Test Results on Seismic Proving Test of BWR Core Internals

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1. INTRODUCTION

The seismic proving test presented this particular report has been conducted from 1986 to 1988 for the Boiling Water Reactor Core Internals (hereinafter, called as BWR-IC). This BWR-CI can be recognized as one of the most significant structural components in the 1100 MWe class of BWR nuclear plants.(1) This test has been conducted in accordance with the former paper titled as "the preliminary study" in this session.

The strength proving test was opened to the public to inform people inside and outside the country. The various test data required for i) verification of the adequacy of the seismic design analysis method, ii) proving the seismic strength of the test model, iii) evaluation of the design strength margin of the test model iv) the seismic safety and reliability, strength of BWR-CI and v) reliability of BWR control rod drive scrammability during S_1 and S_2 seismic waves, were obtained in this test.

This paper presents briefly the summary of the detailed analysis and evaluation for the experimental results obtained through particularly important test stage; strength proving test and marginal vibration test. Moreover, this report is one of the series papers.

2. RESULTS FROM PROVING TEST

The results in the strength proving test and marginal vibration test are described below.

2.1 STRENGTH PROVING TEST

The maximum response acceleration for the main components of the BWR-CI test model under biaxial simultaneous excitation and those under one directional horizontal excitation were compared, as shown in Fig.1. The result exhibited that the responses were not affected by the vertical excitation.

The relation between the test response stress, acceleration at the major measured points and table output acceleration showed an approximate linearity, as shown in Fig.1, and the behavior remains linear, even for the high acceleration levels corresponding to 1.5∿2.0 times the actual design value.

The maximum principal stress for the main components of the model for S_1 and S_2 earthquake wave were measured. The results showed that the all principal stress values were significantly lower than the allowable levels given by the seismic design standard and BWR-CI test model had sufficient strength to withstand seismic excitation having excess levels, as shown in Table.1.

The control rod insertion test with and without excitation for S_1 and S_2 earthquake wave gave the following results.(2) The measured delay time to the scram time without excitation was 0.01 sec for S_1 wave and 0.02 sec for S_2 wave.

Fig. 2 shows the 75% stroke scram time as a function of fuel channel relative displacement amplitude. The measured scram time was 1.21 sec during S_1 wave and 1.23 sec during S_2 wave, respectively. These scram time were less than the specified scram regular time of 1.62 sec. Therefore, it could be concluded that the control rod was inserted satisfactory during S_1 and S_2 earthquake excitation and BWR control rod drive scrammability had been sufficiently proved.

The vibration characteristics of the test model did not vary between tests with and without control rod insertion.

The inspection results for the opened test model, after the strength proving test, proved that abnormal phenomenon (damage or transformation on test model) had not been observed. From these results, the integrity of strength and the supporting capability were proved.

2.2 MARGINAL VIBRATION TEST

Marginal vibration test for the BWR-CI was carried out under the simultaneous S_2 earthquake excitation in the horizontal and vertical directions (horizontal: 19.49 m/s^2, vertical: 2.36 m/s^2, during 40 sec). This excitation results in a fuel channel deflection of $34x10^{-3}$(m). In this test, the acceleration level of the applied S_2 wave was 1.7 times that of S_2 seismic proving test and was almost at the performance capacity of the vibration table. For the BWR control rod scrammability test during the above excitation, it was confirmed that the CRD had sufficient scram performance. The scram time was 1.25 sec, 1.26 sec, respectively, in the case of over $30x10^{-3}$(m) to $34x10^{-3}$(m) amplitude of fuel assembly during huge earthquake.

These scram time were less than the specified scram regular time, 1.62 sec. Moreover, the measured scram time agreed with the calculation result. This agreement has indicated that the calculate method is reasonable.(2)

On the other hand, it was found that the scram time, even on the condition of the 1.7 S_2 wave, was sufficiently under the specified scram regular time for no vibration scram time. Consequently, from these tests and analysis, it was confirmed that the CRD had sufficient scram performance during earthquakes.(2)

The maximum principal stress for the main components of the test model was $16.0x9.80655x10^6$ pa. which was lower than the allowable $43.2x9.80655x10^6$ pa. stress intensity value.

The post test inspection results for the opened BWR-CI test model did not show any abnormality, from the view points of the supporting integrity.

2.3 BWR-CORE AND FUEL ASSEMBLIES VIBRATION CHARACTERISTICS

Fiber scope was used to visually observe the fuel assembly behavior during earthquake excitation in this test. These observation confirmed that the groups of the fuel assemblies were excitated in the same phase during all of the test cases. It was also observed that the gap width between the fuel channel remained almost uniform.

Comparisons were made between the overlapped time history displacement waves of the fuel assemblies located at the different position in the core to confirm the same phase movement by the magnified wave time history, as shown in Fig.3. The examination by analytical magnified figure for the presented overlapped waves, respectively, were conducted. From these comparison and these observation by fiber scope, it could be concluded that the fuel assemblies were excitated in the same phase and their vibrational amplitudes were similar, regardless of their position in the core. Then, from response distribution results, as shown Fig.4, a group of fuel assemblies had one predominant vibration frequency.

Fig. 4 indicates the measured natural frequency for the fuel assembly in relation to the response displacement. These frequencies are based on results obtained from the sinusoidal wave sweep test and earthquake wave vibration test. The natural frequency showed a slight increasing tendensy, as the fuel assembly displacement increases in the region under 10mm. However, it was concluded that the natural frequency of fuel assembly was constant in the 4.7-4.8 Hz range over

the entire region of the large displacement. The analyzed result, indicated by the broken line, is 4.7 Hz and closely coincided with the experimental values. (3) At this frequency, the lateral vibration mode for the fuel assembly coincided with the first mode for a beam with simple supported ends. These results were one of the successful test results, as the actual size test model.

The modal damping ratio, estimated by various data and methods, were larger than the current design value, as shown in Table 2. This table indicates the estimated damping ratio determined by the Curve Fit Method (CFM). CFM can be used to evaluate comparatively accurately, for the presence in the same frequency component of the test model response wave as that of the input wave. Especially, damping ratio of the fuel assembly accurately corresponded with the theoretical damping ratio estimated firstly for the full-scale core test model, as an actual size. Therefore, this was one of the successful test results.(3) This estimated damping ratio was applied to the simulation analysis.

3. CONCLUSION

In this paper, simulation analysis results are abbreviated, but they agreed approximately well with test results as reporting in the last presented paper in this session.

The results of the seismic reliability proving test can be summarized concretely as follows:

3.1 TEST RESULTS EVALUATION

[1] The structural integrity for the BWR-CI test model was verified the sufficient margin in strength. The functional integrity was confirmed for S_1 and S_2 earthquake wave and for more severer earthquakes up to 1.7 S_2.

[2] The control rod scrammability function capacity was also confirmed to be maintained during S_1, S_2 wave and 1.7 S_2 excitation.

[3] Abnormalities were not found, in the inspection. Core Internals supporting function capacity were maintained under the seismic motion.

[4] The following vibrational behaviors of the fuel assemblies were observed. That is, i) fuel assemblies moved in the same phase, ii) the lateral vibration mode of fuel assemblies coincided with the first mode of a simply supported beam at both ends, iii) the vibrational displacement amplitude of fuel assemblies was uniform, regardless of their position in the core.

These results indicate that the assumption on the seismic analysis of the BWR core is reasonable, i.e., a group of fuel assemblies can be replaced with single elastic beam in consideration of the fluid interaction.

Then, the above results are the first successful one in the world, as the actual size model.

REFERENCE

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(2) H.Sato, K.Suzuki, T.Ohno and Y.Watanabe, et.al., (1989) "BWR CONTROL ROD DRIVE SCRAMMABILITY DURING EARTHQUAKES". The ASME 1989 PVP Conference - JSME Co-sponsorship.

(3) Y.Aida, H.Niwa, Y.Sasaki, M.Nakajima and T.Taira., (1989) "VIBRATION ANALYSIS OF BWR CORE FUEL ASSEMBLY", The ASME 1989 PVP Conference - JSME Co-sponsorship.

Table.1 Max Principal stress value

Unit: ×9.80665 ×10⁶ Pa

Test contents / Items / Main Component	Proving test			Marginal vibration test	S_2 wave
	S_1 wave		S_2 A wave	S_2 B wave	
	measured principal stress	allowable value $P_m + P_b$	measured principal stress	measured principal stress	allowable value (reference) $P_m + P_b$
Top Guide (Grid)	7.8	27.0	8.9	16.0	43.2
Fuel aseembly (Channel Box)	6.5	30.5	7.9	13.3	40.7
Shroud	7.5	28.3	13.9	12.3	45.3
Shroud Support	4.7	37.6	8.4	6.8	55.9
		28.3			45.3

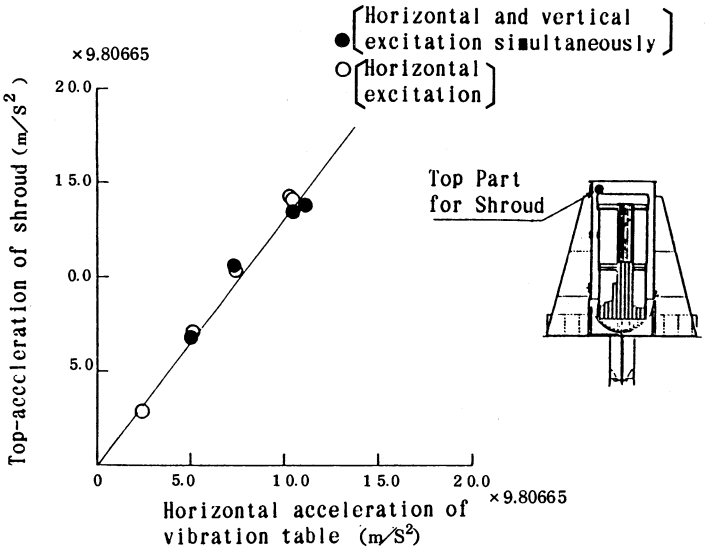


Fig.1 Linear response characteristics(input level vs response) (at S_2 A Wave excitation)

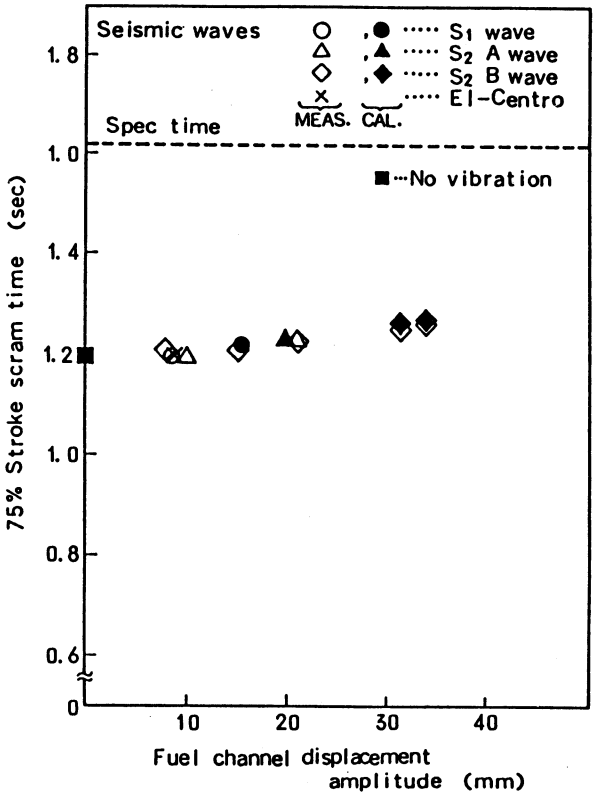


Fig.2 Predicted and experimental result for scram time

Comparison of absolute displacement by over-lap method between CH 73 and CH 47 of fuel assembly obtained by S_1 wave excitation test

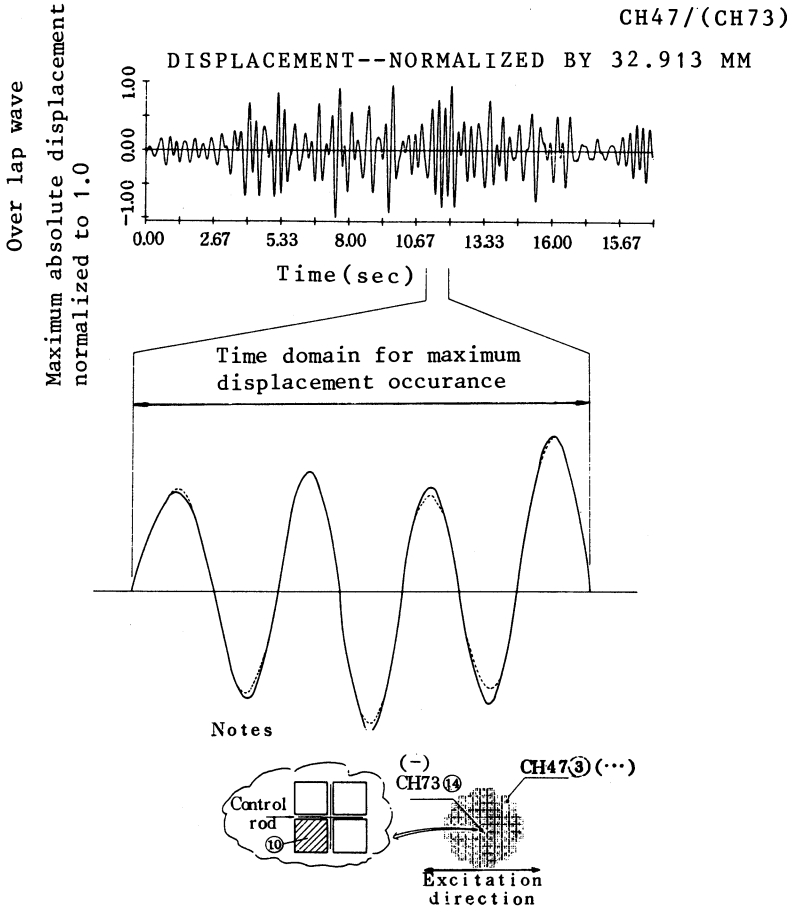


Fig.3 Magnified wave for over-lap wave

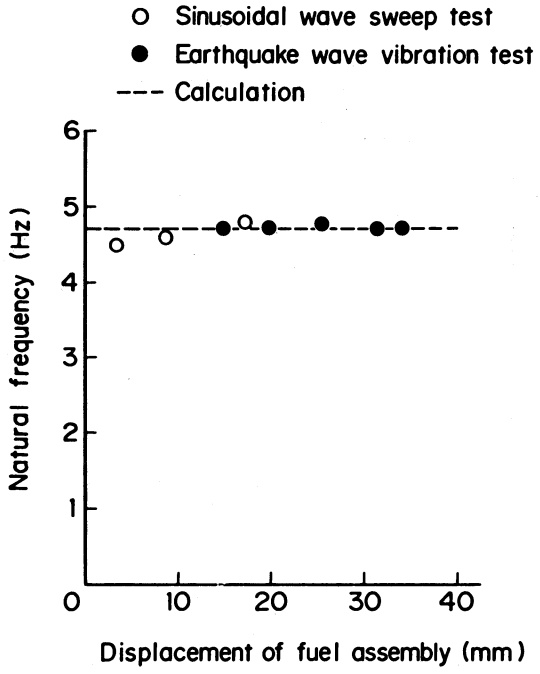
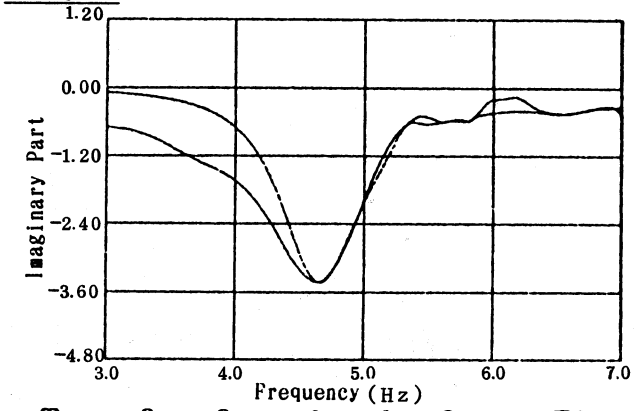


Fig.4 Effect of displacement response on natural frequency of fuel assembly

Table.2 Damping ratio and natural frequency
(Curve Fit Method)

Item / Input wave	Fuel Assembly		Shroud		Control rod guide tube	
	Natural frequency (Hz)	Damping ratio (%)	Natural frequency (Hz)	Damping ratio (%)	Natural frequency (Hz)	Damping ratio (%)
EL. Centro Wave	4.5	10.2	8.1	3.8	15.8	3.5
1.1 S_1 Wave (H+V)	4.7	7.8	8.4	3.8	16.8	4.5
1.25S_2 A Wave (H+V)	4.6	8.9	8.2	3.5	16.6	3.9
1.55S_2 B Wave (H+V)	4.8	8.0	8.2	2.4	16.3	3.8
1.7 S_2 B Wave (H+V)	4.8	8.2	8.3	3.6	16.3	3.5

Sample



Transfer function by Curve Fit Method for 1.7 S_2 B wave
◎ Evaluation : Natural Frequency 4.7Hz. Damping ratio 8.4%