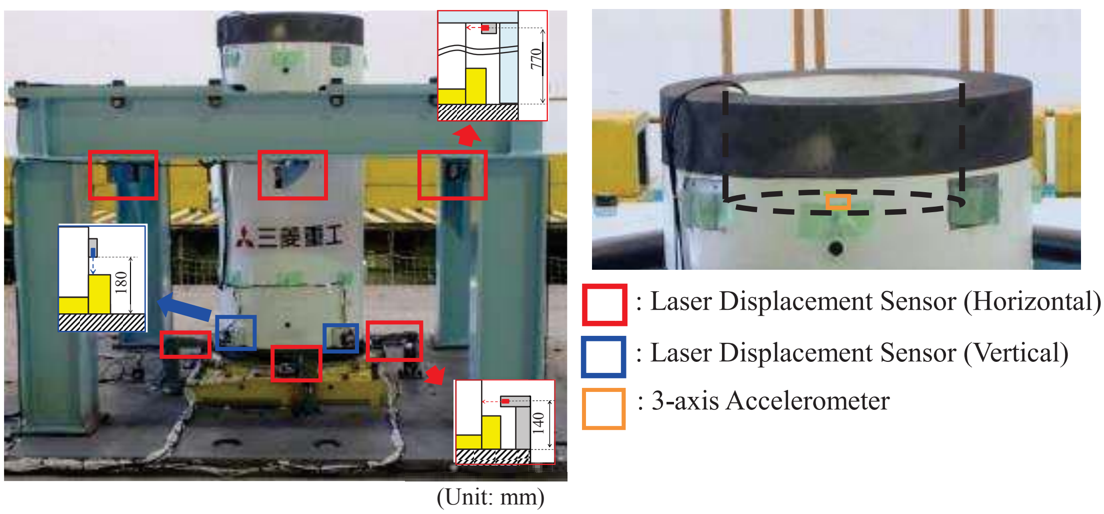


Figure 4 Installation Points of Displacement Sensors and Accelerometer

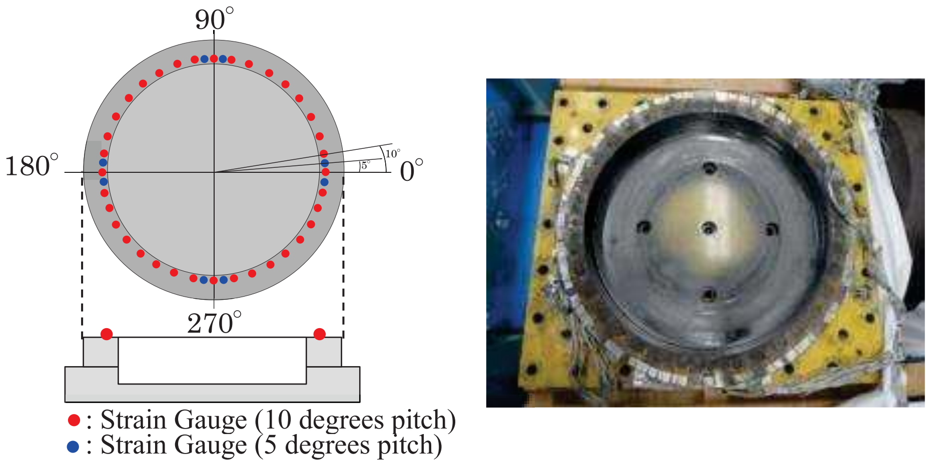
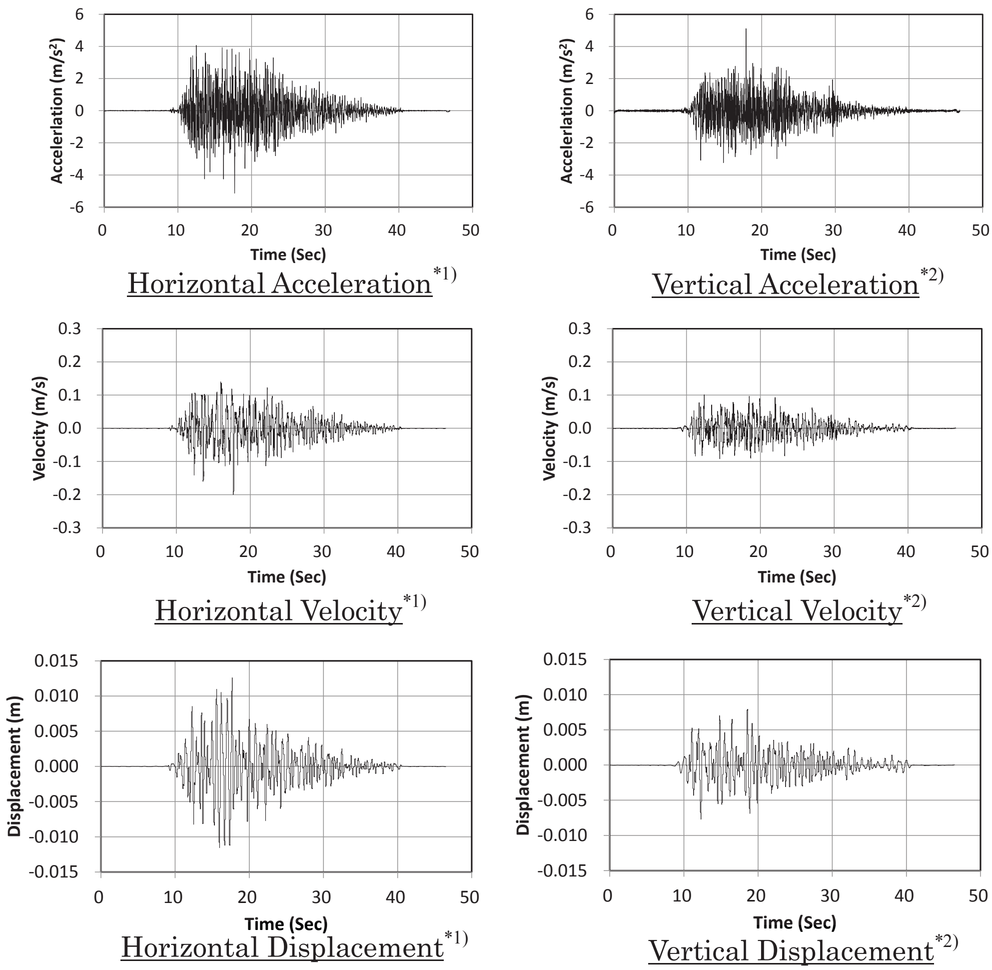


Figure 5 Installation Points of Strain Gauges



(Notes)

*1) X and Y Directions

*2) Z Direction

Figure 6 Seismic Waves

3.2 Test Result

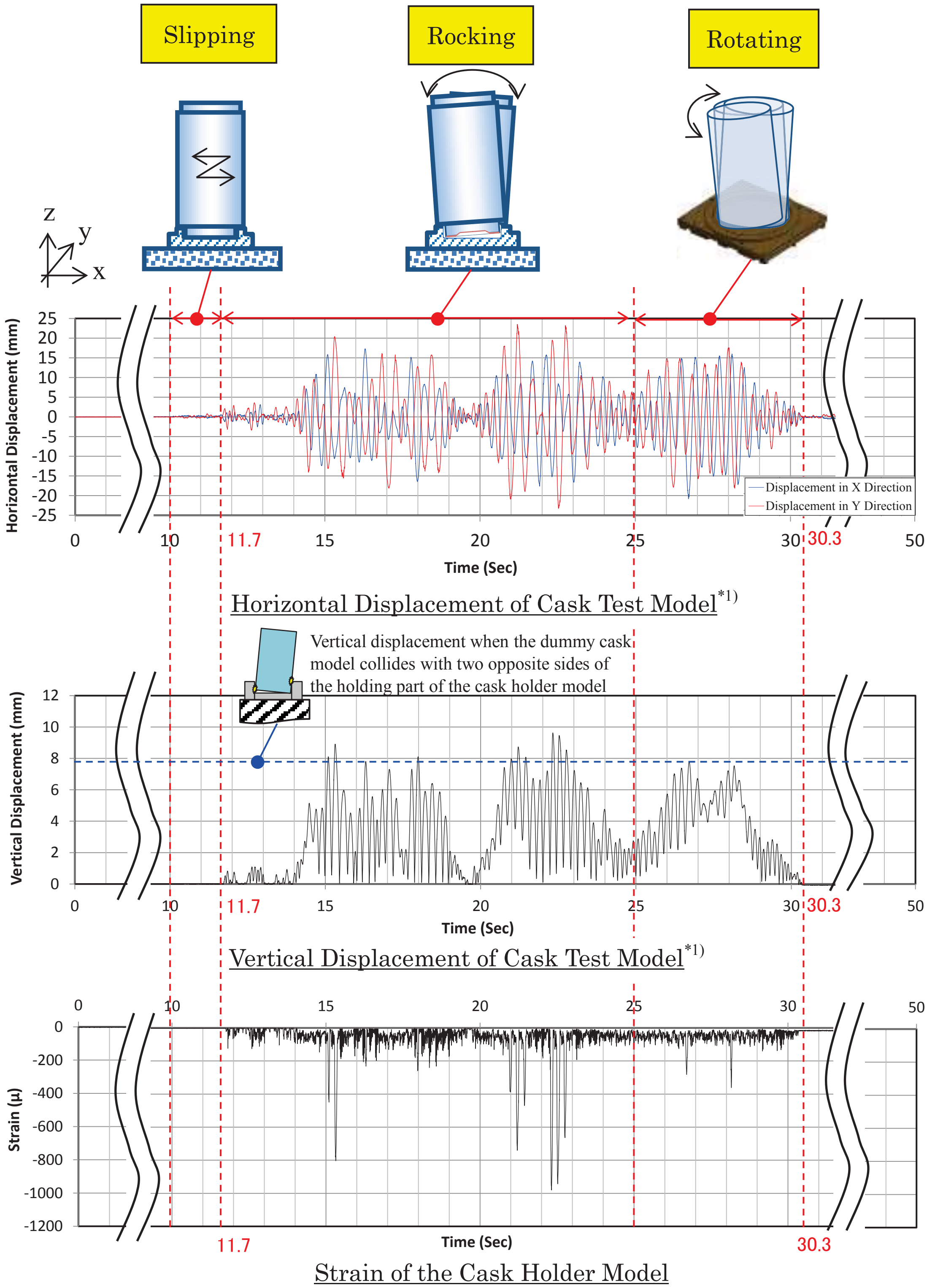
The result of the cask seismic test is shown in Figure 7. The response behavior of the dummy cask model was observed between around 10 and 30 seconds after the start of the test.

From 10 to 11.7 seconds, the vertical response displacement was not recorded, though the horizontal response displacement was slightly confirmed. It seems that the dummy cask model was under "slipping" behavior.

From 11.7 to 25 seconds, the horizontal response displacement of the dummy cask model widely changed frequently between positive and negative values, and also the vertical response displacement varied frequently between positive values and zero in the same phase. Therefore, it seems that the dummy cask model was under "rocking" behavior.

From 25 to 30.3 seconds, the horizontal response displacement of the dummy cask model fluctuated between positive and negative values, however the vertical response displacement remained above zero. It seems that the dummy cask model was under "rotating" behavior.

The peak strains of the cask holder model were recorded at several times during the time period from 11.7 to 25 seconds when the cask response motion was "rocking". They appeared when the dummy cask model reached the vertical displacement at which it collides with the two opposite sides of the holding part of the cask holder model. Especially, the maximum strain of the cask holder model was measured at the same time that the vertical displacement of the dummy cask model was the largest. In addition, it was approx.1000μ, which indicated that the deformation of the holding part of the cask holder model was within the elastic range during the seismic test.



(Notes)

*1) Reference Points for two horizontal displacements and a vertical displacement are shown as Figure 8.

Figure 7 Result of Cask Seismic Test

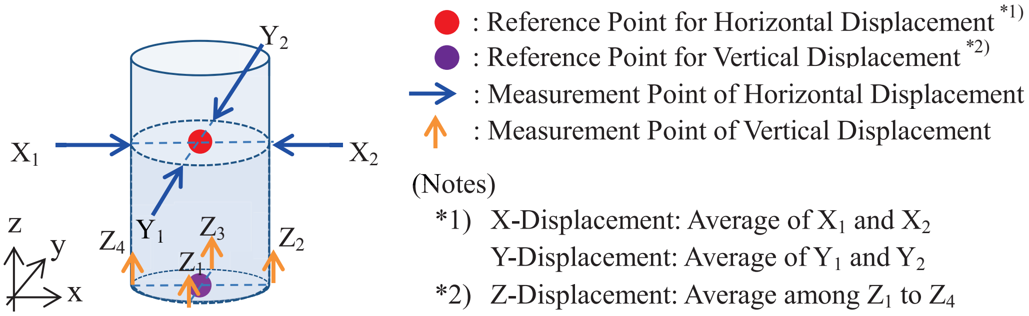


Figure 8 Reference Points for X,Y and Z Displacements

4. Seismic Design Procedure

A reasonable seismic design procedure for the cask holder is needed to prevent an installed cask from exiting out of a cask holder even in an earthquake. Focusing on the "rocking" behavior in which the maximum strain was recorded on a cask holder model as already described, one of the estimate calculations for the collision loads exerted on two opposite sides of the holding part of the cask holder from an installed cask is hereafter proposed, which are to be available for evaluating the structural integrity of the cask holder with static stress analyses.

4.1 Estimate Calculation for Collision Loads

As shown in Figure 9, steps (a) to (d) during the "rocking" behavior are assumed for collision load calculation. The displacements of the cask holder inner surface at the two collision points are calculated according to the law of conservation of energy before and after the collision (Eq.(1)) and the balance of the moment of force after the collision (Eq.(2)), and then the collision loads can be obtained from Eq.(3).

The rotational energy of the cask ($\frac{1}{2}I\omega_2{}^2$) is calculated under the condition that the maximum acceleration of the earthquake ground motion is loaded constantly in step (c). It is assumed that only the gravitational acceleration is exerted in step (a) and that the vertical component of the kinetic energy of the cask is consumed in step (b), while the damping of the cask due to friction against the cask holder is ignored in every step.

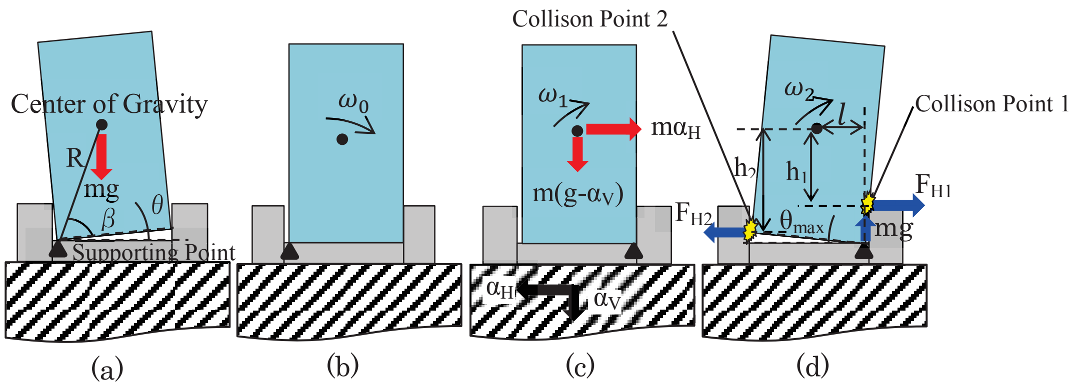


Figure 9 Assumption of Rocking Behavior for Collision Load Calculation

$$\frac{1}{2}I{\omega_2}^2 = \frac{1}{2}k_1{x_1}^2 + \frac{1}{2}k_2{x_2}^2 + mgR(\sin(\theta_{max} + \beta) - \sin(\theta + \beta)) \quad (1)$$

$$h_1 k_1 x_1 = h_2 k_2 x_2 + mgl \quad (2)$$

$$F_{H1} = k_1 x_1,\ F_{H2} = k_2 x_2 \quad (3)$$

where,

I: Inertia moment relative to the supporting point of the cask

ω_2: Angular velocity of the cask immediately before colliding with both inner sides of holding part of the cask holder

k_1, k_2: Stiffness of the collision point 1, 2 (See Figure 9)

x_1, x_2: Horizontal displacement of the cask holder inner surface at the collision point 1, 2

m: Mass of the cask

g: Acceleration of gravity

R: Distance from center of gravity to supporting point (See Figure 9)

h_1, h_2: Vertical distance from center of gravity to collision point 1,2 (See Figure 9)

l: Horizontal distance from center of gravity to supporting point (See Figure 9)

F_{H1}, F_{H2}: Collision load at the collision points 1, 2

4.2 Stress Evaluation Procedure

The cask holder is to be evaluated according to static stress analyses taking into account the collision loads from the installed cask estimated in the manner stated in 4.1.

5. Conclusion

MHI has developed the cask holder with high seismic resistance which can hold a dual purpose cask in the dry storage facilities. The seismic tests were carried out in order to grasp the behavior of a cask installed onto the cask holder, and then it was confirmed that the maximum strain of the cask holder is caused by the "rocking" behavior of the cask. In addition, the maximum strain of the cask holder measured during the seismic tests was within the elastic range.

Furthermore, the seismic design procedure for the cask holder was proposed, in which the cask holder is to be evaluated by using static stress analyses under the collision loads estimated taking the cask "rocking" behavior into account.

In the near future, the cask holders designed through the stress evaluation using the procedure discussed here will be applied in interim storage facilities in Japan.

References

[1]J. Kishimoto, et al., "Design Outline of MSF Transportable Storage casks for Spent Fuels and The First "Type Approval" Experience in Japan", PATRAM2016, Kobe (Japan)