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Seismic Margin Assessment for Research Reactor using Fragility based Fault Tree Analysis

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1. Introduction

The research reactor has been often subjected to external hazards during the design lifetime. Especially, a seismic event can be one of significant threats to the failure of structure system of the research reactor. This failure is possibly extended to the direct core damage of the reactor. Under this background, the objective of this paper is to perform plant-level probabilistic seismic margin assessment based on a fault tree analysis in order to identify the quantitative safety to a seismic hazard. For this purpose, the fault tree for structural system failure leading to the core damage under an earthquake accident is developed. The failure probabilities of basic events are evaluated as fragility curves of log-normal distributions. Finally, the plant-level seismic margin is investigated by the fault tree analysis combining with fragility data and the critical path is identified.

2. Fragility Analysis

A fragility (or vulnerability) analysis calculates the relationship between a specific intensity parameter and the corresponding probability of failure. The fragility of a structure, system, and component (SSC) is defined as the conditional failure probability, P_f, to attain or exceed a specified performance function G under a given measure of specific intensity parameter λ. It can be stated as follows:

$$P_f = P\left(G < 0 \mid \lambda\right) \qquad (1)$$

G is a function of the random variables representing uncertainties in properties, modeling, and loading conditions of a SSC. The performance function can be described in a simplistic form as follows:

$$G\left(S, R\right) = S - R \qquad (2)$$

where S represents the "Strength" of SSC corresponding to the specified loading condition and R represents the "Maximum Response" corresponding to the given hazard intensity parameter. The Eq. (2) can be solved in many different ways such as Monte Carlo simulation, First/Second order reliability methods, random vibration based approach, statistical inference approach, empirical data, field observation, etc. In most implementations, the fragility curves are represented as the cumulative distribution function of a log-normal distribution (Kwag et al., 2014; Kwag, 2016).

3. Fault Tree Analysis

The fault tree analysis (FTA) is utilized for evaluating the failure probability of an accident or the occurrence of undesired top event (TE) in a complex system which is composed of various basic components/events (USNRC, 1981). The FTA can be accomplished by the use of fault tree diagram which represents a graphical decomposition of a TE into intermediate events and basic events by use of logical gates. The basic events are typically expressed by two states (0 and 1 as binary) and statistically independent. The relationship among all events are mainly described by "OR" gate and "AND" gate. The FTA is performed in two routes: (1) a qualitative part and (2) a quantitative part. The qualitative evaluation derives logical expression of the TE and carries out Boolean algebra to obtain minimal cut-sets in terms of combinations of basic events. The quantitative part evaluates the probability of occurrence of the TE and performs the importance measure analysis of the minimal cut-sets to find out the most vulnerable scenario.

4. Results of Fragility based Fault Tree Analysis

4.1. Development of fault tree

The structure failure event leading to the direct core damage in the Pool-type research reactor mainly comes from building failure, pool structure failure, reactor failure and reactor interface structure failure in a conservative perspective. These failures are also subdivided into following failure events of the related structural systems and components. The detailed scenario described by a fault tree is represented in Fig. 1.

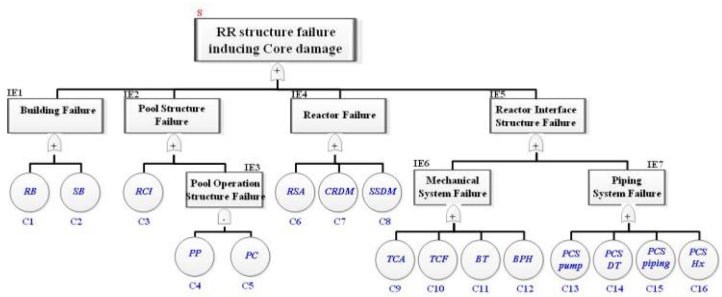

Fig. 1. Fault tree for the failure of research reactor structure leading to the core damage

4.2. Fragility analysis results

From the fault tree formulation, the basic events are identified. The seismic fragilities for these basic events are performed by using the method of chapter 2. The seismic fragility curves are obtained as log-normal distributions having median *Am* and log-standard deviation β. The detailed information is represented in Table 1.

Table 1: Seismic fragility information for basic events

BEs	SSCs	Failure Mode	*Am* (g)	β
C1	RB	Bending	1.70	0.38
C2	AB	Bending	1.90	0.36
C3	RCI	Wall diagonal	2.30	0.36
C4	PP	Support plate	1.40	0.36
C5	PC	Beam	2.00	0.39
C6	RSA	End fitting	2.00	0.39
C7	CRDM	Weldment	1.60	0.39
C8	SSDM	Rod end	1.70	0.39
C9	TCA	Fastener	6.50	0.36
C10	TCF	Bolt	2.70	0.38
C11	BT	Tube bending	8.00	0.37
C12	BPH	Housing	6.30	0.39
C13	PCS pump	Base plate	2.70	0.38
C14	PCS DT	Skirt shell	1.50	0.40
C15	PCS piping	Weldolet	3.00	0.55
C16	PCS Hx	Anchor bolt	1.60	0.41

*BEs: basic events, RB: reactor building, SB: service building, RCI: reactor concrete island, PP: pool platform, PC: pool cover; RSA: reactor structure assembly CRDM: control rod drive mechanism, SSDM: second shutdown drive mechanism, TCA: thermal column assembly, TCF: thermal column flange, BT: beam tube, BPH: beam port housing, PCS: primary cooling system, DT: decay tank, HX: heat exchanger

4.3. Fragility base fault tree analysis

To begin with, qualitatively, the logical/Boolean expression for the constructed fault tree of Fig. 1 is (C1+C2)+(C3+C4·C5)+(C6+C7+C8)+(C9+C10+C11+C12)+(C13+C14+C15+C16) and the corresponding minimal cut-sets (MCS) are C1, C2, C3, C4·C5, C6, C7, C8, C9, C10, C11, C12, C13, C14, C15, C16. Quantitatively, fault tree analysis is conducted by using the obtained fragility curves of Table 1. As a result, the fragility curve for the failure of research reactor structure leading to the core damage is acquired as Fig. 2 having *Am* = 1.0g and β = 0.23. The HCLPF (high confidence low probability of failure) for this is obtained as 0.59g. Finally, with the MCSs and the information of Table 1, the critical path is identified as shown in Fig. 3.

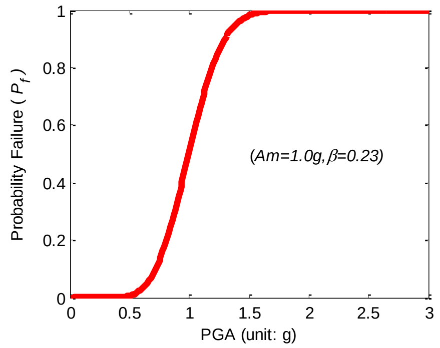

Fig. 2. Fragility curve for the failure of research reactor structure leading to the core damage

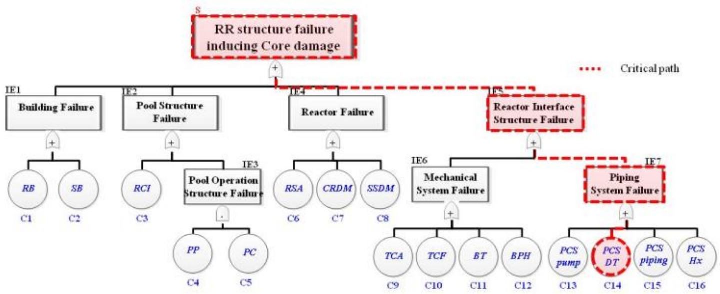

Fig. 3. Critical path

5. Summary and Conclusion

The plant-level probabilistic seismic margin assessment using the fragility based fault tree analysis was performed for quantifying the safety of research reactor to a seismic hazard. For this, the fault tree for structural system failure leading to the core damage of the reactor under a seismic accident was developed. The failure probabilities of basic events were evaluated as fragility curves of log-normal distributions. Finally, the plant-level seismic margin was estimated and the critical path was identified. From this observation, the seismic capability of the whole plant structure system in a core damage level was predicted and the most vulnerable scenario was deduced. This can be fundamentally extended to the mitigation plan of seismic risk.

Acknowledgements

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