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Seismic analysis of RCS with finite element model for advanced PWR

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ABSTRACT

Reactor Coolant Pumps (RCPs) are very important to the safe operation of Nuclear Power Plants (NPPs), especially during the earthquake, which needs detailed seismic analysis of individual RCPs and the boundary conditions, for example, at the nozzles. In this paper, three-dimensional finite element model of Reactor Coolant System (RCS) is constructed from a systematic perspective to perform dynamic evaluation, in which the boundary conditions could be given. The seismic spectrum analysis with three orthotropic directions is performed to obtain the stress and displacement response, which shows that the maximum Tresca stress locates in the connection part of SG with RCP and the maximum displacement occurs at the surge line. Sensitivity analysis of spectrum input angle and stiffness of supports is performed, which may be useful to further design and analysis. Furthermore, direct integration method is used to perform time-history analysis, and the boundary conditions of RCP, the loads, acceleration and displacement at nozzles are obtained, which could support the detailed analysis of RCP components. Besides, the lumped mass model of RCS is also constructed to compare with three-dimensional finite element model, which means that for the complicated geometry the 3-D model is better than the lumped mass model.

1. Introduction

In China advanced passive pressurized water reactors are constructed, in which two Reactor Coolant Pumps (RCPs) are attached to the bottom of each steam generators (SGs) and are an integral part of the primary reactor coolant pressure boundary. RCP casing is welded to SG channel head and supported from SG, without other supports, the connection structure of which is different from the current operational reactors. After the Fukushima accident, more attentions have been paid on the safety and availability of important components and system of NPPs under superposition of internal accidents and extreme natural disasters. Furthermore, detailed seismic analysis of individual RCP needs the boundary conditions at the nozzles. Therefore, RCS whole system including RCP should be investigated.

Many researches have been done on the Earthquake resistance analysis of systems and equipments in nuclear power plants (NPPs), also including earthquake resistance analysis of RCPs. Finite element model of a vertical pump of a typical boiling water reactor is constructed to obtain seismic response through spectrum analysis, and operability of pump-motor unit and stress of pump casting are assessed (Chawla et al., 1998). Static and dynamic analysis to investigate an essential service water pump under design condition, normal operation condition and other service conditions are performed (Wang and Tian, 2004). Response spectrum analysis of equipment cabinet is carried out based on finite element model and validated with experiments (Cho et al., 2011). Besides, dynamic analyses on coolant channel assembly (Parulekar et al., 2004), reactor vessel (Ogino et al., 2005) and spent fuel storage (Lee et al., 2004) are also investigated. In general, specific component is separated from the whole system to build finite element model for performing seismic analysis, which focuses on individual component. Input pipe loads of nozzles come from simplified lumped mass model, and seismic excitation is support location floor response. However, RCPs of advanced passive pressurized water reactors are welded to the channel head of SGs and cold legs without other supports. Therefore, coupling of the whole RCS system, including RCP, should be considered.

Lumped mass stick model with combination of equivalent static method and spectrum analysis are used to perform seismic analysis on large joint structures in NPPs to obtain the whole response. 3-D, lumped-mass stick models are developed to represent steel containment vessel, containment internal structures coupled shield and auxiliary building. And the large solid-shell finite element

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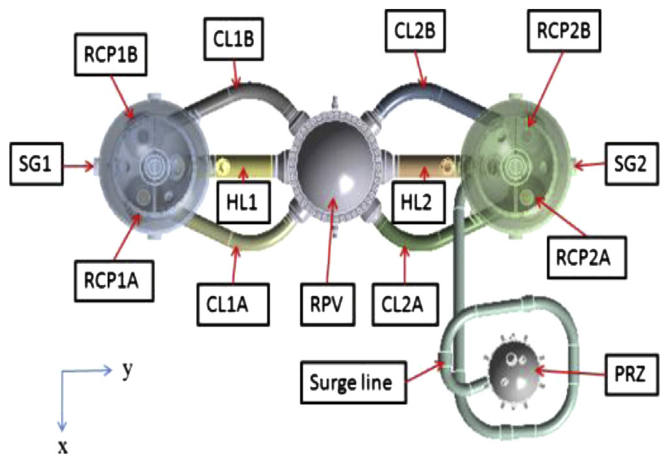

Fig. 1. Top view of geometry model.

model of AP1000 nuclear island is also built and acceleration spectrum seismic analysis is conducted to get the natural frequencies and seismic response (Tuñón-Sanjur et al., 2007). Lumped-mass model of safety related piping system of the typical WWER-440 NPP is developed to obtain seismic analysis by modal and spectrum analysis (Berkovski et al., 2001).

In this paper 3-D finite element model of main components and equipments of RCS is constructed by using ANSYS code to perform dynamic analysis, response spectrum and time-history analysis for obtaining the data of the loads, acceleration and displacement at RCP nozzles, which will be the input data of the boundary conditions for the detail seismic analysis of RCP system.

2. Finite element modeling

Finite element model of RCS is developed to represent reactor pressure vessel (RPV), two SGs, four RCPs, Pressurizer (PZR), the two hot legs (HL, ID (inside diameter) = 787.4 mm), four cold legs (CL, ID = 558.8 mm) and surge line (ID = 457.2 mm), in which mass of U-tubes, reactor internals and other important internal structures are considered according to the design control document Rev.19 (Westinghouse Corporation, 2011). As shown in Fig. 1, the

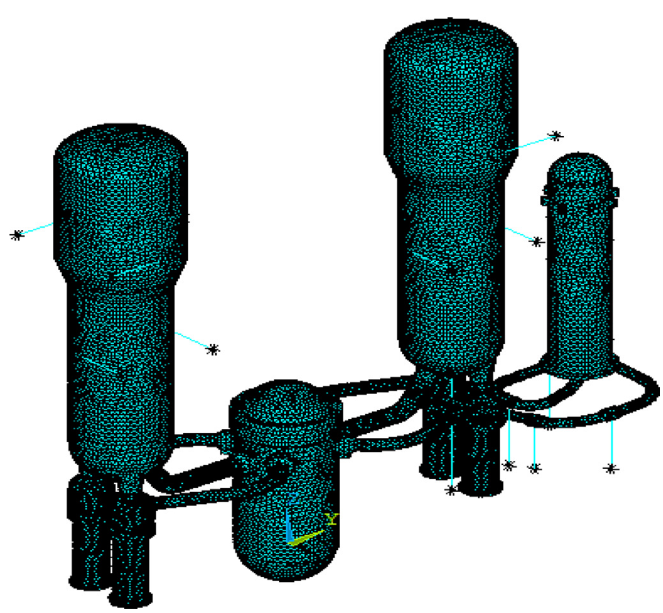

Fig. 2. Finite element model.

Table 1
Number of nodes and elements of each component.

Components	Nodes	Elements
RPV	43,710	22,988
SG (× 2)	68,991	35,795
Pump (× 4)	27,320	16,004
Pressurizer	23,441	11,665
Hot leg (× 2)	5269	2568
Cold leg (× 4)	4628	2263
Surge line	32,924	16,903
Total	385,741	199,681

Table 2
The typical geometrical parameters.

Parameters	Value/mm	Parameters	Value/mm
Inside diameter at hot leg	787.4	Thickness at hot leg	82.6
Inside diameter at cold leg	558.5	Thickness at cold leg	60.0
Inside diameter at surge line	457.2	Thickness at surge line	253.8
Inside diameter at pressurizer	2540.0	Height of pressurizer	12,776.2
Inside diameter of RPV cylinder	4038.6	Thickness of RPV cylinder	203.2
Height of RPV	12,462.5	Thickness of PRV lower head	152.4
Inside diameter at pump discharge nozzle	558.8	Inside diameter at pump suction nozzle	660.4
Height of SG	22,460.2	Inside diameter of upper/lower shell	5334/4191

Table 3
Main parameters of elastic supports of SG and surge line.

Components	Supports	Stiffness/N/m	Length/m
SG	Upper horizontal support	6.44×10^8	3.2
	Middle horizontal support	6.7×10^8	2.78
	Lower vertical support	2.98×10^8	7.53
	Lower horizontal support	2.8×10^8	3.5
Surge line (From bottom to top)	Vertical support 1	2.98×10^8	3.11
	Vertical support 2	1.16×10^8	3.58
	Vertical support 3	2.98×10^8	3.91
	Vertical support 4	199,980	4.19

Table 4
Important natural frequency.

Order	Frequency/Hz	Ratio of effective mass to total mass		
		x	*y*	*z*
1	2.7106	7.429E-05	8.362E-05	7.779E-07
2	2.7415	1.143E-03	1.210E-06	6.385E-09
3	2.8486	2.421E-03	9.776E-04	3.634E-07
4	5.2653	2.421E-03	6.332E-03	1.472E-05
5	5.6326	2.357E-01	1.047E-05	8.591E-07
6	5.6390	4.081E-01	2.545E-07	1.700E-08
7	6.9295	1.817E-07	6.045E-04	4.579E-04
8	6.9307	2.332E-07	6.318E-04	4.324E-04
9	7.7238	1.126E-08	6.278E-02	1.888E-04
10	7.7299	1.332E-08	8.695E-04	1.571E-02
14	8.4885	1.318E-06	4.897E-01	1.706E-05
16	9.2422	3.778E-08	1.021E-03	1.318E-01
17	9.2596	9.665E-09	1.923E-04	5.789E-01
24	14.246	4.669E-06	1.200E-01	1.029E-03
Total		64.99%	68.32%	72.84%

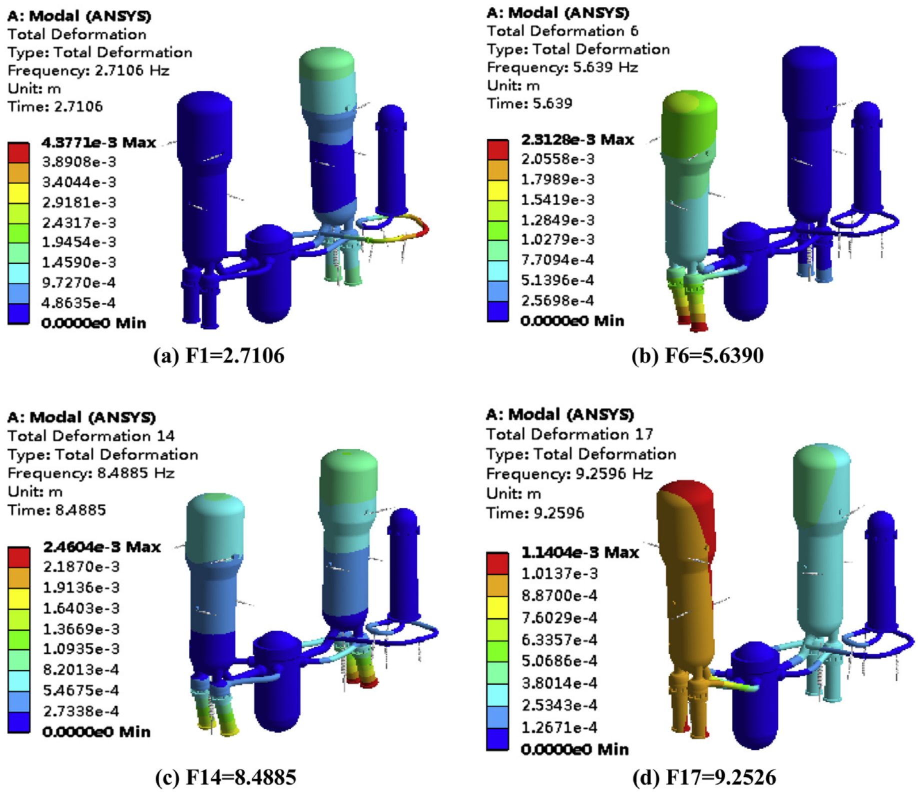

Fig. 3. Typical modal shapes.

top view of geometry model with labels, the loop without PZR is called Loop 1, and the other is Loop 2. In the analysis, SOLID ELEMENT is used to simulate main three-dimension structures, and CONTACT and TARGE ELEMENT are chosen to simulate the connection between different components. The supports of SG and surge line are imitated by COMBINE ELEMENT with proper stiffness, and the support surface of RPV, skirt bottom of PZR, support end of SGs and surge line are restricted. After sensitivity analysis, the employed mesh, shown in Fig. 2, consists of 199,700 elements and 285,700 nodes with surge line and RCP shell mesh refined in the following analysis. Table 1 gives the number of nodes and elements of each component. RCP body material is SA351 CF8A, SG and PRZ materials are A508 GR3 CL2, RPV material is SA508 GR3 CL1, and main leg material is SA376 TP316LN. The typical geometrical parameters are shown in Table 2. Main parameters of elastic supports of SG and surge line are shown in Table 3.

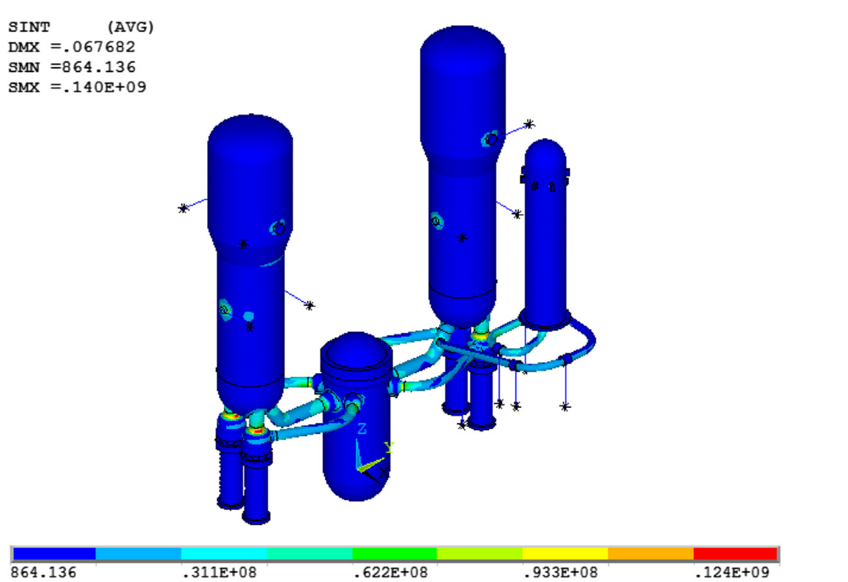

Fig. 4. Stress field under SSE (Unit: Pa).

Table 5
Maximum relative displacement of components under SSE.

Components	Maximum/mm			
	X	*Y*	*Z*	Total
RPV	0.330	0.407	0.330	0.619
SG1	12.38	4.064	3.865	13.59
SG2	9.253	4.942	2.363	10.75
RCP1A	20.38	8.914	3.926	22.59
RCP1B	20.23	8.761	3.924	22.39
RCP2A	15.51	10.62	2.544	18.97
RCP2B	15.49	10.33	2.539	18.79
Surge Line	50.61	44.79	8.776	68.15
Pressurizer	0.134	0.247	0.209	0.350
Hot Leg	5.921	1.031	3.362	6.887
Cold Leg	8.516	2.319	3.692	9.567

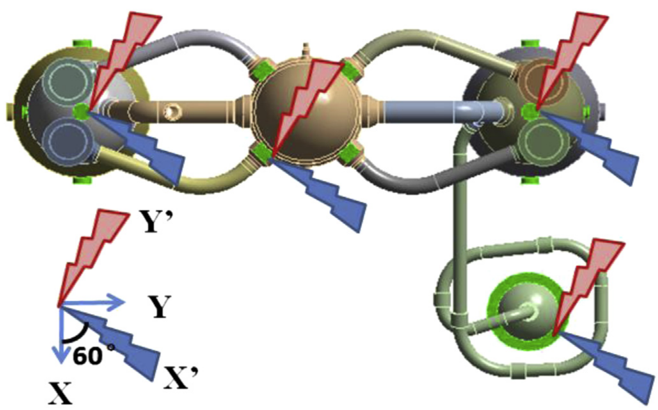

Fig. 5. Schematic diagram of the input spectrum angle.

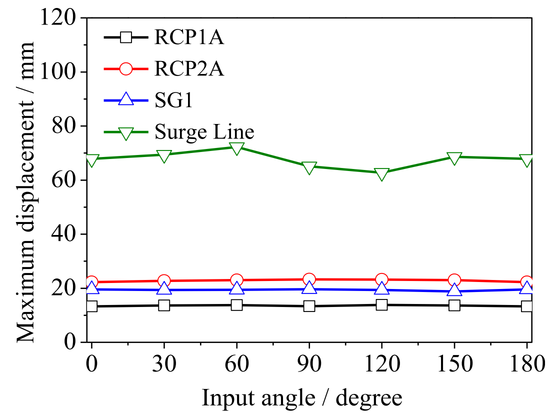

Fig. 7. Displacement vs. spectrum input angle.

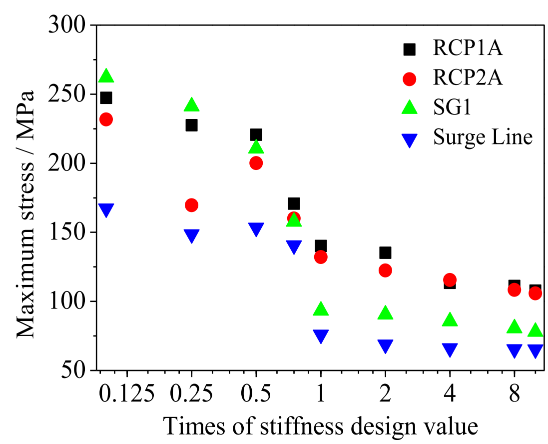

Fig. 8. Stress vs. support stiffness.

3. Seismic analysis with 3-D model

3.1. Modal analysis

After the model is restricted, the Block Lanczos is set as the solve type in modal analysis to get the former 150 modal shapes, and the important natural frequencies of the system and their ratio of effective mass to total mass are listed in Table 4, which shows that the first natural frequency is 2.7106 Hz, less than 33 Hz, which means that the whole model is flexible, and the spectrum analysis and time-history analysis is used for seismic analysis instead of equivalent static analysis by the constructed model.

The typical modal shapes of the system are shown in Fig. 3, in which Fig. 3(a) is for the first natural frequency, Fig. 3(b), (c) and (d) are for the maximum ratio of effective mass to total mass at *x*, *y*, *z* directions, respectively. The analytical results show that the maximum effective mass in all directions are the surge line, RCPs and SGs among the low order type of vibration, and the surge line is a weak component of RCS because of its long structure and special layout. Meanwhile, the vibration of RCPs also predominates in the low order frequencies, because RCPs are welded directly to the SGs

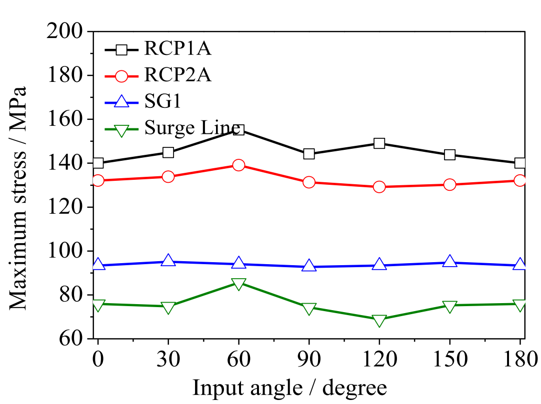

Fig. 6. Stress vs. spectrum input angle.

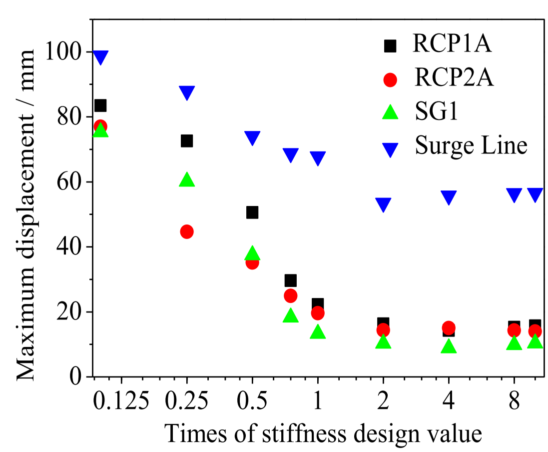

Fig. 9. Displacement vs. support stiffness.

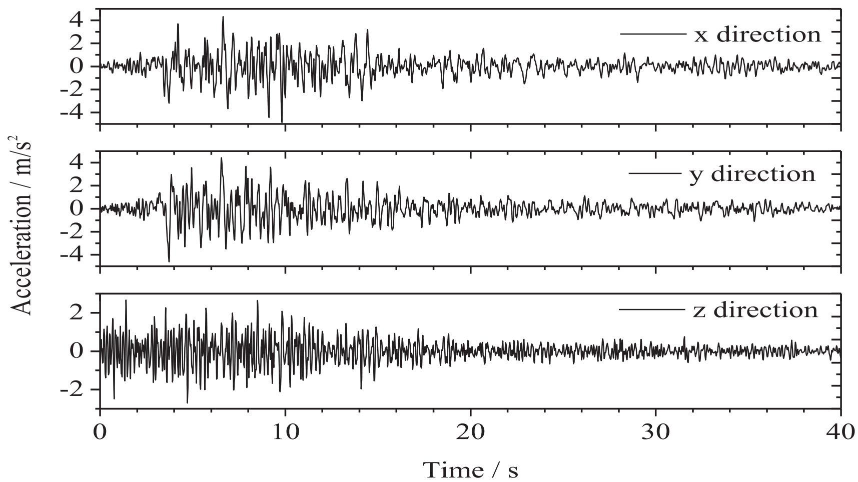

Fig. 10. Floor acceleration time-history.

without any other supports. Steam generators are also likely to vibrate because of the large size with the vertical height of 22.45 m.

3.2. Spectrum analysis

Learning from the modal analysis, the Square Root of Square Sum (SRSS) method is chosen to combine the modals in the spectrum analysis. According to the Nuclear Regulatory Commission Regulatory Guide (NRC, 2006), at least 90% of the effective mass should be accounted in the spectrum analysis. The former 150 natural frequencies contribute 90.88%, 90.51% and 90.50% of total mass in *x*, *y*, *z* direction, respectively. The floor response spectrum for Safe Shutdown Earthquake (SSE) – 4% damping of the system location is chosen as input, and the corresponding peak ground

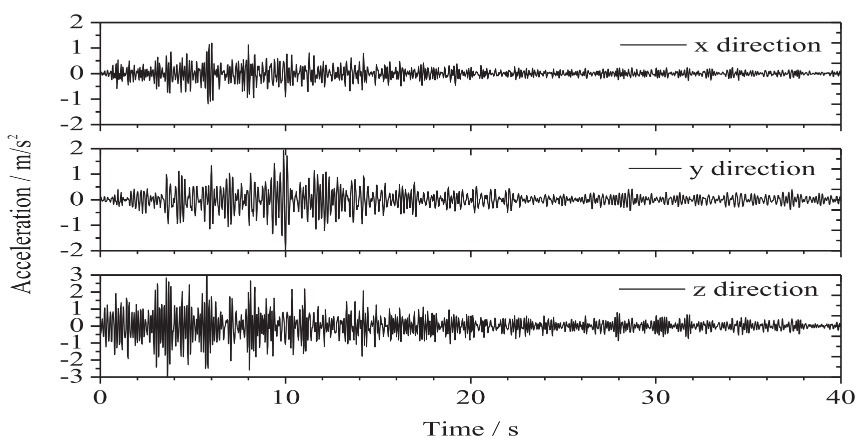

Fig. 11. Acceleration response of RCP1A inlet.

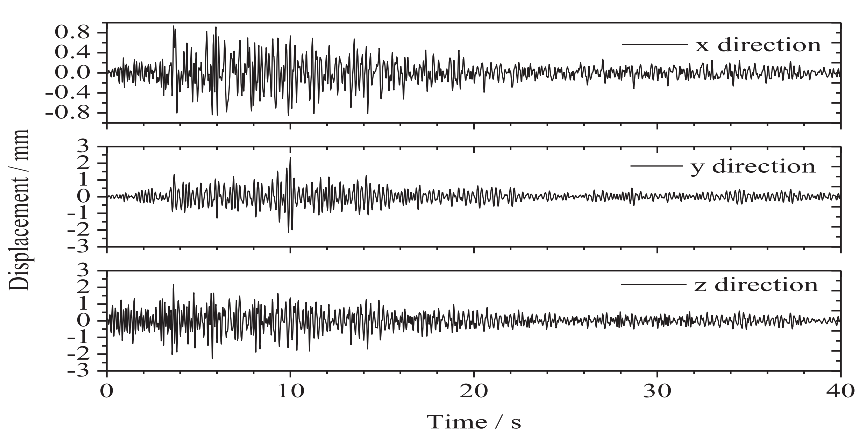

Fig. 12. Displacement of RCP1A inlet.

Table 6
Pipe load at RCP nozzles.

Location	Value	*x* (paralleled to cold leg)	*y* (right hand rule)	*z* (vertical)
Inlet nozzle	Force(N)	7.29×10^5	2.36×10^6	9.84×10^5
	Moment (N·m)	8.21×10^6	2.77×10^6	1.40×10^6
Outlet nozzle	Force (N)	1.86×10^6	5.33×10^5	2.14×10^5
	Moment (N·m)	4.09×10^5	7.18×10^5	8.34×10^5

acceleration (PGA) is 0.3 g for the two horizontal directions, and 0.2 g for the vertical direction from the view of URD (James, 1993; US: Electric Power Research Institute, 1995).

The stress field of RCS under SSE, shown in Fig. 4, indicates that the maximum Tresca stress is 140.03 MPa located at the connection part of SG1 and RCP1A, and the large stress also occurs in the connection parts of coolant pipes and RPV, and supports of SGs, while the stress of other components is quite small and distributes uniformly. The maximum relative displacements of components under SSE are listed in the Table 5, which indicates that the maximum displacement of RCS occurs at the surge line. This is because the dampers constrain the displacement of surge line in the vertical direction, and there is greater freedom in the horizontal direction. And the displacements at the bottom of the RCPs are larger in the *x* direction with slightly different value for the two loops.

In order to study the influence of spectrum input angle on the stress of RCS, the two horizontal spectra, remaining orthotropic, are rotated on *z* axis with 30° in each case to get the seismic response, as shown in Fig. 5, the schematic diagram of the input spectrum angle, and the RCP1A, RCP2A, SG1, surge line are selected as key references. The analytical results show that the stress and displacement responses of RCS vary with the input angle, shown in Figs. 6 and 7, in which the maximum displacement response occurs in the surge line, and the maximum stress appears in the connection part of SG and RCP1A with the horizontal input angle of 60°.

The influence of the support stiffness of SG and surge line is investigated, in which the stiffness of support spring is set as multiples of design values to perform modal and spectrum analysis. The analytical results, shown in Figs. 8 and 9, indicate that the support stiffness has significant impact on the seismic response, because different support causes different frequencies. For instance, the first natural frequency reduces 7.6% when the stiffness is half of design value. As the stiffness is increased, the stress and displacement are reduced.

3.3. Time-history analysis

In order to obtain the acceleration, displacement, force and moment at the RCP nozzles, the dynamic time history analysis is performed through direct numerical integration of the dynamic equilibrium equations, in which the input seismic excitation is the time-dependent floor acceleration. Considering the conservation, three artificial acceleration records, which envelope the design floor response spectrum, are calculated. And on the ground the earthquake duration is 40 s and time step is 0.02 s with a peak acceleration of 4.87 m/s^2 in horizontal direction and 2.70 m/s^2 in vertical direction. One case of the input of floor acceleration in *x*, *y*, *z* directions is shown in Fig. 10, which is obtained by a developed model including the containment and its foundation.

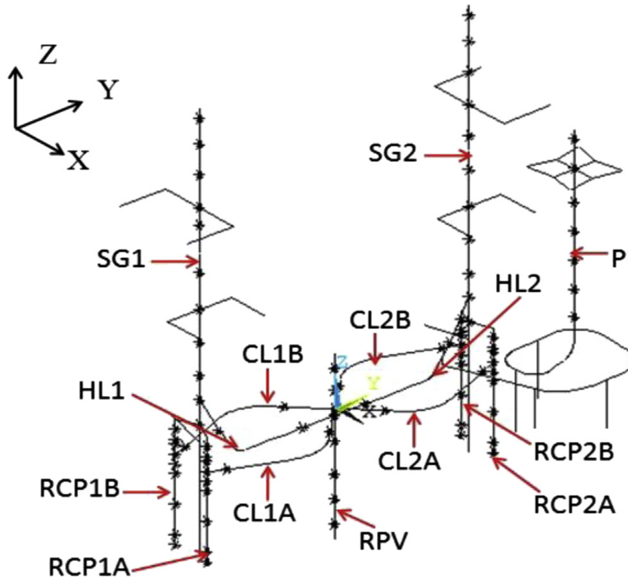

Fig. 13. Lumped mass model of the system.

The direct integration is used to perform transient dynamic analysis, and the Rayleigh damping is chosen to simulate the damping effect of the system as shown in Eq. (1).

$$[C] = \alpha[M] + \beta[K] \tag{1}$$

where, $[C]$, $[M]$ and $[K]$ are the metrics of damping, mass and stiffness, and α and β are Rayleigh damping constants. Each damping of the structure can be presented as Eq. (2).

$$\xi_i = \frac{\alpha}{2\omega_i} + \frac{\beta\omega_i}{2} \tag{2}$$

where, ξ_i and ω_i are the damping ratio and angular frequency of the structure. For SSE, the damping ratio is 4%, and the corresponding values are $\alpha = 1.3702$, $\beta = 0.002335$.

The maximum stress field of RCS during time-history record is 130.97 MPa, located at the connection of the RCP1A and SG1, the

Table 7
Stress and displacement comparison of spectrum and time-history method.

Component	Maximum stress/MPa				Maximum displacement/mm			
	Spectrum	Time-history			Spectrum	Time-history		
		1	2	3		1	2	3
RCP1A	140.03	130.97	126.39	128.17	22.24	17.19	17.11	17.33
RCP1B	132.08	121.17	118.33	124.48	22.19	17.81	17.22	17.57
SG1	93.34	57.12	70.39	73.72	13.27	14.64	16.92	16.80
SG2	85.51	58.19	69.68	76.98	10.78	14.72	16.79	15.91
Surge line	75.93	65.89	56.15	59.85	67.84	23.91	29.51	24.83
Cold leg	94.66	74.87	85.78	78.91	9.567	4.022	4.644	4.621
Hot leg	76.26	51.30	55.92	54.09	6.887	3.454	1.956	2.312

Table 8
Natural frequency comparison of two models.

Order	3-D model	Lumped mass model	Order	3-D model	Lumped mass model
1	2.7106	2.7822	11	8.010	8.3622
2	2.7415	2.7959	12	8.3670	8.5345
3	2.8486	2.9780	13	8.3800	8.8073
4	5.2653	5.4488	14	8.4885	8.8507
5	5.6326	5.6757	15	8.4999	9.2443
6	5.6390	5.7952	16	9.2422	9.2582
7	6.9295	6.9451	17	9.2596	9.4045
8	6.9307	6.9833	18	9.4226	9.4802
9	7.7238	7.7988	19	10.3900	10.6536
10	7.7299	7.9890	20	10.4330	10.7200

similar result obtained from spectrum analysis, and the stress of the middle support parts of steam generator, the connection of cold leg and RPV, and the surge line are at a high level. The acceleration records of RCP1A inlet at *x*, *y*, *z* directions are shown in Fig. 11 and the displacement of RCP1A inlet is shown in Fig. 12, in which the *x* direction is paralleled to cold leg, *z* direction is vertical and *y* direction is based on right-hand rule. The force and moment at RCP inlet and outlet are listed in Table 6, which shows that the acceleration and displacement of *x* direction is much lower than that of the other two directions, because of constrain of the RCP inlet welded with SG and outlet welded with cold leg. The acceleration and displacement of *z* direction is much higher than that of the other two directions, because the RCP casing is welded to the SG channel head and hanging in SG, which resulting in large force and moment at the inlet, and the results will be the input data of the boundary conditions for the further specific seismic analysis of RCP.

The comparison of the stress and displacement obtained from spectrum analysis and time-history method is listed in Table 7, which shows that the stress fields obtained from spectrum analysis and time-history method are similar. The maximum stress and displacement calculated by spectrum analysis is higher than that calculated by time-history method for most components. This is because the spectrum method combines the worst response of each mode, and presents the most probable vibration under the earthquake, and the time-history analysis relies on the input seismic record, and the maximum response of different components may occurs at different moment, which means that the spectrum analysis is an efficient conservative method and time-history analysis is more accurate and realistic.

4. Comparison with lumped mass model

The lumped mass model of the RCS, as shown in Fig. 13, is also constructed, in which the main components and equipments are composed by BEAM, PIPE, and MASS ELEMENT, and the connection between them are simulated by multipoint constraint element, and the supports of SGs and surge line are imitated by COMBINE element with proper stiffness.

Table 9
Maximum displacement comparison of two models.

Model		Displacement/mm						
		RCP1A	RCP2A	SG1	SG2	Surge line	Cold leg	Hot leg
Spectrum	3-D model	22.24	22.19	13.27	10.78	67.84	9.567	6.887
	Lumped mass model	16.35	16.41	8.13	8.52	49.45	8.601	5.382
Time-history	3-D model	17.19	17.81	14.64	14.72	23.91	4.022	3.454
	Lumped mass model	11.09	11.74	10.14	10.86	20.86	3.630	2.944

Table 10
Maximum stress comparison of two models.

Model		Stress/MPa						
		RCP1A	RCP2A	SG1	SG2	Surge line	Cold leg	Hot leg
Spectrum	3-D model	140.03	132.08	93.34	85.51	75.93	94.66	76.26
	Lumped mass model	83.61	83.74	45.50	46.22	55.73	64.47	50.38
Time-history	3-D model	130.97	121.17	57.12	58.19	65.89	74.87	51.30
	Lumped mass model	67.53	67.86	29.70	30.21	43.26	57.10	35.77

The natural frequency, maximum displacement and maximum stress calculated by two models are listed in the Tables 8–10, respectively. Which shows that in the modal analysis the dynamic behaviors of the two models match well. For the modes with the same order, the natural frequency of lumped mass model is a little higher than that of the 3-D model, and the difference becomes more obviously when the order is bigger, which suggests that the lumped mass model has larger stiffness. The displacement and stress calculated by the 3-D model are larger than those calculated by the lumped mass model, especially for the reactor coolant pump and steam generator. This is because the geometry complexity of SG spherical channel head is simulated better by the 3-D model.

5. Conclusions

The three-dimension finite element model and the lumped mass model of the reactor coolant system of advanced PWR are constructed, and through spectrum and time-history analysis, the seismic response of RCS and boundary conditions of RCP nozzles are obtained. The calculated results show:

(1) With the modal analysis, the first natural frequency is lower than 33 Hz which means the whole model is flexible, and the spectrum analysis and time-history analysis is used for seismic analysis. The surge line is a weak component of RCS and the vibration of RCPs also predominates in the low order frequencies.
(2) By the seismic spectrum analysis the maximum Tresca stress is 140.03 MPa located at the connection part of SG1 and RCP1A, which suggests that the SG system including RCP should be analyzed in detail. And the sensitivity analysis of spectrum input angle and stiffness of supports is investigated, which shows that the maximum displacement response occurs in the surge line, and the maximum stress appears in the connection part of SG and RCP1A with the horizontal input angle of 60°., and as the stiffness is increased, the stress and displacement are reduced.
(3) The acceleration, displacement, force and moment at the RCP nozzles are calculated by the dynamic time history analysis, which will be the input data of the boundary conditions for the detail seismic analysis of RCP system.
(4) The displacement and stress calculated by the 3-D model are larger than those calculated by the lumped mass model, especially for the reactor coolant pump and steam generator, which means that for the complicated geometry the 3-D model is better than the lumped mass model.

Acknowledgments

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