Consideration of a Method to Estimate Seismic Response Reduction Coefficient for Liquid Storage Tanks

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15 WCEE
LISBOA 2012

SUMMARY:
In seismic design of cylindrical liquid storage tanks, it is possible to include an absorption effect of seismic input energy due to elastic-plastic buckling deformation. A few Japanese seismic design guidelines have proposed a seismic response reduction coefficient which decreases seismic load based on the effect to absorb seismic energy by plastic deformation. In this study, the practicable and definite analytical method and procedures to estimate the seismic response reduction coefficient were clarified, in which the coefficient was calculated on the basis of the energy balance method and static elastic-plastic finite element analysis. The analysis conditions to obtain the accurate skeleton curve (load-displacement curve) of liquid storage tanks exactly with consideration of dynamic fluid pressure and initial imperfection were proposed. The analytical method to calculate the reduction coefficient was evaluated to be advantage for a back-check to estimate seismic safety margin.

Keywords: Liquid Storage Tank, Seismic Response Reduction Coefficient, Energy Balance Method

1. INTRODUCTION

Seismic resistance of large cylindrical liquid storage tanks which are installed in power and industrial facilities is generally evaluated by using the criterion of buckling (Maekawa, 2012). However, during earthquakes the tanks are not cracked on their sides and the stored liquid does not leak out as soon as the buckling occurs. The function of storing liquid is known to remain in the tanks after buckling because buckling such as the elephant foot bulge seen in large tanks develops gradually and the potential to absorb seismic energy by plastic deformation is relatively large. This indicates the seismic design margin between occurrence of buckling and loss of function is relatively large. In liquid storage tanks with buckling deformation, the effect to absorb the seismic energy gives the seismic response damping effect. Due to this effect, the response of the liquid storage tanks after buckling decreases in comparison to the linear response estimated using the initial damping ratio. The seismic response reduction coefficient represents the ratio of the decreasing linear response for input seismic loads.

In the Japanese regulatory guide for reviewing seismic design of nuclear power reactor facilities (Nuclear Safety Commission of Japan, 2006), the seismic resistance against design basis earthquake ground motion Ss is evaluated from the viewpoint of loss of function and a limited plasticizing for structure and equipment is allowed. Thus, in the Japanese technical code for aseismic design of nuclear power plants, JEAC4601-2008 which shows practical design methods, seismic design for buckling criteria using the response reduction coefficient has been proposed for the design basis seismic motion Ss (Japan Electric Association, 2008). The response reduction coefficient is defined to decrease the working load attributed to horizontal seismic motion. Though the reduction coefficient was determined to be 0.5 in JEAC4601-2008, the response reduction values calculated for individual plants can be used. However, the practicable and definite analytical methods and procedures are not designated in JEAC4601-2008.

In this study, methods to calculate the response reduction coefficient using the energy balance method were focused on and a practicable method to apply to liquid storage tanks was examined. The analysis conditions in the case of using static elastic-plastic finite element analysis were investigated because the static elastic-plastic finite element analysis is useful to conduct buckling analysis but it is difficult to obtain the skeleton curve (load-displacement curve) of liquid storage tanks considering dynamic fluid pressure and initial imperfection. Furthermore, the advantage of the analytical method proposed to calculate the response reduction coefficient was evaluated.

2. BUCKLING DESIGN FOR SEISMIC LOADS USING THE RESPONSE REDUCTION COEFFICIENT

The findings obtained from previous results of dynamic buckling tests using large test tanks (Ito et al., 2003; Iijima et al., 2009) have been summarized as follows.

- The tanks had a certain degree of plastic deformation capacity up to their ultimate state after their buckling occurred. Here, the ultimate state defines loss of function and leakage of stored liquid.
- Loading capacity was not lost rapidly, but decreased gradually after buckling.
- Strain at the out-of-plane deformation caused by the elephant foot bulge developed uniformly as the displacement on the tank top increased and large strain at local positions did not occur suddenly. Additionally, fatigue failure did not occur. These results demonstrated the strain at the out-of-plane deformation caused by the elephant foot bulge could be defined as the index of the allowable limit state.

On the basis of experimental results, a design coefficient of seismic response reduction for cylindrical liquid storage tanks *Ds* was proposed in JEAC4601-2008. The coefficient allows for seismic energy absorption by plastic deformation after buckling when the seismic safety of the tanks was assessed for the design basis seismic motion Ss and it is determined conservatively as 0.5. JEAC4601-2008 designated 0.5 as the standard value and also permitted reasonable *Ds* for individual plants calculated by analytical methods. A method using the magnitude ratio of input seismic motion, which is based on the original definition of the *Ds*, and the energy balance method, which is based on simple formula derived theoretically, were presented for the analytical methods to estimate the *Ds*.

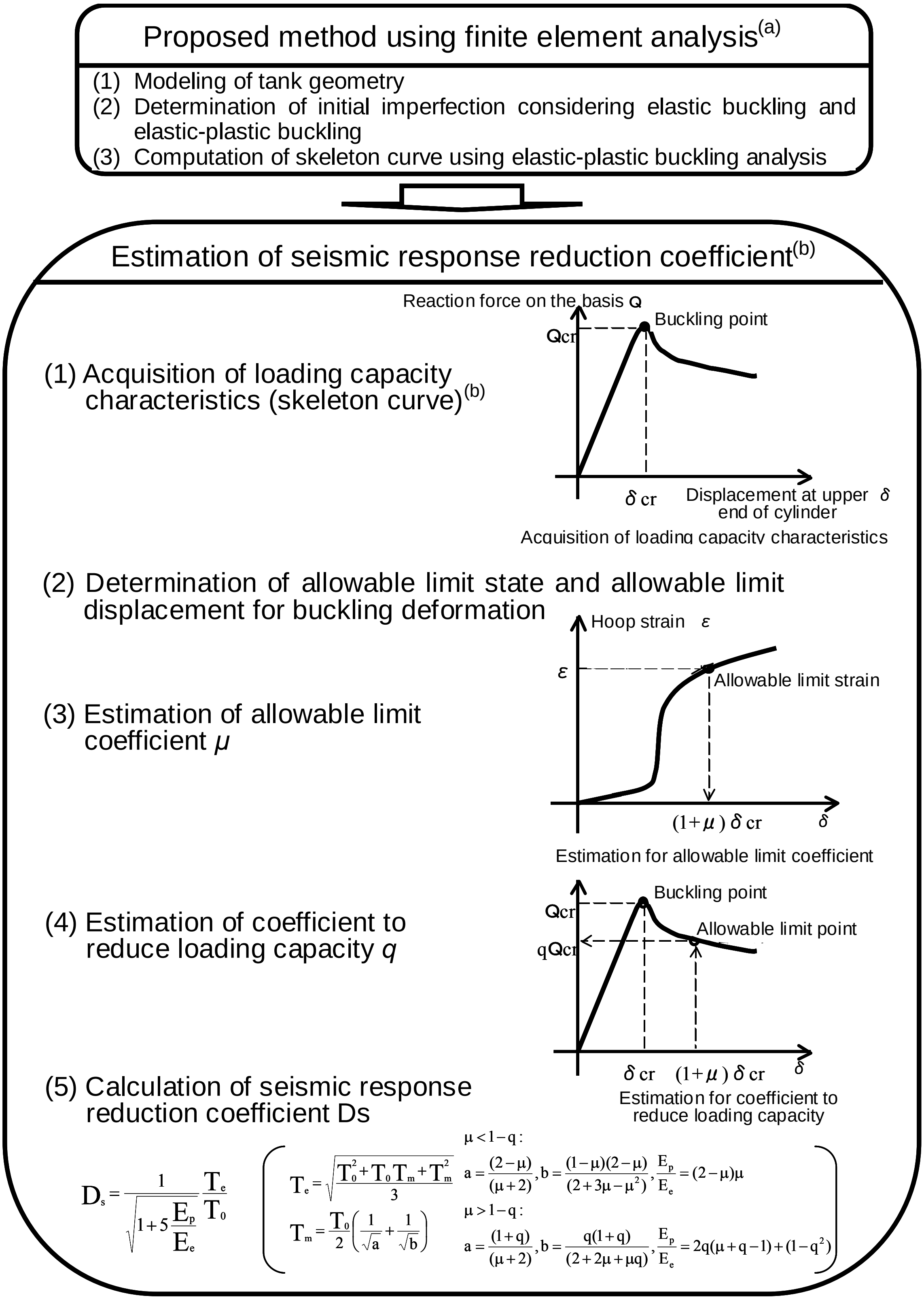
2.1. Method using the magnitude ratio of input seismic motion

The *Ds* in this method is estimated using the magnitude ratio of input seismic motion that causes buckling and results in the ultimate state. The definition is as follows.
Ds = (magnitude of input seismic motion to generate buckling displacement δcr) / (magnitude of input seismic motion to generate allowable limit displacement $(1+\mu)\delta cr$)
where μ is the allowable limit coefficient. The magnitude of input seismic motion can be calculated using nonlinear seismic response analysis and dynamic buckling analysis (Maekawa, 2012).

2.2. Energy balance method

The amount of response reduction in this method is estimated assuming the balance of energy input to tanks due to an earthquake and energy absorbed by plastic deformation is equal. The calculation process for *Ds* based on this method is shown in the lower part of Fig.2.1. The equation and terms used for estimating *Ds* are shown in the figure, where, T_e is effective period (Akiyama, 1997), T_o is vibration period in the elastic system, T_m is the maximum instantaneous vibration period for the elastic system (Akiyama, 1997), E_e is absorption energy by elastic deformation, E_p is absorption energy by plastic energy, μ is allowable limit coefficient, and q is a coefficient to reduce loading capacity.

JEAC4601-2008 includes only approaches to calculate the seismic response reduction coefficient (lower part of Fig.2.1). However, how an accurate skeleton curve of the tanks is obtained depends on users. In this study, using the finite element analysis (FEA) to obtain the skeleton curve was investigated and a practicable and definite method was proposed (upper part of Fig.2.1). When buckling analysis is done using FEA, how the initial imperfection and the liquid pressure load are set have significant influence.



(a) This study proposes the practicable method for estimating skeleton curve accurately without experiments using of actual tanks

(b) JEAC4601-2008 only requires accurate skeleton curve and does not propose the estimation methods.

Figure 2.1. Estimation of seismic response reduction coefficient using FEA based on energy balance method

3. BUCKLING ANALYSIS

In this study, the method to calculate the seismic response reduction coefficient using the energy balance was focused on and the analysis conditions were investigated when the skeleton curve, which was needed to determine the response reduction coefficient, was computed by static elastic-plastic buckling analysis.

Maekawa et al. (2007; 2011) determined that the buckling strength calculated by static elastic-plastic buckling analysis using the finite element method could agree well with the experimental value as long as a simple distribution shape of dynamic fluid pressure was assumed; their conclusion was based on the experimental distribution obtained by vibration tests of tanks. The buckling analysis method was used to obtain the skeleton curve of the tanks and the seismic response reduction coefficient was calculated.

In the case of buckling analysis for cylindrical tanks with liquid inside, the hydrostatic pressure and dynamic fluid pressure must be considered and the geometry initial imperfection must also be considered. JEAC4601-2008 did not provide definite analysis conditions including these factors. Thus, it is necessary to examine and definite the conditions. In this study, for the typical geometry and scale of cylindrical liquid storage tanks installed in nuclear power plants within the geometry range set in JEAC4601-2008 (Table 3.1), the static elastic-plastic buckling analysis using the finite element method was used for examination of practical analysis conditions. The ABAQUS FEA code was used for all buckling analyses in this study.

The analysis model was made using finite elements on the basis of the specifications of liquid storage tanks with uniform wall-thickness in the height direction. As shown in Fig.3.1, this was a symmetric half model with symmetry conditions on the plane of symmetry and the base of the tanks was fixed rigidly. The tank side and roof were modeled using shell elements (S8R5) and rigid elements, respectively. The rigid elements were chosen because the tops of the tanks were generally sufficiently rigid due to reinforcing beams. The material used was carbon steel and the relationship between stress and strain was assumed as an elastic perfectly plastic model.

The seismic response reduction coefficient was calculated using the skeleton curve. The geometry and amount of initial imperfection are important for elastic-plastic buckling analysis to estimate the skeleton curve because these factors affect the load and geometry of buckling remarkably. In this study, the initial imperfection geometry was determined from the buckling shape obtained by elastic buckling eigenvalue analysis and elastic-plastic buckling analysis using a perfect circle. The perfect circle geometry was used as the initial state to conduct the buckling analysis regarding geometry and dimension parameters. The primary buckling mode in the elastic buckling eigenvalue analysis and the deformation shape at the buckling point in the elastic-plastic buckling analysis were chosen as the initial imperfection geometry. The maximum amount of initial imperfection was assumed as half the thickness of the tank wall, which was sufficiently conservative. The elastic-plastic bucking analysis was, then, conducted using the model with these imperfection parameters for obtaining the skeleton curves of liquid storage tanks. The analysis conditions to determine the initial imperfection condition are summarized in Table 3.2.

Furthermore, the influence of the assumed distribution shape of dynamic fluid pressure on the buckling analysis results was investigated. The simple distribution shape has been modeled by Veletos and Yang (1976) and Fischer and Rammerstorfer (1982). The distribution curve including the dynamic fluid pressure generated by the sloshing mode, rigid-body motion mode and shell vibration mode (bulging mode) was proposed. In this study, the approach proposed by Fischer and Rammerstorfer (1982) was used. The cosine θ curve was used for hoop distribution of dynamic fluid pressure (Maekawa et al., 2007). The relationship between loading direction of dynamic fluid pressure and the relative angle is shown in Fig.3.1. The buckling analysis with the conditions shown in Table 3.3 was used to compute the skeleton curve, that is, the relationship between load and displacement.

Table 3.1. Specifications of analysis model

Material	Carbon steel (SS400 in JIS[(a)])
Young's modulus (MPa)	199,800
Yield stress (MPa)	29
Inner diameter of tank (mm)	3,750
Height (mm)	10,100
Wall thickness (mm)	6
Density of fluid (N·mm^3)	9.8×10^{-6}
Liquid level (mm)	9,400
Weight of snow per area (N/m^2)	3,000

(a) Japanese Industrial Standards

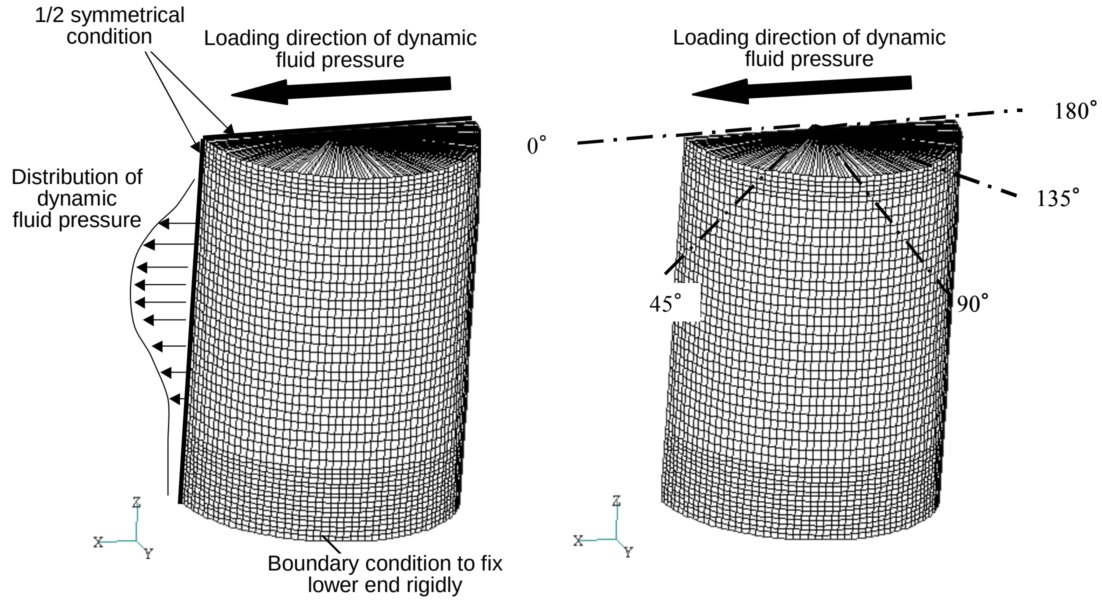
Table 3.2. Analysis conditions for determining initial imperfection condition

Case	Analysis method	Initial imperfection geometry	Loading condition of dynamic fluid pressure
FSI-1	Elastic buckling eigenvalue analysis	None	Loading on the half circumference without negative pressure
FMI-1	Elastic-plastic buckling analysis		Loading on the full circumference without negative pressure
FMI-2			Loading on the half circumference without negative pressure

Table 3.3. Elastic-plastic buckling analysis cases for skeleton curve

Case	Analysis case for initial imperfection	Loading condition of dynamic fluid pressure
FS-1	FSI-1	Loading on half circumference without negative pressure
FM-1	FMI-1	Loading on full circumference without negative pressure
FM-2	FMI-2	Loading on half circumference without negative pressure

Here, the condition of loading on the full circumference without negative pressure means that the negative pressure is forced to be zero at any areas where the inner pressure of the tanks is negative during load increment analysis. It is difficult to assume that the absolute inner pressure of tanks is negative when subjected to seismic motion, thus the way to reproduce an approximation of actual dynamic fluid pressure distribution should be considered. On the other hand, the condition of loading on the half circumference without negative pressure means that valid pressure distribution is set on only one side of the tanks (0° to 90°).



(a)Boundary condition of analysis model (b)Loading direction of dynamic fluid pressure

Figure 3.1. Analysis model

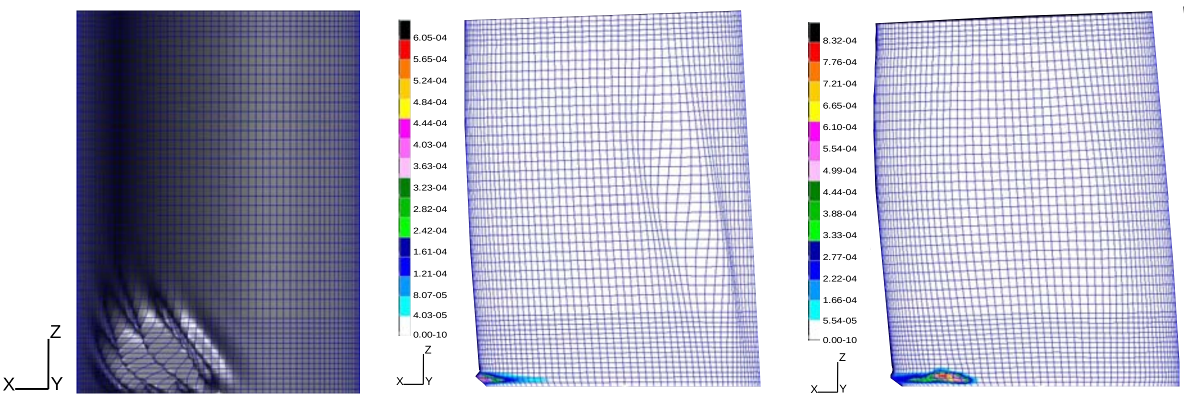
4. ANALYSIS RESULTS AND DISCUSSION

The analysis results for the initial imperfection condition are in Fig.4.1. Fig.4.1(a) shows the result by elastic buckling eigenvalue analysis. The shear buckling mode occurred and the base of the cylinder deformed. Figs.4.1(b) and 4.1(c) show the results of elastic-plastic buckling analysis. These figures show the deformation shape and equivalent plastic strain distribution at the maximum loading point in the calculated load-displacement curve. The typical bending buckling mode occurred on the base of the tanks regardless of loading condition. Also, on the condition of loading on the full circumference without negative pressure, some wrinkles were generated in the side from 90° to 180°.

The skeleton curves were computed by the elastic-plastic buckling analysis for the seismic response reduction coefficient. The geometry and amount of the initial imperfection were set in the tank model and the initial loading balance condition of the model was calculated using dead weight and weight of snow. After that, the buckling analysis was conducted by increment analysis using load due to the dynamic fluid pressure as well as inertial force of the cylinder and snow. Residual out-of-plane deformation magnitude in the liquid storage tanks caused by buckling represents horizontal displacement at the upper end of the tank cylinder and the allowable limit coefficient μ which is the index of the allowable limit state. The residual out-of-plane deformation magnitude corresponding to the upper limit of the allowable horizontal displacement is 1.0% of the cylinder radius and nearly equal to the hoop strain 1.0%. If the hoop strain is up to 1.0%, there are hardly any influences from local deformation on the allowable limit state and there is sufficient fatigue strength. In this study, therefore, the allowable limit state including an appropriate margin was defined as 1.0% of hoop strain.

Fig.4.2 shows the relationship between load and displacement in the analysis case FS-1 along with the equivalent strain history. The history indicated that the calculated buckling mode was elastic-plastic buckling superposing bending buckling on shear buckling. The hoop strain in the vicinity of the allowable limit state (δcr=19.9mm and Qcr=3828kN) is shown in Fig.4.3. Fig.4.4 shows the hoop strain history in the element used for determination of the allowable limit state. In the allowable limit state with 1.0% hoop strain, the displacement at the upper end of cylinder was 19.9mm. Based on the procedure shown in Fig.2.1, μ=1.21 and q=0.73 were calculated.

In the analysis case FM-1, the solution did not converge because buckling of the cylindrical shell under external pressure occurred.



(a)Buckling eigenvalue (FSI-1)

(b)Equivalent plastic strain (FMI-1)

(c)Equivalent plastic strain (FMI-2)

Figure 4.1. Results of elastic buckling analysis and elastic-plastic buckling analysis

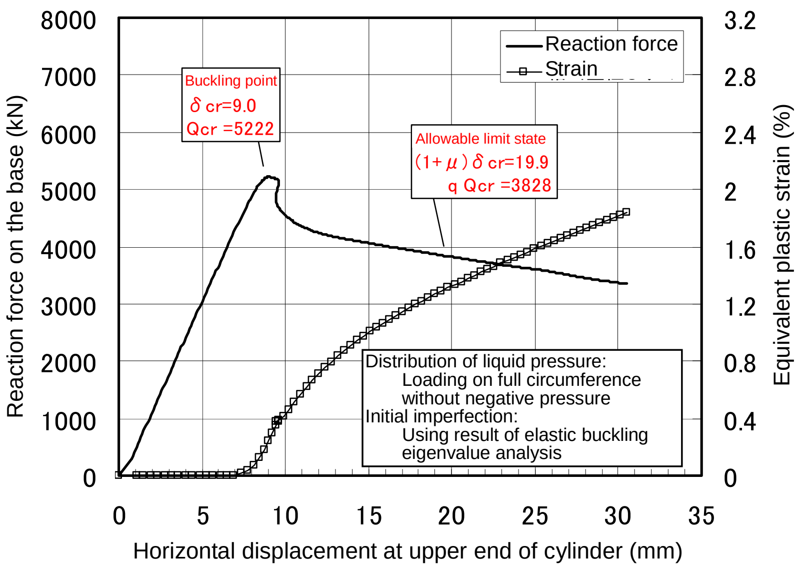


Figure 4.2. Load-displacement curve (FS-1)

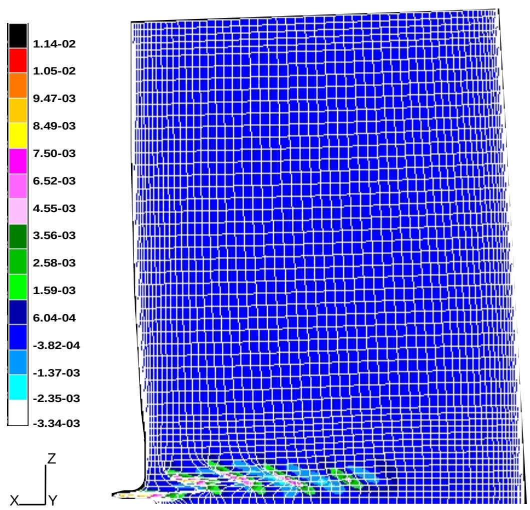


Figure 4.3. Hoop strain (FS-1)

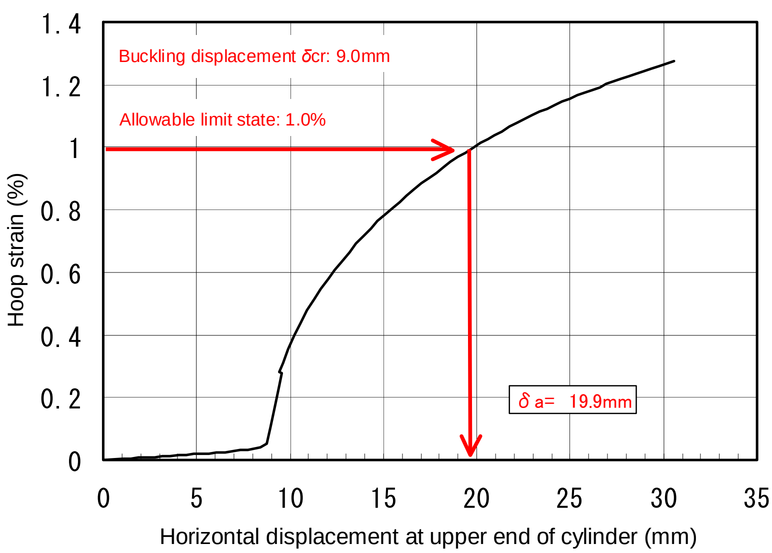


Figure 4.4. Hoop strain history at buckling position (FS-1)

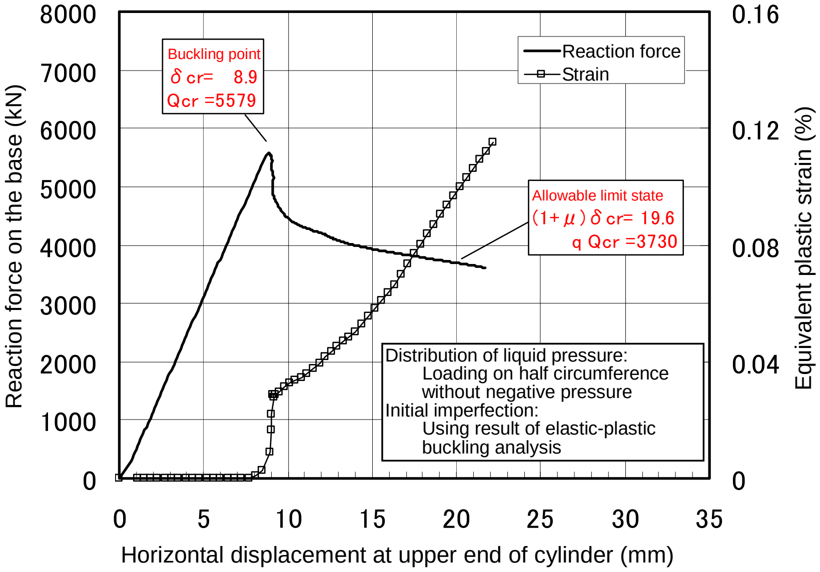


Figure 4.5. Load-displacement curve (FM-2)

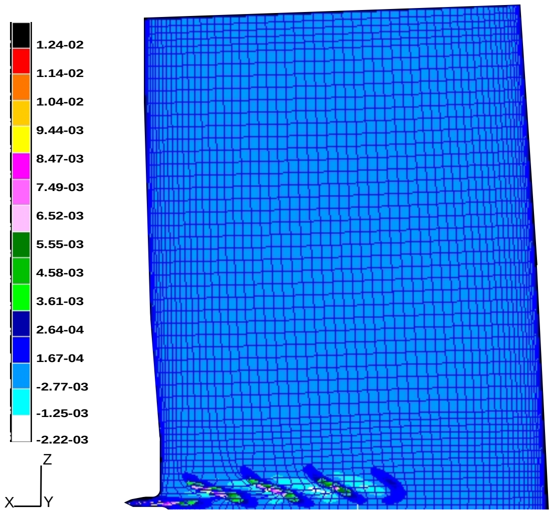


Figure 4.6. Hoop strain (FM-2)

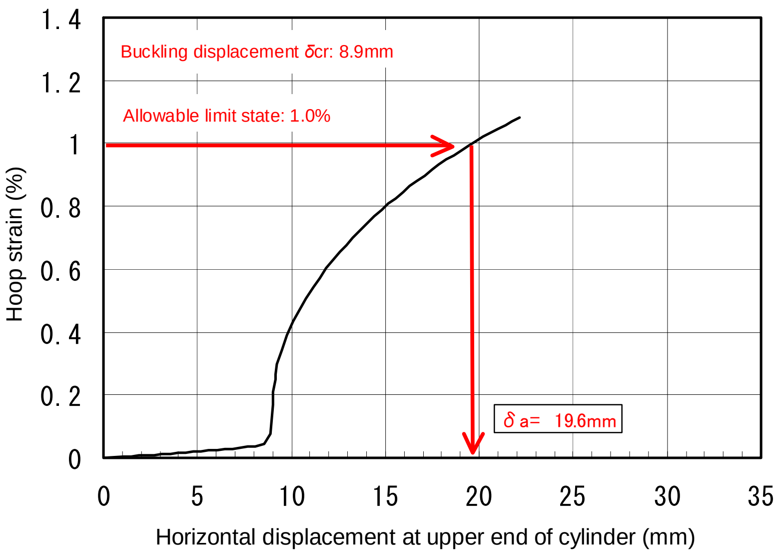


Figure 4.7. Hoop strain history at buckling position (FM-2)

The load-displacement curve in the analysis case FM-2 is shown in Fig.4.5. The hoop strain in the vicinity of the allowable limit state (δcr=19.6mm and Qcr=3730kN) is shown in Fig.4.6. The elastic-plastic buckling superimposing bending buckling on shear buckling occurred the same as in the case FS-1 although the initial imperfection geometries were different. Fig.4.7 shows the hoop strain history in the element used for determination of the allowable limit state. The 1.0% hoop strain corresponded to a 19.6mm displacement at the upper end and μ=1.20 and q=0.67 were obtained.

These results demonstrated the following analysis condition was useful for the practicable buckling analysis; the initial imperfection geometry obtained beforehand by buckling analysis using the perfect circle should be assumed and the dynamic fluid pressure should be loaded on the half circumference without a negative pressure.

5. SEISMIC RESPONSE REDUCTION COEFFICIENT CALCULATED USING THE PROPOSED METHOD

Finally, the seismic response reduction coefficient was calculated through the procedure shown in Fig.2.1. The results are summarized in Table 5.1 and the *Ds* values are shown in *Ds*-μ curves in Fig.5.1. This result showed that the *Ds* value obtained by the static elastic-plastic buckling analysis might be approximately 10% lower than the standard value in JEAC4601-2008 (*Ds*=0.5), indicating a more profitable value. This proposed method is a useful way as a back-check to evaluate the seismic safety margin of liquid storage tanks though it may not be reasonable to calculate individual values by this method in the seismic design.

Table 5.1. Seismic response reduction coefficient and related parameters

Case	Buckling point		Allowable limit point		Allwable limit coefficient μ	Coefficient to reduce loading capacity q	Seismic response reduction coefficient *Ds*
	Qcr (kN)	δcr (mm)	Qcr (kN)	$(1+\mu)\delta cr$ (mm)			
FS-1	5222	9.0	3828	19.9	1.21	0.73	0.43
FM-2	5579	8.9	3730	19.9	1.20	0.67	0.46

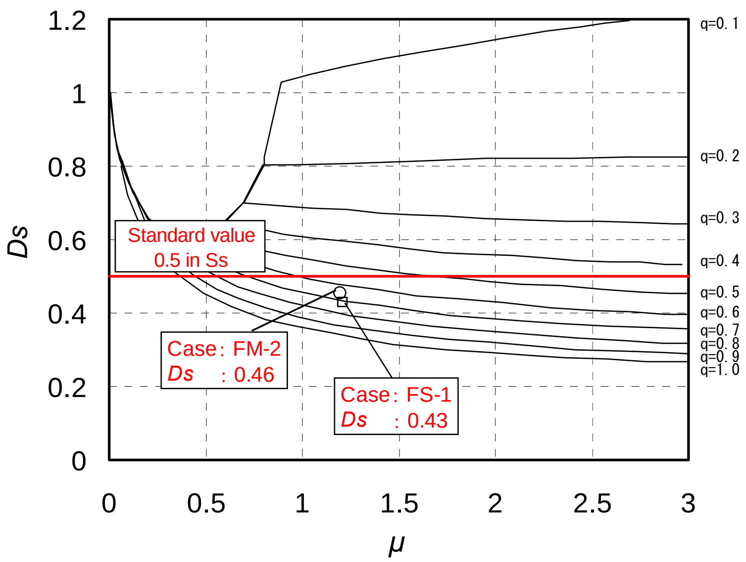


Figure 5.1. *Ds*-μ curve

6. CONCLUSIONS

(1) For seismic buckling design of cylindrical liquid storage tanks installed in Japanese nuclear power plants, the seismic response reduction coefficient has been proposed in the Technical Code JEAC4601-2008. In this study, the practicable and definite analytical method and procedure to calculate the coefficient was clarified. The analysis conditions to obtain the accurate skeleton curve exactly by FEA were also revealed when the energy balance method was used to calculate the coefficient.
(2) The skeleton curve was obtained exactly as follows: the elastic buckling eigenvalue analysis and elastic-plastic buckling analysis were conducted under the loading dynamic fluid pressure distribution on the half circumference without negative pressure to compute the initial imperfection geometry. And then, the static elastic-plastic buckling analysis including the imperfection geometry was done under the loading dynamic fluid pressure distribution on the half circumference without negative pressure.
(3) The seismic response reduction coefficient could be set lower than the standard value proposed in JEAC4601-2008 and the present proposed analytical method should be useful as a back-check to evaluate the seismic safety margin of tanks.

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