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Estimation of post-buckling fatigue damage for LMFBR reactor vessel under seismic load

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1 INTRODUCTION

Estimation of fatigue damage caused by buckling deformation is important to evaluate safety margin in a seismic buckling design criterion for LMFBR reactor vessels, in addition to limiting the buckling strength. An advanced buckling design guideline draft including the seismic margin criterion has been proposed under the sponsorship of MITI to date. An ultimate state in this criterion was defined as the condition that the maximum global displacement δ_{max} reaches a critical displacement δ_u.

The authors have previously proposed an estimation method of the fatigue damage based on the post-buckling fatigue tests with 304 s.s. cylinders at room temperature. However, adoption of a modified 316 s.s. named 316FR s.s is under development as the material of reactor vessel of the updated design of the Demonstration Fast Breeder Reactor.

The buckling tests with 316FR s.s. cylinders were performed under high temperature to obtain the skeleton curve of the relation between load and displacement. And the buckling behaviors under the cyclic loading were compared with those of 304 s.s.

Objectives of the present study are :

(1) To apply the proposed estimation method to a reactor vessel made of 316FR s.s., and clarify the correlation between δ_{max} and fatigue failure.

(2) To verify structural soundness of the ultimate state derived from the seismic margin criterion against the fatigue failure due to the buckling deformation.

2 CYCLIC BUCKLING DEFORMATION OF FBR REACTOR VESSELS

Buckling modes of reactor vessels under horizontal seismic load are shear and/or bending type deformation on the cylindrical portion. The authors had peformed buckling tests with static approach using cylinders which corresponded to the cylindrical portion of the typical reactor vessels of FBR design concepts of Loop and Tank type, as shown in Table 1. The dominant buckling modes are depended on the material, cylindrical parameters as R/t or L/R and applied stress ratio of bending and shear which corresponds to H/R. In the previous tests with 304 s.s. cylinders[4], it had been clarified that the Loop type has bending mode as primary and shear as secondary coupled mode and the Tank type has typical shear mode with diagonal wrinkles. During cyclic loading cracks had been occured at the kinks derived from the coupled bending and shear deformation in the case of the Loop type model LB304 and at the cross points of transversed diagonal wrinkles in the Tank model TS304. LB304 had much less fatigue life because of the severer local deformation and strain as shown in Fig. 1.

The authors have also performed the buckling tests with 316FR s.s. cylinders at high temperature condition which simulated the actual plant of the current design of DFBR. Photographs of residual deformation of LB316-H is shown in Fig.2. The cylinders of both LB316-H and LB316-R buckled firstly with bulge as plastic bending mode near the fixed end of compression field and immediately superimposed by shear wrinkles as the secondary mode and they yielded very complicated and sever deformation due to cyclic loading as same as the previous tests with LB304-R. However, LB316-H at high temperature had slightly smoothed deformation overally compared with LB316-R at room.

Table 1 Parameters of Buckling Test Cylinders

ID of Test Cylinder	LB316-H	LB316-R	LB304-R	TS304-R
Temperature Condition	500℃	Room		
Material	316FR S.S.		304 S.S.	
Design Concept	Loop type			Tank type
Characteristic	Thicker and Longer			Thinner and Shorter
Buckling Mode	Bending and Shear			Shear
Radius/Thickness R/t	100			200
Length/Radius L/R	1.5			1.0
Loading Height/Radius H/R	2.0			1.0

3 CONSIDERATION ON APPLICATION TO 316FR S.S. CYLINDERS

(1) The dynamic buckling behavior

The global behaviors of reactor vessel, such as load and displacement, are controlled by static skeleton curve even in the seismic response. Skeleton based on the load-displacement hysteresis data from the tests with 316FR s.s. cylinders, as shown in Fig.3, was applied to the seismic analyses to simulate the displacement responses.

(2) The buckling mode

Residual deformation of 316FR s.s. cylinders was closely examined by 3-D measuring instrument with laser as shown in Fig.4. The circumferential waves were decomposed into Fourie numbers and compared with those obtained previously from 304 s.s. Figure 5 shows the comparisons between the two at room temperature and at high temperature for 316FR cylinders. These results showed that dominant wave numbers of both materials are almost same and deformation at high temperature had less magnitude than one at room temperature. The latter suggests local deformation and strain at room temperature are slightly severer than at high temperature.

(3) Fatigue curve

In the previous study, fatigue damage evaluation method was suggested based on fatigue failure tests with 304 s.s. cylinders. This method could well estimate amount of damage caused by buckling deformation using uni-axial fatigue curve. Accordingly, it is supposed that a difference of failure life depending on each material can be replaced by one of uni-axial fatigue life. On the other hand, uni-axial fatigue lives of austenitic stainless steels, such as 304 s.s., 316 s.s. and 321 s.s are almost same, and resultantly Wada et al.[3] made a best fit curve from a lot of fatigue data handled using statistics treatment. Another examination showed the best fit curve is applicable also for 316FR s.s. Therefore, this best fit curve was used in the present evaluation.

From these considerations, it is supposed that fatigue damage evaluation method based on test results with 304s.s. cylinders can be applied to reactor vessels with 316FR s.s. in the current designs.

4 APPROACH OF FATIGUE DAMAGE EVALUATION

Damage evaluation was conducted for the reactor vessel of the current Loop type design when maximum response displacement by seismic load reached the ultimate displacement δ_u fixed in the guideline draft as $\delta_u = \min.\{2\delta_{cr}, 5\delta_e\}$. The definitions concerning δ_{cr} and δ_e are shown in Fig.6. In this case, δ_u is limited by $5\delta_e$. Here, the Loop type was selected as much severer case than the Tank type from the previous results.[4],[7] The approaches were as follows.

(1) Seismic Response Analysis

Seismic response analyses were conducted with the nonlinear SDOF system model. Skeleton curve, which characterized nonlinear relation of load and displacement , and cyclic restoring rules were applied to the model as nonlinear spring. Earthquakes named TK4, CONST, ENVELOP waves were used for input accelerations. Response analyses were conducted with varying the magnitude of the input waves, as shown in Fig.7. In this diagram, A_{max} is the peak value of the input, and δ_{max}/δ_{cr} is the normalized peak of displacement response. The peak value of δ_{max} remarkably increases in the region above δ_u according to the increase of input acceleration.

On the other hand, displacement ranges, whose increase was not relatively so large compared with δ_{max} because of the meanvalue offset in the displacement responses after buckling as shown in Fig.8, are more important concerning the fatigue failure.

(2) Histogram Analysis

Histograms of the displacement range versus frequency were analyzed from the displacement response waves. Here, displacement range was divided into 40 ranked steps, and appearance frequency of each displacement range was counted by Rain-flow procedure.

Histogram of δ_{max}/δ_{cr} equal to 3 with ENVELOPE wave is shown in Fig.9.

(3) Calculation of the Usage Factor

Equivalent strain range correlated to each displacement range was established from the buckling test results in the previous study, as shown in Fig.10. Though this correlatioh was derived from the previous tests with 304 s.s. cylinders at room temperature, it was conservatively used for the present evaluation because of the above consideration. The number of cycles to failure of each displacement range was obtained through the best fit curve of uni-axial fatigue data at high temperature condition. Usage factor of fatigue damage was provided by general Minner's law, as shown in the following expression (1).

$$D_f = \sum_{i=1}^{40} \left(\frac{n_i}{N_{fi}} \right) \qquad (1)$$

Here, n_i and N_{fi} mean number of loading cycles and one of cycles to failure for i-th range, respectively.

N_{fi} was obtained from fatigue curve, as shown in Fig.11, through the correlation between displacement range and equivalent strain range.

5 RESULT AND DISCUSSIONS ON FATIGUE DAMAGE EVALUATION

The estimation values of Fatigue damage D_f were calculated at various magnitudes of δ_{max} for 3 input waves as shown in Fig.12. Here, abscissas denote both δ_{max} normalized by δ_{cr} and one by δ_e and D_f equal to unity means failure (wall breakage). From this diagram, it is clarified that D_f is negligible in the pre-buckling region ($\delta_{max}/\delta_{cr} \leqq 1.0$) and less than 0.1 even at the magnitude of δ_u (= 5 δ_e). Hence, fatigue damage at the ultimate state was supposed not to be significant. Limit state from the fatigue failure is also predicted from the diagram, as δ_{max} is at least over four times of δ_{cr}.

Fatigue damage by other load and heat cycles, which are estimated during run of reactor vessel, becomes very small for real damage, because safety factor of 20 is considered to the best fit curve in the current design. In this evaluation high temperature effect such as fatigue strength deteriorates by interaction of creep and fatigue was eliminated because a wall cooling system is adopted for reactor vessel in the current design and it does not really reach creep temperature.

It is thought that the ultimate displacement δ_u fixed in the seismic margin evaluation of the guideline draft for buckling design can secure not only for dynamic unstabilty but also for the wall breakage by buckling deformation.

6 CONCLUSIONS

Buckling mode and load-displacement hysteresis of 316FR s.s. cylinders under the cyclic loading were similar to those of 304s.s.

The following characteristics were clarified from the correlation between D_f and δ_{max} :

(1) The critical displacement generating the fatigue failure is more than four times of the buckling displacement.

(2) The value of D_f remains very small in the range of δ_{max} below δ_u, and remarkably increases in the range above δ_u. Hence, it is concluded that the ultimate state sufficiently maintains the soundness against the wall breakage.

7 ACKNOWLEDGMENT

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Fig.1 Buckling Deformation of LB304-R (Front View)

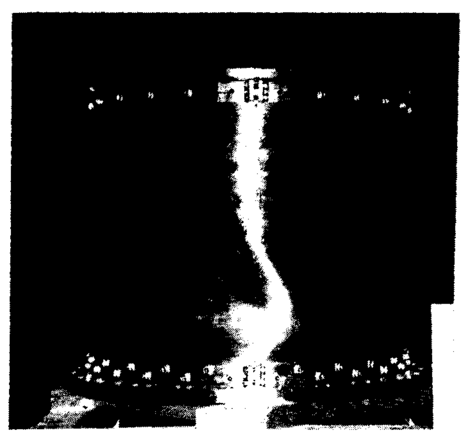


Fig.2 Buckling Deformation of LB316-H (Side View)

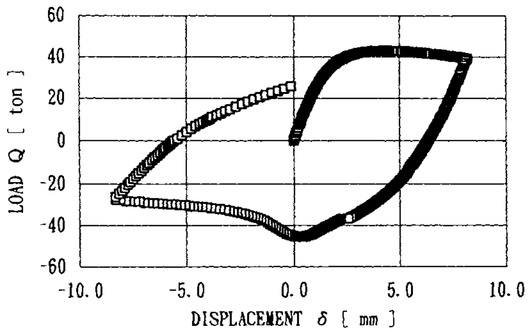
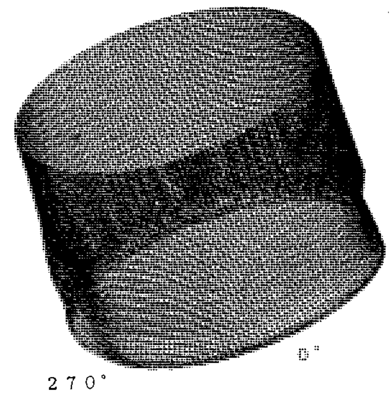
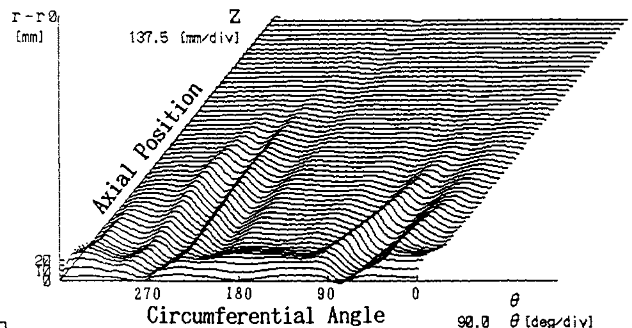


Fig.3 Load-Displacement Hysteresis of LB316-H

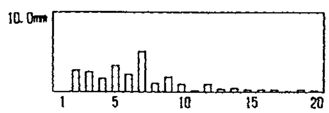


(a) 3D-View

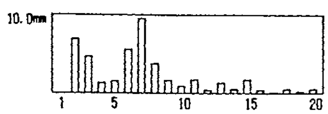


(b) Extension View

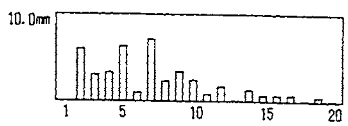
Fig.4 Buckling Deformation Measurement



(a) LB316-H



(b) LB316-R



(c) LB304-R

Fig.5 Wave Number Spectra of Buckling Deformation

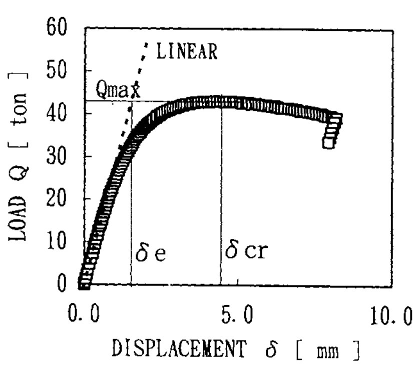


Fig.6 Definitions of δ_e and δ_{cr}

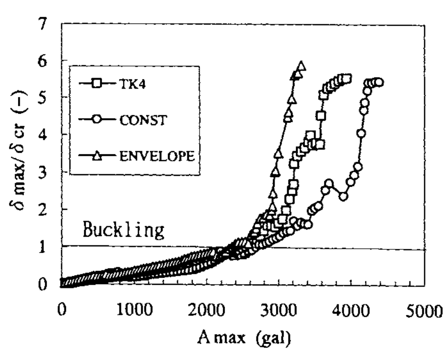
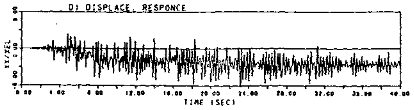
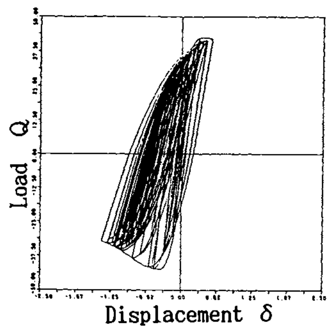


Fig.7 Relations between Max. Input A_{max} and Max. Response of δ



(a) Displacement Wave



(b) Load-Displacement Hysteresis

Fig.8 Seismic Responses after buckling (ENVELOPE, $\delta_{max}/\delta_{cr}=3$)

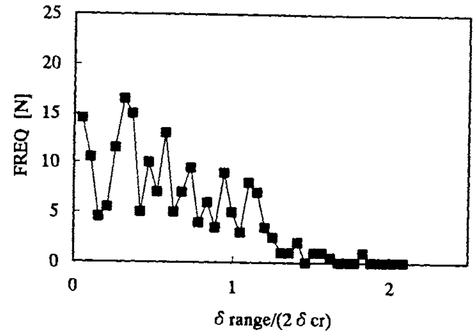


Fig.9 Histogram from Displacement Wave (ENVELOPE, $\delta_{max}/\delta_{cr}=3$)

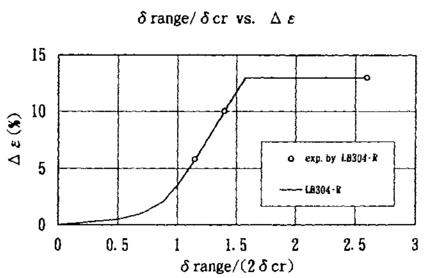


Fig.10 Relation between Displacement Range and Equivalent Strain Range

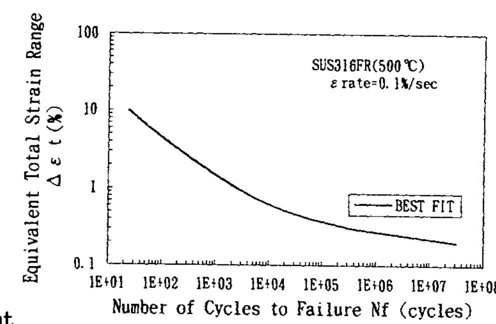


Fig.11 Uni-axial Fatigue Curve

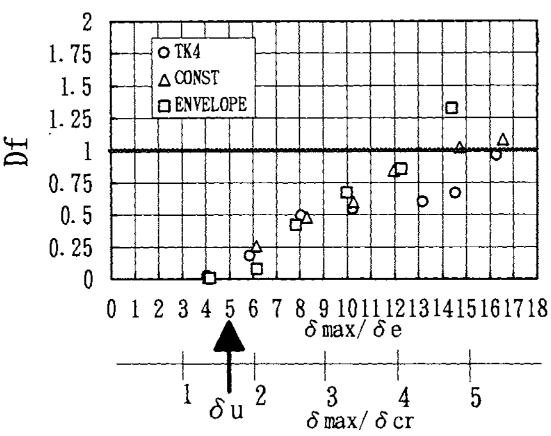


Fig.12 Fatigue Damage Evaluation According to the Maximum Displacement Responses