



## Assessment Procedure for Buckling of Thin Walled Cylindrical Liquid Storage Tanks in Nuclear Power Plants under Seismic Loading (1st Report; Investigation on Elephant Foot Bulge)

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### ABSTRACT

As for thin walled cylindrical liquid storage tanks in nuclear power plants, the current elastic design guideline against seismic loading might result in too conservative component design. Therefore, it is thought possible to make the design guideline more reasonable by taking dynamic response reduction into account. Experiments using scaled models and numerical analyses were carried out, and seismic behavior of thin walled cylindrical liquid storage tanks was simulated to investigate energy absorption capacity and seismic resistance of those tanks. Based on the test and analysis results, assessment procedure for buckling considering post-buckling behavior has been proposed.

In this paper, experiment and numerical analysis results are presented. Dynamic buckling tests were performed using scaled models of thin walled cylindrical liquid storage tanks of nuclear power plants. The input seismic acceleration was increased until the elephant foot bulge occurred, and the vibrational behavior before and after buckling was investigated.

The main results/conclusion obtained in the study were following.

- (1) Buckling behavior and critical loads were clarified.
- (2) Limit condition to maintain storage function.

**KEY WORDS:** cylindrical liquid storage tank, nuclear power plant, dynamic response reduction, seismic behavior, buckling, bending buckling, elephant foot bulge, diamond buckling, energy absorption

### INTRODUCTION

When cylindrical liquid storage tanks are excited by seismic wave, buckling occur at tank wall. As for the buckling patterns of these tanks, bending buckling (diamond and elephant foot bulge) at the bottom portion, shear and compression buckling at the middle portion and nonlinear ovaling vibration at the upper portion, which shows nonlinearity between the input and response level and suddenly occurs for the excessive input level, thus will be called

as “ nonlinear ovaling vibration” hereafter in this paper, should be considered. Many studies have been performed to study behaviors of cylindrical liquid storage tanks under seismic wave. Shibata<sup>[1]</sup> investigated some failures of industrial facilities due to seismic excitation in many countries and summarized some failures of the liquid storage tanks. And he also studied elephant foot bulge phenomena due to natural seismic waves using a mock-up of thin walled tank model<sup>[2]</sup>. As for analytical procedures, Combescure et al.<sup>[3]</sup>, Liu and Uras<sup>[4]</sup> and Ito et al.<sup>[5]</sup> reported dynamic buckling analysis based on finite element methods and Chiba et al.<sup>[6]</sup>, Natsiavas and Babcock<sup>[7]</sup>, Hara et al.<sup>[8]</sup>, and Shih et al.<sup>[9]</sup> reported instability phenomena found at upper portion of liquid storage tanks. Matuura, Kawamoto et al.<sup>[10]</sup> conducted both experiments and analysis systematically on shear buckling of thick walled cylindrical tanks in the plastic region which are cantilever type structures with liquid sodium in them. And they summarized the design guideline. The High Pressure Gas Safety Institute of Japan conducted dynamic buckling tests using large scale liquid storage tank models and a large scale shaking table at Tadotsu<sup>[11]</sup> and Sato et al. also conducted the dynamic buckling tests using small scale liquid storage tank models<sup>[12]</sup> in order to study elephant foot bulge phenomena. However, many of them are based on a certain assumption of elastic behaviors, and while few studies are found on the dynamic buckling behaviors.

In this study, in order to make a design guideline more reasonable by taking dynamic response reduction into account, dynamic buckling tests were performed using large scale liquid storage tanks simulated water tanks for nuclear power plants. Tank models were shaken by seismic waves horizontally and vertically. The threshold for occurrence of elephant foot bulge and the behaviors of post buckling were investigated and the redundancy from buckling occurrence and occurrence of some failures were also investigated.

## TEST MODELS

In this test, a tank, which had various thicknesses, was selected as a test model. This tank wall is composed 4 kinds of plate with different thickness and the bottom layer plate has the largest thickness. Table 1 shows dimensions for the tank model. Here, R is the radius,  $t_m$  is the average thickness, L is the length and H is the liquid level. The tank model was made of aluminum alloy considering excitation capability of the shaking table while actual tanks were made of steel. Length ratio was settled as large as possible in order to make the vibrational phenomena closer to actual one. The length ratio for the tank model is 1/5. For the tank model, hoop stress ratio due to static pressure is 1/5 and less than that due to dynamic pressure 1/3, because the length ratio is different from Young’s modulus ratio. This means that the effects of static liquid pressure are slightly smaller than that of actual tanks. The aluminum alloy was selected in which the ratio between the Young’s modulus and the yield stress is almost the same with that of actual tanks in order to simulate the critical buckling stress. But the material of the aluminum alloy was limited, the yield stress ratio of the test specimen was slightly smaller than that of actual tank. Thus the test specimen is thought to buckle slightly easier than actual tanks. Figure 1 shows the outline of the tank model and Figure 2 shows the photo of the tank model. Actual tanks are fixed to base with bolts, thus the structures around here were also simulated as far as possible and the bolts’ tip were clamped. The snow weight was also simulated by the weight of the tank roof. Moreover, the shape and the rigidity of the roof were simulated considering the effects of liquid pressure due to liquid sloshing.

Table 1 Dimensions of the tank model

R/ $t_m$	L/R	R (mm)	$t_m$ (mm)	L (mm)	H (mm)	Material	Liquid	Mass (Ton)
894	2.4	1100	1.23	2650	2526	Al	Water	10.0

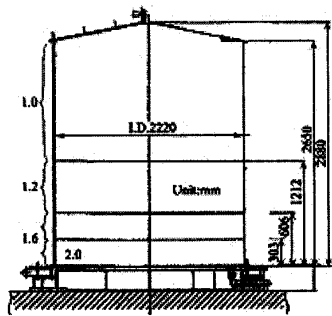


Fig.1 Outline of tank model



Fig.2 Over view of tank model

### EXCITATION METHOD AND INPUT WAVE FOR DYNAMIC BUCKLING TESTS

Tank specimen were installed on the shaking table, and excited horizontally or vertically. Input waves were sinusoidal wave, random wave and an artificial seismic wave. The time histories and the response spectrums of the seismic wave “Se” are illustrated in Figure 3. In the seismic excitation tests, input acceleration level were increased step by step until buckling or some failures occurred. Base input excitation level was set to be 1.0Se.

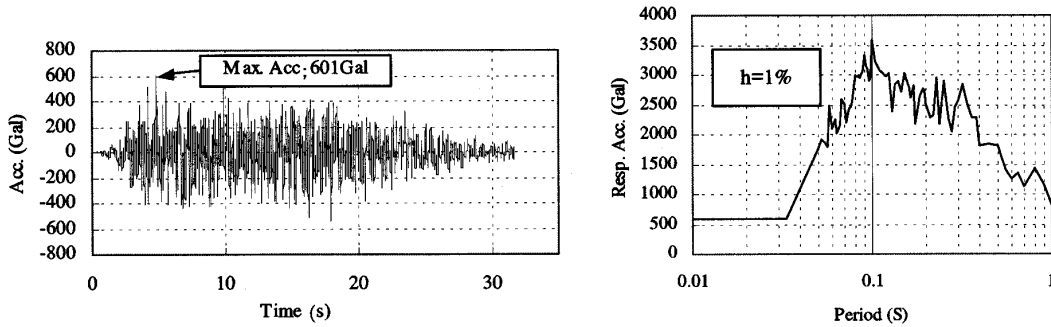


Fig.3 Time history and response spectrum of the seismic wave “Se” (Horizontal direction)

### TEST CONDITIONS

Before performing the seismic excitation tests, excitation tests by random wave with small input level were performed in order to obtain the natural frequency and damping ratio of the tank models. As a first step, vertical excitation tests were performed to study the occurrence of buckling as well as the effects of dynamic liquid pressure due to vertical excitation. And as a next step, horizontal excitation tests were performed to study the threshold of the occurrence of elephant foot bulge and post buckling behaviors. Table2 shows the test conditions.

Table2 Test conditions

	Excite directions	Input level	Test purposes
1. Random wave	•Horizontal •Vertical	160 Gal	Vibration characteristics
2. Seismic wave	Vertical	0.3 ~ 1.1 Se	Study the occurrence of buckling as well as the effects of dynamic liquid pressure due to vertical excitation.
	Horizontal	0.1 Se ~	Study the threshold of the occurrence of elephant foot bulge and post buckling behaviors.

## TEST RESULTS

### Buckling behavior and critical load under the seismic excitation

#### (1) Vertical excitation tests

The large part of tank total weight is dominated by inner water weight and the weight of the structures such as a roof and tank wall is relatively small, so the axial compression stress, which occurs under the vertical excitation, is thought to be small. Therefore it is thought that vertical excitation would not cause large influence on the occurrence of elephant foot bulge. In this section, the effect of vertical excitation on the elephant foot bulge was investigated both experimentally and analytically.

The maximum axial and hoop strain at the portion where elephant foot bulge occurred at after excitation test were plotted for each input level under vertical excitation as shown in Figure 4. In this test, it was confirmed that elephant foot bulge was not observed for the input level more than 1.1Se. It was found that the hoop strain was larger than axial compression one as shown in Figure 4. Figure 5 shows distribution of hoop strain in the tank height direction. In this result, the maximum strain occurred at the middle portion of the 4th wall from the bottom. This tank model is composed of four kinds of plate with different thickness and the top plate was the thinnest. From these data, it is considered that vertical excitation will contribute to increase the hoop strain, but not for the axial strain. In order to inspect the effects of vertical excitation, the distributions of hoop, axial and shear stress in the tank height direction were calculated by FEM using a 3-D shell model respectively. In the FEM analysis, linearity is assumed and liquid is treated by potential theory. In the analysis, three kinds of excitation condition were treated; only the vertical excitation, only the horizontal excitation and both vertical and horizontal excitation. The axial compression stress under the vertical excitation is very small as shown in Figure 6, because the tank structure weight is about 1/20~1/40 of the inner water one as mentioned above. So it is thought that axial compression stress is dominated by horizontal excitation. While, hoop stress partly becomes larger than axial one. This is due to the dynamic liquid pressure, which is brought by the effect with tank wall vibration. Thus, for tanks composed of several plates with various thicknesses, the maximum hoop stress will possibly occur at the upper portion of the tank. When looking at the elephant foot bulge portion, hoop stress due to vertical excitation becomes larger than that due to horizontal excitation. Therefore, it is said that vertical excitation itself is very hard to cause elephant foot bulge because it does not cause large axial compression stress, but it will give some contribution to occurrence of elephant foot bulge, because of large hoop stress.

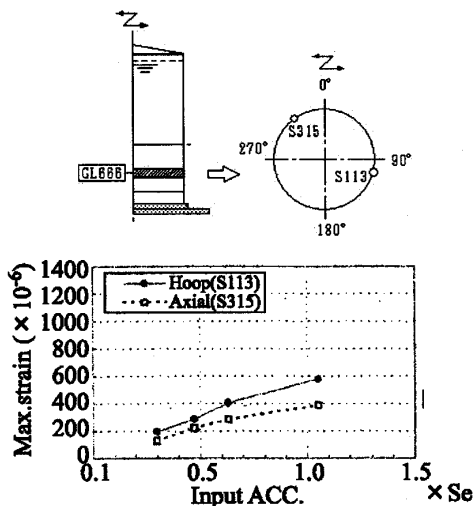


Fig.4 Strain at the bottom portion by vertical excitation

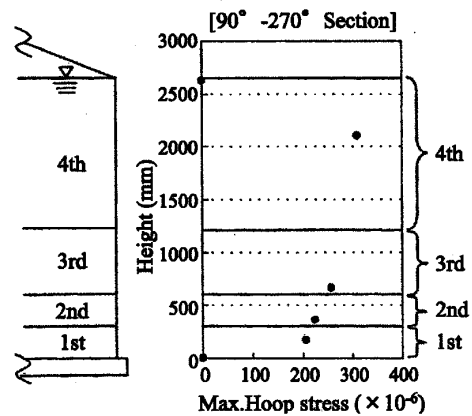


Fig.5 Distribution of hoop strain in the vertical plane under the vertical excitation

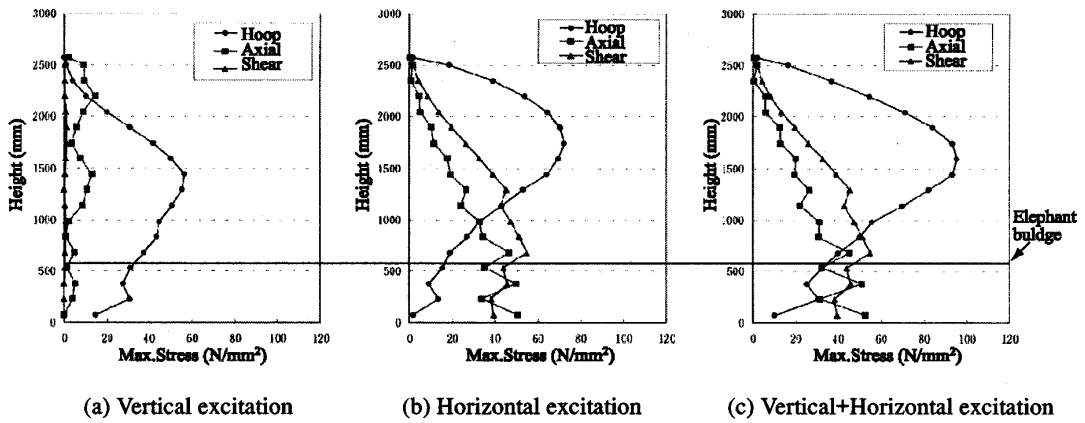


Fig.6 Maximum stress distribution in the vertical plane

**(2) Horizontal excitation tests**

The maximum horizontal acceleration and horizontal displacement at the top of the sidewall were plotted for each input excitation level as shown in Figure 7. In these figures, solid line shows the experimental values and dotted line shows the analytical values obtained by seismic response analyses by using FEM. Here, as the damping ratio, the experimental values were employed. The vertical chain line shows the threshold of occurrence of elephant foot bulge at the tank bottom portion. For this tank model, nonlinear ovaling vibration occurred at 0.2Se and elephant foot bulge at 0.7Se. Residual deformations were observed at the upper portion as well at the input level of elephant foot bulge occurrence. Figure 8 shows the photos of the elephant foot bulge. The validity of the location of elephant foot bulge was also investigated by dynamic buckling analysis by using FEM. Figure 9 shows the analytical result by using 3-D shell model. In this analysis, elephant foot bulge occurred at around welded line for this tank model as well as the test results as shown in Figure 8. This tank model wall is composed of four kinds of plate with different thickness and the bottom plate has the largest thickness. Thus the stress due to bending moment will not necessarily become largest at the bottom portion, though the bending moment will become largest at the bottom portion. This will be main reason for the location of elephant foot bulge.

After occurrence of elephant foot bulge, excitation tests were conducted furthermore with larger input acceleration level. As the results, a crack was observed at the elephant foot bulge portion at 2.7Se level, though any cracks were not observed at the upper portion of the tank wall. Namely, this tank had about 3.9 times margin from the elephant foot bulge occurrence (input level 0.7Se) to a crack occurrence at the elephant foot bulge portion (input level 2.7Se) in view of maintaining storage function. This redundancy is thought to be brought by the elasto-plasticity of elephant foot bulge.

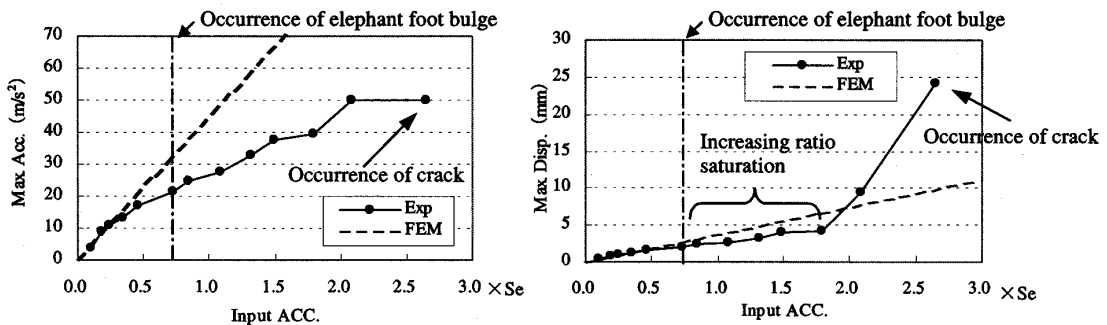


Fig.7 Response Acc. and Disp. for various input Acc.

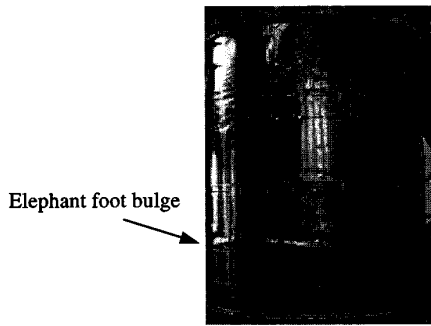


Fig.8 Photo of elephant foot bulge (Test result)

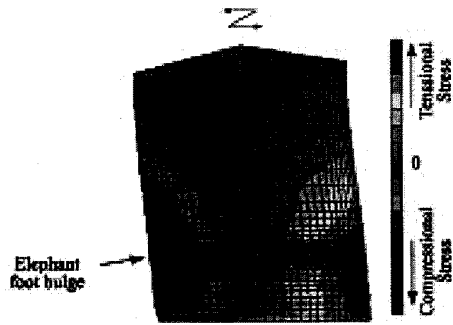


Fig.9 Analytical result by 3-D FEM for dynamic buckling of elephant foot bulge

Figure 10 shows damping ratios for each input acceleration level, which were investigated from the response acceleration time histories. Damping ratio increased along increase of input acceleration level, especially after the elephant foot bulge occurred, it increased rapidly and it was observed up to around 30%. These increases were thought to be mainly brought by the plastic deformation effect of elephant foot bulge, while nonlinear ovaling vibration might cause some effects. In order to confirm validity of the damping ratio, the increasing ratio of accumulated dissipated energy of the tank model was investigated experimentally. The accumulated dissipated energy was calculated by integrating the area of hysteretic curves by response acceleration and response displacement as shown in Figure 11. Because the response acceleration seems equivalent to the inertia force of tank model shows the accumulated dissipated energy obtained by this manner for each input acceleration level. In this figure,  $E_0$  means input energy to the tank model. It is found that the increasing ratio of accumulated dissipated energy is much larger than that of input energy  $E_0$  which is proportional to the square of the input acceleration level. From  $E$  and  $E_0$ , equivalent damping ratio was calculated as  $E/E_0$  and shown in Figure 12 by the symbol  $\square$ . The increasing tendency of  $E/E_0$  is consistent to that of measured damping ratio, thus the measured large damping ratio is thought to be valid.

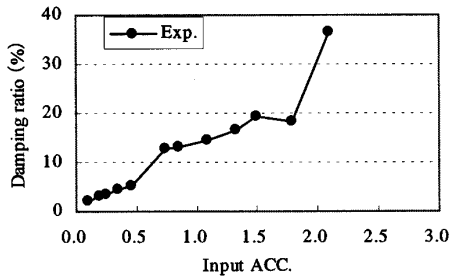


Fig.10 Damping ratio of the tank

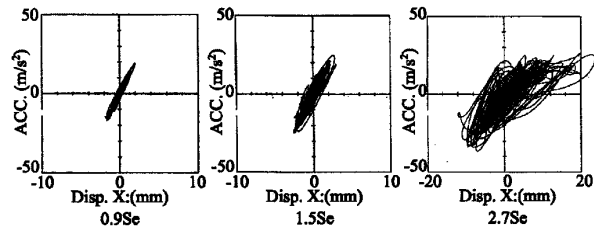


Fig.11 Hysteretic curves by top ACC. and Disp.

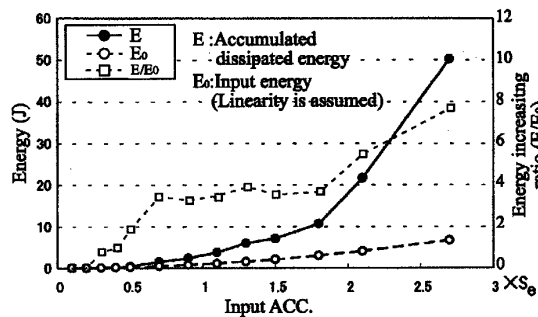


Fig.12 Relationship between accumulated dissipated energy and input ACC.

Finally, for realizing the crack occurrence, the dimension of residual outward bulge of elephant foot was analyzed, because the occurrence of crack is deeply related to fatigue of the wall material. The residual outward bulge of elephant foot bulge is plotted in Figure 13. The residual outward bulge became very large after elephant foot bulge occurrence, and reached up to 16~17mm.

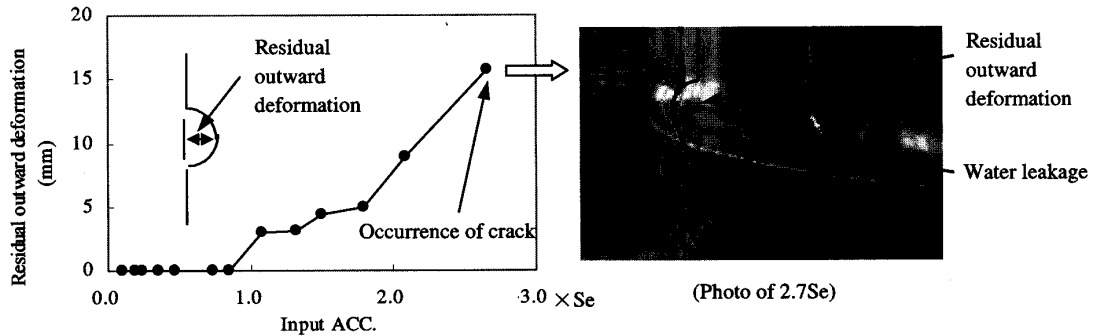


Fig.13 Outward residual deformation of elephant foot bulge

### CONCLUSIONS

In this study, dynamic buckling tests were performed using large scale tank models which simulate the circular cylindrical liquid storage tanks for nuclear power plants. In the seismic excitation tests, elephant foot bulge phenomena and the redundancy from the occurrence of buckling to the occurrence of some failures were investigated in addition to the effects of liquid pressure on elephant foot bulge.

The following conclusions were obtained.

- (1) A large redundancy can be expected from the buckling occurrence to the occurrence of some failures such as cracks because the energy dissipation is thought to be very large due to the plastic deformation at the buckled portion.
- (2) This tank had about 3.9 times margin (from elephant foot bulge occurred at 0.7Se to a crack at the elephant foot bulge portion occurred at 2.7Se) in view of maintaining storage function.

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### NOMENCLATURE

- L : Tank height
- R : Radius
- H : Liquid level
- t : Thickness
- $t_m$  : Average thickness
- Se : Earthquake input acceleration level
- h : Damping ratio
- E : Accumulated dissipated energy
- $E_0$  : Input energy

## REFERENCES

- [1]Shibata, H., 1974, "Survey report on earthquake damage of industrial facilities in the world- Spherical vessels and cylindrical vessels- "(in Japanese), Annual report Ins. of Ind. Science University of Tokyo, Vol.26,No.7,pp.13-18.
- [2]Shibata, H. et al.,1983,"On some results on response observation of liquid storage tanks to natural earthquakes", Proc. of ASME PVP Conf.,Vol.77,pp.21-28.
- [3]Combescure,A. et al.,1981,"On fluid structure interaction and buckling of thin shells under seismic load", Proc. of 6<sup>th</sup> SMiRT, B5/6,pp.1-7.
- [4]Liu, W.K. and Uras,R.A.,1989,"Transient buckling analysis of liquid –storage tanks :Part 1",Proc. of ASME PVP Conf.,Vol.157,pp.35-40.
- [5]Ito, T. et al.,1992,"Study on dynamic buckling simulation methodology for cylindrical shell due to seismic excitation(1<sup>st</sup> report, evaluation of influence of initial imperfection)" (in Japanese),Trans. of JSME,Vol.58,No.552,pp.87-92.
- [6]Chiba, M. et al.,1988,"Dynamic stability of liquid –filled cylindrical shells under periodic shearing forces", Proc. of ASME PVP Conf.,Vol.4,pp.241-253.
- [7]Natsiavas, S. and Babcock,C.D.,1987,"Buckling of the top of a fluid filled tank during base excitation", Proc. of ASME PVP Conf.,Vol.127,pp.333-338.
- [8]Hara, F. and Suzuki,R.,1999,"Simulation analysis of fluid-coupled parametric vibration in a cylindrical shell" (in Japanese), Proc. of JSME Conf.,No.99-1,pp.445-446.
- [9]Shih, C.F. and Babcock,C.D.,1980,"Scale model buckling tests of fluid filled tank under harmonic excitation", Proc. of Century 2 ASME PVP Conf.,80-C2,Vol.66,pp.1-7.
- [10]Matsuura,S. et al.,1995,"Studies on the seismic buckling design guideline of FBR main vessels(5<sup>th</sup> report, applicability of the numerical buckling analysis method)"(in Japanese), Trans. of JSME, Vol.61,No.585,pp.138-146..
- [11]The High Pressure Gas Safety Institute of Japan,1984,"Report on shaking table test of steel cylindrical storage tank"(in Japanese),J. of the High Pressure Gas Safety Ins. of Japan, ,Vol.21,No.9,pp.14-31.
- [12]Sato, Y. et al.,1999,"Nonlinear behavior tests of a LNG tank under severe seismic loading" (in Japanese),Techno Mrine,Vol.836,pp.23-29.