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ANALYSIS OF DCI CASK DROP TEST ONTO REINFORCED CONCRETE SLAB

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ABSTRACT

We conducted the cask drop tests on to the reinforced concrete pad representing the floor of the storage facility in order to confirm the integrity of casks subjected to impact load caused by cask mishandling drop which is one of the technical issues to be considered in the safety analysis for cask and storage house. Also, we conducted simulation analysis using the concrete analysis code which was developed at our laboratory and confirmed its applicability to impact due to cask drop onto reinforced concrete pad.

I INTRODUCTION

It can be assumed that the accident caused by the falling of casks during their handing in the storage facilities is the severest condition structurally, though there have been few demonstration test examples and evaluations made so far with respect to this problem. The object of the present research is to demonstrate and evaluate the structural integrity of casks in case they fall during their handling in the storage facilities. For this purpose, we performed drop tests of fullscale casks on a reinforced concrete (RC) slab representing the floor of the storage facilities, with consideration during storage (cask lifting orientation, drop height, etc.).

Meanwhile, drop analysis was conducted for these drop tests to establish a technique for analyzing the dropping of casks on a reinforced concrete slab.

II DROP TEST

TEST CASK

The outline of its specifications is shown in Table 1. Meanwhile, to verify the margin per 3 different types of drop orientation to be described later, drop tests were conducted at a critical height using 3 test casks. Also, it can be considered that the cask for storing BWR-type spent fuel is generally slender as compared with PWR-type spent fuel and generates a larger stress under the same load condition during horizontal and oblique dropping. So, tests were conducted on the casks for storing BWR-type spent fuel.

TEST RC SLAB

Prior to commencing this research, conceptual design of various types of the cask storage house, was carried out. All these storage houses were designed as Class-C (Japanese Classification for Seismic Degree). The RC slab used in this test was designed and manufactured based on the specifications of the floor slab in these storage houses. The outline of its specifications is shown in Table 2.

TEST CONDITIONS

The test conditions established are shown in Table 3. Drop heights were determined in accordance with the following considerations:

(1) Normal Operating Height

The normal operating height at the time of moving within the storage facilities was determined to be 1.5m based on the lifting condition.

(2) Maximum Lifting Height

The maximum lifting height in the storage house subjected to conceptual design was determined based on the cask carrying in height shown in Fig.1.

(3) Verification of the Cask Margin

To verify a margin in the structural integrity of casks against a drop accident, a critical drop height which permits maintenance of integrity was determined on the basis of prior drop analysis.

TEST RESULTS

Typical examples of test results obtained during the drop test are shown in Fig.2.

The test results show that the strain and acceleration during oblique dropping are sufficiently small compared with those during vertical and horizontal dropping.

For evaluation of integrity against vertical and horizontal orientation, therefore, it can be considered the dropping in the oblique orientation will pose no problem in making such evaluation.

Leak tightness at the lid of the cask was kept against cask drop.

Since the estimated critical drop height is sufficiently height as compared with the above-mentioned drop height, it was verified that the cask had a sufficient margin against a falling accident during operation.

III ANALYTICAL METHOD

Model of Concrete

Stress-strain relationship: A Non-linear stress-strain relationship for concrete as shown in Fig.3 was used for the hydrostatic pressure component of the stress. At loading and unloading, concrete has plastic behavior and elastic recovery, respectively.

Compressive failure: The compressive failure criterion of the this analysis takes the multiaxial stress condition[1] into account as shown in Fig.4 on the assumption that concrete is a homogeneous and isotropic Material.

The failure surface is expressed by octahedral stress. The ultimate strength envelopes of the failure surface in the meridian plane are expressed by the following parabolic equations in terms of octahedral stresses on the basis of test results[2] .

$$\theta = 0^\circ : \frac{\tau_{oc}}{\sigma c} = 0.0689 + 0.6868\left(\frac{\sigma_{oct}}{\sigma c}\right) - 0.0964\left(\frac{\sigma_{oct}}{\sigma c}\right)^2 \tag{1}$$

$$\theta = 60^\circ\mathrm{C} : \frac{\tau_{oc}}{\sigma c} = 0.2040 + 0.8424\left(\frac{\sigma_{oct}}{\sigma c}\right) - 0.1204\left(\frac{\sigma_{oct}}{\sigma c}\right)^2 \tag{2}$$

where,

$$\sigma_{oct} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \qquad \begin{array}{rl} \sigma c & : \text{compressive strength} \\ \sigma_1 + \sigma_2 + \sigma_3 & : \text{principal stress} \end{array}$$

The envelopes which are the intersection of ultimate strength surface and the deviatoric stress plane are given by the following expression.

$$\tau_{oct}(\theta) = \frac{2\tau_{oct}(\tau_{oc}^2 - \tau_{oe}^2)\cos\theta + \tau_{oc}(2\tau_{oe} - \tau_{oc})\sqrt{4(\tau_{oc}^2 - \tau_{oe}^2)\cos^2\theta + 5\tau_{oe}^2 - 4\tau_{oe}\tau_{oc}}}{4(\tau_{oc}^2 - \tau_{oc}^2)\cos^2\theta + (\tau_{oc} - 2\tau_{oc})^2} \tag{3}$$

where,

τ_{oe} : Octahedral shear stress
$\theta = 0°$ calculated by Eq. (1)

τ_{oc} : Octahedral normal stress
$\theta = 60°$ calculated by Eq. (2)

$$\cos\theta = \frac{\sigma_1 + \sigma_2 - 2\tau\sigma_3}{\sqrt{2}\ \{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_2)^2 + (\sigma_3 - \sigma_1)^2\}^{1/2}}$$

When the calculated octahedral shear stress exceeds τ_{oct} in Eq.(3), compressive failure is defined as occurring.

Tensile failure criterion: Tensile failure occurs when one of the principal stresses exceeds the uniaxial tensile strength. The principal stress which exceeds the uniaxial tensile strength is defined as zero, and strains excluding real strains normal to the crack surface are recognized as the crack width. Consequently, the compressive stress in the direction normal to the crack does not yield until crack closure is recognized.

By using the above-mentioned procedures, this concrete tensile model can handle the directions and width of a crack in the concrete element.

Model of Reinforcing Bars

Stress-strain relationship: The stress-strain relationship of reinforcing bars used in this analysis is shown in Fig.5. It is a bilinear approximation and is based on the isotropic hardening rule.

Failure criterion: The Von-Mises yield criterion was applied to the reinforcing bars.

RATE EFFECT

Deformation speed affects the characteristics of the mechanical properties such as yield stress of the material. In this analysis, the rate effect is given by:

$$\sigma d/\sigma s = f\ \{\dot{\varepsilon}\ (t)\}$$

where, σd is the dynamic strength of the material. σs is the static strength of the material and $\dot{\varepsilon}$ is the strain rate. We applied this equation to each element of the model and at each step of the calculation.

ANALYTICAL RESULTS

The calculation was carried for drop heights of 1.5m, 7.5m and 17.0m in the vertical direction. The axisymmetrical model was applied in the analysis as shown in Fig.6. The reinforcing-bar net was modeled by thin-shell elements which have the same reinforcement ratio as a real net of reinforcing bars.

Figures 7 through 9 compare the test results with the calculated results for accelerations and strains at the cask body and penetration depth of the slab. The calculated results are in good agreement with the test results and have an appropriate margin as shown in these figures.

Therefore, it seems that this analytical method can be applied to predict the behavior of a cask dropped onto an RC slab.

CONCLUSION

We confirmed the integrity of casks even if they were subjected to the severe impact load due to free drop onto reinforced concrete slabs caused by mishandling in stage facilities and validated the analytical code for an RC slab subjected to an impact load as a result of such a free drop of a cask.

REFERENCE

1) C.Ito et al., 1991
Design Method of Reinforced Concrete Structure Against The Collision of Missile, CRIEPI REPORT. July.

2) H.Ohnuma, C.Ito, 1986
Ultimate Strength Envelopes of Concrete under Triaxial Compressive Stresses, CAJ REVIEW.

Table 1 CASK SPECIFICATIONS

Materials		X - Type Cask	Y - Type Cask	Z - Type Cask
Lid	Inner Lid	Stainless Steel	Stainless Steel	Stainless Steel
	Other Lid	Stainless Steel	Stainless Steel	Stainless Steel
	Lid Bolt	Stainless Steel	Alloy Steel	Alloy Steel
Body	Wall	Ductile Cast Iron	Ductile Cast Iron	Ductile Cast Iron
	Fin	Ductile Cast Iron	Ductile Cast Iron	Rolled Steel
	Trunnion	Stainless Steel	Stainless Steel	Stainless Steel
Basket Plate		Borated Stainless Steel Stainless Steel	Borated Stainless Steel	Borated Stainless Steel

Weight (ton)		X - Type Cask	Y - Type Cask	Z - Type Cask
Lid	Inner Lid	3.5	4.0	4.8
	Other Lid	2.2	2.2	2.3
Body		78.7	79.9	74.7
Basket Plate		13.8	6.0	10.0
Spent Fuel (52 Assemblies)		14.6	14.6	14.6

Test Spec.	X - Type Cask	Y - Type Cask	Z - Type Cask
Number of S.F.	51(Dummy Weight) 1(Model of BWR Type S.F.)	52(Dummy Weight)	51(Dummy Weight) 1(Model of BWR Type S.F.)
Weight	107.9 ton	112.0 ton	100.4 ton

Table 2 RC SLAB SPECIFICATIONS

Drop Height		Orientation	Cask	Note
Normal Operating Height	1.5m	Vertical ☐ Horizontal ☐	X Y	Varify the cask integrity for free drop the normal operating height
		Oblique		Drop test was not conducted, because the strain growth during oblique dropping was sufficiently small as compared with that duringngng vertical and horizontal dropping by prior drop analysis.
Maximum Lifting Height in Storage House	7.5m	Vertical ☐ Oblique ☐	X Y	Verify the cask integrity for free drop of the maximum lifting height in storage house due to conceptual design:
		Horizontal		Drop test was not conducted, because the cask was not filled up to this height in the horizontal orientation.
Varification of the Cask Margin	17.0m 5.0m 17.0m	Vertical ☐ Horizontal☐ Oblique ☐	X Z Y	Varify a margin in the integrity of casks against a drop accident.

☐ Permormed Drop Test.

Table 3 TEST CONDITIONS

Specification	Value		Note
	6m × 6m × 1.2m : 5 Slabs		For Vertical & Oblique Orientation Drop Test
	6m × 8m × 1.2m : 2 Slabs		For Horizontal Orientation Drop Test
Concrete Strengh	Desigh Strength	240 kg/cm²	
	Measured Strength	320 kg/cm²	Standard Curing
		232 kg/cm²	Job-site Air Curing
Reinforcing Bar	JIS Class : SD30A		
	Designation : D22· D25		
	Reinforcement Ratio : 1.3%		

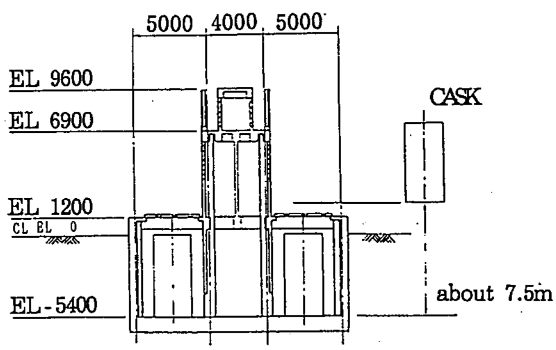

Fig.1 EXAMPLE OF STORAGE HOUSE

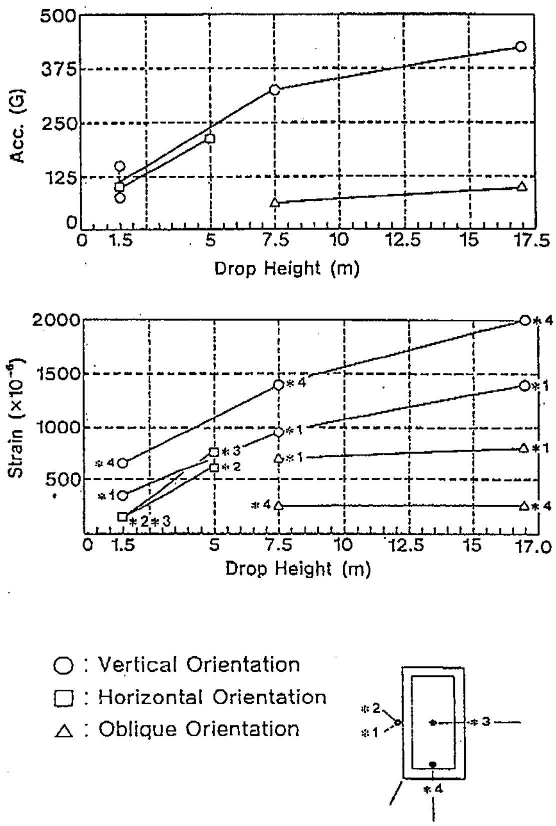

Fig.2 RELATIONS AMONG DROP HEIGHT, STRAIN AND ACCELERATION

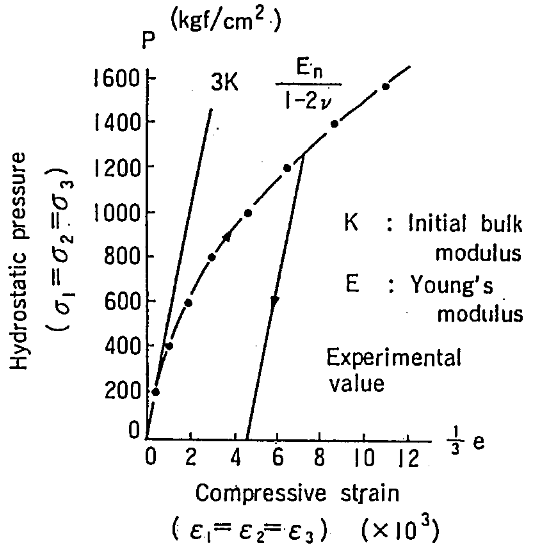

Fig.3 STRESS-STRAIN RELATIONSHIP OF CONCRETE UNDER HYDROSTATIC COMPRESSION

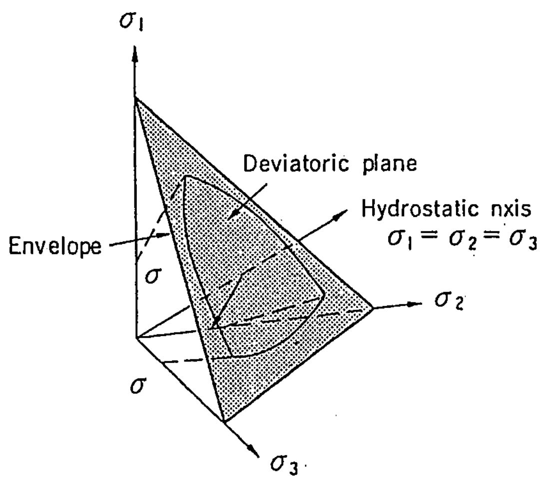

Fig.4 MULTI-STRESS CONDITION

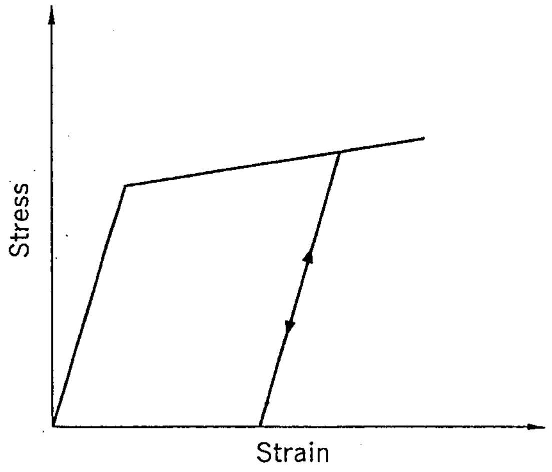

Fig.5 MULTI-STRESS CONDITION

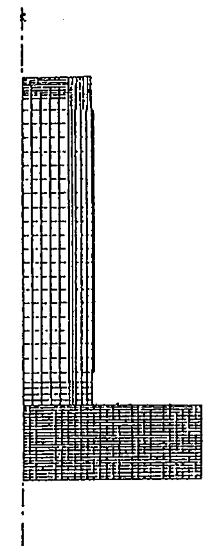

Fig.6 FINITE ELEMENT MODEL

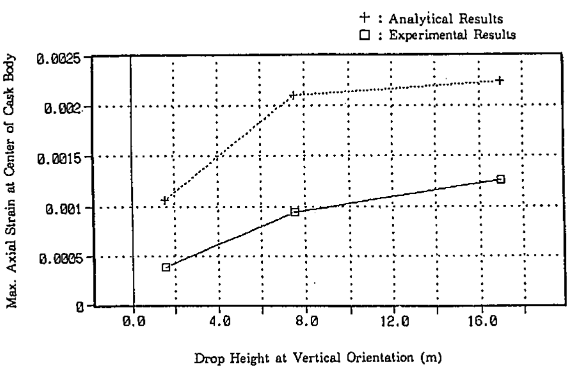

Fig.7 COMPARISON BETWEEN ANALYTICAL AND EXPERIMENTAL RESULTS FOR MAXIMUM STRAIN

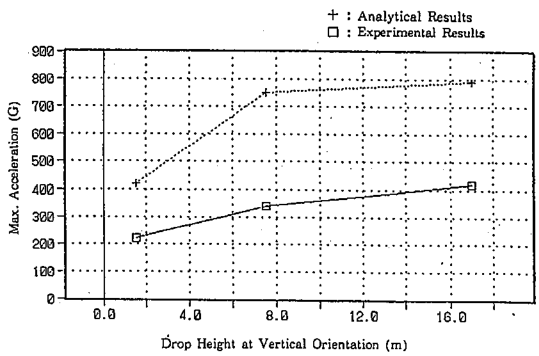

Fig.8 COMPARISON BETWEEN ANALYTICAL AND EXPERIMENTAL RESULTS FOR MAXIMUM ACCELERATION

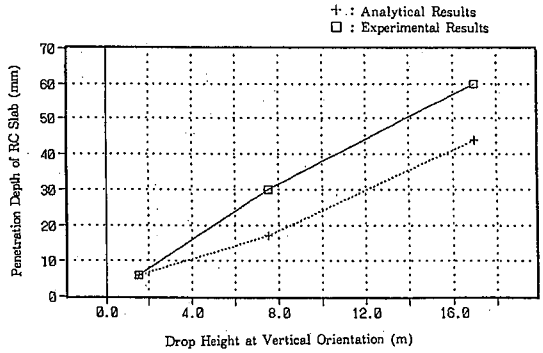

Fig.9 COMPARISON BETWEEN ANALYTICAL AND EXPERIMENTAL RESULSTS FOR PENETRATION DEPTH OF RC SLAB