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THE RESEARCH OF SEISMIC RESPONSE ANALYSIS OF CARR REACTOR COMPLEX

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ABSTRACT

CARR reactor complex includes core vessel, heavy water tank, flow guiding tank, decay tank and reactor pool, etc. There is a lot of light water and heavy water in the complex. A fluid-structure interaction must be simulated in the seismic analysis. The reactor complex is simplified a 3D fluid-solid coupled model which includes fluid elements and solid elements. A modal analysis is performed for the 3D fluid-solid coupled model and obtains natural frequencies and mode shapes under fluid-structure interaction. On the base an equivalent fluid-solid coupled model is built and performed for seismic response analysis.

Keywords: CARR reactor complex, fluid-structure interaction, seismic response analysis

1. INTRODUCTION

According to the contract between Reactor Engineering Research & Design Department, China Institute of Atom Energy and Shanghai Nuclear Engineering Research & Design Institute, CIAE entrusted SNERDI with mechanics analysis and evaluation of CARR reactor complex and fuel assemblies. This paper is the research of seismic response analysis of CARR reactor complex. The results of seismic analysis will provide various seismic loads for stress analysis and evaluation of the internals of CARR reactor complex.

2. STRUCTURE BRIEF DESCRIPTION

The reactor complex is an important component of CARR. It includes core vessel and its internals, heavy water tank, flow guiding tank, decay tank, vertical channels, horizontal channels, structure supports and reactor pool, etc. The reactor core is located in the center of the pool. Decay tank is fixed in the bottom of the pool. Outlet piping of primary coolant loop is guided out of decay tank. Heavy water tank is sited on the upper board of decay tank and is joint with flow guiding tank. Heavy water tank contains heavy water and arranges 9 horizontal channels along its radial. 24 vertical channels and other channels are placed on the bottom board of heavy water tank. The upper of flow guiding tank is installed the radial supports which make the complex and the pool as a whole. The core vessel passes through the middle of heavy water tank and connects with flow guiding tank. The core vessel holds fuel assemblies. The coolant passes through core vessel and decay tank into flow guiding tank and flows out of the reactor from outlet piping. They form the primary loop pressure boundary.[1][2] The structure figure of reactor complex is shown in fig2.1.

3. INPUT LOAD

Design acceleration response spectra of the seismic analysis are shown in Table 3.1 and Table 3.2. Damping rate are 2% and 4%, respective. It is provided by Tsinghua university.[3]

Table 3.1 SL1 seismic design response spectra (damping rate 2%)

horizontal-X	Freq(Hz)	0.170	0.239	0.545	1.009	1.364	2.36	2.630	5.217
	Value(g)	0.053	0.122	0.349	2.146	2.146	0.465	0.444	3.537
	Freq(Hz)	7.058	10.867	11.865	16.053	24.21	39.1	57.5	
	Value(g)	3.537	0.843	1.121	1.121	0.413	0.395	0.215	
horizontal-Y	Freq(Hz)	0.17	0.239	0.475	1.009	1.364	2.36	2.63	5.217
	Value(g)	0.038	0.107	0.236	1.221	1.221	0.367	0.361	5.715
	Freq(Hz)	7.058	9.145	11.865	16.053	24.21	39.1	57.5	
	Value(g)	5.715	1.173	1.416	1.416	0.507	0.457	0.227	
vertical-Z	Freq(Hz)	0.17	0.224	1.009	1.868	2.527	3.323	6.525	10.645
	Value(g)	0.028	0.063	0.320	2.162	2.162	0.504	0.214	0.245
	Freq(Hz)	19.714	39.1	57.5					
	Value(g)	0.221	0.185	0.109					

Table 3.2 SL2 seismic design response spectra **(**damping rate 4%**)**

horizontal-X	Freq(Hz)	0.170	0.239	0.716	1.009	1.364	1.894	2.817	3.704
	Value(g)	0.073	0.151	0.531	1.6	1.6	0.614	0.614	0.769
	Freq(Hz)	4.872	7.558	11.419	16.053	24.21	39.1	57.5	
	Value(g)	2.696	2.696	0.875	0.875	0.516	0.489	0.323	
horizontal-Y	Freq(Hz)	0.17	0.224	0.716	1.009	1.364	1.922	2.817	3.967
	Value(g)	0.054	0.133	0.556	1.215	1.215	0.57	0.57	1.09
	Freq(Hz)	5.217	7.558	9.94	16.053	19.714	39.1	57.5	
	Value(g)	3.171	3.171	1.197	1.197	0.622	0.499	0.34	
vertical-Z	Freq(Hz)	0.17	0.224	1.009	1.744	2.527	3.811	8.668	19.714
	Value(g)	0.039	0.075	0.322	1.569	1.569	0.499	0.275	0.257
	Freq(Hz)	39.1	57.5						
	Value(g)	0.229	0.164						

4. ANSYS METHODS AND CALCULATION CODE

4.1 ANALYSIS METHODS

The reactor complex containing core vessel, heavy water tank and flow guiding tank. and the pool form a whole structure. There is a large number of light water and heavy water in the pool. Therefore fluid-structure interaction is considered in the seismic analysis. 3D fluid elements and 3D structure elements are applied.

4.2 CALCULATION CODE

ANSYS code is applied in the seismic analysis. It is known to a large-scale current FEA code. Mechanical analysis containing solid and fluid; static and dynamic; linear and nonlinear etc. can be performed with ANSYS .

4.3 BASIC THEORY OF FLUID-STRUCTURE INTERACTION IN ANSYS[4]

In fluid-structure interaction analysis, the structural dynamics equation needs to be considered along with the Navier-Stokes equations of fluid momentum and the flow continuity equation. The discretized structural dynamics equation can be formulated using the structural elements. The fluid momentum (Navier-Stokes) and continuity equations are simplified to get the acoustic wave equation using following assumptions:

(1) The fluid is compressible (density changes due to pressure variations).
(2) The fluid is inviscid (no viscous dissipation).
(3) There is no mean flow of the fluid.
(4) The mean density and pressure are uniform throughout the fluid.

The Navier-Stokes equation can be simplified to linear acoustic wave equation:

$$\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - \nabla^2 p = 0 \tag{4-1}$$

where: c = speed of sound ($\sqrt{k/\rho_0}$) in fluid medium
ρ_0 = mean fluid density
k = bulk modulus of fluid
p = acoustic pressure
t = time

Since the viscous dissipation has been neglected, equation (4-1) is referred to as the lossless wave equation for propagation of sound in fluids. The discretized structural equation and the lossless wave equation have to be considered simultaneously in fluid-structure interaction problems. The fluid pressure acting on the structure at the fluid-structure interface will be considered to form the coupling stiffness matrix.

The fluid-structure interaction equation derives as follow:

The matrix operators are introduced for equation (4-1) and the discretized wave equation can be written as follow:

$$\left[M_e^p\right]\left\{\ddot{p}_e\right\} + \left[C_e^p\right]\left\{\dot{p}_e\right\} + \left[K_e^p\right]\left\{p_e\right\} + \rho_0\left[\mathrm{Re}\right]^T\left\{\ddot{U}_e\right\} = 0 \tag{4-2}$$

where: $\left[M_e^p\right] = \frac{1}{c^2}\int_v \{N\}\{N\}^T dv$ = fluid mass matrix (fluid)

$\left[C_e^p\right] = \frac{\beta}{c}\int_s \{N\}\{N\}^T ds$ = fluid damping matrix (fluid)

$\left[K_e^p\right] = \int_v [B]^T[B]dv$ = fluid stiffness matrix (fluid)

In order to completely describe the fluid-structure interaction problem, the fluid pressure load acting at the interface is added to equation. So, the structure equation is written as follow:

$$\left[M_e\right]\left\{\ddot{U}_e\right\} + \left[C_e\right]\left\{\dot{U}_e\right\} + \left[K_e\right]\left\{U_e\right\} = \left\{F_e\right\} + \left\{F_e^{pr}\right\} \tag{4-3}$$

The fluid pressure load vector $\left\{F_e^{pr}\right\}$ at the interface S is obtained by integrating the pressure over the area of the surface:

$$\left\{F_e^{pr}\right\} = \int_s \{N'\}p\{n\}d(s) \tag{4-4}$$

$$p=\{N\}^T\{p_e\} \tag{4-5}$$

where: {N'} = shape functions employed to discretize the displacement components u,v,w (obtained from the structural element)
{N} = element shape function for pressure
{n} = normal at the fluid boundary

Substituting the finite element approximating function for pressure given by equation (4-5) into (4-3):

$$\left\{F_e^{pr}\right\} = \int_s \{N'\}\{N\}^T\{n\}ds\{p_e\} = \left[\mathrm{Re}\right]\left\{p_e\right\} \tag{4-6}$$

where: $$\left[\mathrm{Re}\right] = \int_s \{N'\}\{N\}^T\{n\}ds \tag{4-7}$$

Substituting of equation (4-7) into (4-3) results in the dynamic elemental equation of the structure:

$$\left[M_e\right]\left\{\ddot{U}_e\right\} + \left[C_e\right]\left\{\dot{U}_e\right\} + \left[K_e\right]\left\{U_e\right\} - \left[\mathrm{Re}\right]\left\{p_e\right\} = \left\{F_e\right\} \tag{4-8}$$

Equation (4-2) and (4-8) describe the complete finite element discretized equations for the fluid-structure interaction problem and are written in assembled form as:

$$\begin{bmatrix}[M_e] & [0] \\ [M^{fs}] & [M_e^p]\end{bmatrix}\begin{Bmatrix}\{\ddot{U}_e\} \\ \{\ddot{p}_e\}\end{Bmatrix}+\begin{bmatrix}[C_e] & [0] \\ [0] & [C_e^p]\end{bmatrix}\begin{Bmatrix}\{\dot{U}_e\} \\ \{\dot{p}_e\}\end{Bmatrix}+\begin{bmatrix}[K_e] & [K^{fs}] \\ [0] & [K_e^p]\end{bmatrix}\begin{Bmatrix}\{U_e\} \\ \{p_e\}\end{Bmatrix}=\begin{Bmatrix}\{F_e\} \\ \{0\}\end{Bmatrix} \quad (4\text{-}9)$$

where: $[M^{fs}]=\rho_0[Re]^T$; $[K^{fs}]=-[Re]$ 。

From equation (4-9), we can see that for aproblem involving fluid-structure interaction, the acoustic fluid element will generate all the submatrices with superscript p in addition to the coupling submatrices $\rho_0[Re]^T$ and [Re]. Mass and stiffness matrix form unsymmetric configuration. Therefore, for the coupled (unsymmetric) problem, a corresponding unsymmetric eigensolver must be used.

5. CALCULATION MODELS

Due to the reactor complex of CARR are immerged in the pool, fluid-structure interaction must be considered in the seismic analysis. At first, a 3D fluid-solid coupled analysis model is built. A unsymmetric matrix method is used to perform a modal analysis because mass and stiffness matrix of the fluid-solid coupled model are unsymmetric. A full transient method can be used for the seismic response analysis. Now because of the computer capacity limitation, 3D fluid-solid coupled model is used only in modal analysis which can obtain structural natural frequencies and mode shapes in fluid-structure interaction. On this base, a 3D equivalent fluid-solid coupled model is built to perform the seismic response analysis.

5.1 FLUID-SOLID COUPLED MODEL BUILD

Shell element of ANSYS is used to simulate core vessel, heavy water tank, flow guiding tank and decay tank. Pipe element is used to simulate inlet pipe, outlet pipe and horizontal channels. Beam element is used to simulate the supports of flow guiding tank. Fluid element is used to simulate liquid in the reactor and the pool. The wall of the pool is assumed to be rigid. Fluid-structure interface may be flagged by surface loads at the element faces. Specifying the label will couple the structural motion and fluid pressure at the interface. core vessel, heavy water tank and flow guiding tank were modeled explicitly. Decay tank is modeled only inner cylinder, middle cylinder and top plate. Its bottom plate is regarded as fixed boundary condition. Water effect on horizontal channels, inlet pipe and outlet pipe is considered as additive mass. Intersectant points between horizontal channels and the wall of the pool are regarded as fixed boundary condition. Intersectant points between inlet pipe, outlet pipe and the wall of the pool are also regarded as fixed boundary condition. For vertical channels, only its mass is considered, its stiffness will be neglected.

The analysis model has 26295 fluid elements, 3192 shell elements and 7397 couple elements. In total, there are 27899 elements and 22966 nodes in the model. Simplified finite element model is shown in figure 5.1.

5.2 EQUIVALENT FLUID-SOLID COUPLED MODEL BUILD

When we build the equivalent fluid-solid coupled model the solid model in section 5.1 is adopted and added on additive liquid mass. Additive liquid mass is calculated to base on ASME code appendix N-1450. In this way, we can obtain additive liquid mass of core vessel, heavy water tank, flow guiding tank, decay tank, horizontal channel, inlet pipe and outlet pipe, etc. These additive liquid mass are applied in analysis model.

Boundary conditions in equivalent model are the same with those described in section 5.1 for core vessel, heavy water tank, flow guiding tank, decay tank and horizontal channels, etc. The equivalent model has 2640 shell elements, 188 beam elements and 66 couple elements. In total, there are 2828 elements and 2817 nodes in the model. Simplified finite element model is shown in figure 5.2.

6. CALCULATION RESULTS

6.1 RESULTS OF MODAL ANALYSIS

Unsymmetric matrix method is applied in fluid-solid coupled model. Calculating results of natural frequencies and mode shapes (fluid-solid coupled model) were shown in Table 6.1. Deformed shape plots are shown in fig. 6.1~fig. 6.3.

Subspace iteration method is applied in equivalent fluid-solid coupled model. Calculating results of natural frequencies and mode shapes (equivalent fluid-solid coupling model) are shown in Table 6.2. Deformed shape plots are shown in fig. 6.4~fig. 6.6.

Table 6.1 Natural frequencies and mode shapes (fluid-solid coupled model)

modes	1	2	3	4	5	6	7	8	9	10
Frequency values	14.348	15.272	25.788	32.300	36.204	39.863	42.616	43.273	47.708	51.746
location	outlet pipe	outlet pipe	inlet pipe	inlet pipe	FGT HWT CV	FGT HWT CV	outlet pipe	outlet pipe	outlet pipe	supports
Mode shapes	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=2	beam shape m=2	beam shape m=2	beam shape m=1
direction	Hori. Y direction	Hori. X direction	Hori. Y direction	Hori. X direction	Hori. Y direction	Hori. X direction	Hori. X direction	Hori. Y direction	hori. Y direction	Vert. Z direction
modes	11	12	13	14	15	16	17	18	19	20
Frequency values	51.837	52.243	52.493	52.772	52.866	52.941	52.999	53.121	53.324	54.003
location	outlet pipe	supports	supports	supports	supports	supports	supports	supports	supports	supports
Mode shapes	beam shape m=2	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1
direction	Hori. X direction	Vert. Z direction	Vert. Z direction	Vert. Z direction	Vert. Z direction	Vert. Z direction	Vert. Z direction	Vert. Z direction	Vert. Z direction	Vert. Z direction
modes	21	22	23	24	25	26	27	28	29	30
Frequency values	54.821	55.559	55.745	57.312	59.601	61.402	61.418	63.113	67.385	75.353
location	supports	supports	supports	FGT	inlet pipe	CV	CV	FGT	FGT	DT
Mode shapes	beam shape m=1	beam shape m=1	beam shape m=1	shell shape m=1 n=3	beam shape m=2	shell shape m=1 n=2	shell shape m=2 n=2	beam shape m=1 n=3	shell shape m=1 n=3	shell shape m=1 n=0
direction	Vert. Z direction	Vert. Z direction	Vert. Z direction	Hori.XY direction	Hori. Y direction	Hori. XY direction	Hori.XY direction	Vert. Z direction	Hori.XY direction	Vert. Z direction

Table 6.2 Natural frequencies and mode shapes (equivalent fluid-solid coupled model)

modes	1	2	3	4	5	6	7	8	9	10
Frequency values	13.84	14.77	25.89	33.00	39.18	41.41	41.62	42.046	47.396	50.243
location	outlet pipe	outlet pipe	inlet pipe	inlet pipe	FGT HWT CV	FGT HWT CV	outlet pipe	outlet pipe	outlet pipe	supports
Mode shapes	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=2	beam shape m=2	beam shape m=2	beam shape m=1
direction	Hori. Y direction	Hori. X direction	Hori. Y direction	Hori. X direction	Hori. Y direction	Hori. X direction	Hori. X direction	Hori. Y direction	Hori. Y direction	Vert. Z direction
modes	11	12	13	14	15	16	17	18	19	20
Frequency values	50.795	52.151	52.398	52.489	52.685	52.780	53.019	53.093	53.322	53.958
location	outlet pipe	supports	supports	supports	supports	supports	supports	supports	supports	supports
Mode shapes	beam shape m=2	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1	beam shape m=1
direction	Hori. X direction	Vert. Z direction	Vert. Z direction	Vert. Z direction	Vert. Z direction	Vert. Z direction	Vert. Z direction	Vert. Z direction	Vert. Z direction	Vert. Z direction
modes	21	22	23	24	25	26	27	28	29	30
Frequency values	54.526	54.583	57.669	58.370	59.586	60.694	68.321	68.490	68.680	70.293
location	supports	supports	FGT	FGT	inlet pipe	outlet pipe	CV	CV	HWT CV	FGT CV
Mode shapes	beam shape m=1	beam shape m=1	shell shape m=1 n=3	shell shape m=1 n=3	beam shape m=2	shell shape m=1 n=2	shell shape m=2 n=2	shell shape m=2 n=2	shell shape m=1 n=4	Shell shape m=2 n=2
direction	Vert. Z direction	Vert. Z direction	Hori.XY direction	Hori.XY direction	Hori. Y direction	Hori.XY direction	Hori.XY direction	Hori.XY direction	Hori.XY direction	Hori.XY direction

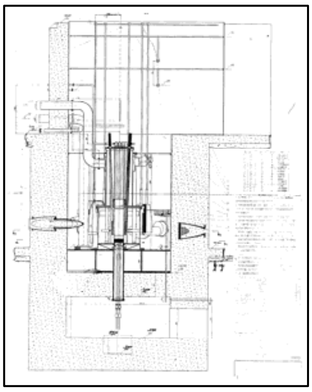

fig 2.1 **The complex structure**

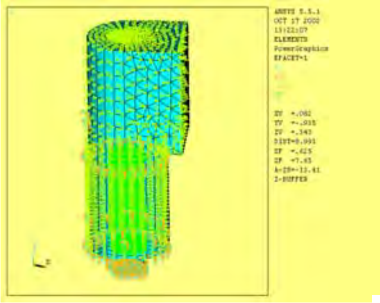

fig 5.1 **Fluid-solid coupled model**

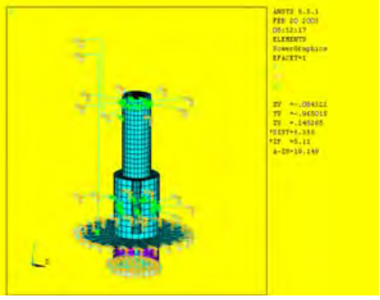

fig 5.2 **equivalent fluid-solid coupled model**

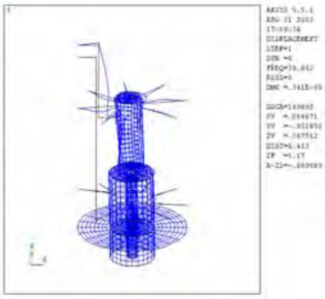

fig.6.1 **6th deformed shape (fluid-solid coupled model)**

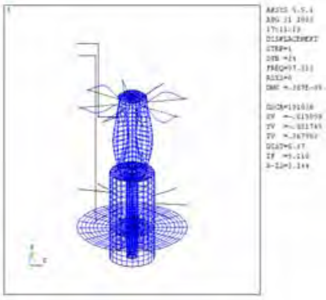

fig.6.2 **24th deformed shape (fluid-solid coupled model)**

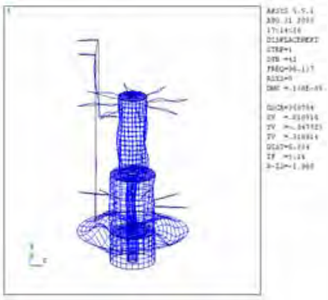

fig.6.3 **42th deformed shape (fluid-solid coupled model)**

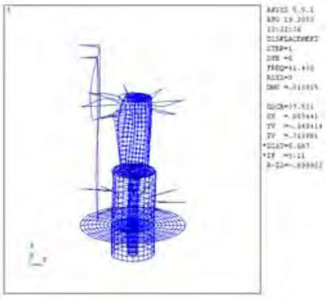

fig.6.4 **6th deformed shape (equivalent f-s coupled model)**

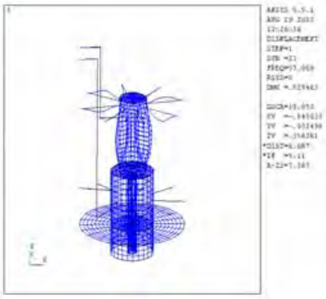

fig.6.5 **12th deformed shape (equivalent f-s coupled model)**

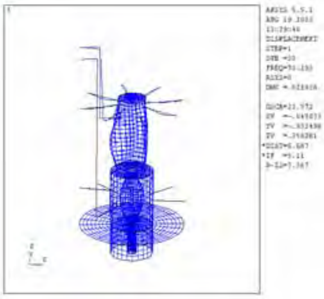

fig.6.6 **30th deformed shape (equivalent f-s coupled model)**

6.2 RESULTS OF SEISMIC RESPONSE ANALYSIS

6.2.1 DISPLACEMENT AND ACCELERATION

Spectrum analysis method is applied in the seismic response analysis. The most displacements and the most accelerations in the seismic load SL1 and SL2 are shown in Table 6.3.

6.2.2 STRESS INTENSITY AND FORCES

The most stress intensity of the components in the seismic load SL1 and SL2 are shown in Table 6.4. The most stress intensity of the structure in seismic load SL1 is shown in figure 6.7. The most stress intensity of the structure in seismic load SL2 is shown in figure 6.8.

Forces of horizontal channels, inlet pipe and outlet pipe in the seismic load SL1 and SL2 are shown in Table 6.5 and Table 6.6.

Table 6.3 displacements and accelerations in the seismic load SL1 and SL2

Structures	max. displacements (mm)		max. accelerations (g)	
	SL1	SL2	SL1	SL2
Core vessel	0.0403	0.0497	0.307	0.403
Heavy water tank	0.0377	0.044	0.263	0.331
Flow guiding tank	0.22	0.270	1.059	1.295
Decay tank	0.130	0.103	0.184	0.279
Supports	0.275	0.382	2.989	4.199
Horizontal channel	0.0169	0.0201	0.124	0.158
Inlet pipe	0.437	0.510	1.460	1.746
Outlet pipe	2.881	2.377	2.333	1.928

Table 6.4 stress intensity of the components in the seismic load SL1 and SL2

structure	max. stress intensity (MPa)	
	SL1	SL2
Core vessel	0.5891	0.7795
Heavy water tank	2.92	3.42
Flow guiding tank	31.0	37.9
Decay tank	33.2	27.5

Table 6.5 Force of the components in the seismic load SL1

structure	FX (N)	FY (N)	FZ (N)	MX (N-m)	MY (N-m)	MZ (N-m)
Hot neutron channel Ⅰ	1605.8	366.70	323.44	1.1807	28.615	71.278
Spare channel	1494.6	789.02	482.69	0.74207	58.074	130.25
Hot source channel	1263.5	887.73	405.99	3.0656	49.242	148.35
Hot neutron channel Ⅱ	1666.4	465.04	254.30	1.8768	22.230	82.568
Hot neutron channel Ⅰ	1964.0	738.76	511.70	3.3532	61.265	100.28
Cold source channel	1868.9	891.86	711.29	0.82527	95.366	153.35
Heat column channel	1338.6	437.76	335.56	2.9710	29.115	80.439
Long tangent channel	1021.0	571.97	245.26	1.1637	24.742	79.770
Hot neutron channel Ⅱ	1242.3	787.09	481.99	1.0944	58.876	137.30
Inlet pipe	9436.4	7783.4	3316.3	4.2462	437.14	767.70
Outlet pipe	7889.9	19574.	15455.	2.9816	6151.6	5103.1
Supports	10319.	62.738	365.25	13.809	127.01	59.353

Table 6.6 Force of the components in the seismic load SL2

structure	FX（N）	FY（N）	FZ（N）	MX（N-m）	MY（N-m）	MZ（N-m）
Hot neutron channel Ⅰ	1839.2	473.39	363.45	1.444	31.991	92.256
Spare channel	1784.5	934.82	563.04	0.8921	67.588	152.18
Hot source channel	1626.9	1024.9	507.69	3.7383	61.479	174.98
Hot neutron channel Ⅱ	2027.6	540.35	312.71	2.4081	27.225	99.545
Hot neutron channel Ⅰ	2275.6	900.19	592.22	3.9713	70.823	122.05
Cold source channel	2146.1	1134.4	802.74	1.011	107.52	194.38
Heat column channel	1562.8	530.43	395.52	3.6409	34.042	95.534
Long tangent channel	1294.0	664.01	307.87	1.3904	30.508	94.445
Hot neutron channel Ⅱ	1459.3	944.82	573.82	1.4050	70.145	164.40
Inlet pipe	11778.	8862.9	4142.2	5.9645	545.39	874.28
Outlet pipe	6270.9	16546.	12176.	3.5681	4812.5	4300.1
Supports	11332.	72.211	513.13	19.459	179.13	73.682

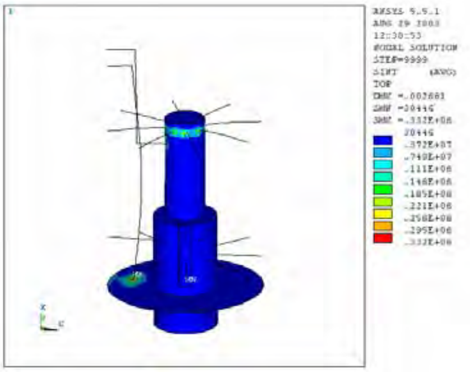

Fig 6.7 Max. stress intensity of the structure in the seismic load SL1

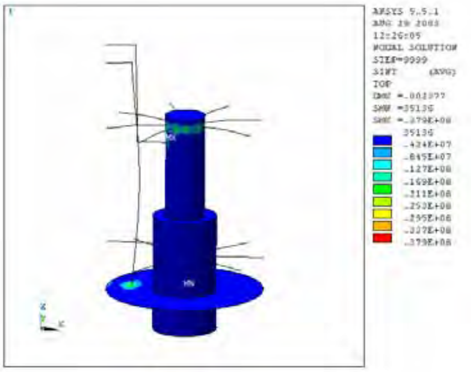

Fig 6.8 Max. stress intensity of the structure in the seismic load SL2

7. CONCLUSIONS

(1) The seismic response analysis of CARR reactor complex is performed in ANASYS. At first, a 3D fluid-solid coupling analysis model is built. Then, natural characteristic of the structure is analyzed in modal analysis method. The last, a 3D equivalent fluid-solid coupled model is built to perform the seismic response analysis.

(2) The calculational results of the seismic response analysis have obtained the most stress intensity and forces of each component in the seismic load SL1 and SL2. The results will provide seismic loads for various components stress analysis and evaluation.

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