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SEISMICALLY INDUCED INTERNAL FLOODING IN NUCLEAR PLANTS

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ABSTRACT

In critical facilities like nuclear plants, it is important that both the structural and the non-structural components remain operational after an earthquake. Seismically induced piping failure may cause internal flooding which may interfere with the safe shutdown of the nuclear facility. For example, non-safety related piping or fire sprinkler piping can span over switchgear and the battery rooms containing critical safety related electrical equipment. These equipment provide DC power to safety systems required for maintaining a safe shutdown. Seismically induced failure of the fire suppression system can cause internal flooding that has the potential to directly compromise appropriate functioning of electrical equipment, or lead to flooding of electrical equipment due to water accumulation. A probabilistic risk assessment for such a case requires determination of potential leakage locations, leakage intensity, flooding scenarios, and leakage fragilities. This paper describes the elements of framework that provides leakage locations, leakage intensity, and the corresponding fragilities which serve as input into a simulation of flooding scenario.

INTRODUCTION

In nuclear power plants, integrity of piping systems and components is critical to maintaining the safe operation of the plants as well as potential shutdown during and after an earthquake. As seen from the sequence of events at Fukushima-Daiichi Nuclear power plant, it is necessary to keep the reactor core cool by circulating coolant for a long time even if the plant is shut down safely during an earthquake. A failure in the piping system or its components can result in a loss of ability to circulate the coolant during or after an earthquake which in turn can increase the risk of radioactivity release. Failure of the overhead fire suppression systems spanning across rooms that contain critical equipment can lead to internal flooding of the nuclear plant. Assessment of such internal flooding scenarios is a crucial aspect of the overall seismic probabilistic risk assessment of the nuclear plant. The fragilities for seismically induced piping leakage serve as an input in the flooding probabilistic risk assessment and helps determine if the failure at certain sprinkler node consequently leads to an electrical component failure (e.g., switchgear, battery charger, battery etc.). Such a case study for a specific fire sprinkler piping in the Service Building of a plant is presented in this paper.

BUILDING DESCRIPTION

The building model represents the Service Building of a representative/generic 3-loop pressurized water reactor (PWR). There are two switchgear rooms and adjacent battery rooms in the model. It is 186 ft. long (with each switchgear room at approx. 87 ft. long) and 51 ft. wide. The model includes the floor slabs, the interior and exterior walls, ramps at two sides of the Service Building for entry and exit, and interior doors. The model includes four separate battery rooms, each of which are approximately 16 ft. wide and 20 ft. long. Figure 1 shows the spatial model for the building.

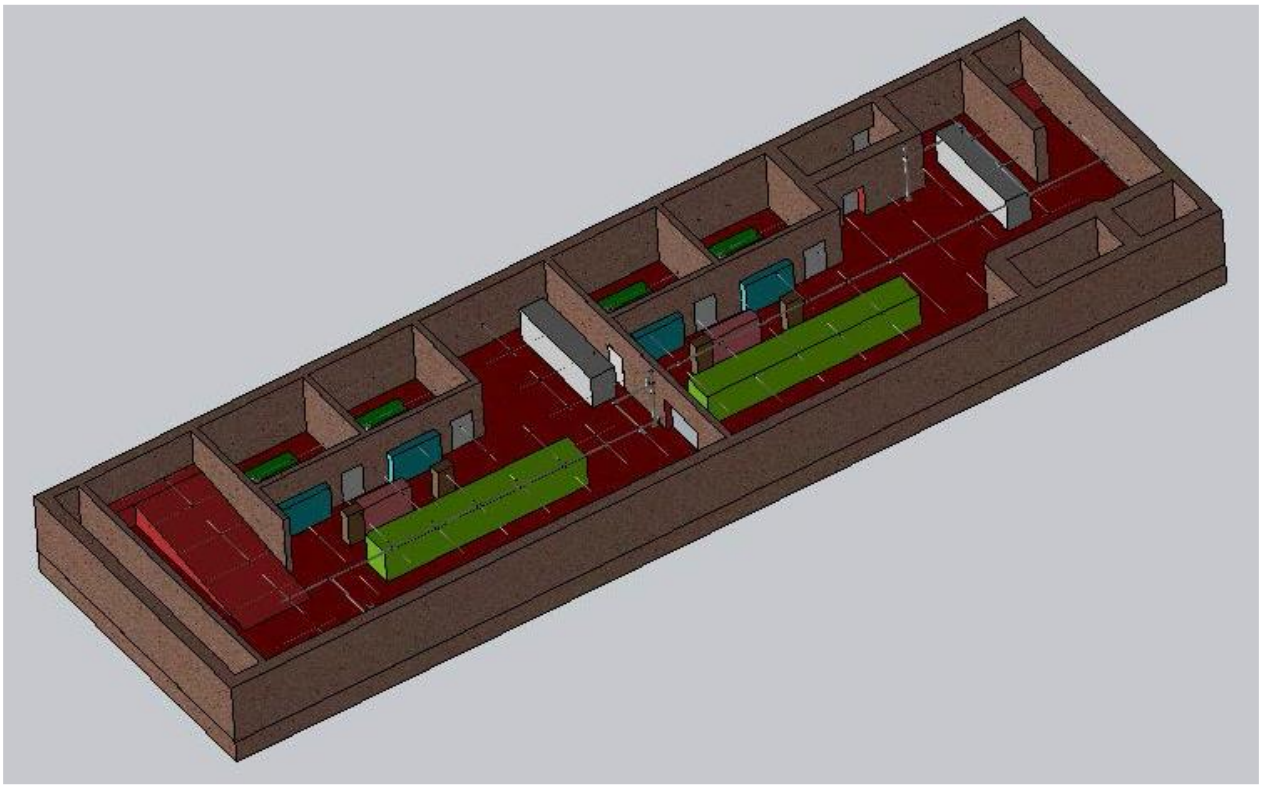

Figure 1. Spatial model for the building with equipment and fire suppression system

EQUIPMENT DESCRIPTION

The switchgear rooms and adjacent battery rooms contain critical and sensitive electrical equipment that provide DC power to safety systems required for safe shutdown following a seismic event. The model contains representations of both primary and secondary critical equipment. The primary equipment includes the batteries in the battery rooms, 4kV voltage switchgear, the 480V load centers, and related components. The secondary equipment includes battery chargers for the batteries, distribution panels, and uninterrupted power supply (UPS) systems. Batteries in the battery rooms are shown in Figure 2. Each green battery block represents 2 rows of batteries for a total of 4 rows of batteries per battery room.

FIRE SUPPRESSION PIPING SYSTEM

The fire suppression piping system comprises of 6 inch vertical water supply standpipes, overhead 4 inch main lines that convey water to the smaller 1.5 inch and 1.25 inch branch lines. The sprinkler-heads are located on the branch lines. The fire suppression system for the two adjacent switchgear rooms is an integrated system in which water is supplied by three standpipes. The fire suppression system is supported by 3ft. long hanger supports attached to the ceiling slab. The placement of the hanger supports are generally at every 16 ft. along the 4-in. main line, are provided for each sprinkler unless sufficiently close to hangers on the main line, and where intersecting lines or long unsupported spans warrant additional hanger supports. The pipes are of varying schedules – Schedule 40, Schedule 80 and Schedule 160. For the switchgear rooms, there is one main 4 inch line running along their length. The span lengths of the smaller branch lines coming off the main 4 inch line are between 8 – 18 ft. Figure 3 shows the plan view of the fire suppression system.

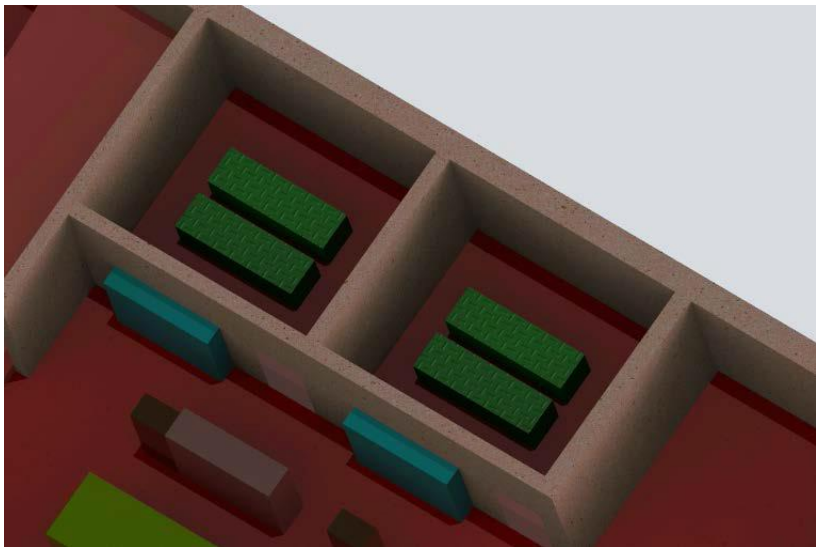

Figure 2. Batteries in Battery Room

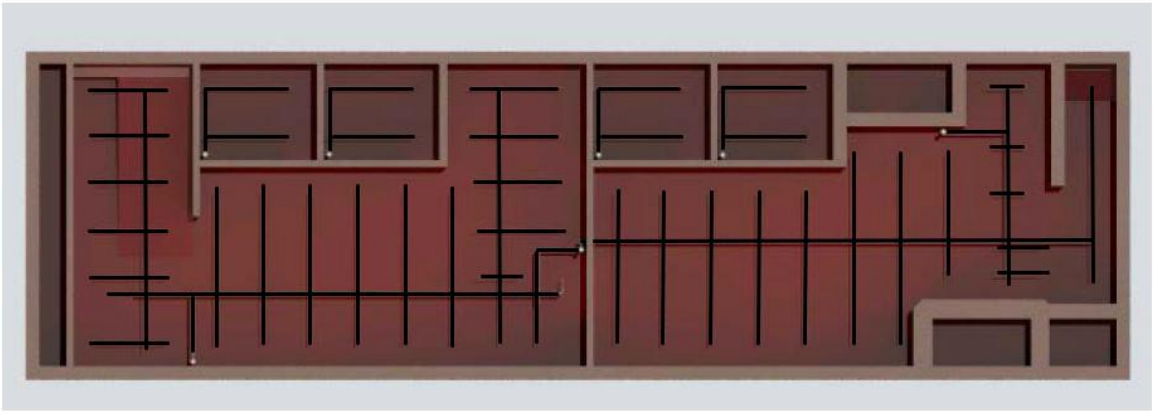

Figure 3. Plan view of the fire suppression system

KEY ASPECTS IN MODELLING FIRE SUPPRESSION SYSTEM

- Each of the battery rooms has its own standpipe, piping and sprinkler system. This system is not connected to the main fire suppression system. Therefore, the main piping system and battery room piping system are modelled separately.

- The 3 vertical water supply standpipes are connected to the floor slabs at the top as well as the bottom. Hence, they are considered to be anchored at these locations.

- Connections at the joints have been modelled as nonlinear rotational springs. Connections at every T-Joint are modeled using 3 nonlinear rotational springs and the connections at every 4-way cross, are modelled by 4 nonlinear rotational springs. As the complete piping system lies in the horizontal plane and earthquake input is considered only in horizontal direction, this model

considers nonlinear behavior of piping joints only due to bending of piping in horizontal direction.

- The rotational springs for hysteretic behavior are characterized by models in *OpenSees* [1]. The hysteretic behavior of nonlinear springs for 1 inch piping is characterized by yield strength *My*, initial stiffness *K1*, hardening stiffness *K2*, and parameter *R*, which controls the transition from elastic to plastic branches as shown in Figure 4. The isotropic hardening parameter defines the increase of the compression or tension yield envelope as a proportion of yield strength after a plastic strain. The material model used is *Giuffré-Menegotto-Pinto Model* [2].

- The hysteretic behavior of T-joint connections in 2 inch and 4 inch piping is characterized by a material that represents a "pinched" moment-rotation response which is modelled using a moment-rotation envelope [3]. Figure 5 compares the experimental and analytical curves for cyclic loading condition in a 2 inch T-joint. The cyclic strength and stiffness degradation properties are determined in this model by considering stiffness degradation during unloading, reloading and strength degradation from the test data.

- The pipe connections to walls are modeled as anchors.

- Table 1 indicates the modal frequencies of the piping system. The frequencies are closely spaced, representative of a typical piping system in a nuclear plant.

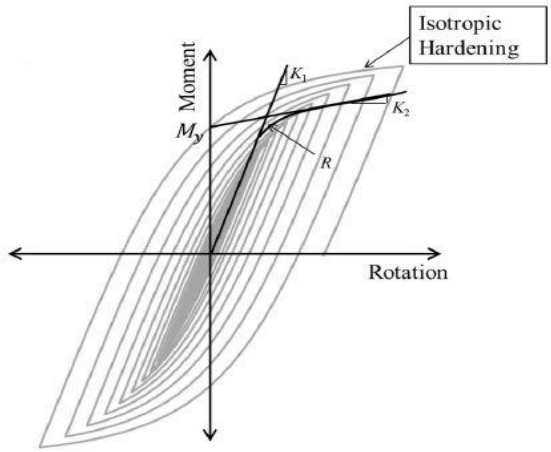

Figure 4. 1 inch rotational spring model

MULTIPLE DAMAGE STATES CONSIDERED FOR SEISMIC FRAGILITY ASSESSMENT

The damage to the piping system is characterized using an alternate form of ASME criterion as illustrated in Figure 6. It is observed from the test data that the rotation corresponding to the collapse moment, M_{cl}, on the moment rotation curve, is a good approximation of the “first leak”. This definition is further extended to define the “moderate” and “severe” damage states (Table 2).

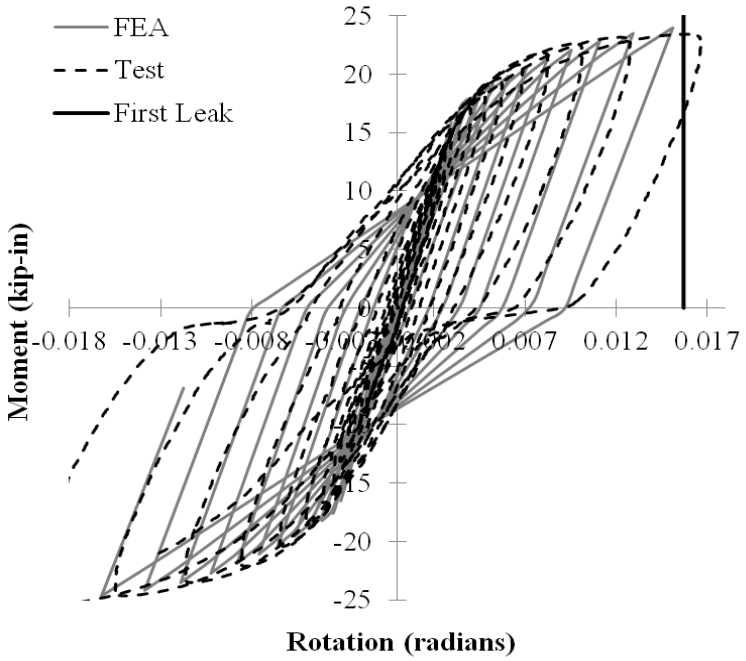

Figure 5. Experimental v/s Analytical Results under cyclic loading condition – 2 inch pipe

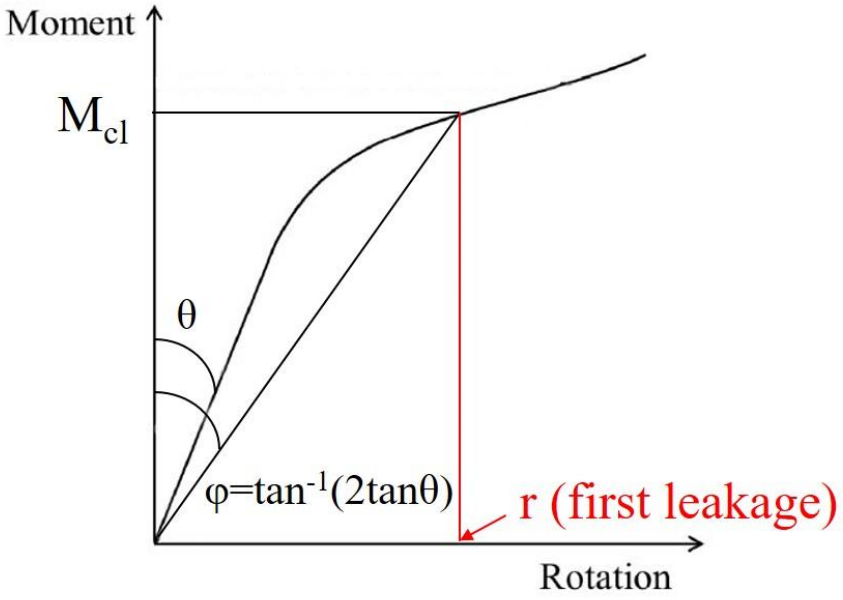

Figure 6. Modified ASME criteria for characterization of limit state

Table 1. Natural Frequencies of the Piping System

Mode	Frequency (Hertz)
1	2.415
2	3.413
3	3.433
4	3.472
5	3.631
6	4.144
7	4.979
8	5.076
9	5.385
10	5.896

LEAKAGE LOCATIONS ON THE PIPING SYSTEM

The piping system is analyzed for a suite of earthquake ground motions consistent with PSHA (32 earthquake ground motions each in the X and Y direction). The PGA's are normalized from 0.3g to 1.5g at intervals of 0.1g.

For the X direction analyses, a total of 10 damage locations are identified for a PGA level up to 1.5g. The locations of damage are increasing in number with the increasing values of PGA. All the damages are for 1 inch pipes.

For the Y direction analyses, two locations of damage are identified for a PGA level up to 1.5g. The damages are for 2 inch pipes.

Figure 7 indicates the locations of damages for PGA levels up to 1.5g, for input in X direction.

Figure 8 indicates the locations of damages for PGA levels up to 1.5g, for input in Y direction.

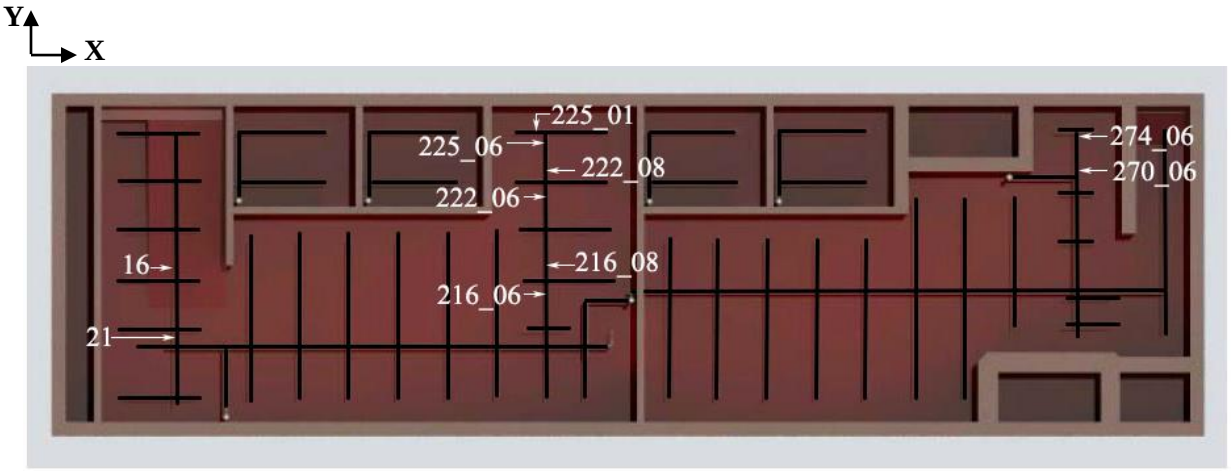

Figure 7. Leakage Locations on Piping System– X Direction Input

Figure 8. Leakage Locations on Piping System – Y Direction Input

Table 2. Multiple Damage States Considered for Seismic Fragility Assessment

Damage State	Criteria
Minor	Φ=2θ
Moderate	Φ=2.5θ
Severe	Φ=3θ

After the identification of locations of failures, incremental dynamic analysis is carried out to generate the seismic fragility curves at the failure locations. Figure 9 indicates the seismic fragility curves for minor damage (first leak) in the X direction. Figure 10 indicates the seismic fragility curves for minor damage (first leak) in the Y direction.

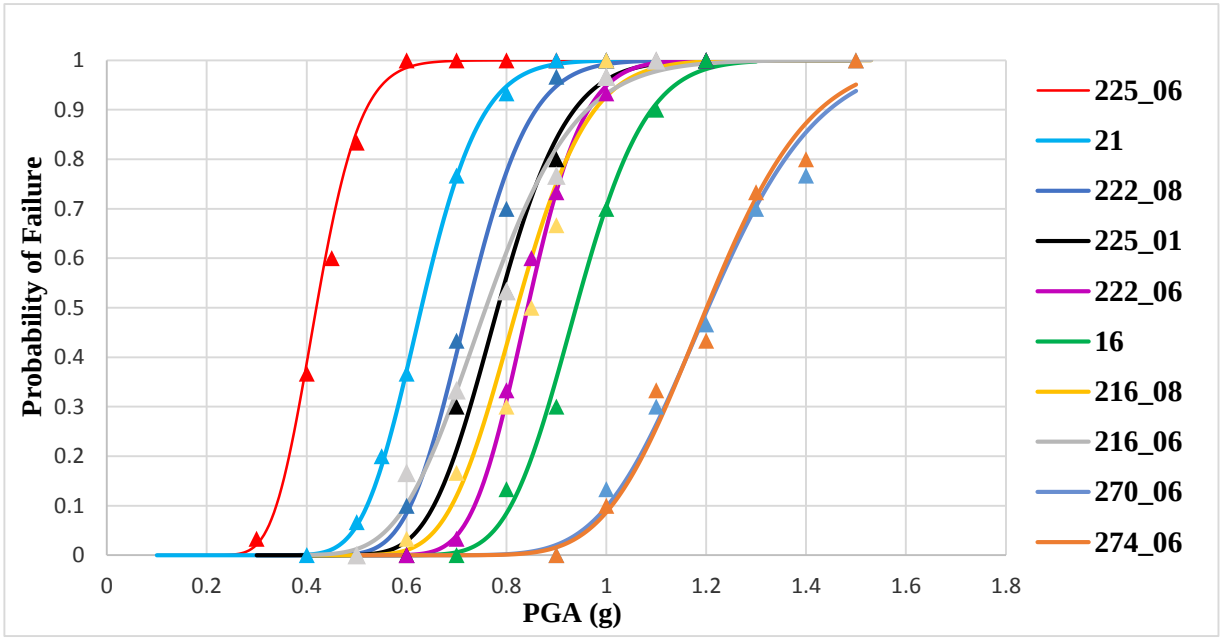

Figure 9. Seismic Fragility Curves – First Leak – X direction input

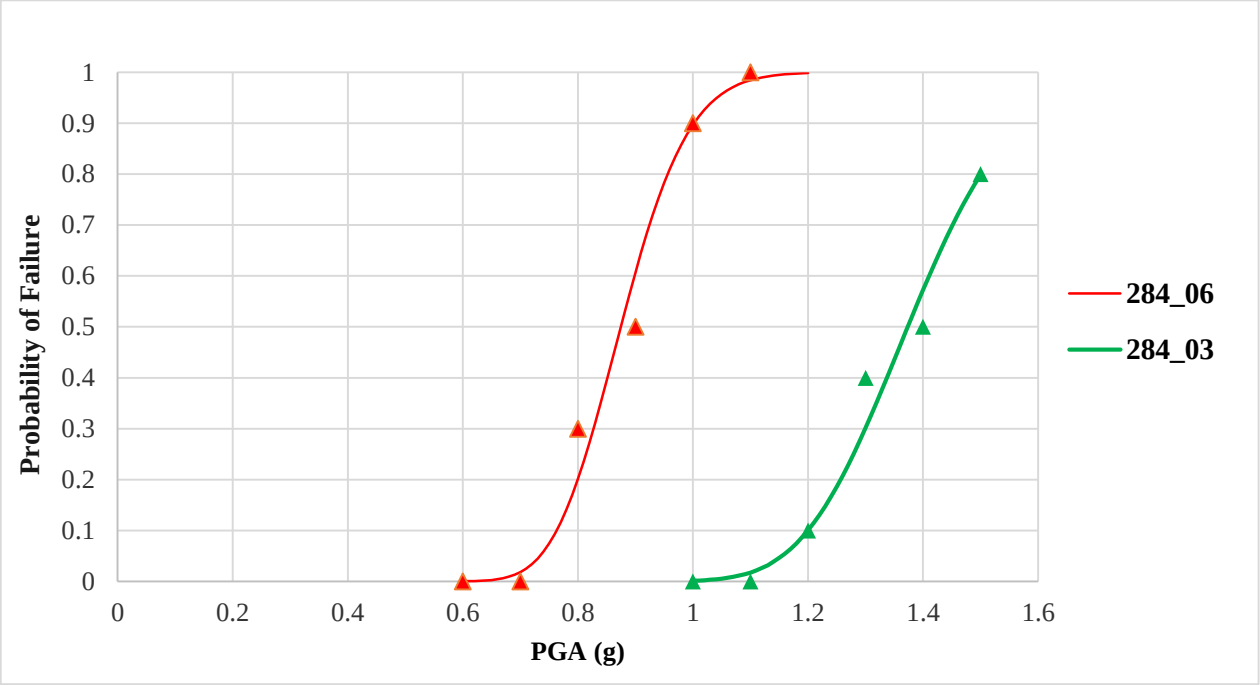

Figure 10. Seismic Fragility Curves – First Leak – Y direction input

EFFECT OF TIME OF FAILURE ON FRAGILITES

The fragility curves given above have been generated without considering the effect of time of failure on fragilities. A continued leakage at each failure location would lead to a specific flooding scenario given the simultaneous leakage from several joints. The layout of the piping system encourages us to have a look at the effect of time associated with failures of the joints. Considering the effect of time will allow us to determine progressive failure locations on the piping system, thereby, altering the flooding simulation scenario. Figure 11 shows the layout of the piping system with specific attention to 2 joints. From seismic fragility analysis, Joint 225_06 is more fragile than Joint 216_08. Yet, for a certain earthquake scenario, joint 216_08 may fail at an earlier time, which would lead to no leakage at joint 225_06. Therefore, the flooding simulation scenario would be altered because the conventional seismic fragility analysis considers continued leakage at each failure location, whereas this is not the scenario in the actual situation. Consequently, it is essential to consider the effect of failure time on the fragilities.

Figure 12 illustrates the fragility surface for the joint 222_08. It can be observed that as we proceed along the time axis, the probability of failure continues to increase. The values for probability of failure reach values corresponding to a time independent fragility curve towards the end of the time axis.

CONCLUSION

The leakage locations on the overhead fire suppression system in service building of a Pressurized Water Reactor (PWR) have been identified for a suite of PSHA consistent earthquake ground motions. The degree of damage has also been determined. The knowledge of damage locations and the corresponding failure probabilities help in the evaluation of internal flooding scenarios. It is concluded that a conventional seismic fragility analysis – which considers continued leakage at each failure location on the piping system, is not appropriate for the evaluation of such internal flooding scenarios. Time dependent

fragility surfaces have been developed, which can be used to create a time dependent progressive failure scenario.

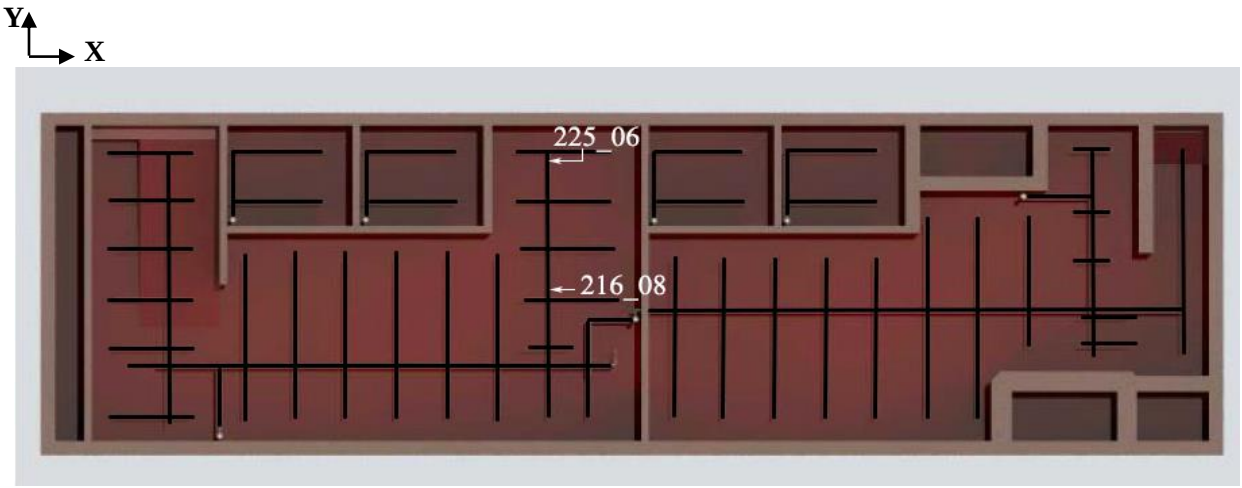

Figure 11. Layout of the piping system

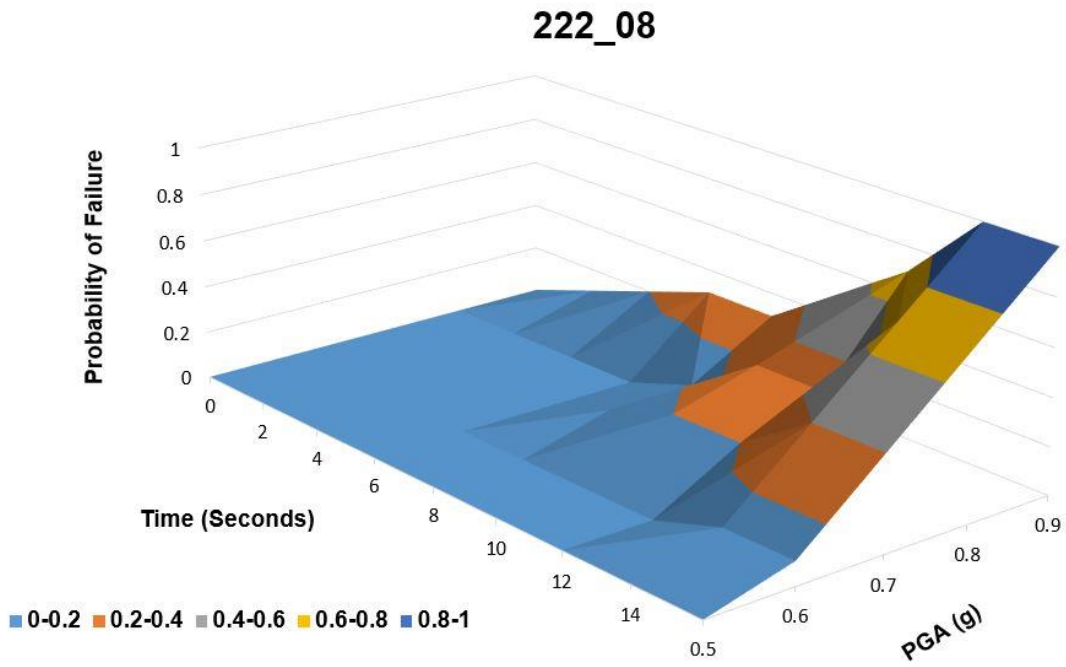

Figure 12. Example of a time depended fragility surface for a joint 222_08

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[3] Lowes, Laura; Mitra, Nilanjan; Altoontash, Arash (2003). *"A Beam-Column Joint Model for Simulating the Earthquake Response of Reinforced Concrete Frames"*. PEER Report 2003/10, Pacific Earthquake Engineering Research Center, University of California, Berkeley.