*Transactions*, SMiRT-25
Charlotte, NC, USA, August 4-9, 2019
Division V

# Seismic Behavior of Coupled Reactor Pressure Vessel and Reactor Coolant Loop

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## ABSTRACT

Seismic evaluation of Reactor pressure vessel (RPV), Reactor coolant loop (RCL) piping, and major equipment supports is a key aspect of Seismic probabilistic risk assessment (SPRA) study. Typically, the loads in the equipment supports are generated using an uncoupled model of the RPV and the RCL piping. In recent years, a number of studies have been conducted to illustrate that an analysis of the coupled system is not only rational but also results in significantly different responses. A coupled model of the RPV and the RCL systems has a few challenges that need to be considered carefully in such an evaluation. In this paper, we present the results from a coupled dynamic analysis of the RPV and its support (nozzle supports and neutron shield tank), 3 reactor coolant loops, and equipment such as reactor coolant pump, steam generator, and pressurizer with the surge line. It is shown that an appreciable reduction in RCL equipment support loads can be achieved by considering the effect of coupling between the reactor vessel and the piping. It is also shown that the system design based upon a single RCL may be over-conservative in such an analysis.

## INTRODUCTION

Seismic probabilistic risk assessment (SPRA) of nuclear power plants has gained significant importance in recent years. As per the NRC Fukushima Near-Term Task Force (NTTF) Recommendation 2.1, plant owners are conducting SPRA to demonstrate an acceptable level of risk. Many plants in the Central and Eastern US are faced with increased seismic hazards particularly in the high frequency region as an outcome of recent seismological studies.

In current practice, the loads in the secondary systems such as equipment supports in the RCL are generated by neglecting the interaction between the primary (RPV) and secondary (RCL) systems. However, studies have shown that such assumptions for external hazards such as seismic have resulted in highly over-designed nuclear power plant systems and excessively high costs (Electric Power Research Institute (EPRI), 2017; Gupta and Gupta, 1995a,b). In this study, we have chosen a 3-loop Nuclear Steam Supply System (NSSS) pressurized water reactor. The system design consists of the reactor vessel, three steam generators and three reactor coolant pumps connected by hot leg (HL), and cold leg (CL) piping. In the next sections, we present the details of the RPV, RCL models and its dynamic characteristics.

## REACTOR PRESSURE VESSEL (RPV) SUPPORT SYSTEM

The schematic of the Reactor Vessel support system is shown in Figure 1. The system is comprised of the reactor pressure vessel, containment internal structure, neutron shield tank, primary shield wall, and nozzle support pads. Modal analysis of the RPV model is performed in ANSYS (ANSYS, 2018) to determine the dynamic characteristics of the model. Table 1 presents the modal frequencies of the uncoupled RPV model.

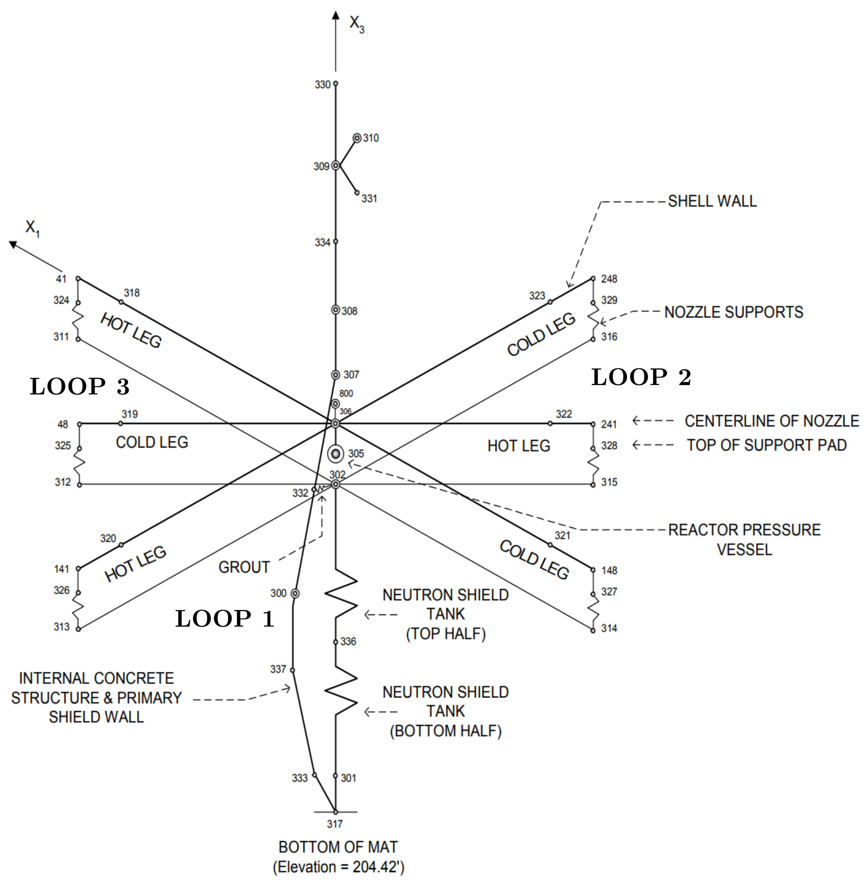


Figure 1. Uncoupled model of Reactor Pressure Vessel (RPV) Support System

Table 1: Modal Frequencies of Uncoupled RPV Model

| Mode | Freq. (Hz) | Mode | Freq. (Hz) | Mode | Freq. (Hz) |
|---|---|---|---|---|---|
| 1 | 4.885 | 7 | 15.962 | 13 | 23.004 |
| 2 | 4.886 | 8 | 16.352 | 14 | 29.479 |
| 3 | 11.797 | 9 | 16.378 | 15 | 29.481 |
| 4 | 11.817 | 10 | 17.539 | 20 | 44.675 |
| 5 | 15.395 | 11 | 17.549 | 25 | 64.846 |
| 6 | 15.539 | 12 | 23.003 | 30 | 96.179 |

**REACTOR COOLANT LOOP (RCL) PIPING**

The schematic of the uncoupled RCL piping model (Loop 3) is shown in Figure 2. The loop 3 contains pressurizer with the surge line, steam generator, reactor coolant pump and loop stop valves. Modal analysis of the uncoupled reactor coolant loop piping model is performed in ANSYS to determine the dynamic characteristics. The modal frequency results are shown in Table 2.

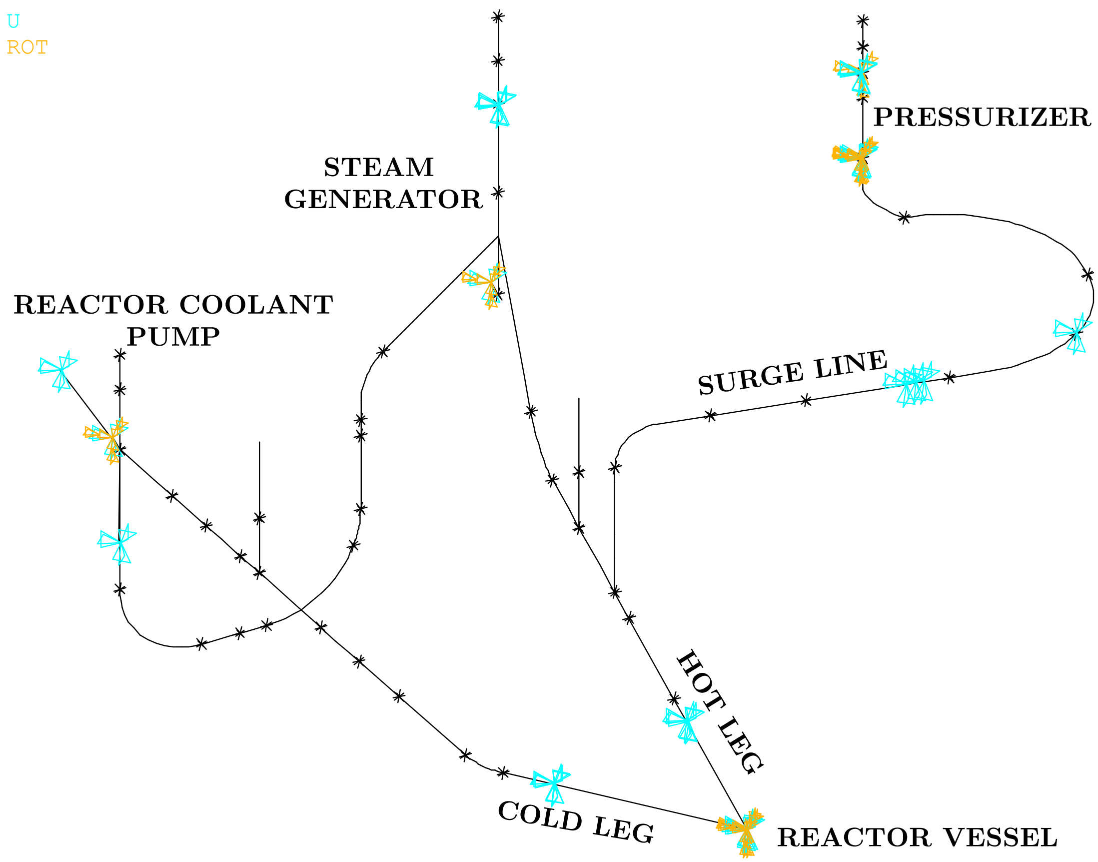


Figure 2. Sketch of the single uncoupled model of Primary Coolant Loop piping (Loop 3)

Table 2: Modal Frequencies of Uncoupled RCL Piping (Loop 3)

| Mode | Freq. (Hz) | Mode | Freq. (Hz) | Mode | Freq. (Hz) |
|---|---|---|---|---|---|
| 1 | 6.54 | 7 | 13.91 | 13 | 22.26 |
| 2 | 6.63 | 8 | 16.01 | 14 | 22.69 |
| 3 | 10.42 | 9 | 16.25 | 15 | 26.76 |
| 4 | 12.09 | 10 | 16.88 | 20 | 32.96 |
| 5 | 12.24 | 11 | 18.56 | 25 | 41.35 |
| 6 | 13.33 | 12 | 20.48 | 27 | 49.73 |

**COUPLING OF THE RPV MODEL AND RCL PIPING**

The Reactor Vessel and its support is combined with the primary coolant loop piping system, and their supports for coupled dynamic analysis. For the case of coupling, the fact that equipment supports in the primary loop are connected to the reactor containment internal structure which is shown in the RPV model (Figure 1), with rigid structural elements so that the earthquake time history input at the bottom of the mat is sufficient to simulate seismic excitation of the coupled model (Figure 1). In this study, we consider two different models for the coupled analysis:

1. RPV model coupled with only a single RCL piping model (loop 3)
2. RPV model coupled with all the three primary coolant loops

The layout of three loop model is shown in Figure 3. In the complete coupled model, loops 1 & 2 are modeled by rotating the loop 3 piping by 120 degrees and 240 degrees respectively. The Hot Leg of Reactor Coolant Loop 3 is connected to Pressurizer thru pressurizer surge line.

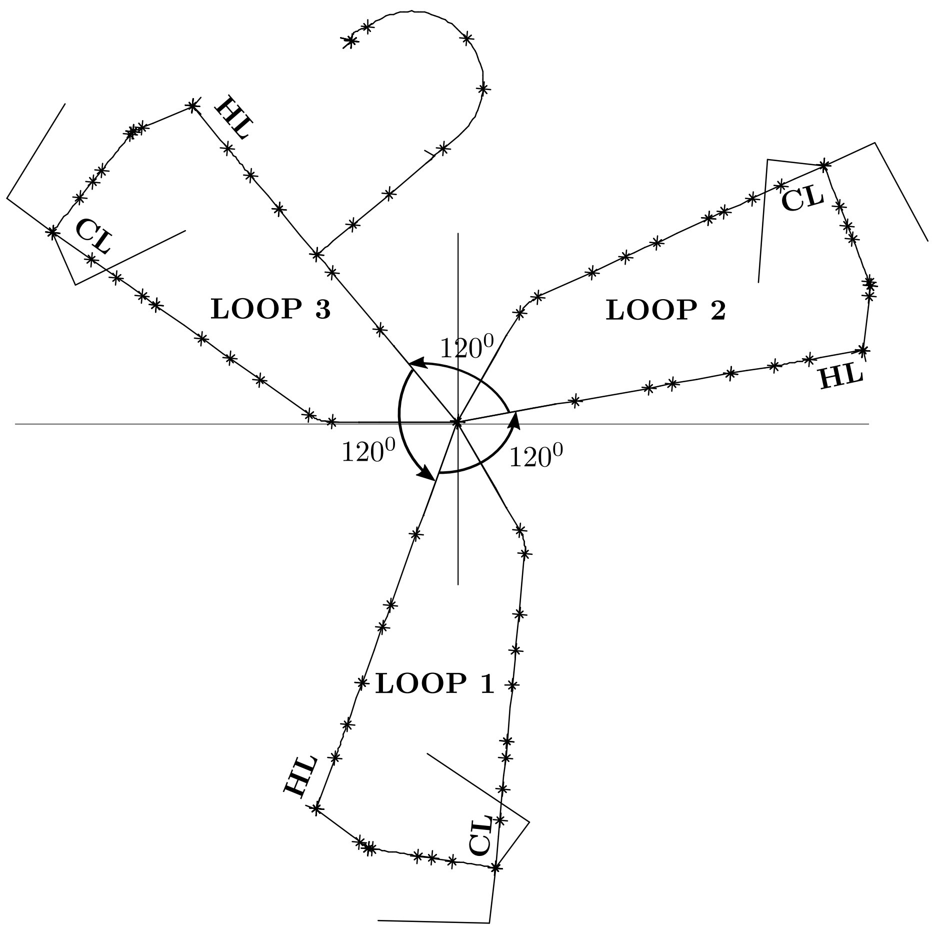


Figure 3. Layout of 3-loop Nuclear Steam Supply System (NSSS) pressurized water reactor

The linear transient dynamic analysis for both the coupled models is performed using the modal superposition method with a constant damping ratio of 5%. The response of the equipment supports is evaluated for design basis earthquake applied in all three orthogonal directions. Table 3 presents the comparison of uncoupled and coupled moment loads (lbs-in) in the vertical direction at the bottom of the neutron shield tank. When only a single primary coolant loop is connected to the RPV model we observe a significant increase in the moment load about vertical axis. This is due to the eccentricity of the entire coupled model, which creates imbalance and increases the torsional effects. Therefore, consideration of only a single RCL loop is inappropriate in a coupled analysis. Next, for obtaining the piping support loads in the secondary system, a coupled model with all the three coolant loops is considered.

Table 4 shows the comparison of uncoupled and coupled piping support loads for the case of design basis earthquake (DBE). Fx, Fy represent the local horizontal directions and Fz represents the local vertical direction. F (inclined) represents the forces as defined by the support directional cosines. Reductions in the support loads up to a factor of 7 are observed. In this paper, the uncoupled piping support loads are obtained using response spectrum method with a constant damping ratio of 1%. The difference in the damping will have an effect on the reductions shown in Table 4. However, these reductions are significantly high and this effect of difference in damping is relatively much smaller. In other words, the reductions shown in Table 4 are primarily due to the coupling effect (Electric Power Research Institute (EPRI), 2017).

Table 3: Comparison of DBE loads (lbs-in) at the bottom of neutron shield tank

| **Location** | **Uncoupled** | **Coupled (All loops)** | **Coupled (Single loop)** | $\frac{\textbf{Uncoupled}}{\textbf{Coupled}}$ **(All loops)** | $\frac{\textbf{Uncoupled}}{\textbf{Coupled}}$ **(Single loop)** |
|---|---|---|---|---|---|
| Neutron Shield Tank: Lower Support | 5.36E+06 | 5.24E+06 | 8.76E+07 | 1.02 | 0.06 |

Table 4: Comparison of DBE piping support loads

| **Location** | **Force (lbs/lbs-in)** | **Uncoupled** | **Coupled** | $\frac{\textbf{Uncoupled}}{\textbf{Coupled}}$ |
|---|---|---|---|---|
| Steam Generator (Lower Support) | Fy | 7.12E+05 | 2.24E+05 | 3.2 |
| | Fz | 1.66E+06 | 3.53E+05 | 4.7 |
| | My | 4.47E+07 | 1.79E+07 | 2.5 |
| Steam Generator (Upper Support) | F (inclined) | 1.08E+06 | 4.03E+05 | 2.7 |
| | F (inclined) | 1.12E+06 | 4.60E+05 | 2.4 |
| RC Pump | Mx | 1.83E+07 | 6.93E+06 | 2.6 |
| | My | 2.94E+07 | 9.91E+06 | 3.0 |
| | F (inclined) | 1.65E+05 | 6.97E+04 | 2.4 |
| | F (inclined) | 2.44E+05 | 8.27E+04 | 2.9 |

Table 4: Comparison of DBE piping support loads

| Location | Force (lbs/lbs-in) | Uncoupled | Coupled | $\frac{\text{Uncoupled}}{\text{Coupled}}$ |
|---|---|---|---|---|
| Surge Line (Intermediate Pipe Supports) | FZ | 4.31E+04 | 6.27E+03 | 6.9 |
| | FZ | 3.87E+02 | 0.52E+02 | 7.4 |
| Pressurizer (Lower Support) | FZ | 3.56E+05 | 1.16E+05 | 3.1 |
| | MZ | 1.78E+05 | 4.74E+04 | 3.8 |
| | F (inclined) | 6.31E+04 | 2.66E+04 | 2.4 |
| | F (inclined) | 6.60E+04 | 2.74E+04 | 2.4 |
| Pressurizer (Upper Support) | MZ | 2.53E+03 | 6.72E+02 | 3.8 |

## CONCLUSIONS

Typically, coupled analysis reduces the dynamic response in a secondary system (RCL in this study). The coupled analysis of RPV-RCL model reduces the loads in the RCL piping as compared to an uncoupled analysis. The uncoupled loads are up to 7 times more than the coupled loads. Therefore, the loads calculated from a conventional uncoupled analysis of the piping system can be excessively high leading to an essentially conservative design. The results from a coupled analysis can be utilized to develop accurate High-Confidence-of-Low-Probability-of-Failure (HCLPF) capacity estimates for SPRA application.

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