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Overview of Nuclear SSCs Seismic Fragility Test 1 : Electrical Panel and Pump

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ABSTRACT

Now nuclear power is playing important role as precious carbon free energy source in worldwide and overview of seismic fragility evaluation for major SSCs of nuclear power plant, how done and acquired results, might be useful for young engineers and new commers. Overview of seismic verification tests to design level were already discussed by reference papers [1] and [2] at SMiRT25. The paper discusses seismic fragility capacity evaluation test acquired fragility data which is now contributing to Seismic PRA in Japan, on Electrical Panel and Pump. Companion paper [3] "Overview of Nuclear SSCs Seismic Fragility test 2" covers Control Rod Insertion.

1. INTRODUCTION

Japan is located in one of the world's highest seismicity areas and seismic safety of Nuclear Power Plants (NPPs) has been one of the key issues related to nuclear safety. Nuclear Power Engineering Corporation (NUPEC) and subsequently Japan Nuclear Energy Safety Organization (JNES), both established by Ministry of Economic Trade and Industry (METI), conducted seismic verification tests to Design Basis Ground Motion(DBGM),for major Structure, System and Components(SSCs) of 1100Mw class PWR and BWR plants during 1981~2002, using the then world's largest shaking table located at Tadotsu in Shikoku, on test model of real or close to real scale. Refs [1] and [2] introduce outline of these tests for piping and heavy components.

Now, Seismic PRA is important tool to evaluate seismic safety of NPPs quantitively in beyond DBGM region. Japanese guide for Seismic PRA is established as Ref. [4], in addition to the deterministic seismic safety evaluation guide Ref. [5] based on the previous capacity data shown in Ref. [6]. To contribute to development of seismic PRA in early stage, JNES conducted trial seismic PRA on four NPPs and screened out test specimens by evaluating Fusel-Vesely values as shown in Fig.1 and conducted fragility tests on screened out components in following steps.

Step 1 : Electrical panel and pump, enhancing vibration table ability up to 6 G* (2002~2004)
*G : Gravity acceleration, 9.8m / s^2

Step 2 : Control rod insertion system , using partial core model to acquire larger acceleration than verification test (2003-2005)

Step 3 : Overall evaluation to develop fragility data set of step 1 and 2 (2004~2005)

Step 4 : Tank, valve, fan, etc (2005-2007)

The paper introduces outline of step 1 and 3*. Ref. [7], a translation of summary report of Step 1,2 and 3, will support further understanding of readers.

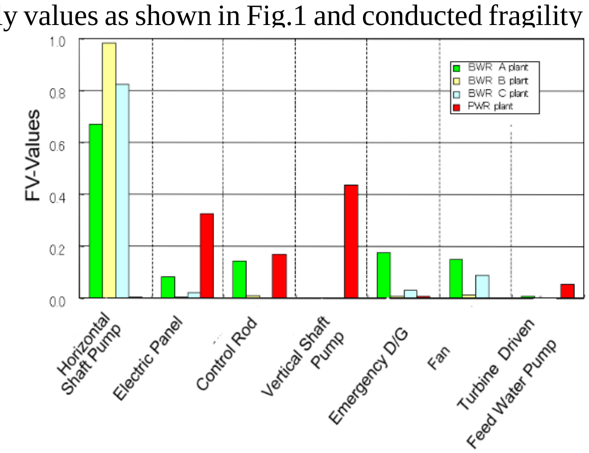


Fig.1 Screen out Test Specimens

* The views expressed in this paper are author's view and do not represent positions or views of any other Organizations.

2.Seismic fragility capacity evaluation test of Electrical Panel

2.1 Outline

Typical real electrical panels directly relating to NPP nuclear safety and critical elements contained in these panels were tested at high acceleration exceeding design level, up to loss of function. By the tests, precise seismic capacity data set of these electrical panels were obtained, which contributed to significant improvement on Core Damage Frequency (CDF) evaluation. And also a method of evaluating seismic capacity of electrical panel was proposed.

2.2 Test composition and test model

The test was composed of actual panel test to confirm function limit and failure mode of electrical panels composing nuclear safety system shown in Table 1, and element test to confirm function limit of electrical elements contained in these panels shown in Table 2, at large seismic motion.

Table 1 Tested electrical panel

Panel	Panel
Reactor Control Center (1/1 full model, 640kg)	Main Control Board (1/1 partial model, 1010kg)
Reactor Protection Rack (〃 〃 , 2160kg)	Reactor Auxiliary Control Board (〃 〃 , 2580kg)
Power Center (〃 〃 , 4050kg)	Logic Circuit Control Panel (1/1 full model , 750kg)
6.9 kV Metal-Clad Switchgear (〃 〃 , 5600kg)	Instrumentation Rack (1/1 full model , 670kg)

Table 2 Tested element

Category	Element / tested number*	Category	Element / tested number*
Relay	Protection , Auxiliary relay / 42	Instrumentation device	Differential pressure and pressure transmitter / 10
Timer	Timer / 9		
Control device	Card / 6, Flat display / 3, Controller, CPU,I/O unit / 9, Test, power, monitor module / 9 Power unit / 4	Circuit breaker (small current)	Magnetic contactor / 18 Molded case circuit breaker / 27
		Switch	Module switch / 9, Key switch / 9, Cam operated switch / 9

* Follow USA Guide (Ref [8]) for test specimen number specified for seismic fragility test of relays.

2.3 Test method and result

2.3.1 Actual panel test

a. Enhancement of test facility

Former fragility value of horizontal shaft pump and electrical panel used for seismic PRA in Japan were 1.6G and 3.6 G respectively. JNES conducted sensitivity analysis of Seismic PRA, which revealed that CDF would be reduced to almost half , by fragility value of critical components around 4~5G and not so significant effect by larger fragility value as shown in Fig.2. So, Tadotsu vibration table ability was enhanced up to 6 G(10 ton capacity), by adding sub table on original table as shown in Fig.3.

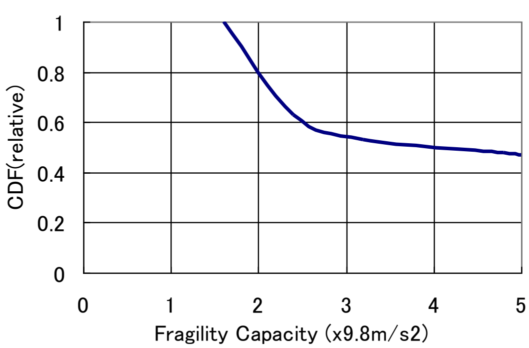


Fig.2 CDF vs Fragility capacity of Horizontal shaft pump

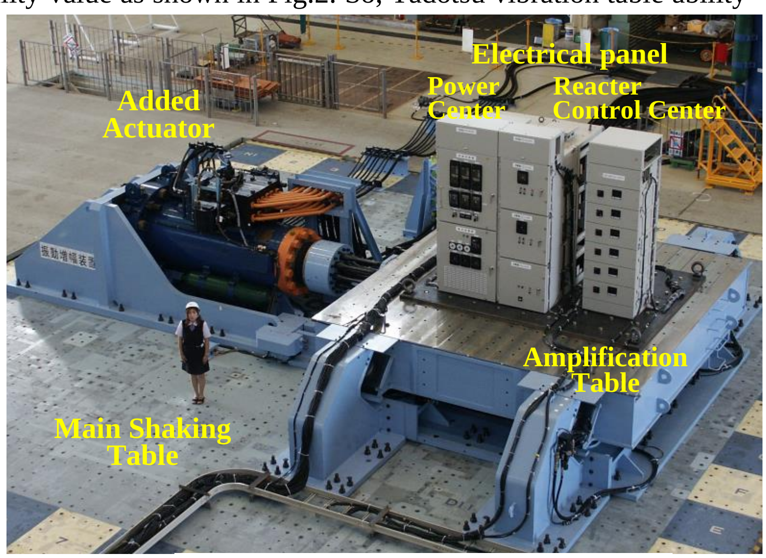


Fig.3 Over view of test facility

b. Input seismic wave

Enveloping seismic wave of Japanese NPPs at the floor test panel located was developed as shown in Fig.4. Its floor response spectrum is shown in Fig.5.

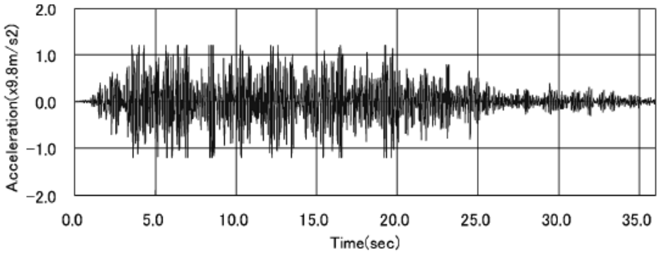


Fig.4 Basis seismic motion

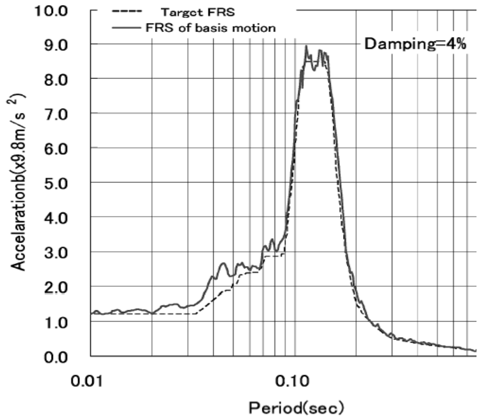


Fig.5 Floor response spectrum of basis seismic motion

c. Test result

Result of actual panel test is shown in Table 3. In these panels, no damage found on panel structure itself and their malfunction were caused by damage of contained elements.
6.9 kV Metal-Clad Switchgear indicated various phenomena and additional element test was conducted on relating elements.

Table 3 Result of actual panel test

Panel	Result
1. Reactor Control Center (35.8Hz)	Error of magnetic contactor caused by auxiliary relay chatter at 6.1G
2. Reactor Protection Rack (29.0Hz)	Error of AC controller card (relay chatter) at 4.3G
3. Power Center (24.2Hz)	Error of breaker closing at 3.7G F-B, Damage of air circuit breaker at 5.0G
4. 6.9 kV Metal-Clad Switchgear (21.2Hz)	Fall out of fuses from GPT at 2.5G, Disconnection of GPT at 3.0G F-B and 3.7G S-S, Damage of vacuum circuit breaker at 4.1G S-S and 4.7G F-B
5. Main Control Board (43.8Hz)	No malfunction up to 5.7G
6. Reactor Auxiliary Control Board (30.7Hz)	No malfunction up to 5.9G
7. Logic Circuit Control Panel (22.2Hz)	No malfunction up to 5.9G
8. Instrumentation Rack (32.7Hz)	No malfunction up to 5.7G

( ): Natural frequency confirmed* F-B: Front -Back S-S : Side-Side
*These panels indicated relatively high value.

2.3.2 Element test

a. Test facilities

Five high acceleration vibration tables, Maximum acceleration 10G or larger, 600~5000kg load, 0.6~1.2m square were used. Fig.6 shows an example.

b. Test result

Table 4 shows summary of element test result.
Regarding 6.9 kV Metal-Clad Switchgear, cause of malfunction was clarified by element test and necessary measure was investigated.

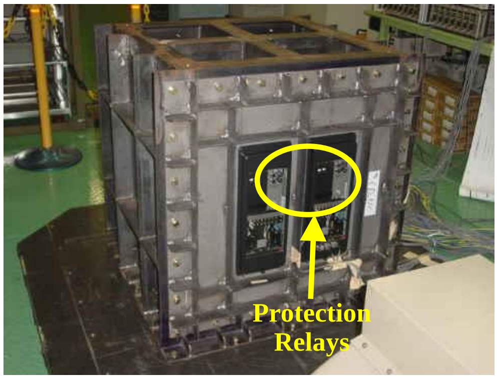


Fig.6 Element test(Protection Relay)

Table 4 Result of element test

Category	Element	Failure
Relay Timer	Protection relay Auxiliary relay Timer	Chatter at 9.5 G F-B 〃 5.9G F-B No malfunction up to 10.1G
Control device	Card Flat display Controller, CPU,I/O unit Test, power, monitor module Power unit	Chatter on AC controller card miniature relay at 8.3G S-S
Instrumentation device	Differential pressure and pressure transmitter	(Flat display through Molded case circuit breaker:) No malfunction up to 9.5~12.7G
Circuit breaker (small current)	Magnetic contactor Molded case circuit breaker Air circuit breaker* Vacuum circuit breaker* Gas circuit breaker Earthed voltage transformer*	 Error of closing at 3.3G F-B Structural damage at 4.4G F-B Structural damage at 3.5G F-B Fall out of fuses at 2.5G F-B and disconnection at 8.8G S-S
Switch	Module switch, Key switch , Cam operated switch	No malfunction up to 10.0G 〃 〃

*Added test elements following actual panel test result

c. Follow of issues found by actual panel test

Actual panel test revealed weak point of 6.9 kV Metal-Clad Switchgear. As for GPT fuse drop, improvement of fuse holder was done as shown in Fig.7 and no malfunction up to 6G was confirmed. As for circuit breaker, damage of element occurred as shown Fig.8 and element test for other type than actual panel test was performed.

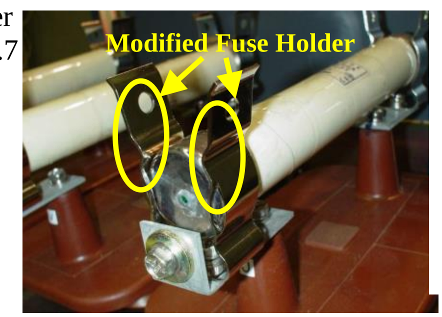


Fig.7 Modified fuse holder

Fig.8 Damage of circuit breaker

2.4 Evaluation method of electrical panel capacity

Electrical panel capacity was evaluated by following steps as shown in Fig.9, at the base of the panel.

- Step1 : Set up response analysis model for each panel simulating the response at actual panel test. Fig.10 shows analysis model of Reactor Control Center, for example.
- Step2 : Calculate response ratio k_i of critical element
  k_i = Response of the panel at the level critical element located / Panel base acceleration
- Step3 : Prepare seismic capacity of critical element f_i (median value)
- Step4 : Seismic capacity F of the panel is estimated from f and k
  $F = \mathrm{Min}\,(f_i / k_i)$

Evaluation example is shown in Table 5.

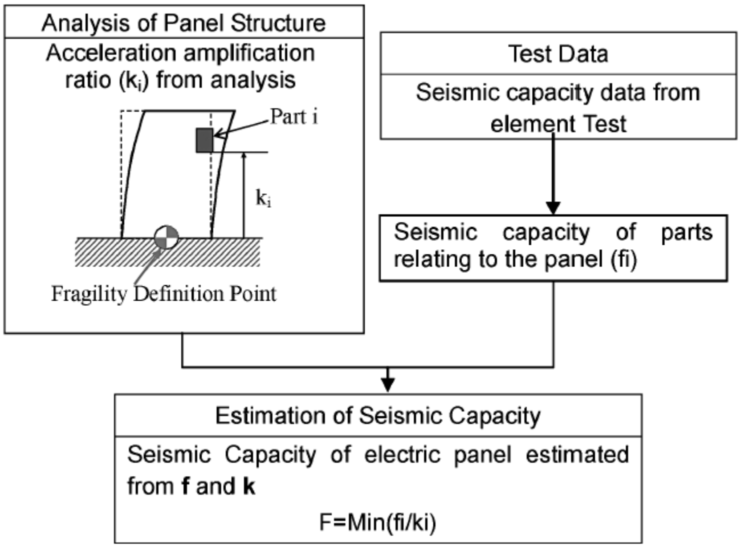


Fig.9 Evaluation scheme of electric panel fragility

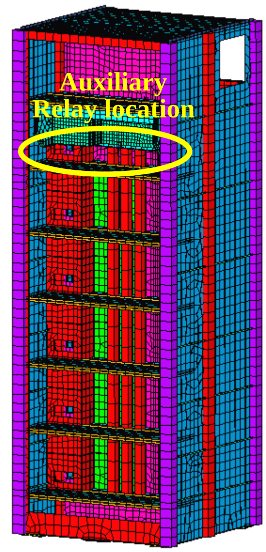


Fig.10 Analysis model of Reactor control center

Table 5 Capacity evaluation of Reactor Control Center

Critical element : Auxiliary Relay	Element capacity : 5.9G(Median)	Response ratio *ki* : 1.3 by analysis model shown in Fig.10
Capacity of Reactor Control Center F = 5.9G / 1.3 = 4.5G at panel base		

2.5 Evaluation result of each panel

Capacity of the panels evaluated by the test is summarized in Table 6.

Table 6 Capacity of panels tested

Panel	Capacity (G)	β *	Critical element
1. Reactor Control Center	4.5	0	Auxiliary relay
2. Reactor Protection Rack	4.4	0.166	AC controller card
3. Power Center	4.4	0	Air circuit breaker
4. 6.9 kV Metal-Clad Switchgear	4.2	-	Vacuum circuit breaker
5. Main Control Board	5.6	0	Flat display
6. Reactor Auxiliary Control Board	9.8	0.020	Module switch
7. Logic Circuit Control Panel	6.7	0.027	Power unit
8. Instrumentation Rack	4.2	0	Differential pressure transmitter

* β indicates logarithmic standard deviation.
0 means no variation at element test and - means one test specimen.

2.6 Summary

By actual panel test, function limit and failure mode of important electrical panels for nuclear safety were directly confirmed. And by the element test, mean value and deviation of capacity β of each elements were acquired. Each capacity of tested electrical panels were larger than the value 3.6 G former used and summarized in JNES report Ref. [7].

3.Seismic fragility capacity evaluation test of Horizontal Shaft Pump

3.1 Outline

Former seismic fragility capacity of horizontal shaft pump was 1.6 G, which was decided from previous vibration test condition and seemed to have large margin. To obtain realistic seismic fragility capacity, Tadotsu vibration table performance was enhanced to 6 G as described in Sec. 2.3.1 a.

A typical horizontal shaft pump, Reactor Building Closed Cooling Water (RCW) Pump, was tested in operation with water loop. By the system test and element test on bearings and liner rings, a simulation model for evaluation of horizontal pump fragility capacity was developed, which evaluated the RCW pump capacity as 8.4G.

3.2 Actual pump system test

3.2.1 Tested pump and test system

Fig.11 shows RCW pump for test and Fig.12 shows overview of test system.
The pump was vibrated up to 6G in operating.

Items	Specification
Flow rate(m^3/ h)	1250
Head(m)	55
Mass(kg)	5.7×10^3
Size(m)	2.8 W, 1.5 H

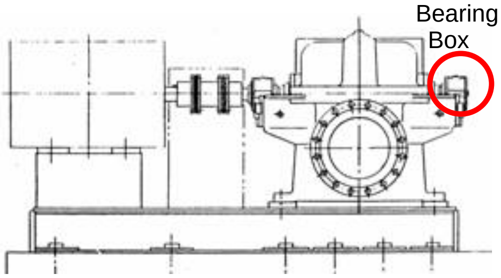


Fig.11 RCW pump for test

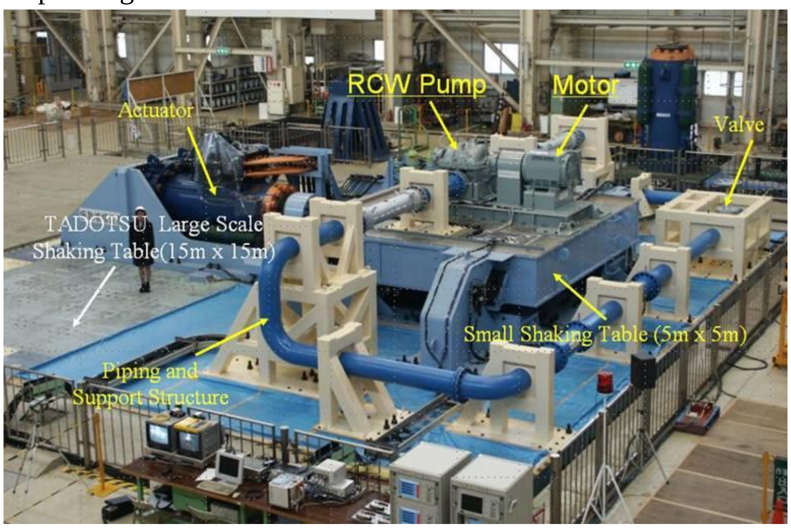


Fig.12 Overview of test system

3.2.2 Test result

No abnormality of pump was found during excitation and no change of pump characteristics before and after excitation found as shown in Fig.13. However, rattling of bearing box increased after seismic vibration test as shown in Fig. 14.

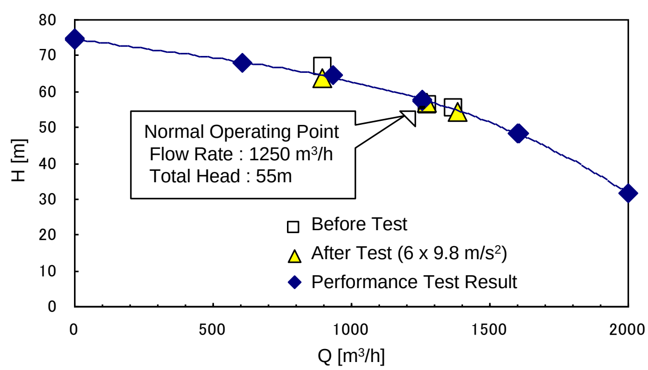


Fig.13 Pump Q-H characteristics

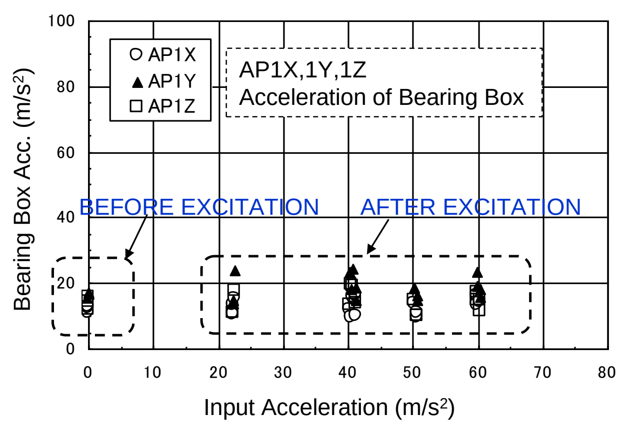


Fig.14 Bearing box Acceleration

3.3 Element test on bearing

3.3.1 Outline

After the test, ball surface wear was found by decomposition inspection of bearing as shown in Fig.15. Bearing was considered as critical element of the pump and element test of bearings up to39 G were performed using the test device shown in Fig.16, on bearings shown in Table 7, in condition shown in Table 8.

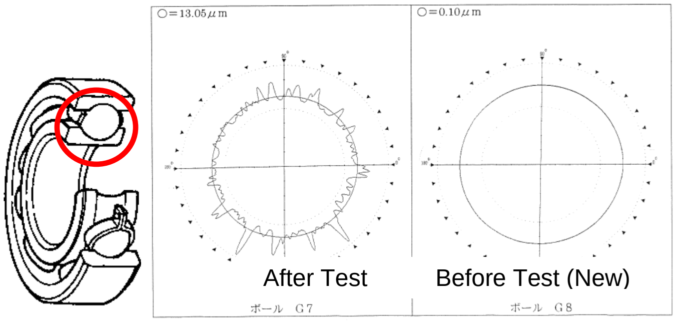


Fig.15 Ball surface roughness by wear
(Ball Bearing 6310)

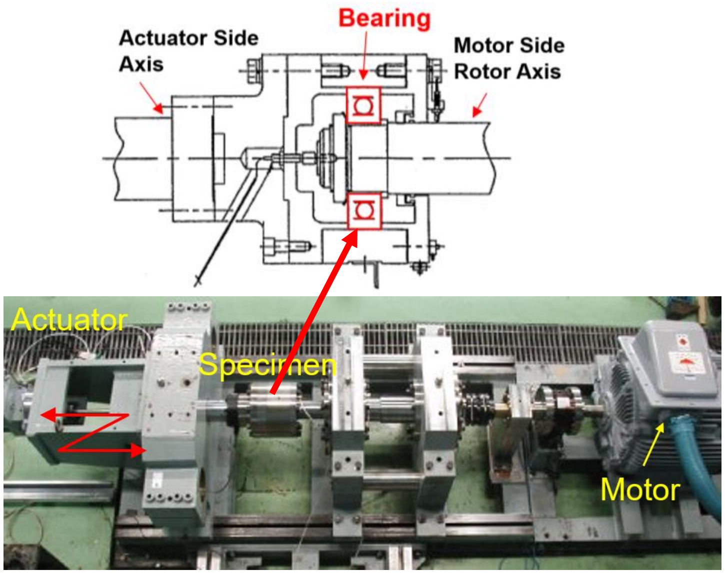


Fig.16 Bearing test device test condition

Table 7 Tested bearings*

ELEMENT		SIZE(TYPE)
Radial Bearing	Ball	110mm O.D.(6310) 170mm O.D.(6316)
	Slide	60mm I.D. 80mm I.D
Thrust Bearing	Ball	110mm O.D.(6310) 170mm O.D.(6316) 170mm O.D.(7316B)
	Slide	127mm I.D.
Liner Ring	Flat	270mm I.D. 175mm I.D. 267mm I.D. 88mm I.D. 195mm I.D.
	Groove	95.5mm I.D.

*Number of specimen : 3 for each

Table 8 Example of bearing element test condition (for type 6310)

Test	Sinusoidal excitation	Seismic wave excitation
Purpose	Evaluation of vibration characteristic	Evaluation of fragility capacity and failure mode
Maximum Load kN	~10	~33
Equivalent Acceleration $\times 9.8\ m/s^2$	~12	~39

3.3.2 Test result

Data of rattling motion of bearing due to surface wear of ball or slide bearing was acquired as shown in Fig.17. Load Pc at which rattling initiate is important for latter consideration.

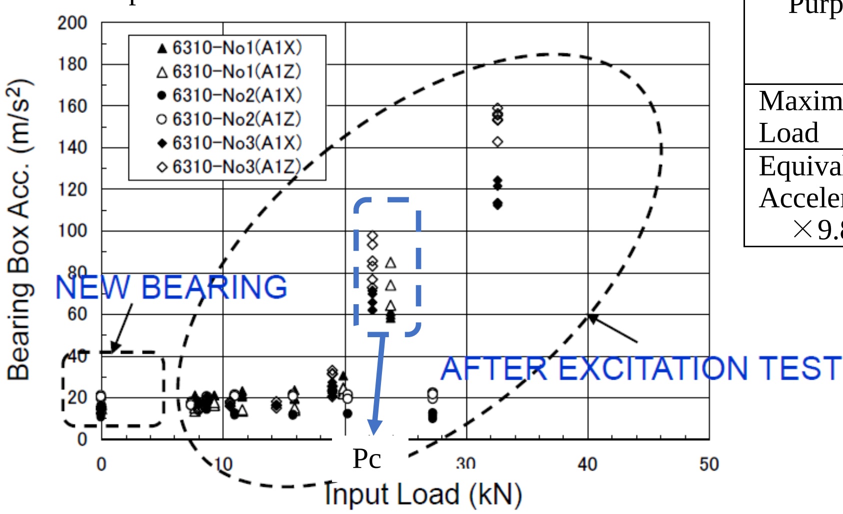


Fig.17 Rattling motion of bearing box

3.3.3 Evaluation

Table 9 shows comparison of bearing specification and element test results.

Based on the data, limit load of deep slot ball bearing were considered as 1/ 3 of thrust limit load of bearing maker Coa.

Table 9 Limit load of deep slot ball bearing

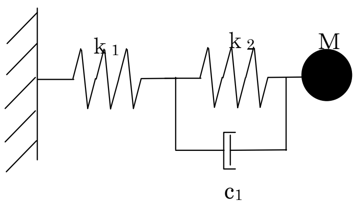
	Bearing type	6316	6310
Bearing specification	Thrust limit load Coa (kN)	56.8	25.0
Element test result	Damage load of bearing Pc (kN)	20 to 30	20 to 30
Pc / Coa		1/3 to 1/2	4/5 to 6/5
Limit load of deep slot ball bearing		To be set as 1/3 Coa	

3.4 Development of procedure for evaluation of horizontal shaft pump fragility capacity

Horizontal shaft pump fragility capacity evaluation procedure was developed as following.

a. Develop seismic response analysis model of the pump capable to simulate bearing thrust load
b. Evaluate seismic input acceleration by a, which cause limit load of bearing
c. Result of b is fragility capacity of the pump

The model was developed as Fig. 18, using element test data. The model well simulated the behaviour of the bearing thrust load at actual pump system test as shown in Fig.19.



M:Mass of rotating part
k1:Stiffness of bearing box
k2: Stiffness of bearing
(evaluated by element test data)
c1:Damping factor (〃 〃)

Fig. 18 Analysis model of horizontal shaft pump

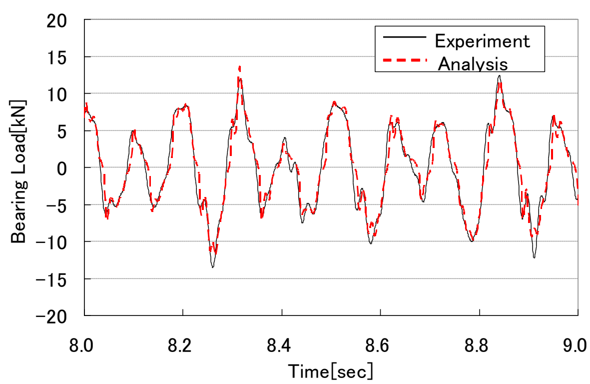


Fig.19 Bearing thrust load at 6G excitation of actual equipment test

3.5 Fragility capacity of horizontal shaft pump

Based on procedure shown in Sec.3.4 using the data of actual pump system test and element test for bearing, fragility capacity of a typical horizontal shaft pump was evaluated as shown in Table 10.

Table 10 Example of horizontal shaft pump fragility capacity

Pump	Fragility capacity (medium value)	Logarithmic standard Deviation β
RCW pump	$8.4 \times 9.8 m/s^2$	0.21

3.6 Summary

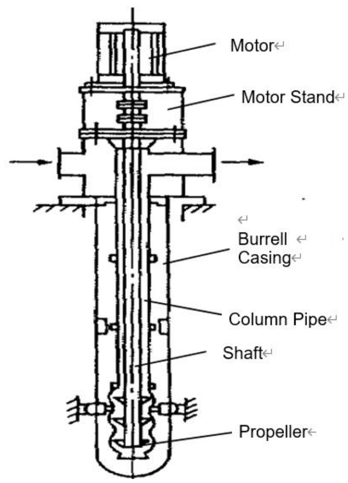
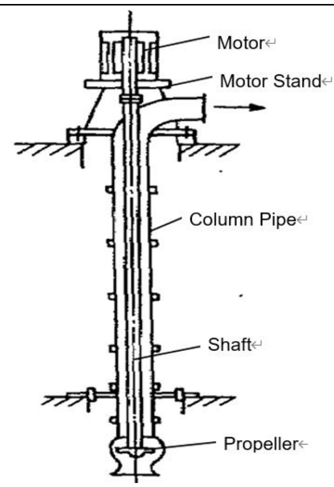
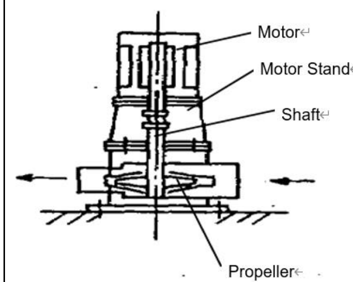
By actual pump system test, function ability of horizontal shaft pump up to 6 G, four times larger than previous value, was confirmed. By element test, bearing wear which affects to pump function was examined and simulation analysis model was investigated. Based on these, procedure for evaluation of horizontal shaft pump fragility capacity was proposed. These are summarized in JNES report Ref. [7].

4.Seismic fragility capacity evaluation test of Vertical Shaft Pump

4.1 Outline

Pit barrel type pump representing following three types of vertical shaft pump used in PWR and BWR was selected as the specimen. The actual pump system test using Reactor Heat Removal(RHR) pump, in operation with water loop,was conducted at Tadotsu vibration table.

Table 11 Type of vertical shaft pump in PWR/BWR

<table>
<tr><td>Pit barrel type
(BWR, 500 / 800 / 1100 MW）</td><td>Vertical cross flow type
(BWR / PWR)</td><td>Vertical single- stage floor type
(BWR / PWR,500 / 800 MW)</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>・RHR Pump
・LP Core Spray Pump
・HP Core Spray Pump</td><td>・Sea Water Pump</td><td>・RHR Pump
・Core Spray Pump</td></tr>
</table>

Regarding critical element of vertical shaft pump, Liner Ring, Shaft Bearing and Thrust Bearing were selected and element test up to function loss of each were conducted. Based on actual pump system test result, an simulation analysis model of vertical shaft pump was developed.
By the model and element test result of critical elements, fragility capacity of various type of vertical shaft pump used in BWR and PWR were evaluated.
The value obtained were larger than the value previously used .

4.2 Actual pump system test

4.2.1 Tested pump and test system

Fig.20 shows overview of test system using RHR pump of 1100 MW BWR. The pump, as shown in Table 12, was vibrated up to 2.3G Horizontal and 1.5G Vertical enhanced seismic wave enveloping DBGM of Japanese BWR, in operating.

Table 12 Specification of tested pump

Size and weight	15.0 m length, 61×10^3kg
Flow rate	1691m^3/ h
Water head	92 m

Fig.20 Whole view of actual pump system test

4.2.2 Test result

Result of actual pump system test is summarized in Table 13.

There found no abnormality of pump operation during excitation and decomposition inspection after the test.

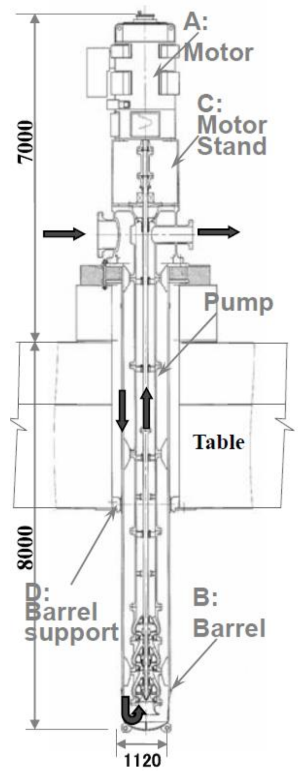


Table 13 Actual pump system test result

	Item	Portion interested	Result (G: 9.8m / s^2)	Previous Research*1
Horizontal excitation	Maintenance of pump function (Response Acceleration)	A:Motor (top)	(up to) 14.0 G*2	(up to) 2.5 G
		B:Barrel(bottom)	(up to) 31.0 G*3	(up to) 10.0 G
		C:Motor Stand	Fragility of bolts were examined	- (new evaluation)
	Nonlinear response	D:Barrel support gap	Confirmed relationship between gap size and response	- (new evaluation)
Vertical excitation	Maintenance of pump function	A:Motor (top)	(up to) 2.3G	
		B:Barrel(bottom)	(up to) 2.2 G	

*1 Ref. [6]

*2 Fastening bolt of motor yielded at 12G

*3 Barrel yielded by corrosion with support

An analysis model incorporating impact effect of barrel -support collision was developed.

4.3 Element test

Fragility capacity and dispersion of Liner Ring, Shaft Bearing and Thrust Bearing of typical vertical shaft pump shown in Fig.18 were evaluated .

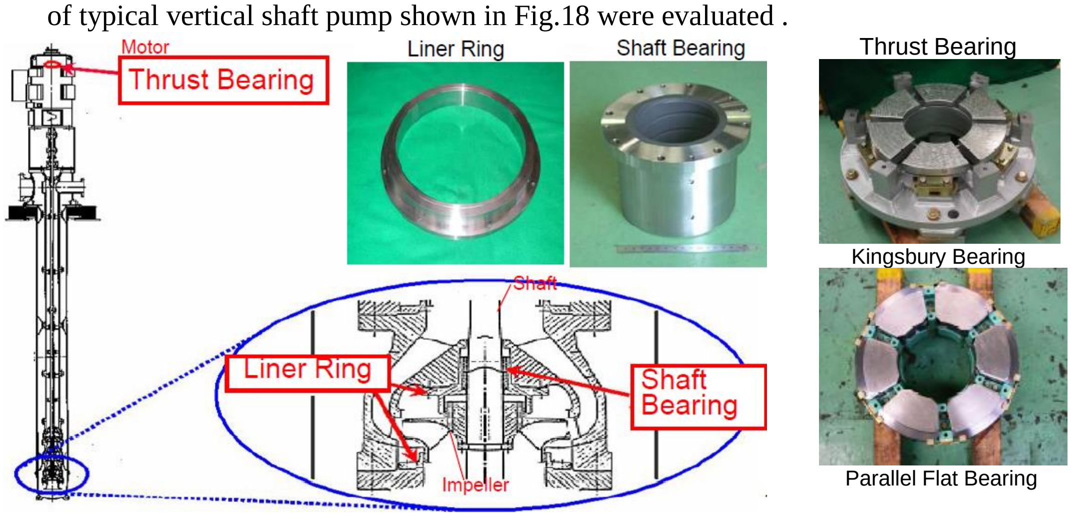


Fig.21 Pump elements tested

4.4 summary

Fragility capacity of vertical shaft pump was summarized as Table 14, according to result of actual pump system test and element test. These are summarized in JNES report Ref. [7].

Table 14 Fragility capacity of vertical shaft pump

Type	Evaluated damage mode	Fragility capacity (median)
Pit barrel (long)	Motor function maintained	14.0 G at motor top
Pit barrel (short)	〃 〃	14.0 G 〃 〃
Vertical cross flow(PWR)	Yield of fastening bolt for motor stand	6.3 G 〃 〃
Vertical cross flow(BWR)	〃 〃	4.3 G 〃 〃

5. JNES and USNRC-BNL collaboration on Seismic fragility capacity test

JNES continued collaboration with USNRC on seismic fragility capacity test as same as on former seismic verification test. USNRC, collaborating with BNL, evaluated the result of fragility capacity test of JNES, comparing that of USA. Their insight is summarized in Ref. [11], including detail introduction of JNES test results, Ref. [7]. Ref. [11] might be a good guide for new comer to know more detail in this field.

CONCLUSION

Outline of fragility capacity tests of essential components for seismic PRA, Electrical Panel, Horizontal Shaft Pump and Vertical Shaft Pump conducted by JNES, are introduced. Capacity data acquired were exceeded the value previously used. These were quoted into Japanese seismic PRA guide Ref. [4] and are now contributing to get more precise Seismic PRA evaluation.

The author hopes this paper will be a guide for new comer in this field and contribute to knowledge and experience transfer to next generation.

ACKNOWLEDGEMENT

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