Paper 288

Proceedings of the Eleventh International Conference
on Computational Structures Technology,
B.H.V. Topping, (Editor),
Civil-Comp Press, Stirlingshire, Scotland

Structural Integrity Evaluation of Reactor Pool Working Platform: Guide Tubes and Refuelling Cover in a Research Reactor

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Abstract

The objective of this study, presented in this paper, is to design the reactor pool working platform (RPWP) including the guide tubes and refuelling cover, and to evaluate the structural integrity of those during and after the seismic events. Their three-dimensional finite element models are developed by utilizing the MIDAS program. To evaluate their structural integrity, the response spectrum analysis has been performed under the seismic loads of SSE (Safe Shutdown Earthquake). The analysis results show that the maximum stress values under the seismic loads are within the specified code limits. It is also confirmed that the impact does not take place under the SSE event. Therefore, any damage to the structural integrity is not expected when the working platform including the guide tubes and refuelling cover are installed and utilized in the reactor pool.

Keywords: reactor pool working platform, guide tubes, refuelling cover, research reactor, response spectrum analysis, structural integrity, hydrodynamic mass effect.

1 Introduction

Research reactor is one of the nuclear reactors, which serves primarily as a neutron source. The neutrons produced by a research reactor are used for neutron scattering, neutron radiography, neutron activation analysis, neutron transmutation doping, non-destructive testing, analysis and testing of materials, testing of fuel and structural materials for nuclear power engineering, production of radioisotopes, research and public outreach and education, etc. The efficient use of neutrons is significantly influenced by how the reactor structure assembly (RSA), the place where nuclear reaction takes place, in the reactor pool can be accessed without the risk of safety and how to prevent the rise of radio-activated flow induced by the primary cooling system from going up to the reactor pool top. For this, several facilities have been needed in the reactor pool and their structural integrities have to be investigated. Under this circumstance, the reactor pool working platform (RPWP) including guide tubes and refuelling cover are newly devised and structurally evaluated in this study.

The RPWP is installed in the middle of reactor pool, which is above the top of RSA. The guide tubes and refuelling cover are mounted on the surface of RPWP. The design of the RPWP, guide tubes and refuelling cover which are classified into Non Nuclear Safety (NNS) and seismic category II structures has been performed in accordance with the appropriate codes and standards. For evaluating the structural integrity of them, the static and the response spectrum analysis have been performed under the specific loading combinations. Their stresses are thoroughly searched. The possibility of impact between the top of RSA and the bottom of refuelling cover is investigated as well. Finally, it would be confirmed whether the proposed design and the structural evaluation results of the RPWP, guide tubes and refuelling cover provide the improvement of safety and efficient operation of the research reactor.

2 Design for RPWP including guide tubes and refuelling cover

The RPWP including guide tubes and refuelling cover are installed in the reactor pool of a research reactor as shown in Figure 1. The main function of the RPWP covers the reactor pool, supports the guide tubes and a refuelling cover, provides working place near the RSA, and suppresses the rise of radio-active flow induced by the primary cooling system. The guide tubes provide the ways to have the radioisotopes irradiated. The refuelling cover protects the RSA and supports some on-power loading guide tubes.

The design of RPWP, guide tubes and refuelling cover has been performed according to the guideline of AISC N690 code [1] and US NRC Regulatory Guides. As shown in Figure 1, the RPWP is constituted by the base frame covered by removable gratings and checkered plates. The base frame consists of H-section (W200 x 46.1), C-channel (field manufacture) and L-angle (L76 x 76) beams, and is mounted by bolting on the bracket attached to the embedded plates of the pool liner. The guide tubes in holes for the radioisotopes and the neutron transmutation doping are composed of the base plate, the guide cell pipes and the angle frames. The refuelling cover is composed of the frame, two meshed structures, and two guide cell pipes. Materials of the RPWP, guide tubes and refuelling cover are made of austenitic stainless steel 304L (S.S 304L) and Al 6061 T6 to prevent the corrosion and the radio-activation, respectively. The specific material properties are shown in Table 1.

The AISC N690 is used as a guide for design, manufacture and inspection for the RPWP, guide tubes and refuelling cover. As per codes and standards, the RPWP, guide tubes and refuelling cover are classified as shown in Table 2. They are designed to meet the allowable limits defined in AISC N690 code for several load combinations.

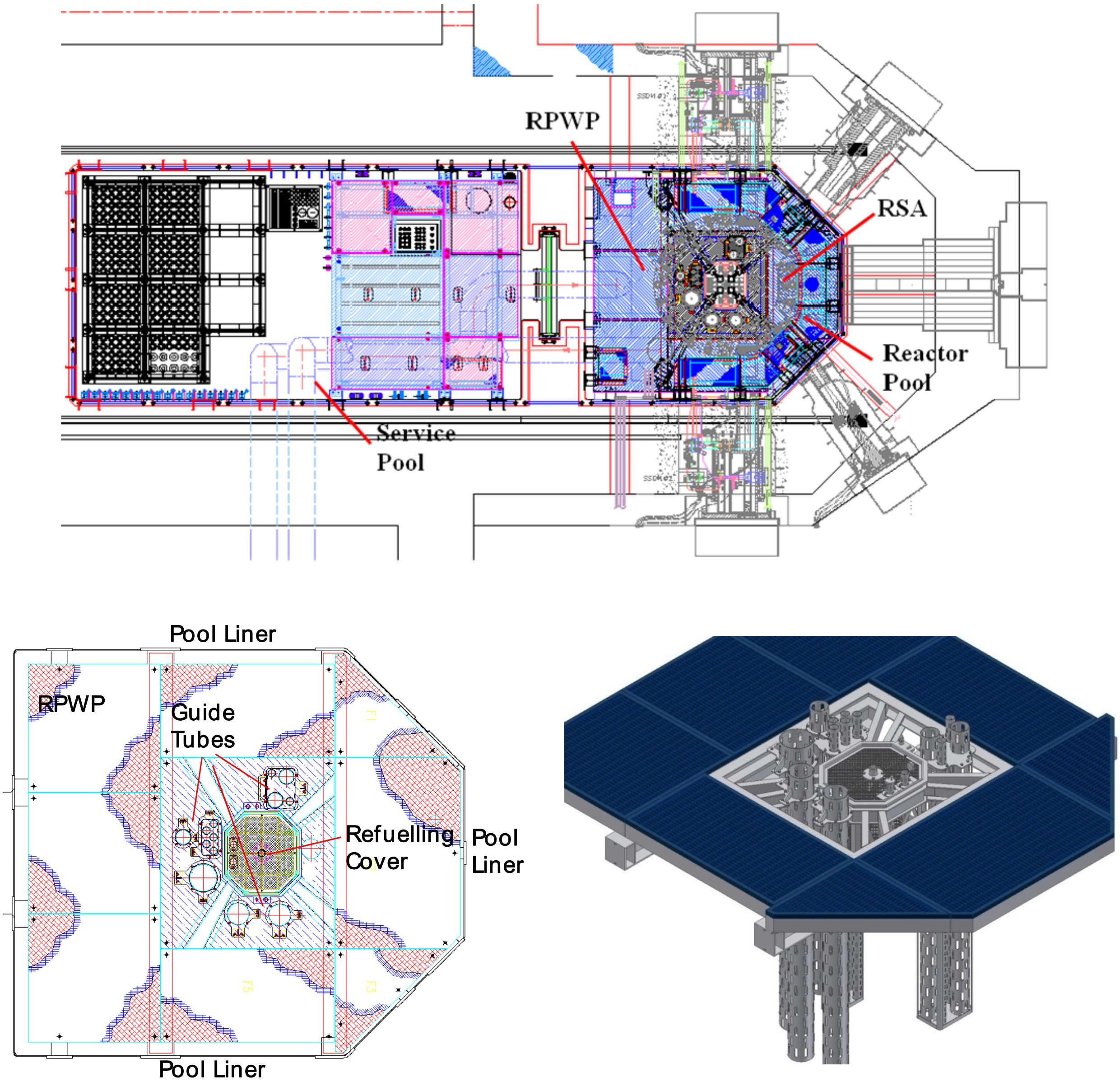


Figure 1: Configuration of RPWP, guide tubes and refuelling cover in reactor pool

Material	Stainless steel 304L	Al 6061 T6
Young's modulus (GPa)	193.1	70
Density (kg/m^3)	7930	2650
Poisson's ratio	0.3	0.33
Yield strength, F_y (MPa)	172	270

Table 1: Material properties of RPWP, guide tubes and refuelling cover

Component	Safety Class[(1)]	Seismic Category[(2)]	Quality Class
RPWP, guide tubes, refuelling cover	NNS	II	T

NOTES
(1) Defined in American National Standard ANSI/ANS-51.1 [2]
(2) Defined in Regulatory Guide 1.29 [3]

Table 2: Design classification of RPWP, guide tubes and refuelling cover

3 Structural integrity evaluation for RPWP including guide tubes and refuelling cover

3.1 Governing equations of motion

The equation of motion of the RPWP, guide tubes and refuelling cover subjected to earthquake excitation is expressed in the matrix form as

$$[m]\{\ddot{x}\}+[c]\{\dot{x}\}+[k]\{x\}=[m]\{r\}\ddot{u}_g \tag{1}$$

Where $\{x\}$ is the displacement vector relative to the ground; $[m]$, $[c]$ and $[k]$ are mass, damping and stiffness matrices, respectively; $\{r\}$ is the influence coefficient vector; $\ddot{u}_g$ is the earthquake acceleration. Hydrodynamic effect on the RPWP, guide tubes and refuelling cover is reckoned by the added mass effect [4-5].

For solving the above governing equation of motion, the response spectrum method is applied in this study as it not only provides comparatively accurate responses of the system but also costs less computational efforts in comparison to other methods. In the response spectrum method, after the peak response quantities are obtained in each mode of the system, the maximum responses are predicted by using the proper combination method for earned peak individual modal responses such as SRSS (Square Root of Sum of Squares), CQC (Complete Quadratic Combination) or ABS (Absolute Sum). In this study, SRSS method is adopted to combine the peak modal responses of the system as follows [6];

$$R_o=\left(\sum_{n=1}^{N}R_{no}^2\right)^{1/2} \tag{2}$$

Where n is the mode and N is total number of modes; R_{no} is the maximum response of n^{th} mode; R_o is the maximum response of system. This can be applied to the combination for earned maximum responses in each direction.

3.2 Finite element model and load conditions

The 3-D finite element model of the RPWP, refuelling cover and guide tubes in Figure 2 is developed by utilizing MIDAS program. All parts of the RPWP, refuelling cover and guide tube structures are modeled as beam elements, rigid link elements, distributed masses and point masses. For modeling of the beam structure of them, beam element which has total six translational and rotational degrees of freedom along each coordinate system is used. The weights of structural members, dead load and part of the live load are considered as the distributed masses. In addition, since the RPWP, refuelling cover and guide tubes are submerged in and influenced by water, the hydrodynamic mass effect is taken to account. The hydrodynamic added masses are calculated by considering the mass of the water surrounding H-beams, channels, angles, etc [4]. And these are considered as the point masses in the finite element model. The calculated hydrodynamic masses in terms of each section are represented in Table 3. Total hydrodynamic masses of the RPWP, guide tubes and refuelling cover are 1493 kg, 929 kg and 790 kg in *x* (EW), *y* (NS) and *z* (Vertical) direction, respectively.

Section (mm)	$(M_H)_x$ [kg/m]	$(M_H)_y$ [kg/m]
H - W200 x 46.1	25.73	64.73
Channel - C 50 x 125 x 10t	12.27	2.25
Channel - C 90 x 125 x 10t	12.27	7.3
Channel - C 30 x 125 x 10t	12.27	0.81
Rectangular tube - 256 x 363	149.03	82.87
Rectangular tube - 151 x 326	113.52	30.44
Circular pipe - OD 142, 3t	15.84	15.84
Circular pipe - OD 256, 3t	51.47	51.47
Circular pipe - OD 196, 3t	30.17	30.17

Table 3: Hydrodynamic mass of RPWP, guide tubes and refuelling cover

The boundary conditions of the RPWP are shown in Figure 2. The translationally fixed and rotationally freed boundary conditions are imposed on the end of the RPWP since it is bolted to the support bracket attached to the embedded plate. The refuelling cover and guide tubes are connected to the RPWP by rigid link elements. Most parts of the RPWP are made up as S.S 304L. The parts of the refuelling cover are made up as S.S 304L. The parts of the guide tubes are made up as Al 6061 T6. The material property of the RPWP, guide tubes and refuelling cover is shown in Table 1. The weight of main beams such as H- /channels/angle beams, guide tubes, refuelling cover and checkered plates/grating is about 1600 kg and about 750 kg, respectively. The live load acting on the RPWP is 500 kgf/m^2. The enveloped floor response spectra for SSE at the installing position of the RPWP are shown in Figure 3. A 7% damping is considered for the horizontal and vertical floor response spectra (FRS) since the boundary condition of this structure is similar to the bolted steel with bearing connection [7].

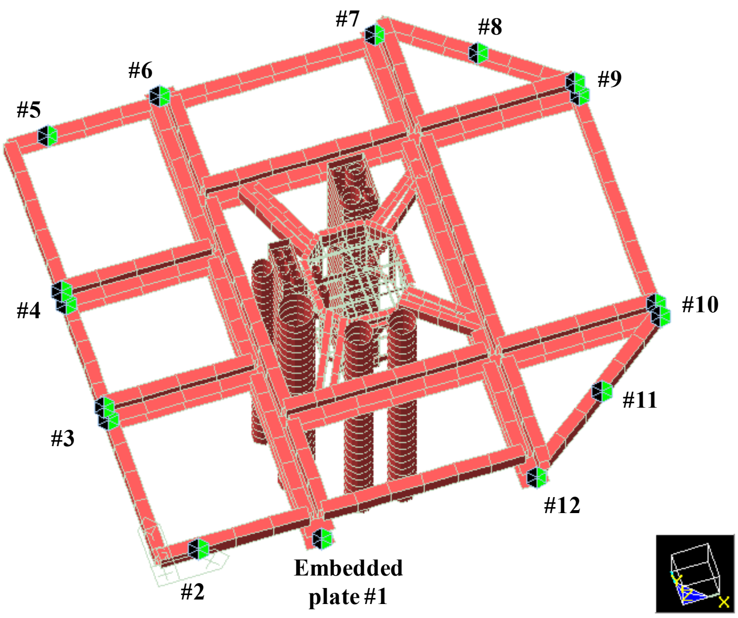


Figure 2: Finite element model and boundary condition of the RPWP, guide tubes and refuelling cover

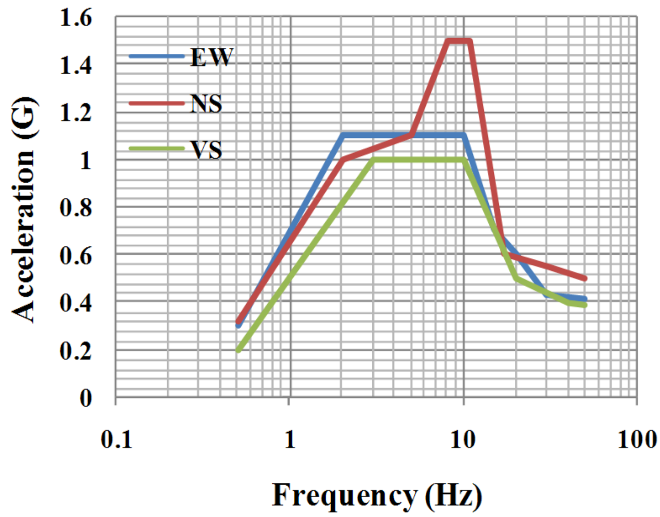


Figure 3: Floor response spectra for SSE at the installing position of RPWP, guide tubes, refuelling cover

3.3 Estimation of Structural Integrity

For the estimation of the structural integrity of the RPWP, guide tubes and refuelling cover in accordance with AISC N690 code, following conditions are applied. Allowable stresses are checked by following equations;

$$F_t = 0.6F_y \tag{3}$$

$$F_a = \frac{F_y}{2.15} - \left[\frac{\frac{F_y}{2.15} - 6}{120}\right]\frac{kl}{r}, \quad \frac{kl}{r} < 120 \text{ or } F_a = 12 - \frac{1}{20}\left(\frac{kl}{r}\right), \quad \frac{kl}{r} > 120 \tag{4}$$

$$F_v = 0.4F_y \tag{5}$$

$$F_b = 0.6F_y \tag{6}$$

Where F_t, F_a, F_v and F_b are the allowable tensile, compression, shear and bending stress, respectively; kl/r is the slenderness ratio which are composed of the effective element length, kl and the radius of gyration, r.

Combined stress ratios are checked by following equations. Specifically, Components under compression and bending stress condition are checked by Equation (7). Components under tension and bending stress condition are checked by Equation (8).

$$\frac{f_a}{0.60F_y} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \le 1.0 \quad \frac{f_a}{F_a} > 0.15 \tag{7a}$$

$$\frac{f_a}{F_a} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \le 1.0, \quad \frac{f_a}{F_a} \le 0.15 \tag{7b}$$

$$\frac{f_t}{F_t} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \le 1.0 \tag{8}$$

Where f_a denotes the calculated compression stress; F_a denotes the allowable compression stress; f_{bx} and f_{by} denote the calculated bending stress in the x and y direction, respectively; F_{bx} and F_{by} denote the allowable bending stress in the x and y direction, respectively; f_t denotes the calculated tensile stress; F_t denotes the allowable tensile stress.

Load combinations and allowable stresses are shown in Table 4. Design loadings considered in this study are the dead load, live load and seismic load. The dead load is the vertical load due to the weight of permanent structural and non-structural components of a structure, such as H-/channel/angle beams and gratings/checkered plates. The live load is the load superimposed by the use and occupancy of the structure and human not including the seismic load and impact load. The seismic load is the loads experienced by the system during an earthquake excitation. Seismic load input is used as the enveloped floor response spectra for the SSE.

Cases	Load Combinations	Allowable Values
Normal	Dead Load + Live Load	U
Extreme environmental	Dead Load + Live Load + SSE	1.6U

Where U denotes allowable stresses.

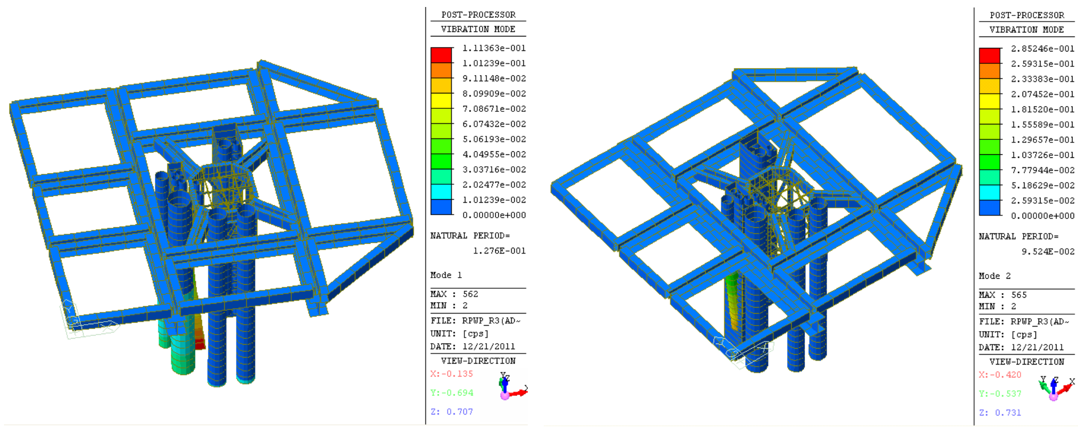
Table 4: Load combinations and allowable values

3.4 Static analysis

The static analysis is performed to check the stress levels for the structural components of the RPWP, guide tubes and refuelling cover when they are subjected to the normal load combination which has the dead and live loads.

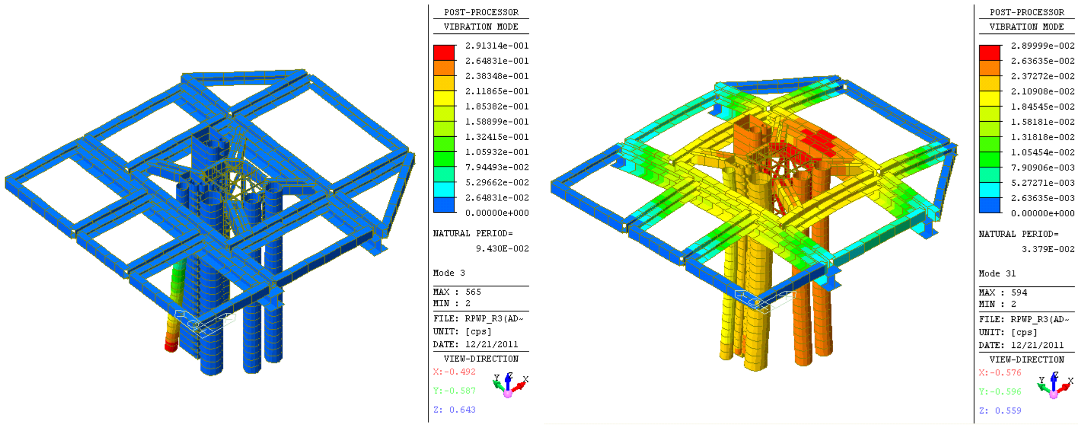
3.5 Seismic analysis

In order to investigate the dynamic characteristics of the RPWP, guide tubes and refuelling cover, modal analysis of the developed finite element model is performed. The typical measures of the dynamic characteristics, natural frequencies and mode shapes are obtained. Figure 4 summarizes four mode shapes in the structural model of the RPWP, guide tubes and refuelling cover. It is observed that the first natural frequency of the whole system is 7.84 Hz. The structurally fundamental frequency of the RPWP is 29.59 Hz except for the local effect of the guide tubes and refuelling cover.



(a) 1st mode (7.84 Hz) (b) 2nd mode (10.50 Hz)

Figure 4: Natural frequencies and mode shapes of the RPWP, guide tubes and refuelling cover



(c) 3rd mode (10.60 Hz) (d) 31th mode (29.59 Hz)

Figure 4: (continued) Natural frequencies and mode shapes of the RPWP, guide tubes and refuelling cover

The response spectrum method has been applied to evaluate the structural responses of the RPWP, refuelling cover and guide tubes under the seismic event. For the modal and directional response combination, the SRSS method in Equation (2) is used to predict the maximum responses as above mentioned, and total 400 modes are considered to take into account a modal effective mass of 90% of the model.

4 Numerical results

Tensile, shear, and combined stresses of each RPWP, guide tubes and refuelling cover are estimated. Then, the maximum stresses of the RPWP under normal and extreme environmental loading conditions are obtained. The results show that the weakest case is made in the channel element of the RPWP around the refuelling cover and guide tubes. Maximum stresses of the RPWP are summarized in Table 5. Figure 5 shows the bending stresses of the RPWP under extreme environmental condition as an example. In addition, the maximum stresses of the refuelling cover and the guide tubes under normal and extreme environmental loading conditions are investigated. Maximum stresses of the refuelling cover and the guide tubes are summarized in Table 6 and 7, respectively. Figure 5 shows the bending stresses of the refuelling cover and the guide tubes under extreme environmental condition as an example. These analysis results show that maximum tensile, shear and combined stresses under any loading conditions are within the AISC N690 code limits.

	Maximum stress (MPa)			
	Normal			
	Tensile	Shear	Bending	Combined stress ratio
Calculated stress	-8.77	9.01	16.75	0.29
Allowable Stress	103	68	103	1.0
	Extreme environmental			
	Tensile	Shear	Bending	Combined stress ratio
Calculated stress	11.88	11.63	38.13	0.36
Allowable Stress	165	110	165	1.0

Table 5: Maximum stress of the RPWP

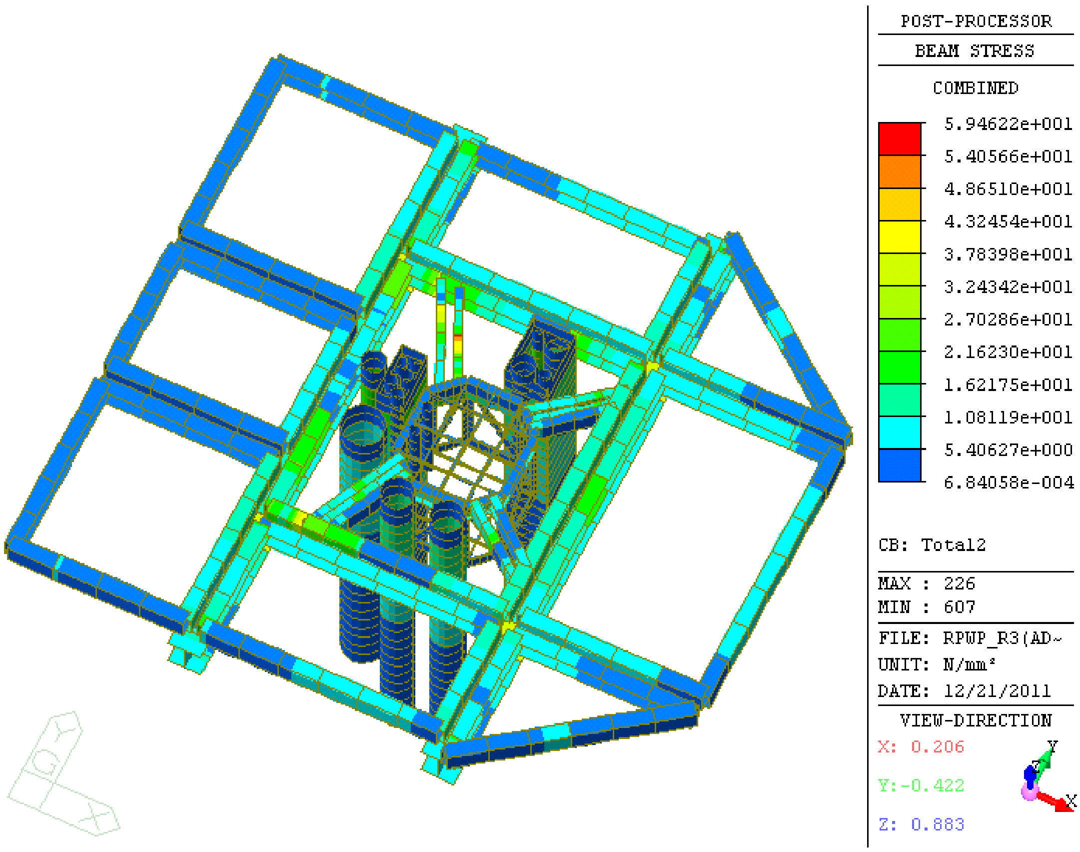


Figure 5: Bending stresses of the RPWP, refuelling cover and guide tube under extreme environmental condition

	Maximum stress (MPa)			
	Normal			
	Tensile	Shear	Bending	Combined stress ratio
Calculated stress	0.1	0.08	1.61	0.03
Allowable Stress	103	68	103	1.0
	Extreme environmental			
	Tensile	Shear	Bending	Combined stress ratio
Calculated stress	0.1	0.76	5.93	0.05
Allowable Stress	165	110	165	1.0

Table 6: Maximum stress of the Refuelling Cover

	Maximum stress (MPa)			
	Normal			
	Tensile	Shear	Bending	Combined stress ratio
Calculated stress	0.06	0	0	0
Allowable Stress	162	108	162	1.0
	Extreme environmental			
	Tensile	Shear	Bending	Combined stress ratio
Calculated stress	0.1	1.51	24.19	0.13
Allowable Stress	259	172	259	1.0

Table 7: Maximum stress of the Guide Tubes

Moreover, in order to check whether the refuelling cover contacts the top of the upper guide structure (UGS) of RSA or not, the maximum vertical displacements of the RPWP, refuelling cover and guide tubes are analyzed under the assumption of small vertical displacement of RSA. Figure 6 shows the maximum vertical displacements of the RPWP, refuelling cover and guide tubes under extreme environmental loading condition. This result demonstrates that since the maximum vertical displacement generated in the RPWP, refuelling cover and guide tubes is 1.21 mm which is less than 2 mm distance between the bottom of refuelling cover and the top of UGS, the impact does not take place. Thus, we can confirm that any damage on the structural integrity of the RPWP, refuelling cover and guide tube structure is not expected based on these results.

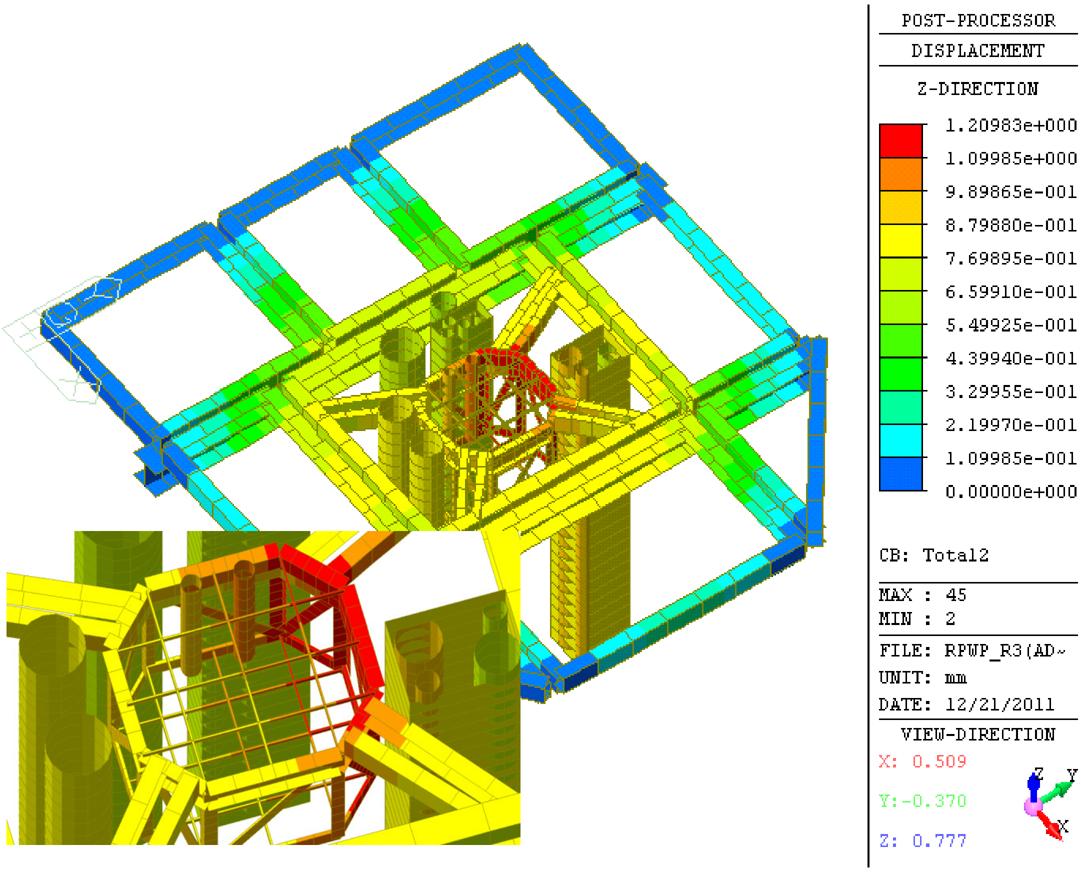


Figure 6: Displacement of the RPWP, refuelling cover and guide tubes under extreme environmental condition

5 Conclusion

In this paper, the designs of the RPWP, guide tubes and refuelling cover, and the structural integrity evaluation under seismic loads have been performed. The design has been implemented according to the AISC N690 code and US NRC Regulatory Guides. The evaluation of structural integrity has been demonstrated by using finite element method. The RPWP, guide tubes and refuelling cover were modelled by using the beam and rigid elements, and the distributed and point masses. Then, static analysis, modal analysis and response spectrum analysis of the RPWP including refuelling cover and guide tubes were performed. The modal analysis results show that the first natural frequency is 7.84 Hz and the structurally fundamental frequency of the RPWP is 29.59 Hz except for the local effect of the guide tubes and refuelling cover. Through the numerical results of the response spectrum analysis, it is observed that any damage to the structural integrity does not happen because the maximum stresses due to seismic loads are within the allowable stresses and the stress ratio is less than “1” which is with the guidance of the AISC N690 code. In addition, the investigation of whether the bottom of refuelling cover is in contact with the top of the UGS of RSA demonstrates that the impact in between does not occur. Finally, the validity of the design and structural integrity of the RPWP, guide tubes and refuelling cover has been demonstrated through these proper design process and confirmed numerical results.

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