SMiRT–12 / K. Kussmaul (Editor)

E12/1

THE EFFECT OF SEISMIC MOTION CHARACTERISTICS ON THE INELASTIC RESPONSE REDUCTION OF CYLINDRICAL SHELL STRUCTURES

Y. Hagiwara[1], K. Yamamoto[1] and H. Akiyama[2]

[1]Central Research Institute of Electric Power Industry, Abiko, Japan
[2]University of Tokyo, Tokyo, Japan

ABSTRACT

Reactor vessels of FBR are cylindrical shell structures, whose critical failure mode during earthquakes is plastic buckling in shear or bending mode. In buckling prevention of the vessels, it is of primary importance to realistically evaluate the plastic response reduction effect in the pre-buckling stage. Though the authors have already proposed a empirical formula to estimate the response reduction effect, the formula depends only on the pre-buckling ductility factor in the evaluation for the purpose of easy design practice. In this study, the effect of seismic motion characteristics on the response reduction effect was investigated both experimentally and numerically, and a improved version of the empirical expression of the reduction factor was proposed. In this new method, the response reduction effect is evaluated by an initial acceleration amplification factor in addition to the ductility of structures.

1. INTRODUCTION

The plastic shear/bending buckling of reactor vessels is one of the most critical issues in the seismic design of FBR. It is necessary to prevent the large deformation and the large strain which appear after buckling at the thin cylindrical walls of the vessels. However, it is not a easy task to achieve it under the severe seismic loading conditions in Japan, because the vessels have to withstand large thermal stress as well, so any rigid structural concept which can improve the buckling strength can not be taken. Certain rationalized seismic design methodologies are required for the safe and cost-effective design of FBR.

The Central Research Institute of Electric Power Industry (CRIEPI), commissioned by the Ministry of International Trade and Industry, is carrying out the demonstration test and research program of buckling of FBR (FY1987~), which is preparing the seismic buckling design guideline of FBR (Akiyama et al., 1989). A tentative draft of the guideline was prepared in FY1989 (Akiyama et al., 1991). As one of the keys of the design rationalization, it used the nonlinear response reduction concept, which reduces the seismic design load expecting the seismic response reduction caused by the plastic energy absorption prior to buckling (Hagiwara et al., 1989; Kawamoto et al.,. 1989; Nakagawa et al., 1989). For the conventional reactor building, excluding those buildings with any seismic isolation devices, the draft guideline require a set of equations for the prevention of the plastic shear/bending buckling with the form of Eq. (1). In the equation, the response reduction factor which reduces the seismic load evaluated by the linear seismic analysis is introduced.

$$D_s C \alpha \frac{Q_i}{Q_{al}} < 1 \qquad (1)$$

where, D_s = response reduction factor, C = response amplification factor by vertical seismic loading, α = load safety factor, Q_i = seismic load evaluated by linear seismic response analysis, Q_{al} = allowable buckling load.

D_s is defined by following ratio of the loads under the seismic motion amplitude when the elasto-plastic buckling occurs to the structure.

$$D_s = \frac{\text{the load actually applied when the buckling occurs}}{\text{the load evaluated by the linear analysis}} \quad (2)$$

Each term in Eq. (1) is evaluated by following equations.

$$D_s = \frac{1}{\mu} \quad (3)$$

$$Q_{al} = \frac{Q_{cr}}{\nu} \quad (4)$$

where, μ = nonlinearity factor, Q_{cr} = buckling load, ν = strength safety factor.

The nonlinearity factor μ is defined by Eq. (5), and evaluated by an empirical expression, Eq. (6).

$$\mu = \frac{\delta_{cr}}{\delta_e} = \frac{\delta_{cr}}{Q_{cr}/k_0} \quad (5)$$

$$\mu = 1 + 1.5\, exp\left(-8 \frac{S_y}{E} \frac{R}{t}\right) \quad (6)$$

where, δ_{cr} = buckling displacement, δ_e = displacement when a linear system reaches buckling load, k_0 = initial stiffness, R / t = radius / thickness, S_y / E = yield stress / Young's modulus.

Equation (1) is a direct application of the well-known nonlinear response reduction concept (Veletsos and Newmark, 1960), disregarding the factor C which expresses the contribution of vertical seismic loadings to the horizontal response (Akiyama et al., 1991). μ is an equivalence of the ductility factor in the general seismic design methodology.

Attentions should be paid in applying the response reduction concept to the nuclear facilities, because it was originally developed for the seismic design of general buildings. The first particular consideration is on the damping factors. Equation (3) implies the equivalence of displacement between the nonlinear system and the linear system. This displacement-equivalence is usually applicable to the structures that have relatively lower natural frequencies. Though the fundamental natural frequencies of the reactor vessels of FBR are not so low (typically 6~7 Hz in Japanese demonstration FBR), the applicability of Eq. (3) have been confirmed by the dynamic buckling tests, the pseudo dynamic buckling tests and the numerical analyses performed in the research program (Kawamoto et al., 1991; Kokubo et al., 1991; Hagiwara et al., 1991). The remarkable response reduction was caused by the small damping factors established or assumed in the tests and the simulations, referring to the damping factor $h = 0.01$ practiced in the design study of Japanese DFBR. Riddell and Newmark studied on the effect of damping on the response reduction and implies the Newmark's original response reduction is appropriate for $h = 0.05$, but too conservative for smaller damping factors (Riddell and Newmark, 1979; Rockwell International / EPRI, 1990). " $1/\mu$ " shows similar values to the Riddell-Newmark's damping dependent reduction factor for the damping factors smaller than 0.02.

The second problem for the application of the nonlinear response reduction, which is the main topic of this paper, is the spectral characteristics of the floor responses of the nuclear facilities. Because of the resonance of the reactor buildings, there usually exist "peaks and notches" on the floor response spectra (FRS) even after any spectrum broadening. When the fundamental natural frequency of a structure "falls" down into one of the notches of FRS, the response reduction factor may not be conservative any more, because the inelastic responses are generally determined by the spectral characteristics at the considerably lower frequency than the linear natural frequency. Though one of the effective measure for this problem might be the introduction of the equivalent linearization, it requires iterative procedures or pre-defined rules for the equivalent frequency/damping, which would force designers to perform a full set of special seismic analyses only for the buckling prevention, adding to the analysis for the evaluation of the primary stress. One of the other measures may be explicitly require to "fill" the notches to eliminate them, however, it may cause excessive conservatism.

In this paper, a new expression of the response reduction factor is presented, for the conservatism in the application to the FBR buckling problem. At first, results of preliminary analyses and the proposal of the new expression are discussed. Then, results of dynamic buckling tests of cylindrical shells, and numerical analyses is presented, which shows the applicability of the proposed method.

2. PRELIMINARY ANALYSES AND THE PROPOSED RESPONSE REDUCTION METHOD

2.1 The conditions of the analyses

In order to improve the expression of the response reduction factor, certain spectral characteristics of seismic excitation have to be incorporated into the expression. In this preliminary analyses, the acceleration amplification factor is selected for the key parameter, and its relation to the response reduction was examined through nonlinear SDOF simulations .

Two nonlinear SDOF models of pre-buckling nonlinear response of reactor vessels were prepared, one for the shear-buckling with $\mu = 1.5$ and the equivalent damping factor $h_{eq} = 0.093$, the other for the bending-buckling with $\mu = 2.0$ and $h_{eq} = 0.205$. The skeleton curves and the hysteresis rules were decided from the examination of the pseudo-dynamic buckling tests of cylinders (Hagiwara et al., 1991). The fundamental natural frequencies were 6.5Hz and the damping factors were 0.01 for both models.

In order to examine the response reduction rules, particular seismic excitations that the old expressions Eq. (3) would not be conservative were necessary. 50 simulated seismic time histories were generated from Kanai-Tajimi spectrum for the purpose. The peak frequency of K-T spectrum were set at less than 6.5Hz for most cases. Ohsaki's envelope functions for magnitude 7 and 8 were used to get the time histories.

2.2 Acceleration amplification factor

The acceleration amplification factor is defined as follows.

$$\text{Acceleration amplification factor}: \frac{S_A(T_0)}{ZPA} \qquad (7)$$

where, $S_A(T)$ = acceleration response spectrum at period T (in this study, with damping $h = 0.01$), ZPA = Zero Period Acceleration of $S_A(T)$ ($= S_A(0)$) or the maximum value of the acceleration time history of the seismic excitation.

Obviously, the acceleration amplification factor is large at the peaks of FRS and small at the notches. It implies the potential of the response reduction at each frequency, and is expected to have certain relations to the response reduction factor D_s. $D_s \cdot (S_A(T_0)/ZPA)$ means the actual acceleration amplification factor of a nonlinear system. It is a preferable feature of the acceleration amplification factor that it is easily determined from FRS in the practical application.

2.3 The proposed expression of the response reduction factor

Figure 1 shows the results of the simulations. Eq. (3), $D_s = 1/\mu$, is not conservative in some cases as intended. $ZPA/S_A(T_0)$ has good correlation with D_s. Figure 1 also shows three lines which indicate $a = D_s \cdot (S_A(T_0)/ZPA) = 1, 2, 3$, and a is smaller that 2 in most cases when $D_s > 1/\mu$. Based on the numerical results, following expression was proposed. Figure 2 shows the response reduction factor D_s determined by Eq. (8) as the function of $S_A(T_0)/ZPA$.

$$D_s = \begin{cases} 1/\mu & ; S_A(T_0)/ZPA \geq 2\mu \\ 2\,ZPA/S_A(T_0) & ; 2 < S_A(T_0)/ZPA < 2\mu \\ 1 & ; S_A(T_0)/ZPA \leq 2 \end{cases} \tag{8}$$

3. DYNAMIC BUCKLING TESTS

3.1 Objectives

In order to collect knowledge on the dynamic buckling problem under seismic excitation, dynamic buckling tests using a shaker table were performed. In this chapter, the test results regarding the nonlinear response reduction and the effect of the seismic motion characteristics is summarized in order to confirm the applicability of the proposed expression of the response reduction.

3.2 Test conditions

The test apparatus is an idealized nonlinear SDOF system which includes a cylindrical shell and a large mass connected to the shell (Fig. 3) . Three kinds of test models were prepared, which have non-dimensional geometry similar to the reactor vessels of FBR. The material of the models are aluminum alloy, A3003P-O, whose material characteristics under room temperature is similar to SUS304/316's under the operating temperature of FBR, regarding the yield stress / Young's modulus ratio and the strain hardening characteristics (Table 1). The large mass (weight : 5.2 t) is supported on linear bearings with negligible friction, and connected to the upper flange of the test model with a load cell inserted. The lower flange of the model is fixed to the base plate of the test apparatus with a stiff supporting cylinder.

The test apparatus was anchored to the dynamic buckling test facility, that is a electrohydraulic one-dimensional (horizontal) shaker table specially prepared for these tests, and the dynamic buckling tests with seismic excitation were performed. Two seismic motions were used in the tests. ENVELOPE is an simulated seismic motion whose spectrum envelops a several FRSs calculated for an assumed hard rock site and half-embedded reactor buildings. FR4 is a floor response for an assumed relatively-soft rock site and a surface-mounted reactor building. The frequencies of the reactor vessels were assumed to be 6.5 Hz in all conditions, and the time axes of the seismic motions were scaled in order to the model-mass SDOF systems' natural frequencies (14.3~18.5Hz) correspond to 6.5Hz under the scaled time. ENVELOPE, in the original time scale, has high $S_A(T_0)/ZPA$ at 6.5 Hz and longer duration. On the contrary, FR4 has low $S_A(T_0)/ZPA$ and shorter duration. Figure 4 shows the time histories and the acceleration response spectra of the seismic motions (as well as the other seismic motion TK4 used in the chapter 4, to save space) for the original time scale.

Table 2 shows the test conditions. For each condition, 3~4 models were prepared, and an incremental excitation for one of the models was performed at first to know the trend of response under different excitation amplitude. Then, for each of the remaining 2~3 models, low-amplitude excitation was performed at first to know the linear response characteristics of the system, and finally high-amplitude excitation was performed to cause buckling on the model.The acceleration and the displacement responses of the model, the mass and the table, and the load were measured in each test. The strain distribution on the model was also measured.

3.3 Test results

Figure 5 shows the typical load-displacement relations of the models with $R/t = 100$ (AL100) measured in the dynamic buckling tests. Remarkable hysteresis was observed in each test. In the both tests shown in Fig. 5, bending buckling occurred at the bottom of the cylinder, and the elephant-foot type bulge appeared. In the case of the models with $R/t = 200$ (AL, AL200), shear-buckling appeared around the shells' both sides. In the case of $R/t = 156$ (AL156), the bending buckling appeared at first, then followed by shear deformation.

For all tests, the response reduction was observed. However, as expected, the response reduction factor D_s was not smaller than $1/\mu$ (Eq. (3)) in some cases, especially in the cases using FR4 as excitation. Figure 6 shows typical results on the response reduction effect, one for " $D_s = 1/\mu$ " is conservative , and the other is not.

3.4 Applicability of the proposed response reduction factor

Based on the test results, the applicability of the proposed expression of the response reduction factor (Eq. (8)) was examined. Figure 7 shows the comparison of the load actually applied to the cylindrical model, the load evaluated by the old expression of the response reduction factor ($D_s = 1/\mu$; Eq. (3)) and the lower limit load in the new expression (Eq. (8)), $Q_i \cdot 2ZPA/S_A(T_0) =$ Weight $\cdot ZPA \cdot 2$. Consequently, " $D_s = 1/\mu$ " with μ determined by the tests was not conservative in 3 cases out of 5, and in 1 case with μ determined by Eq. (6). However, the new expression Eq. (8) (with Eq. (6)), was always conservative because of the limitation of D_s based on the acceleration amplification factor.

4. NUMERICAL ANALYSES

4.1 Objectives

Nonlinear SDOF numerical analyses were performed in order to reconfirm the applicability of the proposed expression of the response reduction factor under various seismic excitation conditions.

4.2 Numerical Models

The numerical model used here is the Ramberg-Osgood (R-O) model modified by Jennings for nonlinear seismic analysis (Jennings, 1964). According to Jennings, the skeleton curves are expressed by following equation. The hysteresis rule is defined by the Masing rule.

$$\frac{\delta}{\delta_0} = \frac{Q}{Q_0}\left[1 + \alpha \left|\frac{Q}{Q_0}\right|^{\gamma - 1}\right] \qquad (9)$$

where, δ/δ_0 , Q/Q_0 = non-dimensional displacement and load, α , γ = arbitrary positive constant.

R-O model was confirmed to be applicable to the pre-buckling nonlinear response of cylinders through comparisons with the dynamic buckling tests shown in the previous chapter. In this analyses, the arbitrary constants $\alpha = 0.25$ and $\gamma = 7$ were used , which give good approximation of the test results.

The analyses were performed for the natural frequencies, 4.5Hz, 5Hz, 5.5Hz, 6Hz, 6.5Hz, 7Hz; which covers the region of the fundamental natural frequencies of the reactor vessels. The viscous damping factor was 0.01. In the analyses, the seismic motions stated below with arbitrary amplitude were applied to the models, and the nonlinearity factors μ were reversely determined from the load and the displacement response after the analyses.

4.3 Seismic motions

Two seismic motions FR4 (see section 3.2) and TK4 were used for the simulation. The time histories and the spectra were already shown in Fig. 4. TK4 is a floor response for an assumed hard rock site and a half-embedded reactor building. It has steep peaks and notches on the acceleration spectrum. Both TK4 and FR4 have notches at 6 ~ 6.5 Hz on their spectrum, and their $S_A(T_0)/ZPA$ at the frequencies are so low (= 2 ~ 3) that $D_s = 1/\mu$ (Eq. (3)) would not be conservative. The overall range of their $S_A(T_0)/ZPA$ is 2 ~ 9 for TK4 and 2 ~ 6 for FR4 between 4.5Hz and 7Hz.

4.4 Results

Figure 8 shows the results of the simulations on the response reduction factors for the two seismic motions. The solid bold curves in the figure show $1/\mu$, the old expression of the response reduction factor D_s. Some numerical results with the natural frequencies between 6 Hz and 7 Hz give D_s larger than $1/\mu$. The figures also shows horizontal thin lines, which indicate " $2\,ZPA / S_A(T_0)$ " for the natural frequencies stated right of the figures. According to the new expression of D_s (Eq. (8)), the " $2\,ZPA / S_A(T_0)$ " gives the limitation of D_s. The almost all plots of D_s have smaller values than " $2\,ZPA / S_A(T_0)$ ", with only a few exceptions which have values slightly larger than the new expression. Consequently, the conservatism of the new expression was confirmed by these results.

5. CONCLUSIONS

The new expression of the nonlinear response reduction factor was proposed for the application to the anti-buckling design of FBR reactor vessels under seismic loadings. The new expression is a simple modification of the conventional response reduction concept practiced in most building seismic design codes, with special attention on the spectral characteristics of the nuclear facilities' floor response. It is easy to incorporate the new method into the current seismic design methodology of the nuclear facilities, because only the acceleration amplification factor, which can be determined from FRS, is used to modify the ductility-based reduction factor. The conservatism of the new method was confirmed through the examination of the dynamic buckling tests and the numerical simulations.

ACKNOWLEDGMENT

This study was carried out as part of the project of the Ministry of International Trade and industry, titled "Verification Tests of Fast Breeder Reactor Technology", which has been conducted since 1987.

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

Hagiwara, Y., et al. 1989. Post buckling behavior during earthquakes and seismic margin of FBR main vessels. ASME PVP - Vol. 175. : pp. 91 ~ 96

Kawamoto, Y. et al. 1989. Buckling behavior of cylindrical shells under seismic loading. ASME PVP - Vol. 175. : pp. 97 ~ 104

Nakagawa, M., et al. 1989. Post buckling behavior of short cylindrical shells under lateral seismic loads. SMiRT-10. Vol. E. : pp. 235 ~ 240

Veletsos, A. and Newmark, N. M. 1960. Effect of inelastic behavior on response of simple system to earthquake motions. Proc. of 2nd WCEE : pp. 895~912

Kawamoto, Y., et al. 1991. Reduction of seismic responses of shell structures with nonlinear deformation characteristics. SMiRT-11. Vol. E. : pp. 257 ~ 262

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

Hagiwara, Y., et al. 1991. Dynamic buckling and nonlinear response of FBR main vessels under earthquake loading. Proc. of the 1st JSME/ASME joint international conference on nuclear engineering. Vol. 1. : pp. 601~606

Newmark N M. and Riddell, R. 1979. A statistical study of inelastic response spectra. Proc. of 2nd U. S. national conference on earthquake engineering. : pp. 495~504

Rockwell International / EPRI. 1990. A simplified inelastic seismic analysis method for piping systems. EPRI Report NP-6809.

Jennings, P. C. 1964. Periodic response of a general yielding structure. Proc. of ASCE. Vol. 90. No. EM2. : pp. 131~166

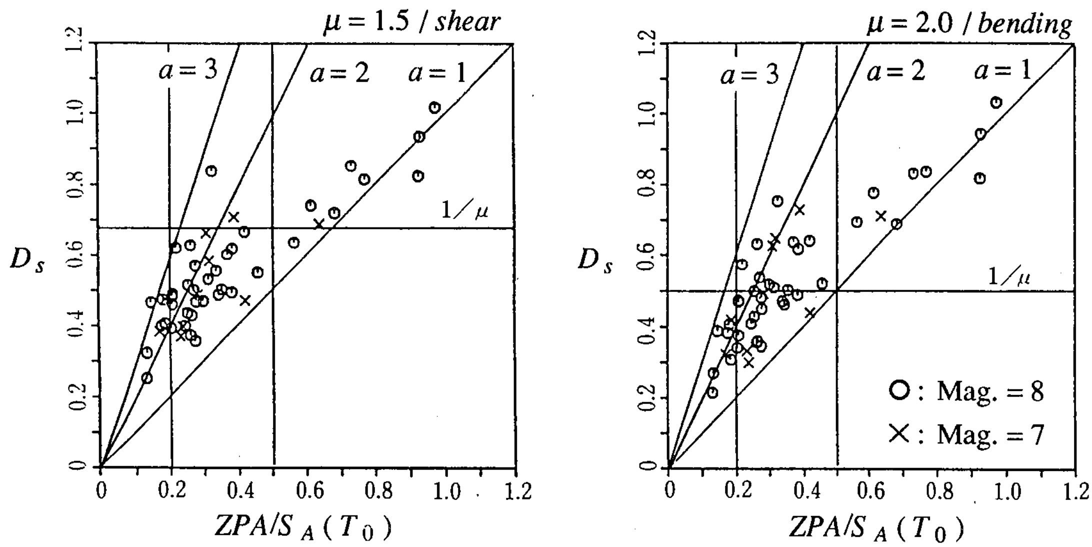


Fig. 1 Results of the preliminary analyses ($a = D_s \cdot (S_A(T_0)/ZPA)$)

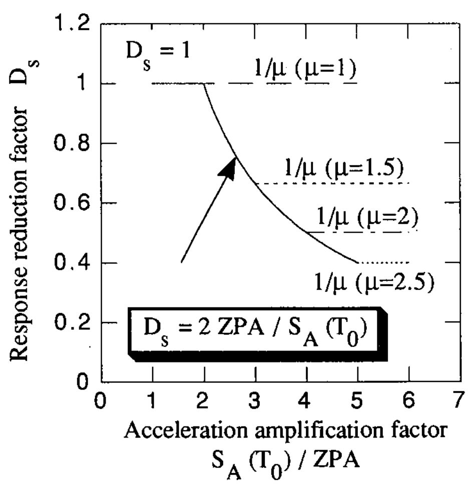


Fig. 2 Proposed expression of the response reduction factor

Table 1 Aluminum alloy cylindrical models for the dynamic buckling tests

Model			AL	AL200	AL100	AL156
Diameter	$2R$	mm	635	635	500	500
Thickness	t	mm	1.6	1.6	2.5	1.6
Length	L	mm	320	320	375	375
Height of Load. Pt.	H	mm	480	480	535	535
Young's Modulus	E	kgf / mm^2	6600	6850	6800	6850
0.2% offset stress	$\sigma_{0.2}$	kgf / mm^2	4.5	4.4	4.0	4.4
$(R / t) \cdot (\sigma_{0.2} / E)$			0.135	0.127	0.059	0.100
Dominant buckling mode			shear	shear	bending	bending

Table 2 Test conditions of the dynamic buckling tests

Name	Model	Excitation	No. of models
AL/ENV	AL	ENVELOPE	3
AL200/FR4	AL200	FR4	4
AL100/ENV	AL100	ENVELOPE	4
AL100/FR4	AL100	FR4	4
AL156/ENV	AL156	ENVELOPE	4

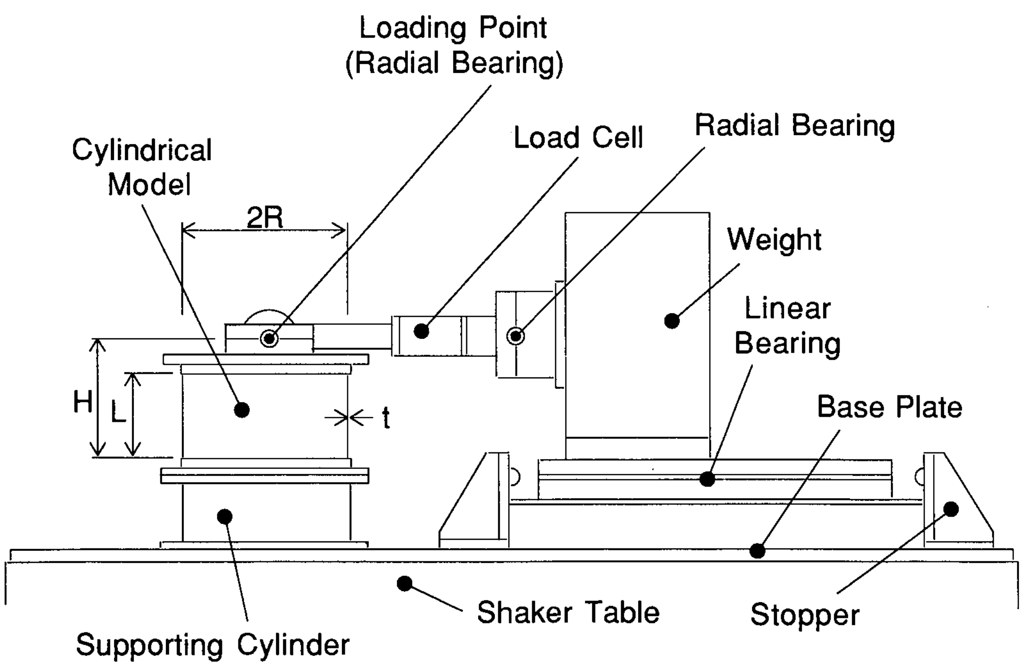
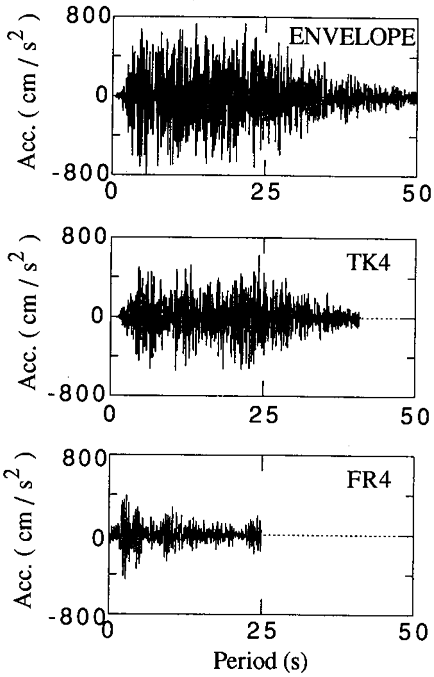
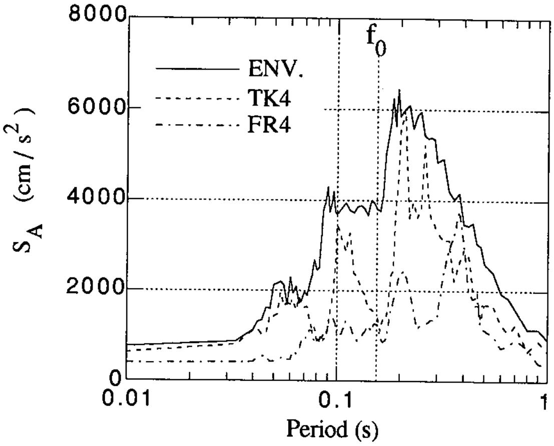


Fig .3 Test apparatus of the dynamic buckling test



Accerelation time histories



Acceleration response spectra

Fig. 4 Seismic Motions

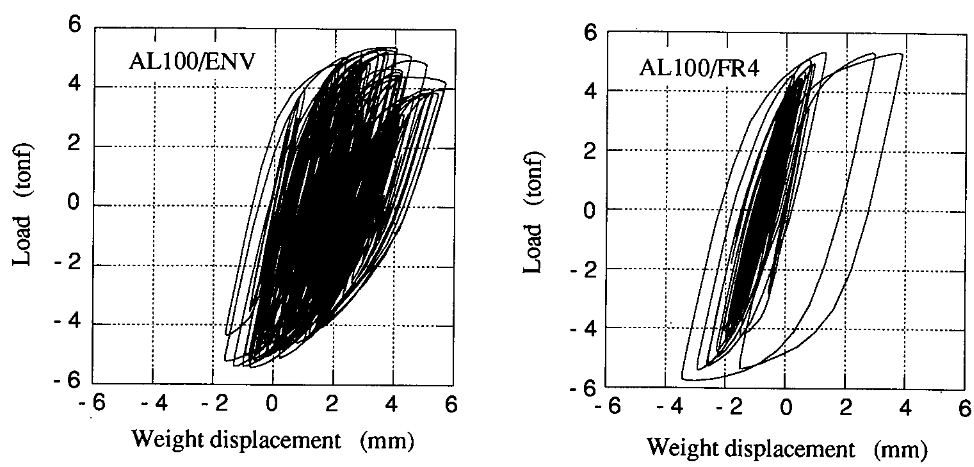


Fig. 5 Load-displacement relations in the dynamic buckling tests

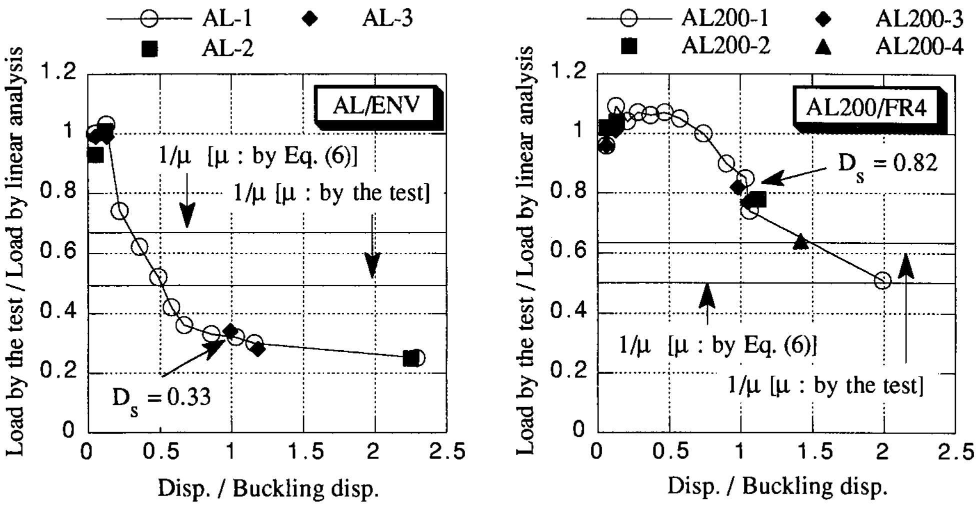


Fig. 6 Response reduction effect in the dynamic buckling tests

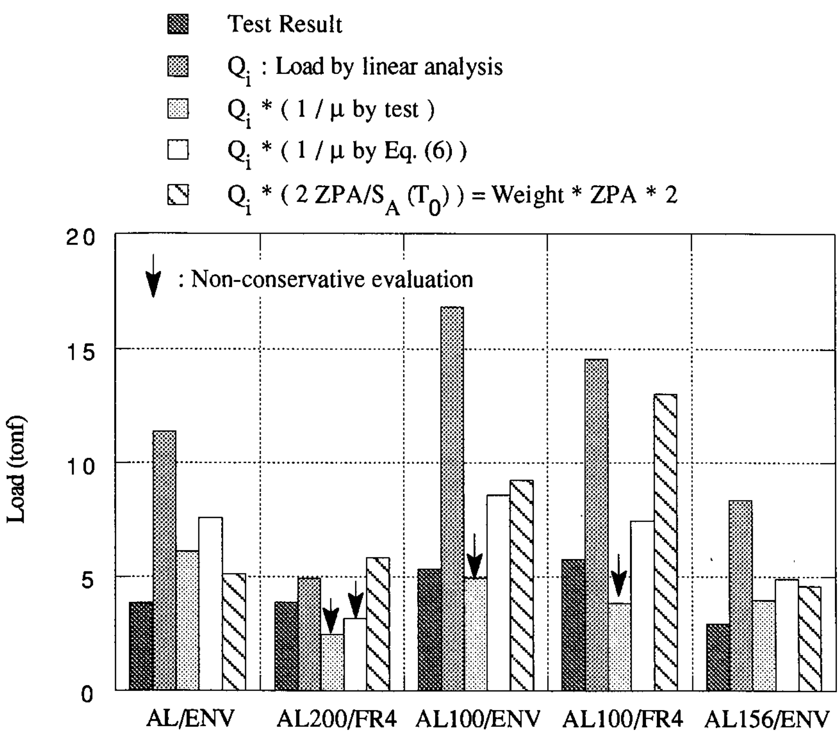


Fig. 7 Buckling load evaluation of the dynamic buckling tests

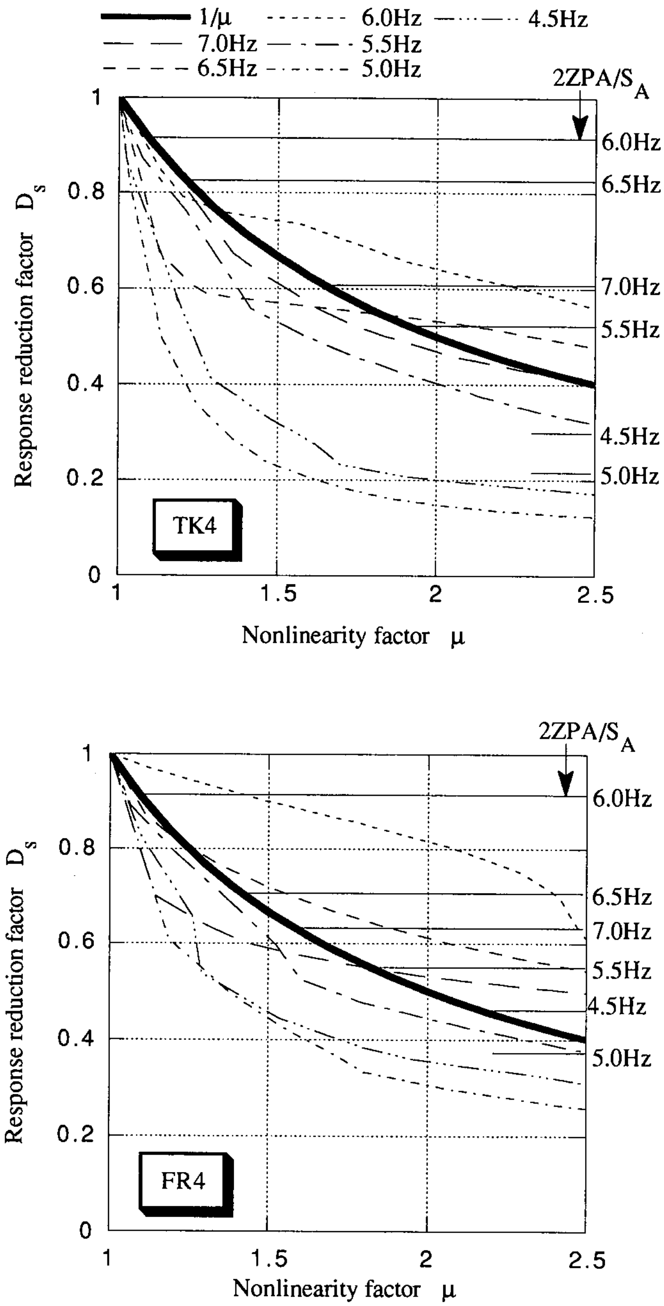


Fig. 8 Response reduction factor by formula and analysis