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Recent Advances in Seismic Response Analysis of Cylindrical Liquid Storage Tanks

Akira Maekawa
Institute of Nuclear Safety System, Inc.
Japan

1. Introduction

Japan is in a seismically active area and experiences many damaging earthquakes with loss of life. In 1995, the Hyogoken-Nanbu earthquake caused major destruction in Kobe City and in 2011 the Great Eastern Japan earthquake and tsunami caused major destruction in the Pacific coast areas of northeastern Japan. Additionally, recent relatively less destructive earthquakes include the 2003 Tokachi-Oki earthquake, the 2004 Niigataken Chuetsu earthquake, the 2005 Miyagiken-Oki earthquake, the 2007 Noto-Hanto earthquake, and the 2007 Niigataken Chuetsu-Oki earthquake.

In particular, the Great Eastern Japan, Noto-Hanto, Miyagiken-Oki, and Niigataken-Chuetsu-Oki earthquakes occurred near nuclear power facilities and have been accompanied by enhanced public concern for seismic safety of nuclear plants. Within the Japanese national government, the Nuclear Safety Commission revised the *Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities* (Nuclear Safety Commission of Japan, 2006) in 2006. This revised *Regulatory Guide* required seismic safety design of buildings, structures and equipment for larger seismic motions. In addition, seismic probabilistic safety assessment (seismic PSA) (American Nuclear Society, 2007; Atomic Energy Society of Japan, 2007) was urged, for which accurate evaluation techniques for seismic response of equipment installed in the nuclear power plants were needed.

Large cylindrical liquid storage tanks in nuclear power plants are classified as equipment requiring high seismic safety because many are containers storing cooling water used in normal plant operation and in accidents. Their seismic evaluation is done on the basis of the *Technical Codes for Aseismic Design of Nuclear Power Plants* (Japan Electric Association [JEA], 2008) published by the Japan Electric Association. The seismic evaluation methods used in the conventional seismic design of the tanks (Kanagawa Prefecture, 2002; High Pressure Gas Safety Institute of Japan [KHK], 2003; Architectural Institute of Japan [AIJ], 2010) such as the *Technical Codes* examine the bending vibration mode (beam-type vibration) which mainly affects the seismic resistance of the tanks, but they do not consider high order vibration modes (oval-type vibration) which are excited in the tank wall by large vibrations and cause oscillation patterns that look like petals of a flower. Therefore, it is necessary to reveal the influence of oval-type vibration on vibration characteristics and seismic safety and to consider the vibration in the seismic design of the tanks (Japan Society of Civil Engineers, 1989). However, research on oval-type vibration has only been of academic interest, including reports on fluid-structure interaction which causes oval-type vibration (Japan Society of Mechanical Engineers, 2003) and nonlinear behavior of oval-type vibration (Chiba, 1993). Though analysis techniques such as finite element methods are available as seismic evaluation methods at present, numerical seismic analysis of the tanks considering oval-type vibration has not been established because advanced techniques such as fluid-structure interaction analysis and nonlinear dynamic structure analysis are needed to simulate the oval-type vibration behavior.

In addition, capacity to resist buckling is an important evaluation item in seismic deign of cylindrical liquid storage tanks. Buckling is a dangerous mode for tanks which drastically lowers their structural strength (proof force) and collapses their geometries. In the ultimate buckled state and post-buckling, the cylindrical liquid storage tanks are deformed largely and display nonlinear inelastic behavior. Therefore, it is desirable to take into account the nonlinear inelastic dynamic behavior when evaluating seismic safety of the tanks. The conventional seismic design of tanks (Kanagawa Prefecture, 2002; KHK, 2003; JEA, 2008; AIJ, 2010) uses evaluation equations for static buckling derived from static buckling tests and the assumption of a linear response. However, the evaluation equations have not been validated sufficiently from the viewpoint of the dynamic liquid pressure effect in tanks subjected to seismic motions. Though a few dynamic experiments and development of numerical methods for buckling of cylindrical liquid storage tanks were done in the past, the developed numerical methods could simulate the experimental results only qualitatively (Fujita et al., 1992; Toyoda et al., 1997).

As described above, the conventional seismic design assumes linear behavior of the tanks and does not include nonlinear behavior in post-buckling. However, it is necessary to develop accurate seismic response analysis methods for the cylindrical liquid storage tanks to ensure seismic safety and conduct accurate seismic PSA for mega earthquakes. Therefore, an accurate dynamic analysis method to evaluate dynamic nonlinear behavior of the cylindrical liquid storage tanks subjected to seismic motions was proposed and validated by the dynamic experiment in this chapter. The research was done for the liquid storage tanks installed in nuclear power plants such as refueling water tanks and condensate water tanks. In this chapter, previous studies are overviewed and then sequential research findings on the dynamic analysis method are summarized.

First, the seismic damage modes of the cylindrical liquid storage tanks are explained briefly. Especially buckling modes caused by earthquakes are introduced. Secondly, the vibration behavior of the tanks is explained. Thirdly, previous studies are overviewed with regard to vibration characteristics and seismic evaluations. Special focus is given to the seismic response analysis and dynamic buckling evaluation. Fourthly, research studies concerned with oval-type vibration are summarized. Finally, the author's study regarding dynamic nonlinear analysis method for seismic response of the cylindrical liquid storage tanks is described and the method is shown to be suitable for actual tanks based on comparison with experimental results.

2. Seismic damage modes of cylindrical liquid storage tanks

Many typical examples of seismic damage modes of cylindrical storage tanks have been reported and many seismic damage analyses (see for example, (Fujii et al., 1969; Rahnama &

Morroe, 2000; Suzuki, 2008)) have been conducted. The damage modes of the tanks from the above analysis results are summarized as follows:

1. Buckling in the side walls
2. Failure of the tank roofs and their junctions
3. Sliding and lifting
4. Local fracture on the bases of the tanks and uneven settlement
5. Failure of anchor bolts
6. Cracking of annular parts of the base plate

The buckling modes of the side walls of tanks include shear buckling and bending buckling. The bending buckling includes diamond buckling and elephant foot bulges. These buckling modes are associated with geometry parameters of the tanks such as height to radius ratio and radius to thickness ratio. Figure 1 shows the relationship between the buckling modes and geometry parameters. Shear buckling occurs for small ratios of height to radius and bending buckling predominantly occurs for large ratios. Shear buckling is caused by shear force and brings about many large diagonal wrinkles in the center of a tank side wall. A typical example of diamond buckling is shown in Fig. 2. Diamond buckling is one of the bending buckling modes caused by the bending moment and it is generated on the base of a tank. When the buckling occurs, the cross section at the buckling region bends inward and has many wrinkles. Because the deformation is drastic, the structural strength (proof force) of the tanks decreases suddenly. Diamond buckling became widely know after it occurred in many wine storage tanks in the 1980 Greenville-Mt. Diablo earthquake. The elephant foot bulge is another bending buckling mode. This buckling mode was widely seen in the 1964 Alaska mega earthquake, the 1971 San Fernando earthquake and the 1994 Northridge earthquake and can cause spill incidents of liquid in the tanks through crack penetration. A typical example of the elephant foot bulge is shown in Fig. 3 (Ito et al., 2003). In the elephant foot bulge, the buckling cross section expands outward in a ring and the structural strength (proof force) decreases relatively gently through a gradual increase of the expansion. The occurrence condition of diamond buckling and the elephant foot bulge depends on the circumferential stress due to the internal pressure in the tanks, that is, hoop stress (Akiyama et al., 1989). The former occurs when the hoop stress is smaller and the latter occurs when the hoop stress is larger. In the 1995 Hyogoken-Nanbu earthquake, many observations of diamond buckling and elephant foot bulges were made in cylindrical liquid storage tanks.

The failure of tank roofs and their junctions is mainly caused by sloshing. This occurred in the 1964 earthquakes in Niigata and Alaska. More recently, the roofs and junctions of some petroleum tanks failed in the Kocaeli earthquake in Turkey and in the Chi-Chi earthquake in Taiwan, both in 1999. In Japan, a few petroleum tanks also failed in the 2003 Tokachi-Oki earthquake. In all three of these earthquakes, the floating roofs were damaged and fires broke out.

The sliding of tanks and lifting of base plates were observed in the 1964 Alaska earthquake. Local fracture on the bases of tanks, uneven settlement and failure of anchor bolts occurred in the 1995 Hyogoken-Nanbu earthquake. In the 1978 Miyagiken-Oki earthquake, cracking of annular parts of base plates occurred in petroleum tanks and stored petroleum leaked out.

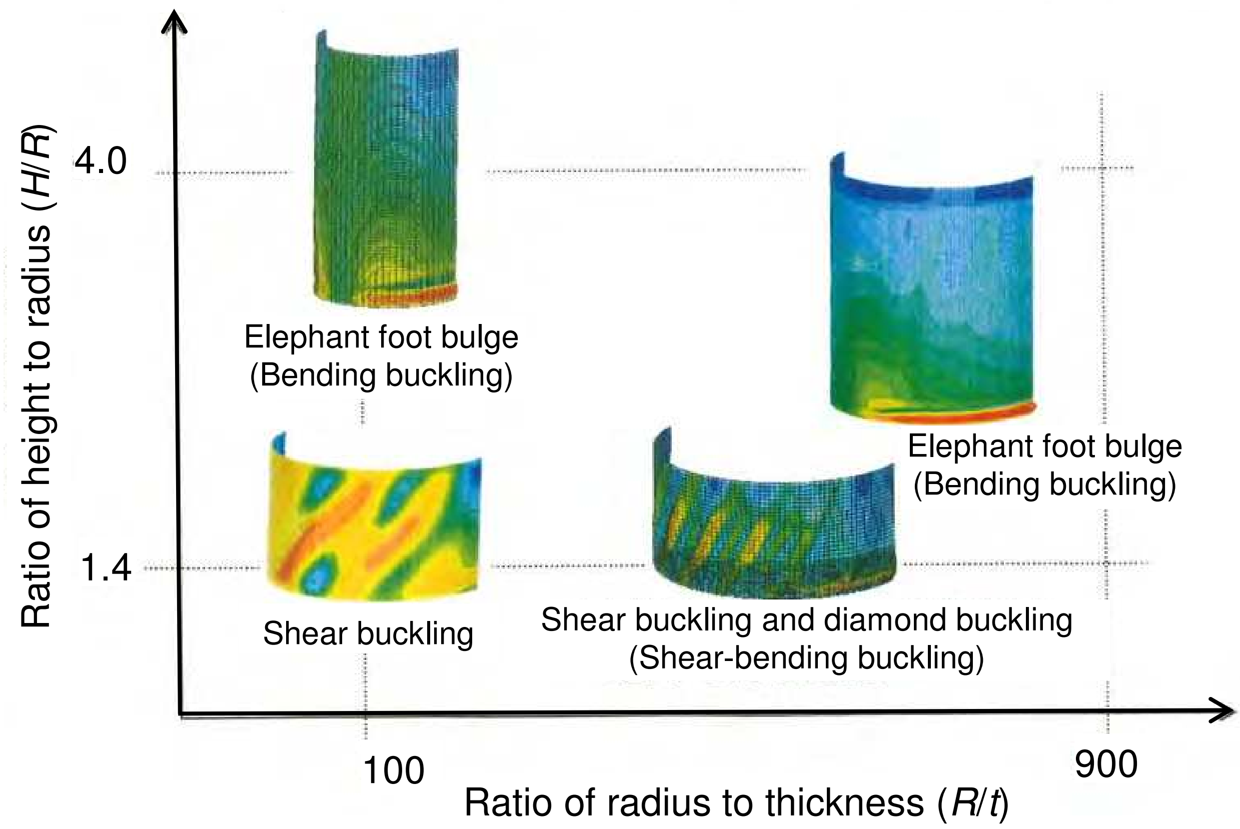

Fig. 1. Buckling modes of cylindrical tanks and geometry parameters.

Fig. 2. Typical mode of diamond buckling.

Fig. 3. Typical mode of elephant foot bulge. (Ito et al., 2003)

3. Classification of vibration behaviour in cylindrical liquid storage tanks

The vibration modes of the cylindrical liquid storage tanks are classified roughly into sloshing and bulging. The sloshing represents vibration of the free liquid surface and the bulging represents vibration of the tank structure. In large cylindrical tanks, shell vibration occurs because the side wall is relatively thinner compared to the radius length, which is regarded as a cylindrical shell. The modes of bulging including shell vibration are generally distinguished using the axial half wave number *m* and circumferential wave number *n*. The modes with $m \geq 1$ and $n = 1$ are the beam-type vibration and the modes with $m \geq 1$ and $n \geq 2$ are the oval-type vibration. Typical examples of the vibration modes are shown in Fig. 4 (Fujita & Saito, 2003). The figure shows the vibration modes of cylindrical tanks which are free on the top and rigid on the bottom; it is easy for readers to understand these modes of oval-type vibration. However, actual tanks have the vibration condition which is rigid on the top because of their fixed roofs.

In general linear analysis, vibration modes with $n \geq 2$ are not excited when a perfectly axisymmetric cylindrical shell such as a tank is vibrating. However, the oval-type vibration actually occurred in the vibration experiment using reduced models of cylindrical tanks (Kana, 1979; Fujita et al., 1984; Maekawa et al., 2010). Additionally it is not possible to say that the influence of oval-type vibration on seismic load of the tanks can be ignored (Clough et al., 1979).

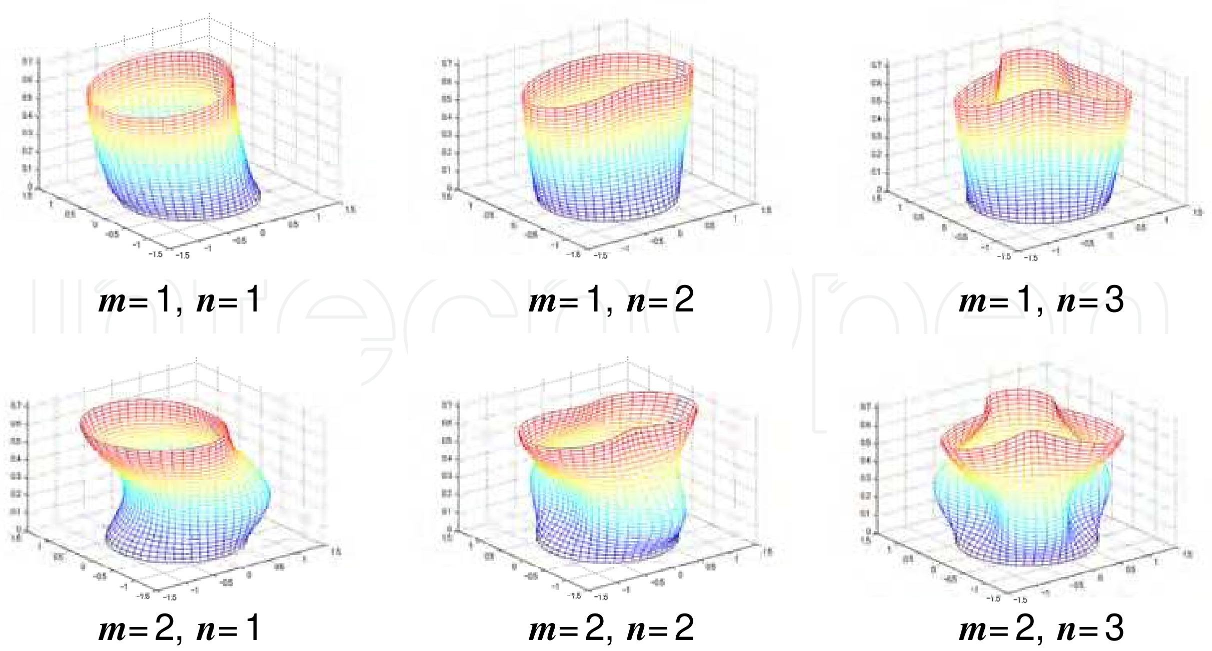

Fig. 4. Typical vibration modes of tanks: *m*, axial half wave number; *n*, circumferential wave number. (Fujita & Saito, 2003)

4. Overview of previous studies on vibration characteristics and seismic resistance of cylindrical liquid storage tanks

In cylindrical liquid storage tanks, the liquid and the structure compose the coupled vibration system between fluid and structure and show complex vibration characteristics. Jacobsen (1949) and Werner and Sandquist (1949) were the first to study the influence of the contained liquid on dynamic behavior of cylindrical tanks. Their studies focused on only hydrodynamic behavior of the contained liquid assuming rigid containers. In the 1950s, the National Aeronautics and Space Administration (NASA) actively investigated the vibration behavior of rocket fuel tanks and then developed many empirical and analytical methods of sloshing and coupled vibration between fluid and structure (Abramson, 1966). The studies on sloshing developed as a specific field and their overview was done by Ibrahim et al. (2001). As for seismic evaluation of cylindrical liquid storage tanks, Housner (1957) proposed seismic response analysis method in 1957 which became known as Housner's theory and it has been adopted in some seismic design guidelines for cylindrical tanks. In this theory, the dynamic liquid pressure is calculated based on two separate pressures due to the horizontal inertia force of liquid and sloshing of the free liquid surface when cylindrical liquid storage tanks are subjected to seismic motions. However, tanks are assumed to be rigid bodies. Since Housner's proposal, many researchers have studied seismic evaluation methods. Veletsos and Yang (1976) and Fischer and Rammerstorfer (1982) proposed seismic response analysis methods of cylindrical liquid storage tanks assuming flexible structures for them by simplifying the vibration mode shape of the tanks. Moreover, Fujita (1981) also proposed seismic response analysis method in which tank structure was modeled by finite elements, the liquid pressure in tanks was expressed using velocity potential theory and series solution and coupled vibration between tank structure and contained liquid was considered. Ma et al. (1982) proposed an analysis method in which both tank structure and contained liquid were modeled by finite elements. The studies mentioned above focused on development of vibration response analysis methods of tanks subjected to seismic motions. Rammerstorfer et al. (1990) and Shimizu (1990) summarized research prior to 1990 on seismic evaluation methods of cylindrical liquid storage tanks. In their reviews, a few topics including bending vibration (beam-type vibration) and sloshing were covered, but not oval-type vibration. At present the behavior of oval-type vibration including the influence on seismic resistance of tanks remains unclarified.

Since the 1990s the issues of seismic study of cylindrical liquid storage tanks have shifted to dynamic buckling behavior. Though the buckling problem of cylindrical tanks was studied in the mid 1960s (NASA, 1968; Timoshenko et al., 1964), only the structural strength of an empty cylinder was investigated. The buckling problem of cylindrical liquid storage tanks subjected to seismic motions was in the limelight in the 1964 Alaska earthquake and in the 1971 San Fernando earthquake. In the 1980s Yamaki (1984) studied buckling behavior of cylindrical tanks filled with liquid systematically. In those studies, static buckling behavior was examined using small cylindrical tanks. Various dynamic buckling experiments were performed using different sizes of cylindrical tanks (Shin & Babcock, 1980; Niwa & Clough, 1982), and at the same time the occurrence mechanism of the buckling in the tanks was researched theoretically. In Japan, some dynamic buckling experiments were conducted using large scale models of cylindrical liquid storage tanks (Katayama et al., 1991; Tazuke et al., 2002). These experiments focused on proving tests of actual tanks, investigating the occurrence mechanism of the elephant foot bulge, and reflecting the experimental results into the seismic design. The experimental objects were vessels of fast breeder reactor and tanks for liquid natural gas. Toyoda and Masuko (1996), Fujita et al. (1990) and Akiyama (1997) studied the dynamic buckling of vessels and tanks vigorously and systematically, and Akiyama's proposal was adopted in a few guidelines for industrial tanks and vessels. However, the dynamic buckling behavior was not always clarified and Fujita et al. (1990) only examined the influence of oval-type vibration on seismic behavior of tanks. The numerical analysis methods, which could take into account fluid-structure interaction due to the contained liquid, were developed to simulate these experimental results but were not sufficient because of limited analysis conditions. Ito et al. (2003) conducted a dynamic buckling experiment on tall cylindrical liquid storage tanks such as the refueling water tanks installed in nuclear power plants. In their experiment, the ultimate state of the cylindrical liquid storage tanks was clarified but no numerical simulation development was discussed. Nowadays, seismic PSA should be performed as part of the seismic evaluation in nuclear power facilities. This requires that accurate failure modes and structure strength must be grasped for the ultimate state of equipment such as tanks. Therefore, it is urgent that the dynamic buckling simulation methods be established.

On the other hand, oval-type vibration has been studied from the standpoint of vibration engineering and the vibration behavior of a cylindrical shell, that is shell theory, has been investigated. Shell theory was studied from the 1920s and was systematically summarized by researchers such as Timoshenko and Woinowsky-Krieger (1959). The study on oval-type vibration of cylindrical liquid storage tanks was started in the 1960s as investigations of vibration and dynamic instability of a cylindrical shell partially filled with water. Chiba et al. (1984, 1986) conducted vibration tests using small cylindrical containers and undertook a theoretical study using Donnell's shell theory. More recently, Amabili (2003) investigated nonlinear response of oval-type vibration using Donnell's nonlinear thin shell theory vigorously. The contents of studies in the research field were reviewed by Amabili and Païdoussis (2003). However, these studies focused on nonlinear vibration characteristics and the instability region of oval-type vibration. Recently Maekawa et al. (2006) and Maekawa and Fujita (2007) clarified the influence of oval-type vibration on the resonance frequency and amplitude ratio of beam-type vibration in cylindrical tanks by vibration tests using a test tank. Their findings indicate that it is necessary to simulate oval-type vibration accurately in the seismic response analysis of cylindrical liquid storage tanks.

5. Present status of dynamic analysis of cylindrical liquid storage tanks in Japan

Cylindrical liquid storage tanks have a simple cylindrical geometry, but generate complex vibration behavior. In large tanks, the vibration behavior is a coupled system between the liquid and the tank structure because the tank walls are relatively thin and deformable. In the coupled system, various vibration modes simultaneously occur during earthquakes because the natural frequencies of most of the modes are in the exciting frequency range of the earthquakes. In the seismic design of tanks, the beam-type vibration which is the bending vibration mode is evaluated as the vibration mode which dominantly affects seismic response of the tanks. However, the vibration behavior of tanks is complex because oval-type vibration also actually occurs, which is a high order vibration mode and oscillation occurs with a petal-like pattern in the side wall. Highly advanced simulation techniques are needed to analyze such a complex vibration behavior. In conventional seismic evaluation methods, structural analysis is conducted assuming a hydrodynamic pressure distribution of liquid in the tanks as the load distribution with added mass based on velocity potential theory. However, the accuracy of time history analysis using conventional analysis methods is not good. Actually, the time history analysis of the hydrodynamic pressure distribution for successive fluid-structure interaction analysis is needed to simulate the behavior of beam-type vibration and oval-type vibration accurately.

The conventional seismic evaluation of cylindrical liquid storage tanks (Kanagawa Prefecture, 2002; KHK, 2003; JEA, 2008; AIJ, 2010) is performed assuming the tank structure responses linearly and using evaluation equations for static buckling obtained on the basis of static buckling tests. However, an accurate buckling analysis method with dynamic effects and consideration of fluid-structure interaction has never been proposed. Though attempts were made to simulate dynamic buckling behaviors of cylindrical tanks (Fujita et al., 1992; Toyoda et al., 1997), accurate simulation methods were not realized.

Most recently Maekawa and Fujita (2009) proposed an accurate seismic response analysis and a dynamic buckling analysis for cylindrical liquid storage tanks. The proposed dynamic analysis method using explicit finite element analysis was validated by a dynamic seismic experiment which indicated that the analysis accuracy was good for evaluation of seismic response (vibration response and sloshing) and buckling behavior of cylindrical liquid storage tanks.

6. Proposed dynamic analysis method

The conventional seismic response analysis for cylindrical liquid storage tanks (Kanagawa Prefecture, 2002; KHK, 2003; JEA, 2008; AIJ, 2010) is appropriate as a conservative seismic design method but it is not appropriate for grasping actual phenomena during earthquakes.

Maekawa and Fujita (2008) have proposed a nonlinear seismic response analysis method for cylindrical liquid storage tanks. In this method, the tank structure is three-dimensionally modeled using shell elements which can consider geometric nonlinearity (Belytschko et al., 1984), the contained liquid is modeled using solid elements which can calculate fluid behavior according to Euler's equation, and the fluid-structure interaction between the contained liquid and the tank structure is calculated by the arbitrary Lagrangian-Eulerian method (ALE method) (Hirt et al., 1974). Maekawa and Fujita (2008) compared analysis results obtained by their proposed method with experimental results and demonstrated that the nonlinear vibration behavior caused by the influence of oval-type vibration as well as the behavior of oval-type vibration could be simulated by the proposed method.

Maekawa and Fujita (2009) also applied their proposed method to dynamic buckling analysis. A nonlinear inelastic analysis and a large deformation analysis were conducted considering material nonlinearity to simulate plastic deformation and response in the post-buckling. The characteristics of the proposed method and the conventional dynamic buckling analysis method (Fujita et al., 1992; Toyoda et al., 1997) are compared in Table 1. As summarized there, the seismic response by the proposed method can be simulated more accurately and realistically.

Figure 5 shows an analysis model of a cylindrical tank used to validate the proposed method. This is a detailed finite element model of a test tank used for the dynamic buckling experiment presented in later sections. The numbers of nodes and elements are 424,460 and 410,482, respectively. Figure 6 shows a photo of the test tank.

In the analysis model, the Lagrange elements are used for the structure part and the Euler elements are used for the fluid part in the model. The Belytschko-Lin-Tsay shell elements (Belytschko et al., 1984) based on Mindlin theory are used for modeling the tank structure. The shell elements can consider geometric nonlinearity and shear deformation. The shear deformation is formulated by rotating a cross section vertical to the center of a shell element surface and the nonlinear constitutive equations are expressed by only linear terms using an approach to remove the rigid body motion. For the present analysis case, a 200-kg weight on the tank top was assumed as an added mass rigidly fixed on the top of the model. The imperfection distribution from a perfect circle of the cylinder obtained by profile measurement was set in the model. The material constants used in the analysis are listed in Table 2. The stress-strain relationship of aluminum alloy used in the cylinder was obtained by a material test and was approximated by multiple lines for the elasto-plastic input condition. The material constants of steel and polycarbonate were nominal values.

The fluid part is modeled by solid elements which use Euler's equation as the fundamental equation. Using Euler elements, the fluid moves from one element to another element to reproduce the pressure change due to vibration. For the present analysis case, the properties of water were set for the 95% water level of the model and the remaining 5% part was assumed as empty because air and void elements were used. The ALE method is used for the fluid-structure interaction analysis.

In the analysis, static pressure of the liquid in the tank and the dead weight of the tank structure should be considered. Hence, the load balance in the static state was calculated by loading gravity force to the model before the dynamic analysis. The mass-proportional damping with 100% damping ratio was assumed to obtain the stationary solution quickly. Next, the analysis model was impacted using a triangular wave, the free vibration of the model was excited, and then the natural frequency of the primary beam-type vibration was obtained by frequency analysis of the response. Based on its natural frequency of 30.45 Hz, 31 Hz was chosen as the excitation frequency. Finally, the dynamic buckling simulation was performed using sinusoidal waves with 31 Hz as input in which the liquid pressure change was calculated successively. The input acceleration 2.5 G was chosen based on the experimental conditions described in the next section. The analysis conditions are summarized in Table 3. Time history analysis was conducted by an explicit integral method using the finite element analysis code LS-DYNA (Livermore Software Technology Corporation, 2003).

From the viewpoint of convergence, it is difficult to solve all problems when large deformation problems such as buckling are solved by an implicit method which often is used in the general finite element method. Therefore, the explicit method was applied to the seismic response analysis, which is a long time analysis, though the method has been used for only extremely short time analyses such as impact analysis until now. This was possible due to the rapid progress which has been made in computer calculation performance.

Items	Proposed method	Conventional method (Fujita et al., 1992; Toyoda et al., 1997)
Behavior of water contained in the tank	Contained water modeled by solid elements; fluid-structure interaction calculated sequentially	Contained water not modeled; added mass considered.
Oval-type vibration	All modes considered	Higher order modes not considered
Sloshing	Analyzable	Non-analyzable
3D modeling	3D model for both axisymmetric and non-axisymmetric structures using shell elements	Axisymmetric model using axisymmetric elements
Solving method	Explicit method	Newmark β method (Implicit method)
Geometry nonlinearity	Rigid body motion removed to allow use of a simple constitutive equation with linear terms for efficient calculation and better analysis accuracy	Complicated constitutive equation with high order nonlinear terms used for better analysis accuracy
Material nonlinearity	Elasto-plastic model using multiple line approximation of stress-strain relationship	Elasto-plastic model using multiple line approximation of stress-strain relationship

Table 1. Comparison of the proposed and conventional dynamic buckling analysis methods

Materials \ Items	Young's modulus (MPa)	Poisson's ratio	Density (kg/m³)	Bulk modulus (MPa)
Aluminum alloy (A5052) (cylinder)	69,420	0.33	2,680	–
Steel (flange and platform)	203,000	0.3	7,800	–
Polycarbonate (top plate)	1,960	0.3	11,900	–
Water (in the tank)	–	–	1,000	2,200

Table 2. Material constants for analysis

Items	Analysis conditions
Structure	Model using nonlinear shell elements
Water	Model using solid element with Euler's equation
Air	Model using solid elements with voids
Weight	Model using mass elements
Fluid-structure interaction analysis	ALE method
Time-history analysis	Explicit time integration method
Damping	Rayleigh damping (3% at resonance point)
Excitation wave	Sinusoidal waves similar to those in the experiment
Excitation acceleration	2.5 G
Excitation frequency	31 Hz
Excitation direction	Horizontal (0°–180°)

Table 3. Analysis conditions

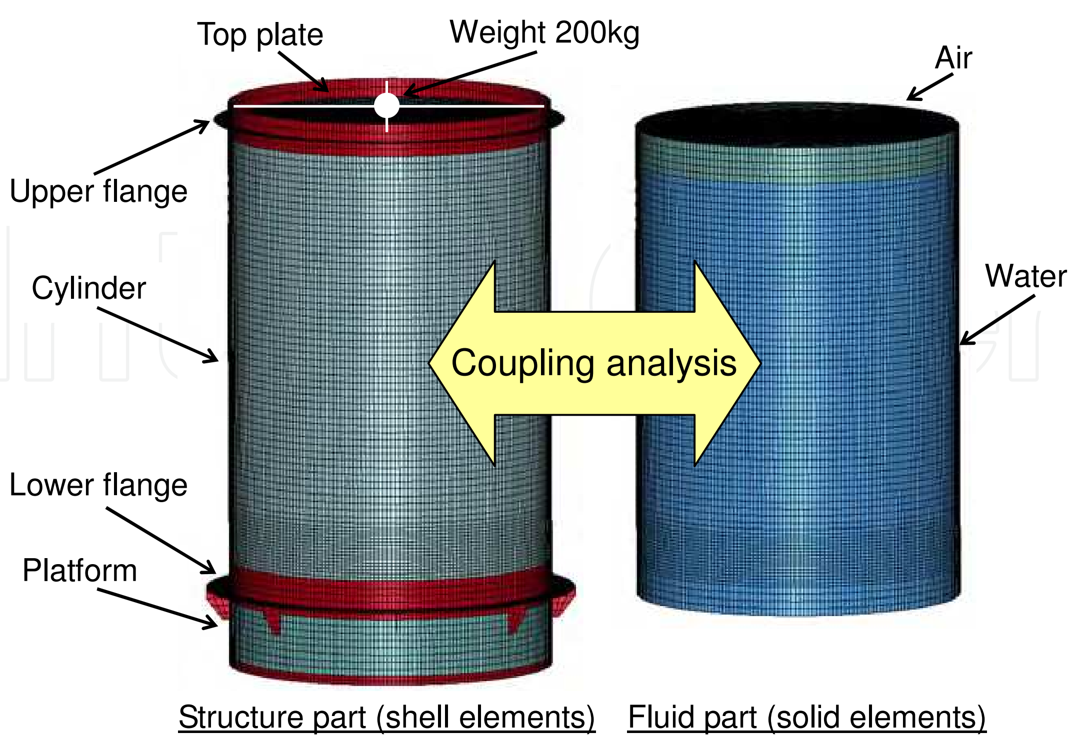

Fig. 5. Analysis model of 1/10 reduced-scale cylindrical liquid storage tank.

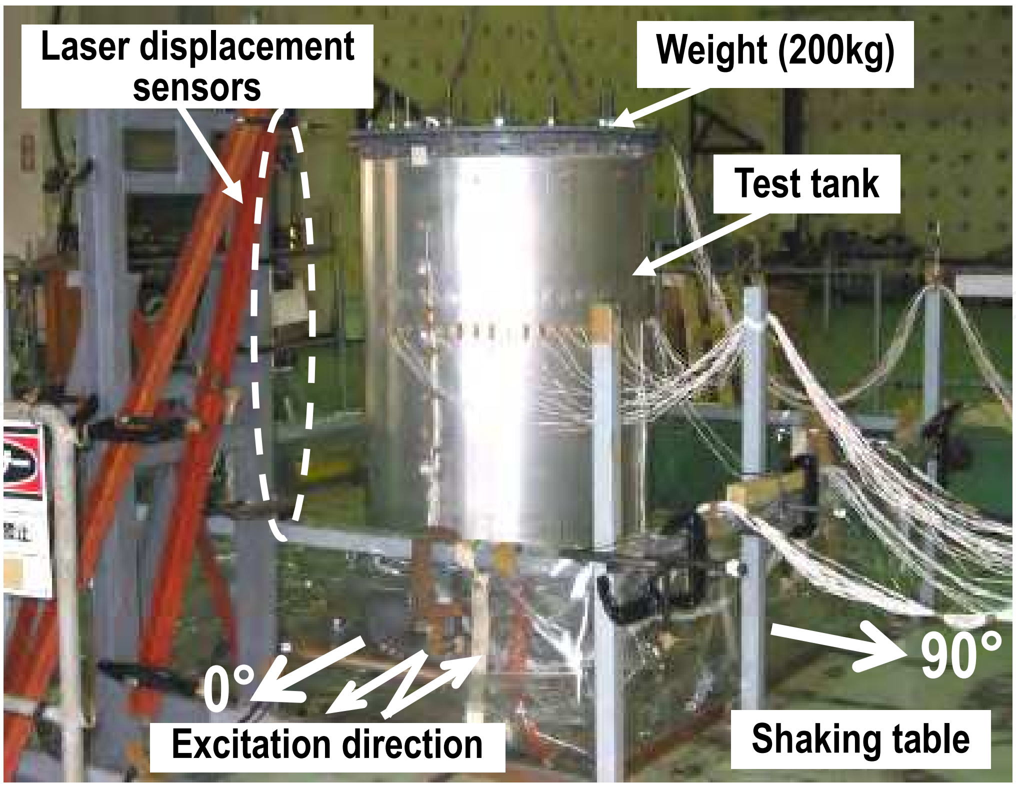

Fig. 6. Test tank of 1/10 reduced-scale cylindrical liquid storage tank.

7. Dynamic buckling experiment

The dynamic buckling experiment (Maekawa et al., 2007) of the test tank shown in Fig. 6 was conducted using a large shaking table setup to validate the proposed method. The test tank was a 1/10 reduced-scale model of the large cylindrical storage tanks installed in nuclear power plants such as condensate water tanks which are classified as equipment requiring the highest seismic safety. A 200-kg doughnut-shaped weight was put on the top of the tank to amplify the response of the tank during shaking.

The dimensions and measurement locations of the test tank are shown in Fig. 7. The test tank was an aluminum alloy cylinder with a wall thickness of 1 mm. The cylinder was fixed using steel flanges at both ends. A polycarbonate transparent board was used for the roof of the tank to look in the tank. The cylinder was made by shaping an aluminum alloy plate and using TIG welding. The shape imperfection from a perfect circle was measured by optical digital profilometry and the imperfection distribution was set in the analysis model. For the important geometry parameters in buckling, the height to radius ratio was 2.67 and radius to thickness ratio was 450. The test tank was fixed on the shaking table using a steel platform with a 2-mm wall thickness. The shear force and bending moment of the whole tank were estimated using strain generated in the platform during excitation. The behavior of beam-type vibration was measured using accelerometers on the top of the tank. Laser displacement sensors were put in the 0° direction at four heights of 290, 680, 870 and 1200 mm. The displacement changes of beam-type vibration and oval-type vibration were measured at the 1200-mm height and the other heights, respectively. In Fig. 7, many strain gauges were attached in the range from -18° to 138° at the 700-mm height. The mode shape of oval-type vibration was examined from the magnitude of strain in each position.

Occurrence of the oval-type vibration was observed by a video camera at the 90° position. The test tank was partially filled with water to the 95% level (to a height of 1140 mm) and it was excited horizontally between 0° and 180° using sinusoidal waves. The acceleration amplitude of the sinusoidal waves gradually increased and decreased at the start and end, respectively because other frequency components, except the excitation frequency, were not included. The natural frequency of primary beam-type vibration of the tank was examined by a frequency sweep test. The natural frequency of 27 Hz was chosen as the excitation frequency. Three exciting tests were conducted while changing the magnitude of the input acceleration.

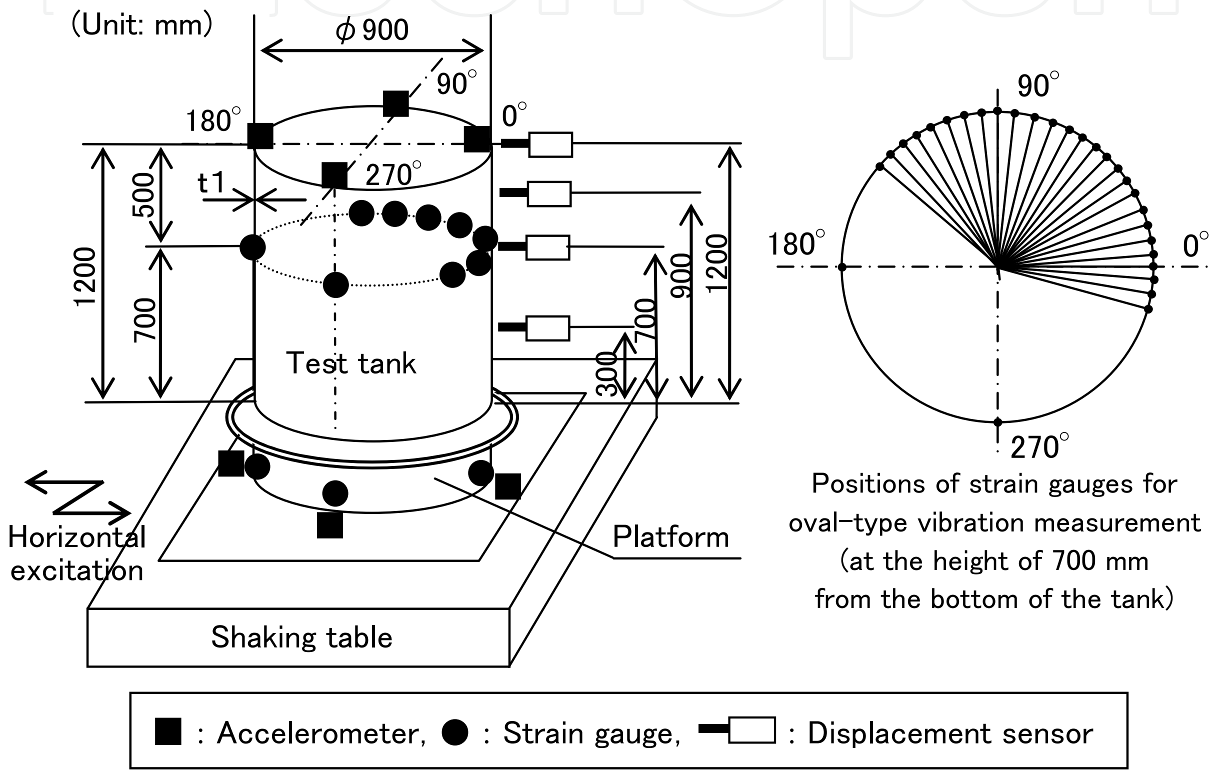

Fig. 7. Dimensions and measurement locations of test tank.

8. Dynamic buckling experiment results

Some distinct pictures expressing the dynamic behavior of the tank side wall are shown in Fig. 8. The vibration behavior of the wall is represented using lighted and shaded reflections from a spot light. The reflection of light in the center region of the cylinder was wide and narrow in the axis direction and indicated geometric change of the wall with time. Namely, oval-type vibration occurred and oscillation was large.

As shown in Fig. 9, plastic deformation was retained in the test tank after the experiment. The deformation in the side wall of the tank was probability caused by shear buckling and the deformed denting inward in the base was caused by bending buckling, specifically diamond buckling. Comparison of the maximum values of the shear stress and bending stress and the design allowance values indicated bending buckling occurred predominately because only the measured bending stress exceeded the design allowance value as shown in Table 4.

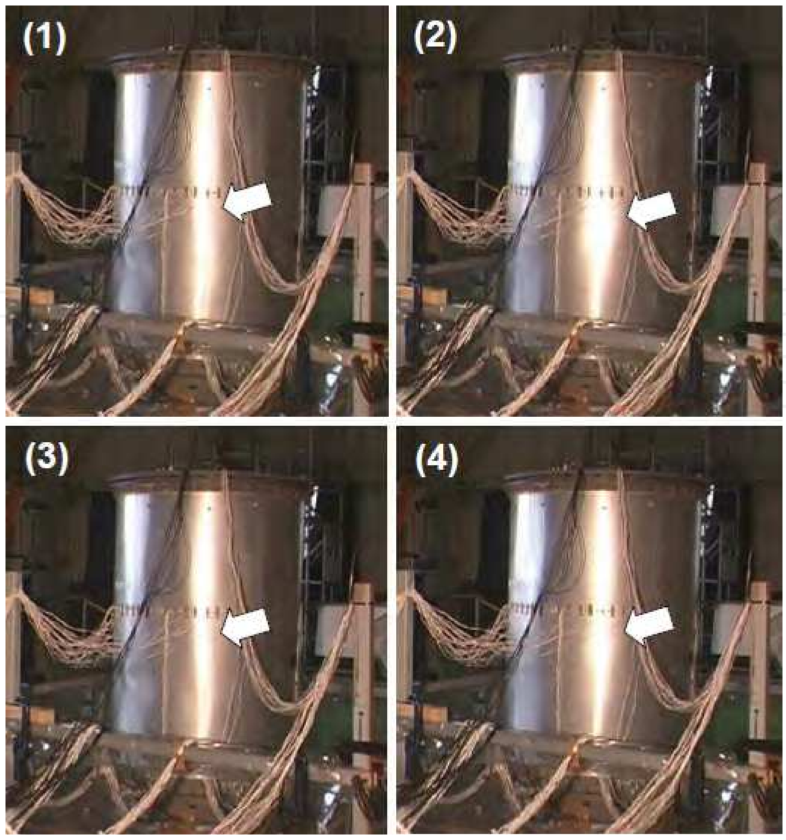

Fig. 8. Oval-type vibration occurring in the side wall of the test tank.

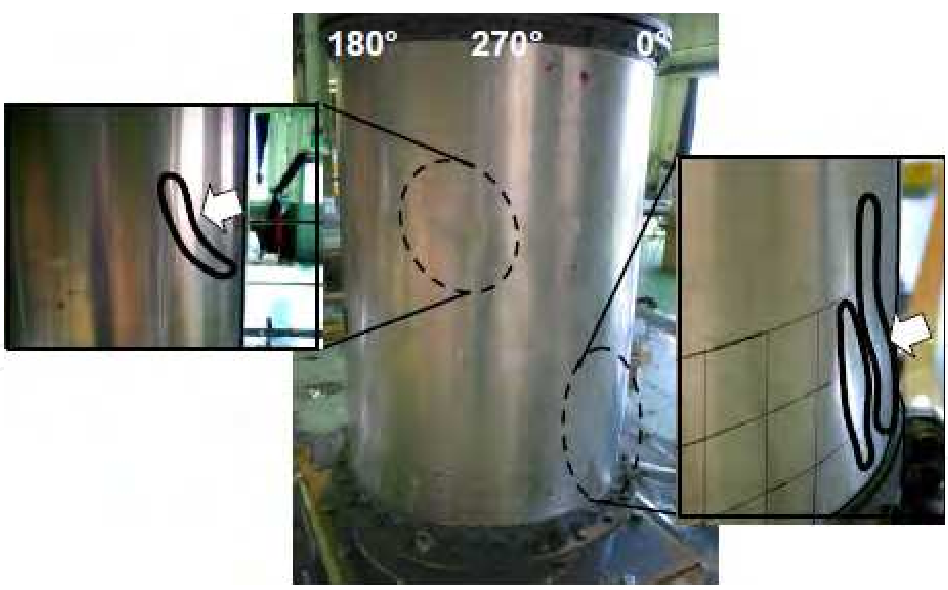

Fig. 9. Plastic deformation remaining in the tank wall after buckling.

	Experimental values (N/mm²)	Design allowance values (N/mm²)
Bending stress	97.18	47.02
Shear stress	33.45	54.65

Table 4. Comparison of buckling stresses

9. Results of proposed dynamic analysis

The time history analysis was conducted by the proposed method based on the analysis conditions in Table 3. Figure 10 shows distortion shape of the model after the analysis. The deformation factor was ten. Oval-type vibration occurred with large deformation of the wall. The bending buckling (diamond buckling) occurred with deformed denting inward in the base. These behaviors were similar to the experimental observation. Figure 11 shows the measured deformation shapes of a cross section of the test tank at a height of 700 mm. These shapes represent modes of oval-type vibration excited in the experiment before and after buckling. These modes were different, indicating the influence of buckling. Figure 12 shows the deformation shapes of a cross section of the model obtained by the analysis. It was found that the analytical shapes were similar to those in Fig. 11. Namely, the proposed dynamic analysis method was demonstrated to simulate the experimental results accurately. Figures 13 and 14 show the pressure distributions of liquid in the tank model obtained by the analysis at the corresponding times to Fig. 12. Figure 13 shows liquid pressure distributions of the cross section at a height of 700 mm and Fig. 14 shows the vertical section between 0° and 180°. The shape of the liquid pressure distributions in Fig. 13 corresponded to the mode shapes of oval-type vibration, for example, the regions are indicated by arrows. This indicates that the proposed method can simulate phenomena caused by the fluid-structure interaction in the tanks accurately. Consequently from the above results, the proposed dynamic analysis method is judged to be able to simulate oval-type vibration, liquid pressure behavior, buckling modes, and buckling response accurately.

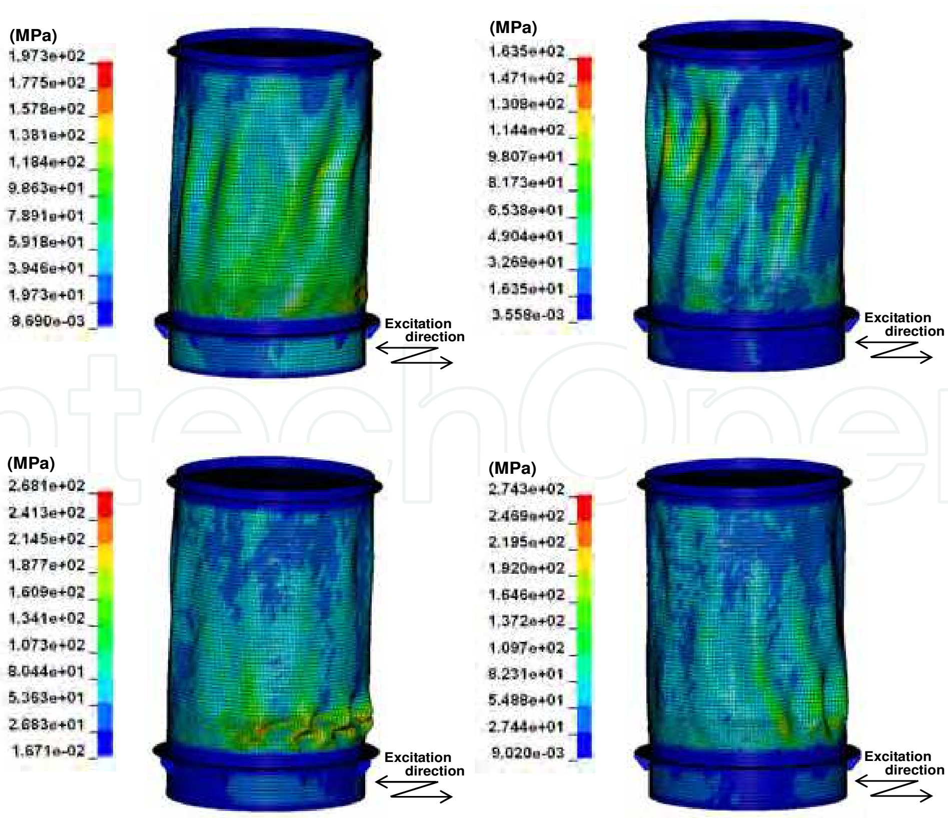

Fig. 10. Distortion shape and von Mises stress contour plots (displacement factor, 10) before (upper) and after (lower) buckling.

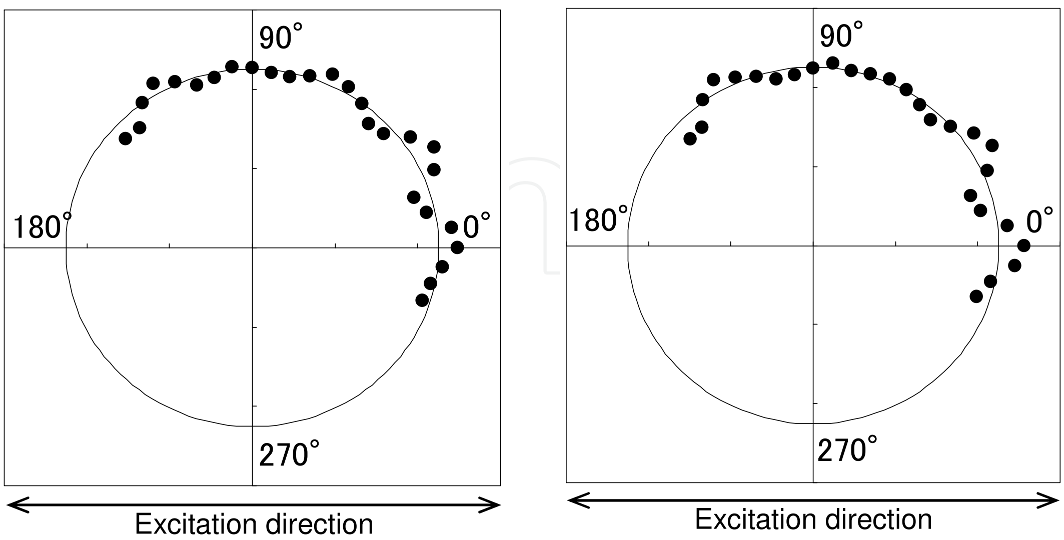

Fig. 11. Measured mode shapes of oval-type vibration in test tank at 700-mm height before (left) and after (right) buckling.

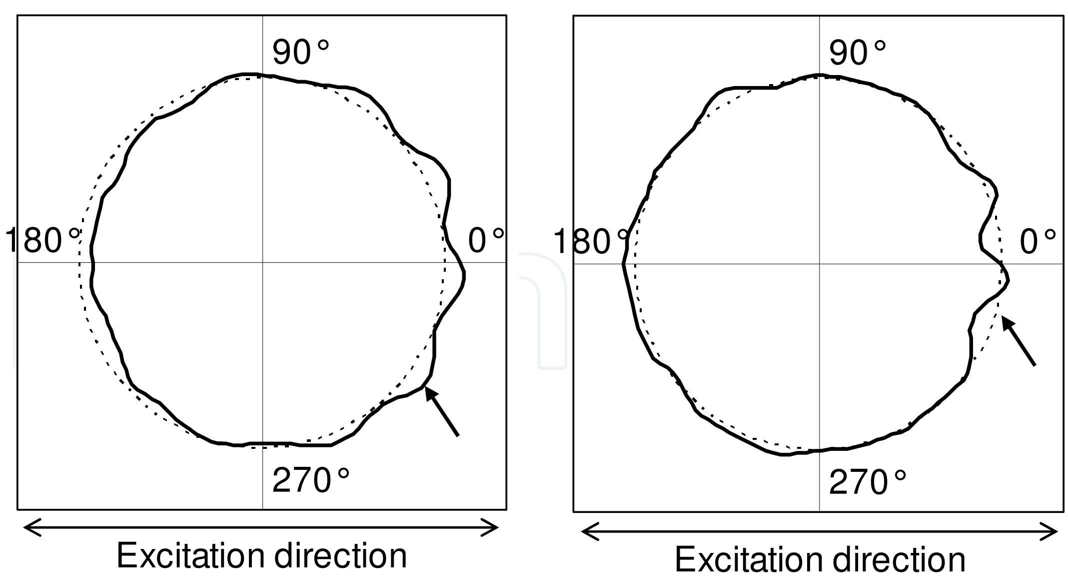

Fig. 12. Calculated mode shapes of oval-type vibration in tank model at 700-mm height before (left) and after (right) buckling.

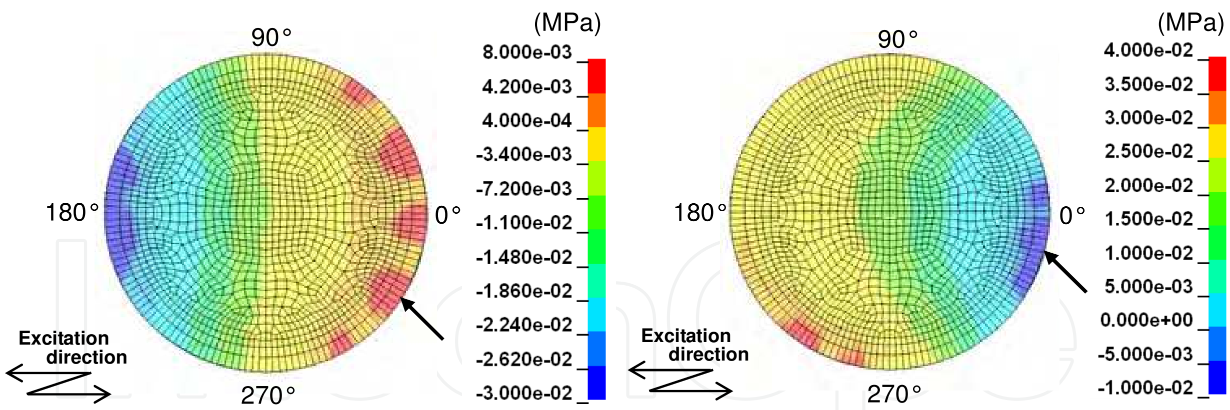

Fig. 13. Calculated liquid pressure distributions at 700-mm height before (left) and after (right) buckling.

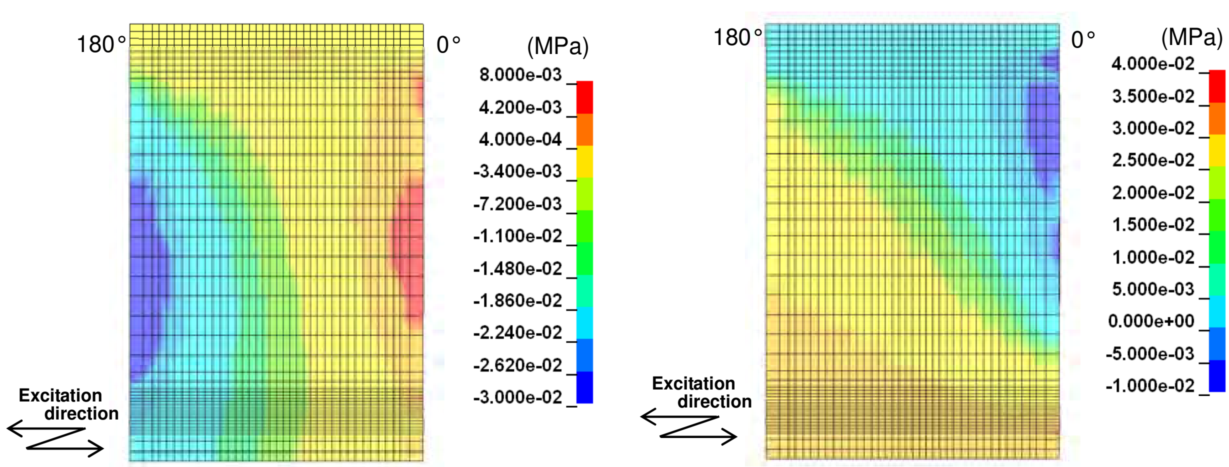

Fig. 14. Calculated liquid pressure distributions vertical section between 0° and 180° before (left) and after (right) buckling.

The mode shape of oval-type vibration excited was then discussed in detail using the proposed method. Figures 15 and 16 show the oval-type vibration behavior before and after buckling, respectively. The mode shape of oval-type vibration before buckling was specific and the circumferential wave number n=12 was dominant. On the other hand, the mode after buckling was unstable and non-uniform. This might be associated with the change of vibration characteristics of the tank model due to the development of buckling on the base of the tank model. As described above, the vibration behavior of cylindrical liquid storage tanks including oval-type vibration can be examined by numerical simulation using the proposed dynamic analysis method.
The dynamic behavior of the liquid pressure distribution also was discussed using the proposed method (see Figs. 13 and 14). In the liquid pressure distribution before buckling, a large dynamic liquid pressure occurred due to the large beam-type vibration. The change of liquid pressure due to oval-type vibration occurred locally. In the pressure distribution after buckling, the change of the dynamic liquid pressure due to beam-type vibration and oval-type vibration was not clear. The change of liquid pressure before and after buckling might also be attributed to the change of the vibration characteristics due to buckling.

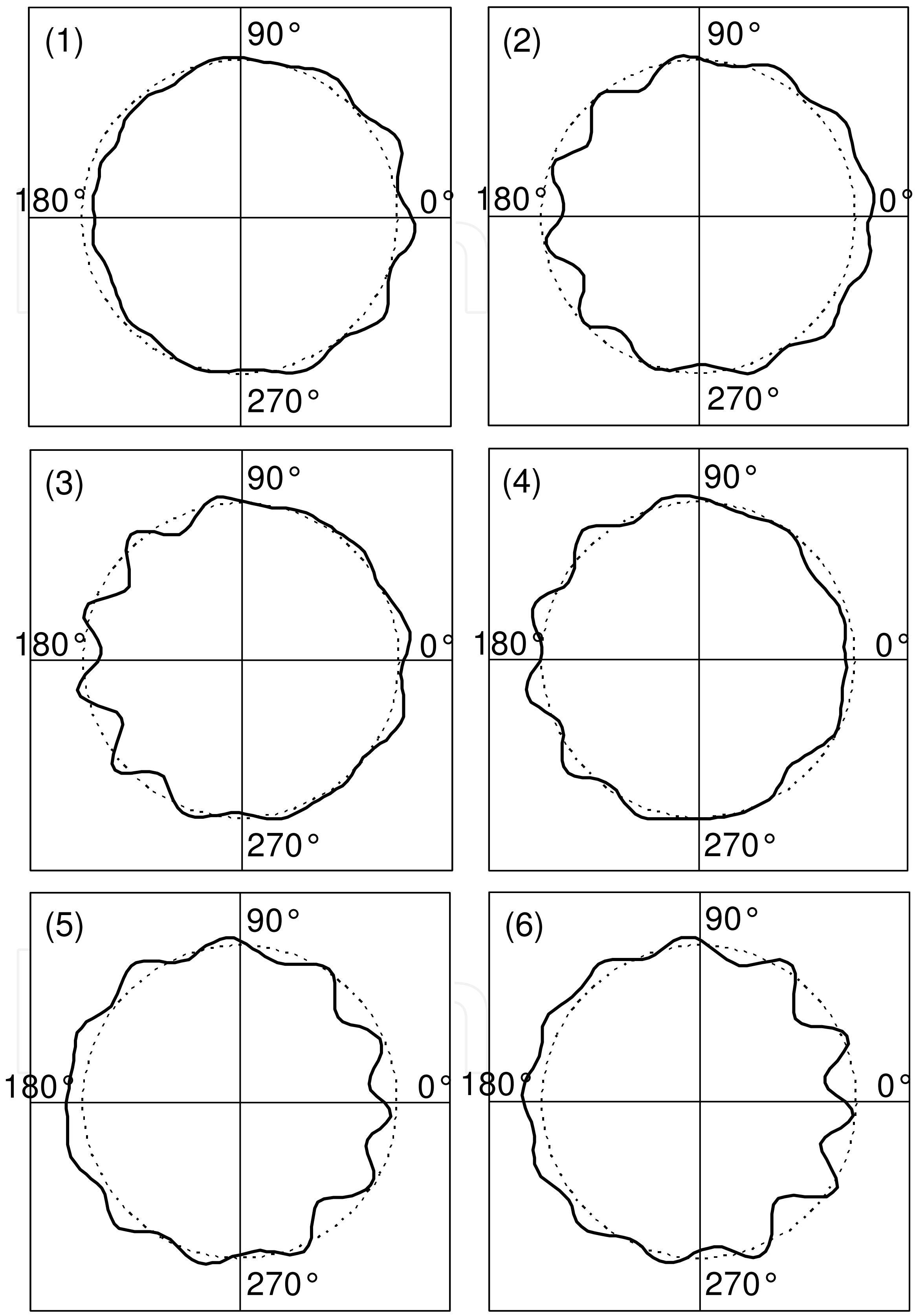

Fig. 15. Mode shape variation of oval-type vibration before buckling
(time course: from (1) to (6)).

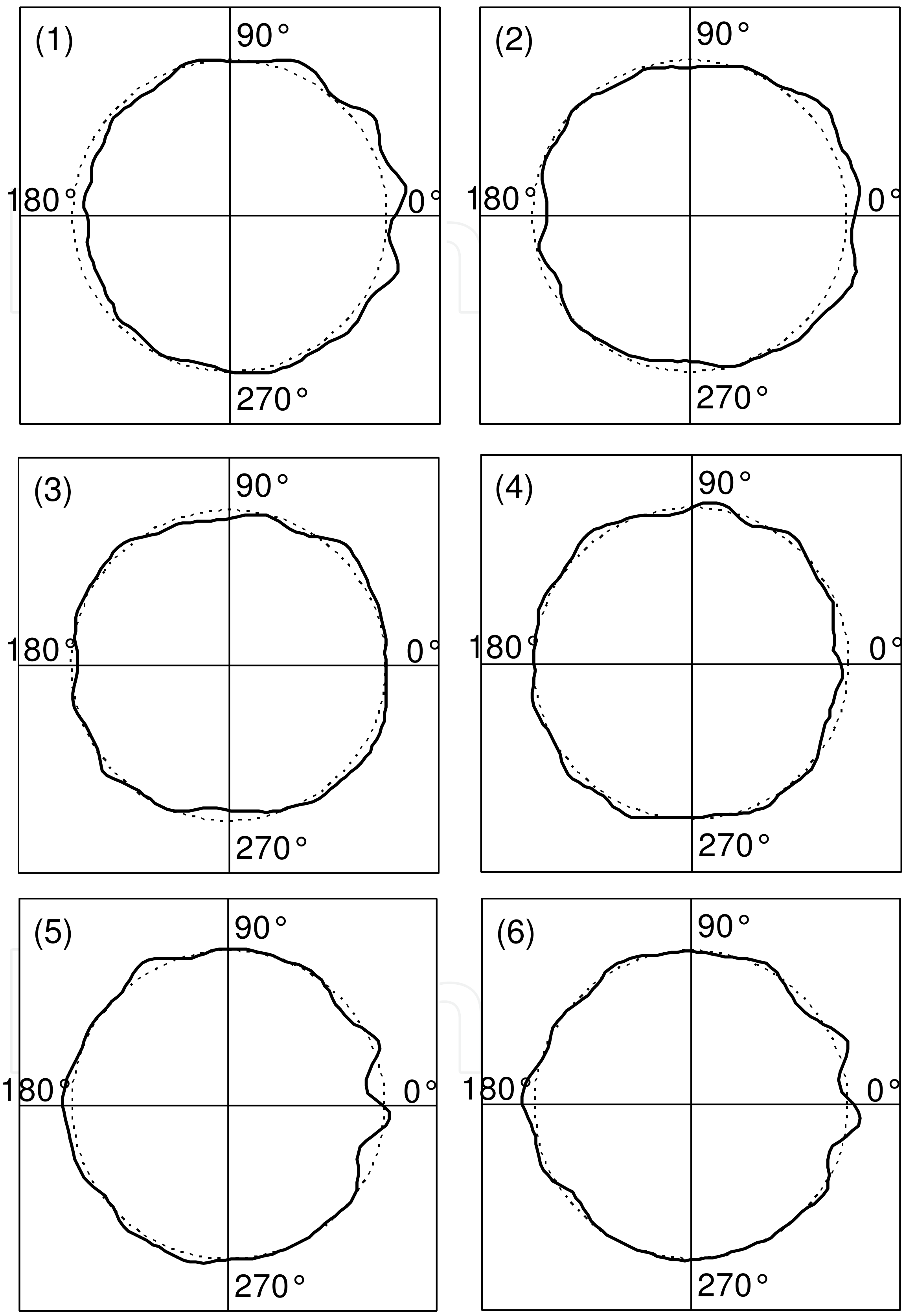

Fig. 16. Mode shape variation of oval-type vibration after buckling
(time course: from (1) to (6)).

The detailed analysis results of the dynamic liquid pressure distribution are shown in Figs. 17 and 18. The two figures show the vertical distribution of dynamic liquid pressure at the 0° position before and after buckling, respectively. Here, a qualitative discussion was done because the lines of the graphs were ragged which could be attributed to the roughness of the mesh division and inherent properties of the explicit method. The two figures suggested that the dynamic liquid pressure distribution was caused by beam-type vibration and the distribution shape was typical of that in thin-walled and flexible cylindrical liquid storage tanks. The distribution shapes before and after buckling differed. The difference was thought to be associated with the change of vibration characteristics of the tank due to buckling.

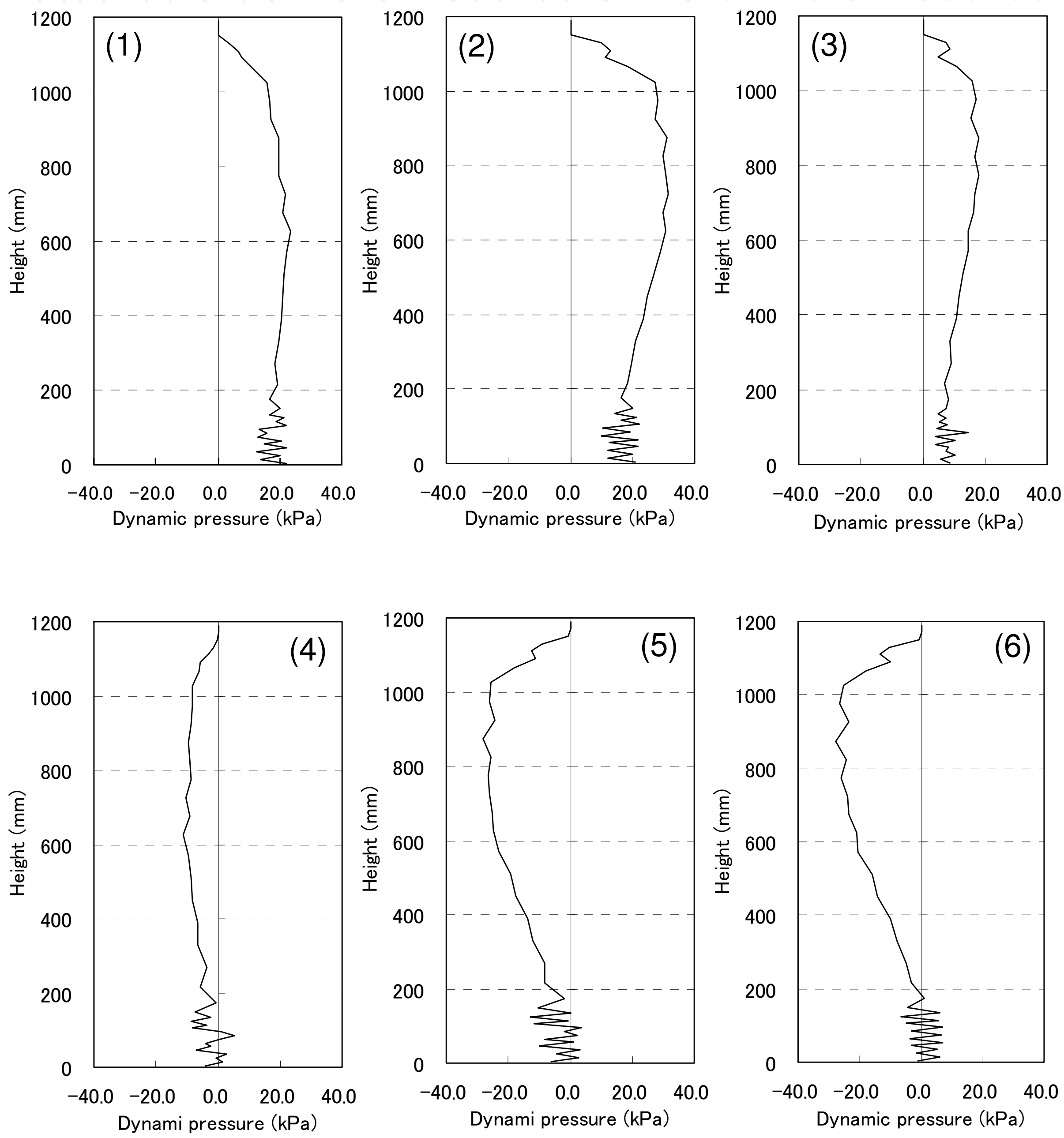

Fig. 17. Calculated vertical distributions change of dynamic liquid pressure at 0° position before bucking (time course: from (1) to (6)).

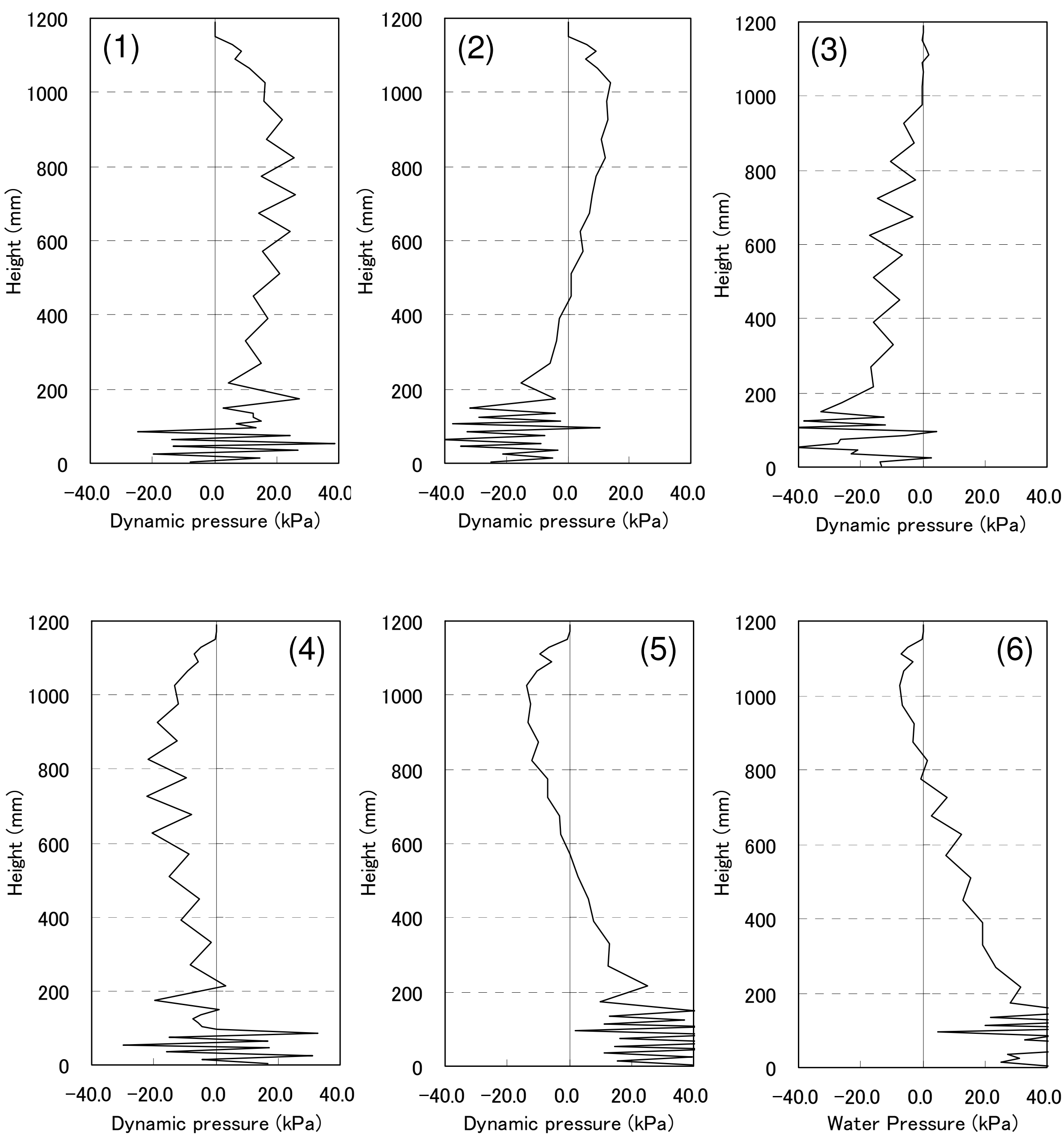

Fig. 18. Calculated vertical distributions change of dynamic liquid pressure at 0° position after buckling (time course: from (1) to (6)).

The acceleration and buckling loads obtained from the dynamic experiment and the analysis are summarized in Table 5. The shear force and bending moment agreed well between them. The load that worked on the tank was well estimated by the analysis. Hence, the proposed dynamic analysis method can estimate dynamic behavior and buckling behavior of liquid storage tanks accurately even though the seismic response of the tanks was unknown. The input acceleration in the analysis agreed with that in the experiment. This indicates that the input magnitude to increase buckling, that is, the magnitude of seismic motion, is predicable by the proposed dynamic analysis method.

In conclusion, it is demonstrated that the proposed dynamic analysis method can simulate the vibration response of cylindrical liquid storage tanks, the pressure behavior of the contained liquid and the buckling behavior accurately. Moreover, the buckling load and input magnitude to increase buckling can also be predicted accurately.

	Dynamic buckling experiment	Dynamic buckling analysis
Input acceleration (G)	2.37	2.61
Shear force (kN)	47.3	59.4
Bending moment (MN·mm)	61.8	67.7

Table 5. Input excitation and associated base shear and base bending moment

10. Applicability to actual tank

The test tank and model described above are approximately a 1/10 reduced-scale model of an actual tank with uniform wall thickness. However, actual tanks are of many dimensions and shapes, and so research on larger tanks of different shapes would help assess the applicability of the proposed dynamic analysis method to actual tanks. Some dynamic buckling experiments using large-scale test tanks have been conducted. Ito et al. (2003) recently did a dynamic buckling experiment using a test tank similar to the refueling water storage tanks installed in nuclear power plants. The applicability of the proposed dynamic analysis method was assessed by using their experiment results as a benchmark (Maekawa & Fujita, 2010).

A photograph of their tank is shown in Fig. 19 (Ito et al., 2003). It was a 1/5 reduced-scale model. The tank, which had an internal diameter of 2200 mm, cylinder height of 2650 mm and water level of 2526 mm, had a non-uniform wall thickness with thickness decreasing in the height direction and was made of aluminum alloy. The height to radius ratio was 2.4 and the radius to average thickness ratio was 894. The experiment results showed the occurrence of oval-type vibration in the wall and bending buckling (elephant foot bulge) in the base; the type of bending buckling was different from that of the 1/10 reduced-scale test tank. Figure 20 shows the analysis model, which has 125,767 nodes and 131,712 elements. The Belytschko-Lin-Tsay shell elements (Belytschko et al., 1984) were used for the tank structure and solid elements with Euler's equation were used for the contained fluid. The coupling analysis between fluid and structure used the ALE method (Hirt et al., 1974) to estimate dynamic fluid-structure interaction. The free liquid surface was made by modeling the contained liquid and gas as solid elements in order to simulate sloshing. The same seismic wave as that used in the experiment was used as input. The magnitude of input acceleration was 2.7 Se (1600 Gal instantaneous maximum acceleration). In the experiment, buckling was caused and developed by the seismic wave of 2.7 Se.

The natural frequency of primary beam-type vibration of the analysis model was 16.6 Hz and that agreed with the experiment value of 16.8 Hz, showing the appropriateness of the model. The analytical result for the seismic wave is shown in Fig. 21. The side wall of the model was severely deformed inward, representing the occurrence of oval-type vibration. The wall in the base of the model locally came outward, showing the occurrence of elephant foot bulge. These results confirm that the proposed method can simulate the occurrence of oval-type vibration and the elephant foot bulge. In addition, Fig. 22 shows the simulation of sloshing of the contained liquid. The boundary between the liquid and air was heaved up, representing sloshing of the free liquid surface. Finally, these results demonstrate that the proposed method can also accurately simulate the vibration characteristics and buckling behavior of tanks with various shapes.

Fig. 19. Large test tank of 1/5 reduced-scale cylindrical liquid storage tank. (Ito et al., 2003)

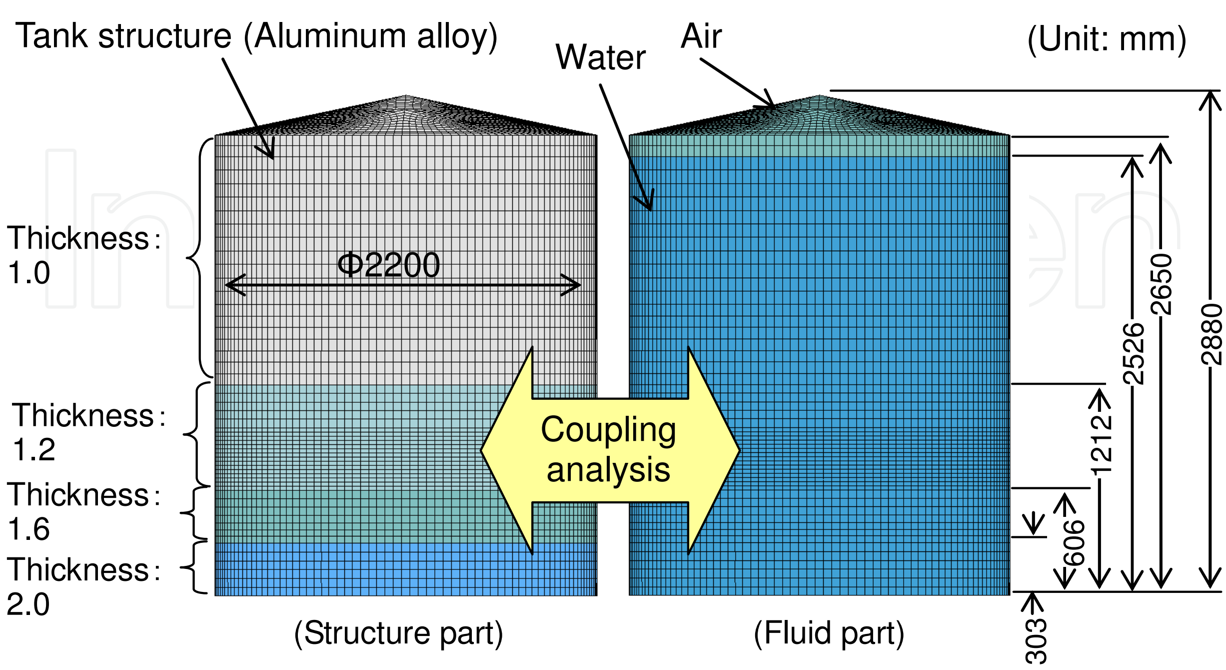

Fig. 20. Analysis model of large-scale tank.

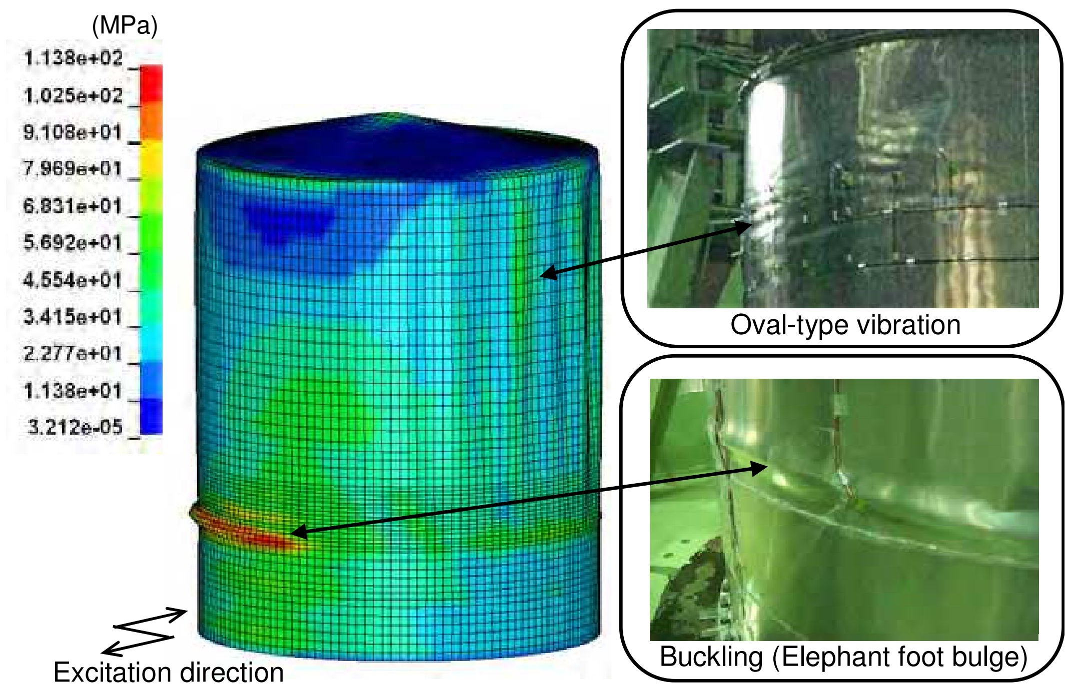

Fig. 21. Simulation of oval-type vibration and elephant foot bulge.

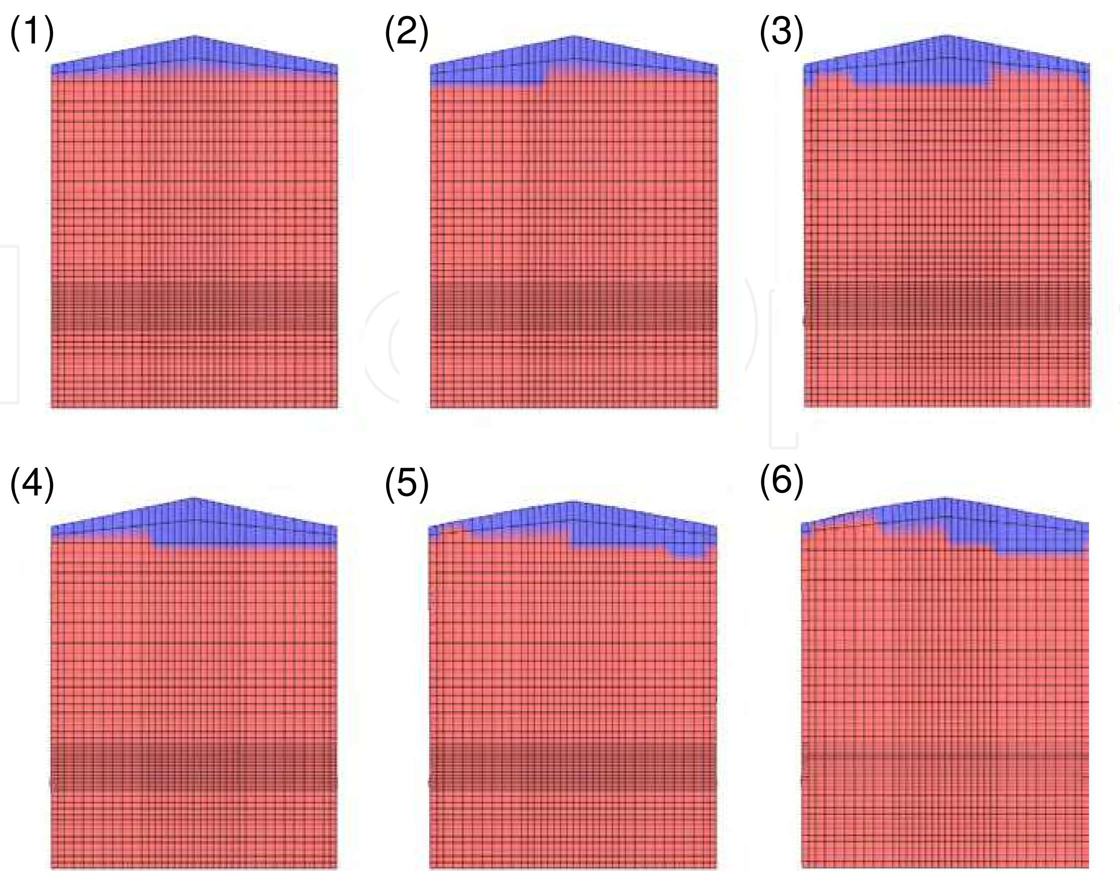

Fig. 22. Simulation of sloshing before (1) and during ((2) to (6)) excitation. The contained liquid is shown in red and the air in blue.

Comparison of analysis and experiment results for the 1/10 and 1/5 reduced-scale models show that the proposed method can simulate seismic response such as vibration response and sloshing and buckling behavior such as buckling mode and buckling load accurately. Consequently, the proposed dynamic analysis method is versatile and can be used to analyze many types of tanks. Additionally it is concluded that the method can adequately evaluate the seismic resistance of tanks such as their seismic safety margin (Maekawa et al., 2011).

11. Conclusions

The past and present research studies on seismic response analysis for cylindrical liquid storage tanks were reviewed. In addition, a new dynamic analysis method of seismic response for cylindrical liquid storage tanks which was developed by Maekawa and Fujita was introduced. The dynamic analysis method to evaluate seismic response (vibration and sloshing) and buckling was proposed and validated by the experimental results. The conclusions obtained are summarized as follows.

1. A new dynamic analysis method was proposed for evaluating seismic response and buckling behavior of cylindrical liquid storage tanks. In the method, the tank structure was three-dimensionally modeled by nonlinear shell elements which allowed geometric nonlinearity to be considered, the contained liquid was modeled by solid elements that calculated fluid behavior according to Euler's equation, and the fluid-structure

interaction between contained liquid and tank structure was evaluated by the arbitrary Lagrangian-Eulerian method.

2. In the proposed method, the explicit method was applied to the seismic response analysis, which is a long time analysis, though the method had been used for only extremely short time analysis such as impact analysis until now. The time history analysis results using the explicit method could reproduce the vibration and buckling behavior accurately.
3. A dynamic buckling experiment was conducted by using the 1/10 reduced-scale model of an actual tank. The experiment values were compared with the analysis results by the proposed method. The analysis and experiment results were in good agreement, especially with vibration response, buckling mode and buckling load. The results demonstrated that the proposed method could accurately simulate the seismic response of the tank.
4. The experiment and analysis values were compared for a 1/5 reduced-scale model. The proposed method was judged to be versatile and applicable to many types of tanks.
5. It was concluded that the proposed method could adequately evaluate the seismic resistance of tanks such as their seismic safety margin.

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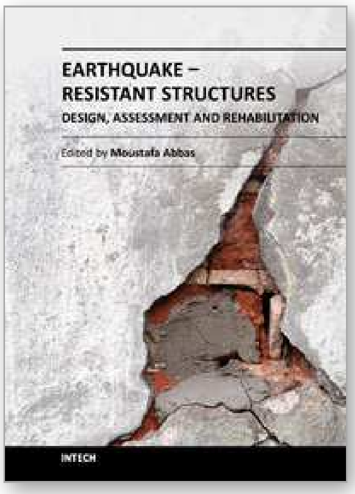

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