PSEUDO-DYNAMIC BUCKLING EXPERIMENT OF THIN CYLINDRICAL SHELLS UNDER BIAXIAL SEISMIC LOADS

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Abstract

Pseudo-dynamic buckling experiments are performed to study the dynamic buckling characteristics of the main vessel of a fast breeder reactor when subjected to seismic loads. The effects of axial loads on the horizontal seismic responses in pre- and post-buckling states of thin cylindrical shells are investigated. The buckling tests use model cylinders made of aluminum plate and a biaxial loading test apparatus. The axial seismic loads reduce the lateral load carrying capacity of the shells in the pre- and post-buckling region so that they amplify the horizontal response displacement. An amplification factor that accounts for the effects of the vertical loads is presented and its validity is verified experimentally.

1. INTRODUCTION

The buckling strength of the cylindrical part of a reactor vessel is one critical point in the seismic design of a fast breeder reactor (FBR). The Central Research Institute of Electric Power Industry and nuclear power plant makers worked together on a project researching the buckling strength of FBR structures, which was sponsored by the Ministry of International Trade and Industry of Japan (Akiyama, et al. 1989).

Much of the research on the buckling problems of cylindrical shells that has been done in the project can be applied to the design of buckle-resistant nuclear reactor vessels. A tentative draft of the seismic buckling design guidelines has been proposed (Akiyama, et al. 1991). We proceeded to refine the design methodology through both buckling experiments and structural analyses.

The nonlinear elastic-plastic response characteristics of dynamic events were taken into account in investigating the structural integrity of the vessels. The stable post-buckling behavior under dynamic loads leaves a safety margin even if the applied load exceeds the critical buckling load.

During a seismic event, the vessel is simultaneously subjected to horizontal and vertical loads. The effects of the vertical loads on the horizontal buckling behavior have not been clarified. In this study, buckling behavior under biaxial seismic loads is investigated by experiment and simulation analysis.

2. EXPERIMENT

2.1 Test Apparatus

Biaxial pseudo-dynamic buckling experiments were conducted using the test apparatus shown schematically in Fig. 1. The pseudo-dynamic testing is a computer-assisted on-line testing method that slows down the event to permit precise measurement during dynamic events. It has been applied to the tests of horizontal buckling (Kokubo, et al. 1991 and Ishihama, et al. 1992). Here, the vertical and horizontal hydraulic actuators are used to provide the inertial forces. The actuators attached to the rigid support frame are connected to the upper flange of the model by the connecting links.

The model shells are 640 mm in diameter and 320 mm height, which corresponds to about one twenty-fifth the size of a demonstration class FBR reactor vessel size, and are made from 1.6 mm thick aluminum plate by rolling and welding. The ratio of radius to thickness (R/t) is 200. The initial imperfections of the shells are less than 50% of the thickness. The material properties and the size of the shells are shown in Table 1.

2.2 Test Conditions

The natural frequencies of the prototype reactor are 6.5 Hz in the horizontal direction and 9.0 Hz in the vertical. The test model system reduces the time to one fifth of the actual time so that the equivalent acceleration is maintained. An analytical model of the pseudo-dynamic test is shown in Table 2 and the test conditions in Table 3. The floor response spectra of the input waves are shown in Fig. 2. The horizontal maximum accelerations are selected so that the vibration responses exceed the buckling displacement δ_{cr} .

The dead weight of the vessel's internal structures is considered a static tensile force in the direction of the cylinder axis. Vertical accelerations at seismic levels S2 and 1.5 times S2 are applied. Under the conditions in test case 8, the vertical wave is shifted so that the maximum vertical force occurs at the horizontal buckling time.

2.3 Test Results

The relation between the maximum response displacement and the horizontal input acceleration is shown in Fig. 3, for both the experimental and analytical data. The response displacement with vertical seismic input is larger than that without it.

The energy absorption E_d can be calculated from the hysteresis loop. It can also be obtained from the equivalent velocity V_d :

$$V_d = \sqrt{2E_d / M},$$

(1)

where M is the mass of the test system.

Better correlation between the maximum response displacement and the velocity V_d equivalent to the absorption energy is obtained as shown in Fig. 4. The vertical excitation contributes to the increase in the energy absorption by the horizontal response.

The typical load-displacement relation under the test conditions is shown in Fig. 5. Skeleton curves extracted from the load-displacement relations are shown in Fig. 7, comparing the result of case 8, with vertical excitation, to that of case 2, without vertical load. The vertical load acting in the axial direction is shown for the horizontal response displacement in the figure along with the horizontal response force. The reductions in the horizontal load-carrying capacity due to the axial compressive force are observed. The reduction is pronounced after the response exceeds the buckling displacement.

Fig.1 Test Apparatus

Table 1 Test Model

	Prototype	Model
Material	Type 304 SS	Aluminum
Young's modulus E (GPa)	159.	73.
Yield stress σ_y (MPa)	108.	40.2
Radius R (mm)	8000.	320.
Thickness t (mm)	40.	1.6
Length L (mm)	8000.	320.
Loading Height H (mm)	12000.	480.

Table 2 Vibration Model

	Horizontal: X	Vertical: Z
Mass M (kg)	1.67 x10 ³	1.47 x 10 ³
Stiffness K (MN/m)	69.6	118.
Natural frequency f ₀ (Hz)	32.5	45.0
damping factor ζ	0.01	0.01

Table 3 Test Conditions

Test Case No.	Input Max. Accel. (cm/s ²)		Static Tensile Force (kN)	Symbol
	Horizontal	Vertical		
1	1500	-	-	Hor.
2	2250	-	-	Hor.
3	2000	-	14.7	Hor.+Fs
4	2000	210	14.7	Hor.+S2+Fs
5	1850	210	-	Hor.+S2
6	2000	210	-	Hor.+S2
7	2000	315	-	Hor.+S2x1.5
8	2000	210	-	Hor.+S2'

Fig. 2 Acceleration Response Spectrum of Seismic Waves

Fig. 3 Horizontal Response Displacement

3. DISCUSSION

3.1 Numerical Simulation

As we got only a few data points for input acceleration, simulation analysis was carried out to investigate the dependency of the response on the input acceleration.

Analysis using a two-degree-of-freedom model with hysteresis restoring force is carried out to simulate the nonlinear response. The equations of motion are

$$M_x \ddot{X} + C_x \dot{X} + F_x(X, F_z) = -M_x \ddot{Y}_x \tag{2}$$

$$M_z \ddot{Z} + C_z \dot{Z} + F_z(Z) = -M_z \ddot{Y}_z, \tag{3}$$

where M is the mass, C is the damping coefficient, F is the restoring force and Y is the seismic input, while the suffix x indicates the horizontal direction and z indicates vertical direction.

The horizontal restoring force F_x is defined by the load-displacement relation with simplified hysteresis rules based on the experiment (Nakagawa, et al. 1989 and Hagiwara, et al. 1989). This force is a function of the horizontal displacement X and the vertical load F_z , so the horizontal motion is coupled to the vertical one. The cylinders are assumed to be elastic in the axial direction within the experimental region, and the vertical equation of motion is linear and is independent of the horizontal motion.

The reduction of the horizontal load-carrying capacity is considered. The reduction rate is defined as a function of the axial load and the horizontal displacement history.

The relation between maximum displacement and input acceleration shown in Fig. 3 is compared to the experimental results and the load-displacement relations shown in Fig. 6. The analytical results agree well with the experiment in both the maximum response and the energy absorption.

The dynamic behavior of the cylindrical shells under biaxial seismic loadings, including post-buckling behavior, can be well explained by the simulation model.

3.2 Response Amplification Factor

The vertical seismic load contributes to increasing the horizontal energy absorption and the response displacement is amplified. The increase in the energy is related to the energy received from the vertical seismic wave. Here we assume that half of the vertical energy input contributes to the increase in the horizontal response. The response amplification factor C is introduced:

$$C = \sqrt{1 + 1/2 \{T_v \cdot vSa(T_v)/T_0 Sa(T_0)\}^2}, \tag{4}$$

where $Sa(T_0)$ is the acceleration response spectrum for the horizontal seismic motion at the fundamental period T_0 of the structure due to horizontal vibration and $vSa(T_v)$ is the acceleration response spectrum for the vertical seismic motion at the fundamental period T_v of the structure due to vertical vibration.

Fig. 4 Displacement-Energy Relation

Fig. 5 Load-Displacement Relations (Experimental)

Fig. 6 Load-Displacement Relations (Analytical)

Fig. 7 Skeleton Curves

Fig. 8 Amplification Factor

As buckling estimation must be done at the critical state, the horizontal response spectrum S_a may be that for the acceleration which generates the critical buckling level response. The response amplification factor C is shown in Fig. 8 for the spectrum ratio $T_{vv}S_a/T_0S_a$. The value C' , which is calculated assuming that the whole vertical input energy may contribute to the horizontal response, is also shown in the figure by the broken line. The predicted values for C are comparable to the experimental ones. The experimental amplification factors are the ratio of the critical horizontal acceleration amplitude A_{cr} to that with the vertical excitation. The critical acceleration A_{cr} at which the response displacement reaches the buckling displacement δ_{cr} is determined from the simulation data shown in Fig. 3 for the same vertical excitation level. The response amplification factors are accurately predicted by the formula based on the energy spectra.

4. CONCLUSIONS

The following results were obtained for the effects of the axial compression load on the horizontal buckling response from biaxial pseudo-dynamic tests and numerical simulations.

The lateral load-carrying capacity of the shells in the pre- and post-buckling region is reduced and the horizontal response displacement is amplified by the axial compression force.

The numerical model with hysteresis restoring force, which is determined interactively by the axial load, can well simulate the dynamic properties of the buckling system under biaxial seismic excitations.

The response amplification factor presented can be used to accurately predict the increase in horizontal displacement due to vertical excitation.

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References

- Akiyama, H., et al. (1989), Demonstration Test and Research Program of Buckling of FBR, SMiRT-10, Vol. E, pp. 215-222
- Akiyama, H., et al (1991), Outline of the Seismic Buckling Design Guideline of FBR - A Tentative Draft -, SMiRT-11, Vol. E, pp. 239-250
- Nakagawa, M., et al. (1989), Post Buckling Behavior of Short Cylindrical Shells under Lateral Seismic Loads, SMiRT-10, Vol. E, pp. 235-240
- Hagiwara, Y., et al, (1989), Post buckling Behavior during Earthquakes and Seismic Margin of FBR Main Vessels, ASME PVP Conf. Vol.175, pp. 91-96
- Hagiwara, Y., et al, (1991), Dynamic Buckling and Nonlinear Response of FBR Main Vessels under Earthquake Loading, The 1st JSME/ASME Joint Conf. on Nuclear Eng. pp. 601-606
- Kokubo, K., et al. (1991), Corroboration of Dynamic Characteristics of FBR Main Vessels by Pseudo-dynamic and Dynamic Buckling Experiments, SMiRT-11, Vol. E, pp. 251-256
- Ishihama, K., et al. (1992), Corroboration of Dynamic Characteristics of FBR Main Vessels by Pseudo-dynamic Experiments, Seismic and Environmental Qualification of Equipment (Inst. of Mech. Engineers, London)