Transactions of the SMiRT 27
Yokohama, Japan, March 3-8, 2024
Division VII

A MINIMALISTIC COMPUTATIONAL TESTBED FOR EVALUATING FRAGILITY ASSESSMENT, RECORD SELECTION, AND INTENSITY MEASURE OPTIMALITY FOR NUCLEAR POWERPLANTS

Angeliki Gerontati[1], Nikolaos Karaferis[2], Nevena Šipčić[3], Dimitrios Vamvatsikos[4], Paolo Bazzurro[5], Charles Droszcz[6]

[1] PhD Candidate, National Technical University of Athens, Greece (agerontati@mail.ntua.gr)
[2] PhD Candidate, National Technical University of Athens, Greece
[3] PhD Candidate, University School of Advanced Studies IUSS, Pavia, Italy
[4] Associate Professor, National Technical University of Athens, Greece
[5] Professor, University School of Advanced Studies IUSS, Pavia, Italy
[6] Engineer, Géodynamique et Structure, Paris, France

ABSTRACT

Recent advances in Performance-Based Earthquake Engineering (PBEE) have followed their own evolutionary path over the past two decades. Focusing on the assessment of conventional buildings and infrastructure, several innovative proposals on improving fragility assessment have appeared over the years, focusing on record selection, improved intensity measures, as well as novel uncertainty propagation approaches. Whether these are also useful for nuclear powerplant assessment remains a question. Partially owing to the well-established practice and guidelines, introducing novelty in such procedures faces significant hurdles in terms of modeling, computational power, and complexity. In an effort to overcome said difficulties in the context of the METIS Euratom project, we propose a minimalistic computational testbed comprising simplified models of a building, one or more components, and a bare-bones fault tree to tie them together and propagate uncertainties. The METIS simplified testbed is realized in open source, using Python and OpenSees to offer a fast assessment platform, whereby one can test any number of ideas in a setting that resembles a real case study. Among them are important questions, such as the influence of aftershocks, or clustered seismicity in general, new uncertainty propagation techniques, the use of hazard-consistent record selection approaches in place of selection based on the uniform hazard spectrum, as well as the use of new intensity measures that can potentially reduce the aleatory uncertainty in the estimates of risk. Focusing on the latter, we present an example of application of the testbed and its results.

INTRODUCTION

The seismic safety of nuclear powerplants (NPPs) operates under well-established norms designed to ensure their safe operation, mitigate risks associated to nuclear energy, and safeguard public health and the environment. Introducing innovative methodologies within these practices can pose significant challenges as the bar for entry into practice is already high. For example, seismic fragility assessment is mainly governed by EPRI (2018); while fairly comprehensive, it has not yet considered advancements realized over the past decade for conventional structures, such as hazard-consistent record selection (Bradley 2010; Lin *et al*. 2013; Kohrangi *et al*. 2017; Spillatura *et al.* 2021), improved intensity measures (Vamvatsikos and Cornell 2005; Bojórquez and Iervolino 2011; Kazantzi and Vamvatsikos 2015; Eads *et al.* 2015; Kohrangi *et al.* 2016), as well as novel uncertainty propagation approaches (e.g., Liel *et al.* 2009, Dolsek 2009; Vamvatsikos and Fragiadakis 2010; Vamvatsikos 2014).

To be able to introduce such novel procedures, one needs to account for intricate modeling needs, high computational demands, and (eventually) regulatory compliance. Moreover, inherent challenges stem from the nature of nuclear powerplants themselves. These facilities comprise a multitude of interrelated

Structures, Systems, and Components (SSCs), typically at short periods of vibration, which collectively contribute to the overall complexity of ensuring their safety and robustness. Whether something that has been developed for (typically moderate-to-long-period) conventional buildings can apply equally effectively to NPPs is question that remains to be answered for every single case.

To address such challenges and offer a practical entry point into this specialized domain, a streamlined computational testbed is developed. This testbed is open source, harnessing the flexibility and accessibility of Python (Python Software Foundation 2008) and OpenSees (2006). It serves as a valuable and versatile proof-of-concept tool, empowering researchers to delve into innovative concepts and strategies within a framework that emulates real-world conditions. At its core, this testbed comprises a reduced-order structural model, featuring simplified representations of the reactor building and of a single non-structural component. It is complemented by a tailored fault tree, built to investigate scenarios that could lead to the loss of core cooling capacity, a pivotal concern in NPP safety.

To showcase the testbed's capabilities, we tackle the issue of alternative Intensity Measures (IMs) and how they can impact the overall risk estimation of the top event within the fault tree. These can include old stalwarts, such as Peak Ground Acceleration (PGA) and the 5%-damped spectral acceleration at distinct periods, as well as relative newcomers, e.g., the average spectral acceleration, AvgSa, estimated as the geometric mean of spectral ordinates over a range of periods (Vamvatsikos and Cornell 2005). For added fun, the fragility evaluation includes examining common cause failures among the tree's components, exploring three scenarios of perfect, partial, and no correlation. This comprehensive analysis generates fragility curves, illustrating the probability of the investigated top event occurring. Subsequently, these curves are utilized alongside hazard curves, estimated for the METIS case study site in Italy (METIS 2021), to compute the Mean Annual Frequency (MAF) of occurrence for the top event.

STRUCTURAL MODEL DESCRIPTION

Reactor building

The structure under study is based on the AP1000 advanced reactor design. The AP1000 is an advanced Pressurized Water Reactor (PWR) nuclear powerplant design that was developed by Westinghouse Electric Company. The modelling data are taken from Willaume and Noret (2011) following the suggestions of the Electrical Power Research Institute (EPRI 2007).

The structural model, formed using OpenSees, consists of three sticks representing the Coupled Auxiliary and Shield Building (ASB), the Steel Containment Vessel (SCV), and the Containment Internal Structure (CIS). The three sticks have a concentric arrangement, where they are connected only at the base and do not significantly influence each other. The sticks are horizontally separated in Figure 1 (left) for illustration purposes. Each stick consists of discrete masses and elastic beams. The fundamental period of the reference structure, as determined from the modal analysis, is 0.26s. The three substructures exhibit semi-independent vibration behaviour, with ASB tower contributing more significantly to the observed vibrational movement of the entire structure.

The simulation of the reactor building also involves the impact of the underlying soil on the dynamic response of the structure, by employing a simplified model referred to as the "cone model." It was originally employed by Wolf (1998) and according to this model the half-space of soil beneath the structure behaves as a truncated semi-infinite rod, with its area varying as a cone of the same material properties. The cone is represented as a lumped-parameter system, incorporating mass-spring-damper components. The model operates under the assumption that the soil can be approximated as a linear elastic medium with a uniform stiffness throughout its depth. The foundation of the structure is depicted as a rigid mass, interconnected with the underlying soil through both a spring and a dashpot element. The spring component signifies the soil stiffness, while the dashpot component represents the damping characteristics of the soil.

Non-structural component

The selected non-structural component is a service water pump, as detailed in EPRI (2018). This pump is considered to be located at the uppermost level of the CIS tower within the nuclear powerplant. It is a vertical pump column, where the critical part is the motor stand. This is represented within the model as a 3D structure, consisting of a single mass located on top of a beam-column element and is illustrated in Figure 1 (right). Its behavior is mildly nonlinear, characterized by an elastic-perfectly-plastic force-deformation response, which culminates at an ultimate ductility of 1.25. Additionally, the pump exhibits a moderately pinching hysteresis behavior and has a fundamental period equal to 0.101s.

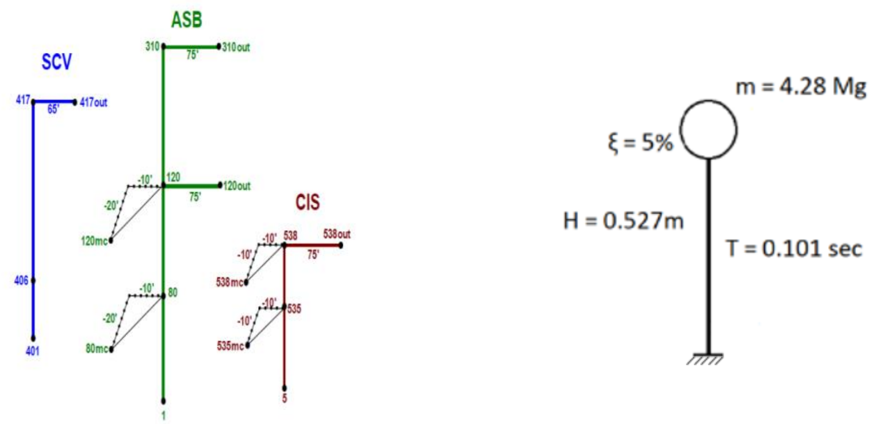

Figure 1: Simplified simulation models of the reactor building (left) per EPRI (2007) and pump motor stand (right).

FAULT TREE ANALYSIS

Probabilistic Risk Assessment (PRA) analyses of NPPs are utilized to systematically evaluate the potential risks and safety of such facilities. These comprehensive assessments examine various aspects of a plant's operation, design, and external factors to gauge the probability and consequences of different accident scenarios. Single-Unit PRAs concentrate on evaluating the risks associated with an individual nuclear powerplant unit examining the SSCs of the plant.

A valuable tool used to delve deeply into the understanding of how failures or errors in individual SSCs can potentially propagate during external events, such as earthquakes, is Fault Tree Analysis (FTA). FTA offers a systematic and rigorous approach to model these interdependencies, fundamentally built upon the concept of “fault trees.” These fault trees provide a structured way to represent the relationships between various events and conditions within a complex system (Lee *et al.* 1985). Comprising key components, a fault tree is used to analyze and prevent undesired events, with the central focus on the “top event.” Within the realm of nuclear safety assessment, this is a specific safety-critical event, such as a core meltdown or the failure of an emergency safety system.

A fault tree also incorporates “basic events”, which encompass individual components, systems, or actions that could potentially contribute to the occurrence of the top event. Basic events serve as the fundamental building blocks of the fault tree and encompass a wide array of factors, such as equipment failures, human errors, external events, and other relevant elements that have the potential to impact the nuclear powerplant safety. The execution of an FTA involves assigning probabilities to each basic event within the fault tree and propagating them to estimate the probability of the top event.

The dependencies between these basic events play a pivotal role in evaluating the overall risk. To account for these interconnections, complex probabilistic calculations are utilized. To depict the intricate relationships between various events contributing to the top event, fault trees utilize logical gates, predominantly "AND" and "OR" gates. The choice of these gates depends on the nature of the interactions being modelled. An "AND" gate signifies that all of its input events must occur simultaneously for the top event to transpire. It represents scenarios where multiple factors must coincide to trigger the top event, highlighting dependencies and the necessity for specific conditions to occur simultaneously. Visually, it is depicted as a semi-circle with a flat bottom. Conversely, an "OR" gate indicates that at least one of its input events must occur for the top event to transpire. It models scenarios where multiple factors can independently lead to the top event, showing that any one of these contributing factors could result in the undesirable outcome. This gate is visually represented as a semi-circle with a convex bottom.

Proposed fault tree

- In support of the model, we have closely examined a simplified fault tree (

Figure *2*), specifically crafted to evaluate the risk associated with a "Loss of Core Cooling" (LoCC) scenario within the nuclear powerplant. This event is connected to an "AND" gate, implying that two identically structured intermediate paths must simultaneously occur to trigger it; each one is referred to as "Loss of Shutdown Path." This setup accounts for the system's redundancy, where twin cooling subsystems are in place, each fully capable of supporting the reactor's requirements.

Further, each "Loss of Shutdown Path" is linked to an "OR" gate, and the failure of at least one of five distinct events is sufficient to activate it. These events represent a series of components or events, including the "Loss of Emergency Feedwater System" Gate, "Bus" failure, "Emergency Diesel Generator" failure, "Steam Generator" failure, and "Loss of Cooling Water Supply" Gate.

Within this structure, the intermediate event "Loss of Emergency Feedwater System" can be dissected into two basic events, the "Emergency Feedwater Pump" and the "Emergency Feedwater Piping and Tank" failures. Each of these basic events can independently contribute to the failure of the intermediate event. Similarly, "Loss of Cooling Water Supply" can also be deconstructed, with "Well Water Pump" failure and "Well Water Piping" failure connected through an "OR" gate.

It's noteworthy that certain critical components, such as the "Well Water Piping", "Steam Generator" and "Emergency Feedwater Piping and Tank" appear twice in the fault tree but essentially refer to single pieces of equipment in each case, not two. While the absence of redundancy for these singular components may appear to introduce higher risk, it's essential to consider that they are characterized by an exceptionally low probability of failure, contributing to the overall safety of the system.

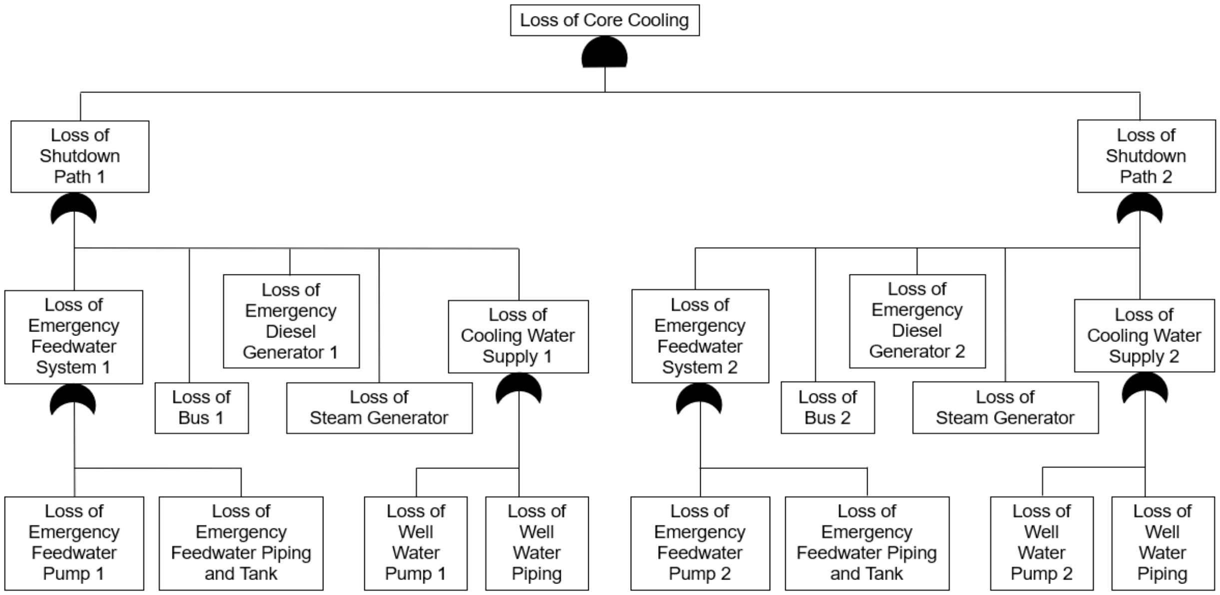

Figure 2: “Loss of Core Cooling” fault tree.

Table 1: Given failure probabilities and fragility parameters conditioned on PGA.

Basic event	**Fragility median (μ)**	**Fragility dispersion (β)**	**Probability of failure**
Well Water Piping	–	–	1.10E-11
Emergency Feedwater Piping and Tank	–	–	7.70E-12
Bus	2.04g	0.40	–
Steam Generator	1.42g	0.38	–
Emergency Diesel Generator	1.72g	0.31	–
Emergency Feedwater Pump	1.39g	0.31	–

FRAGILITY ANALYSIS

Fragility parameters of basic events

The initial stage of FTA involves assigning probabilities to each basic event in the fault tree. To ensure a thorough analysis, a wide range of sources and techniques are employed to determine these probabilities. Specifically, historical data and past events provide direct failure probabilities for the “Well Water Piping” and “Emergency Feedwater Piping and Tank”, as detailed in Table 1. Additionally, the same table includes fragility parameters conditioned on PGA, which have been established through expert judgment.

For the fragility estimation of the “Well Water Pump,” which is akin to the service water pump previously described, a thorough evaluation of its response is conducted. This specific basic event is of paramount importance as it delineates the fault tree's performance at a critical level. A series of two-component ground motions, totaling 25 pairs of records, were chosen across 10 intensity levels and various conditioning periods. The intensity levels correspond to return periods of 40, 150, 475, 1000, 2500, 5000, 10000, 20000, 50000, and 100000 years. Records were selected via the Conditional Spectrum approach (Jayaram *et al.* 2011, Kohrangi *et al.* 2017) from the ESM (Lanzano *et al.* 2019), NGA-West2 (Ancheta 2013), and GNS (Van Houtte *et al.* 2017) databases. In essence, they were chosen to meet some general criteria, such as minimum V_{s30} of 400 m/s, plus their selection was optimized per intensity level to ensure matching the distribution of spectral ordinates conditioned on the intensity measure of choice, allowing scaling factors up to 10 for the initial 9 intensity levels and up to 13 for the final one. The process of record selection was performed for four distinct intensity measures, Sa(0.01s), Sa(0.10s), and Sa(0.25s), along with AvgSa spanning the range of 0.10s to 0.40s.

The initial step of the performance evaluation of the pump involves dynamic analyses of the entire reactor building, employing the selected suite of ground motion records. Adopting a cascading approach, for each ground motion scenario, the acceleration response histories of the floor housing the “Well Water Pump” are recorded and subsequently used as input for the dynamic analyses of the pump model. Following the estimation of the pump’s response, failure is deemed to occur when said response exceeds the pump displacement capacity, assumed to follow a lognormal distribution with a median value of 0.0029m and a dispersion of 0.38. The resulting fragility curves for the pump heavily depend on the selected IM. Specifically, the one corresponding to Sa(0.1s) has the low dispersion of 0.15, by virtue of being better correlated to the response of the T=0.101s pump. Others show almost double the dispersion at about 0.30.

Top event fragility analysis

The performed assessment entails the use of Monte Carlo simulation, combined with dynamic analyses of the pump and analyses of the fault tree, to estimate the fragility of the “Loss of Core Cooling” event. To illustrate the impact of interdependencies among basic events, three separate correlation scenarios are examined. The first scenario considers no correlation, meaning that there is little to no correlation among the basic events. Each event is considered independently, for example the “Loss of Emergency Feedwater Pump” 1 doesn’t impact the “Loss of Emergency Feedwater Pump” 2. The second scenario involves perfect correlation, where the same basic events have the exact same behaviour, i.e. the event pairs of “Loss of Emergency Feedwater Pump” 1 and 2, “Loss of Bus” 1 and 2, “Loss of Emergency Diesel Generator” 1 and 2, “Loss of Well water Pump” 1 and 2. This implies that if one event occurs, it determines the behavior of other event with the same characteristics happening concurrently. Finally, the last scenario is partial correlation, where there is some (imperfect) level of interdependence among identical basic events. In this case study, we assume a 50% correlation, indicating a moderate level of interdependence among the events.

For each correlation scenario, the analysis follows a set of predefined steps. Firstly, the probability of failure for each basic event is determined by one of the available options described in the previous subsection. Subsequently, a set of N random binary values, with N set to 10,000 in this instance, is generated for each event using a base-2 number system. Here, a value of 0 signifies no occurrence, while a value of 1 denotes an occurrence of the event. To generate these N values, the algorithm by Leisch et al. (1998) is employed, which produces multivariable binary distributions with a predefined correlation structure. The “mvbin” software tool (GitHub, 2021), which incorporates the algorithm of Leisch et al., is utilized requiring two key inputs, the marginal distributions for each variable (i.e., the univariate distributions for each binary variable) and the intended correlation structure among these variables. With knowledge of the status of each basic event (0 or 1), and the logical gates connecting them, a fault tree analysis is carried out. The expected output of each realization is also a value of 0 or 1; therefore, the probability of the top event occurring is estimated simply by calculating the ratio of the number of failure occurrences to the total number of realizations.

Figure 1Figure 3 *Figure 3*displays the lognormal fragility curves generated for each analyzed IM and across the scenarios of 0%, 50% and 100% correlation among similar basic events. As expected, higher correlation among basic events corresponds to an increased probability of the top event happening. In terms of medians, the fragility curves shift to the right as the period of the intensity measure increases. Therefore, the leftmost fragilities correspond to Sa(0.01s), or essentially PGA, while the rightmost to Sa(0.25s), which also happen to closely match the ones of AvgSa. Interestingly, the dispersions achieved follow a different trend. PGA has the lowest dispersion at 0.45, while other IMs reach 0.5.

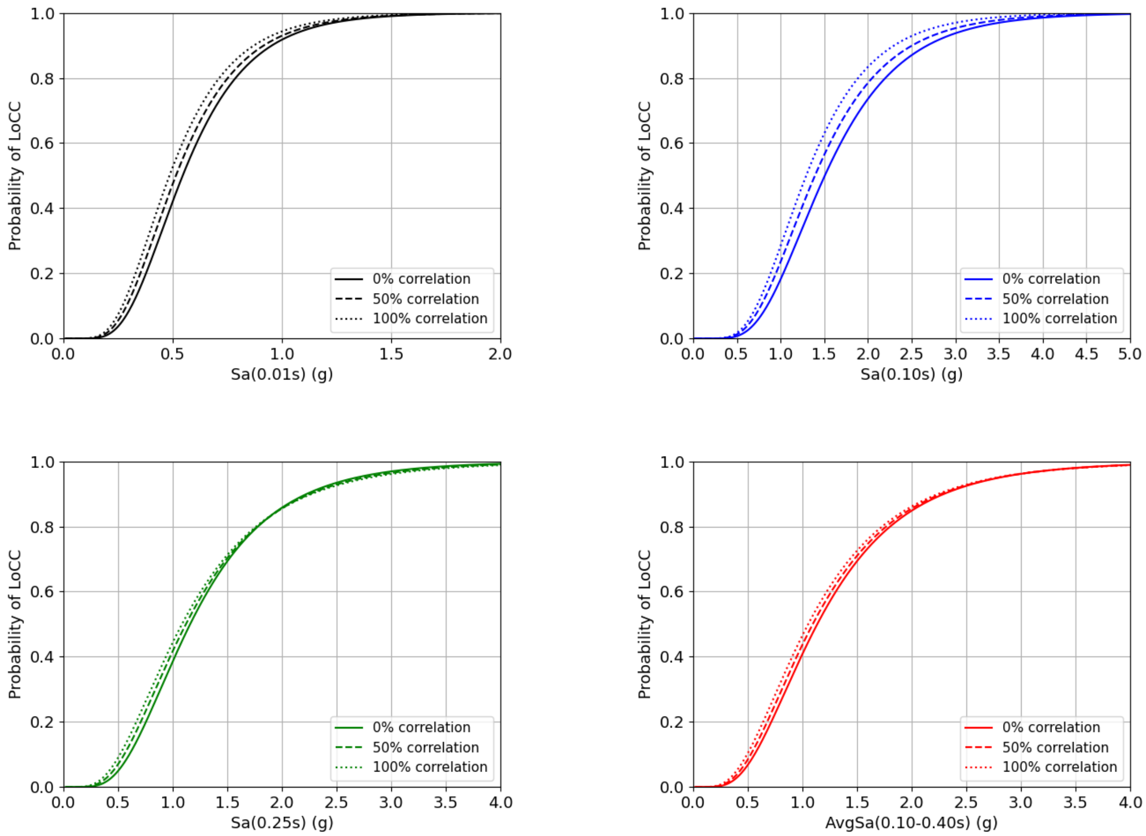

Figure 3: Lognormal fragility curves for loss of core cooling computed using three cases of correlation of the occurrence of same basic events and four alternative IMs.

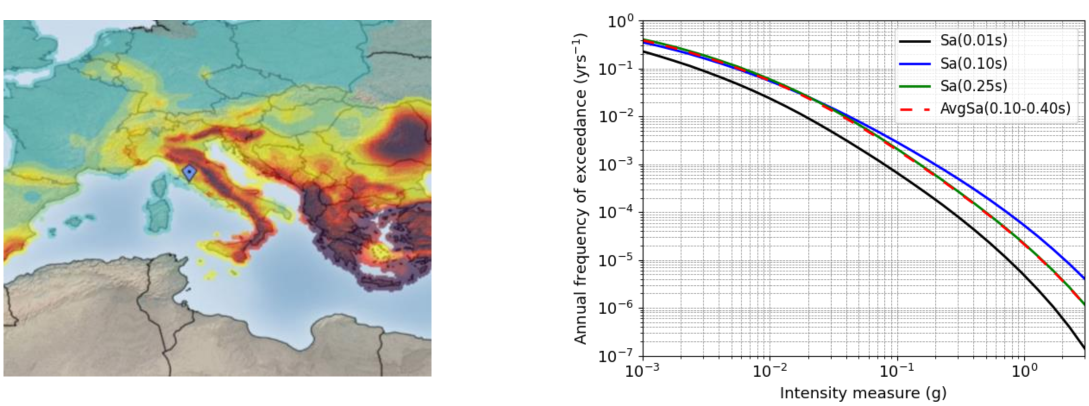

Figure 4: The seismic hazard for the METIS case study site in Tuscany, Italy per ESHM20: (left) PGA hazard map (extracted from EFEHR website[1]), and (right) the estimated hazard curves for four distinct IMs (estimated from the METIS Consortium).

1 http://hazard.efehr.org/en/home/

PERFORMANCE ESTIMATION

The final stage of PRA entails determining the level of risk. This involves combining the results obtained from the fragility analysis of the fault tree with the seismic hazard data for the METIS case study site (METIS 2023) on the coast of Tuscany, where a hypothetical nuclear installation is investigated, (Figure 4). A detailed Probabilistic Seismic Hazard Analysis (PSHA) was performed for this region, utilizing both historical and instrumental earthquake information. The computed hazard curves for the IMs of Sa(0.01s), Sa(0.10s), Sa(0.25s) and AvgSa(0.10-0.40s) are presented in Figure 4 (right). Ultimately the MAF loss of core cooling (λ_{LoCC}) is estimated as:

$$\lambda_{LoCC} = \int_0^\infty \mathrm{P}(\,\mathrm{LoCC} \mid IM\,)\ \left|\mathrm{d}\lambda_H(IM)\right| \tag{1}$$

where P(LoCC | *IM*) represents the probability of loss of core cooling occurring given a ground motion intensity *IM*, and $\lambda_H(IM)$ signifies the annual frequency of intensity level *IM* being exceeded.

Table 2: Mean annual frequency of loss of core cooling in years^{-1}

Correlation	Sa(0.01s)	Sa(0.10s)	Sa(0.25s)	AvgSa(0.10-0.40s)
0%	5.03E-5	4.95E-5	4.21E-5	4.79E-5
50%	5.96E-5	6.06E-5	5.04E-5	5.52E-5
100%	6.93E-5	7.06E-5	5.92E-5	6.40E-5

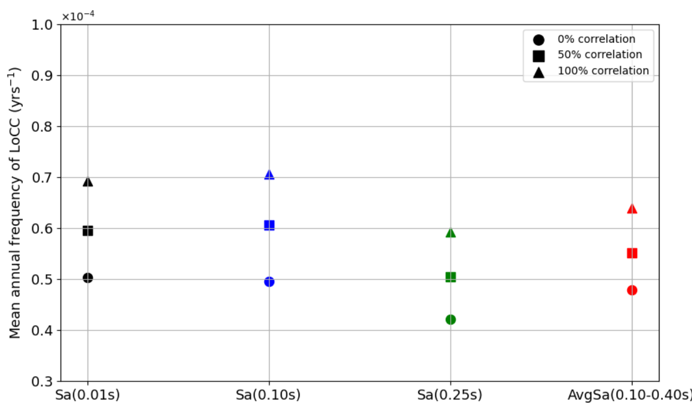

Figure 5: Mean annual frequency of loss of core cooling in years^{-1}.

RESULTS

Table 2 displays the outcomes of the PRA, while Figure 5 provides a visual representation of the MAF of LoCC occurrence to facilitate a simpler comparison. In all scenarios examined, a clear link emerges, as an increased correlation among the same basic events heightens the probability of the top event happening. It is important to note that within this simplified fault tree, the performance of some events is contingent on fragility assessments solely associated with PGA, rather than being tied explicitly to the examined IM. Nevertheless, it is recognized that the behavior of the well water pump, subjected to nonlinear response history analysis using the corresponding IM, governs the progression of core cooling loss in this particular case. It should be noted that had we used a generic set of ground motion records, we could have found estimates that would differ with the IM, sometimes by factors of 2 to 5. Instead, only minor differences appear, a testament to the hazard-consistency of CS-selected ground motion records. While there seems to be little benefit to this exercise, the consideration of alternative IMs comes with non-negligible merits: The reduced dispersion of a more efficient IM, in this case Sa(0.1s), allows us to efficiently perform the resource-intensive nonlinear response history analyses of the pump, using far fewer records than those required by PGA (here Sa(0.01s)) with no loss of fidelity.

CONCLUSIONS

Evaluating novel methodologies in nuclear seismic engineering, whether exploring innovative intensity measures or handling intra and inter-correlations among events that might trigger undesired occurrences in a nuclear power plant, requires substantial analytical commitment. To tackle this challenge, we introduce a streamlined model designed to achieve a harmonious blend of practicality and reliability in safety assessments. Our approach revolves around crafting an efficient yet realistic structural model coupled with a tailored fault tree. By prioritizing fundamental elements, this model provides simplified representations of the reactor building and a critical non-structural component. Within this framework, we explore conceivable scenarios that could lead to the undesired event of core cooling loss. For instance, we scrutinize the impact of the chosen intensity measure, evaluating three distinct correlation scenarios of perfect, partial, and no correlation in the occurrence of basic events that lead to loss of core cooling. Upon this basis, four different intensity measures are tested relative to their ability to accurately assess risk while reducing fragility dispersion, showing how such improvements can provide a benefit to more comprehensive full-model risk assessments.

ACKNOWLEDGEMENTS

We would like to thank Mr. Pablo Alfonso Garcia de Quevedo Iñarritu for creating the structural model of the reactor building in OpenSees and Dr. Philippe L.A. Renault who provided the Fault Tree as part of a presentation for METIS. Funding has been provided by the European Commission through the Horizon 2020 Project “METIS – Methods and tools innovations for seismic risk assessment” with Grant Agreement number 94512 and the Marie Skłodowska-Curie Project “YADES – Training on improved resilience and sustainable reconstruction of cultural heritage areas” with Grant Agreement number 872931.

REFERENCES

Ancheta, T. D., Darragh, R. B., Stewart, J. P., et al. (2013). Pacific Earthquake Engineering Research Center. US.

Bradley, B. A. (2010). A generalized conditional intensity measure approach and holistic ground-motion selection. *Earthquake Engineering & Structural Dynamics, 39*(12), 1321-1342.

Bojórquez, E., & Iervolino, I. (2011). Spectral shape proxies and nonlinear structural response. *Soil Dynamics & Earthquake Engineering, 31*(7), 996-1008.

Dolsek, M. (2009). Incremental dynamic analysis with consideration of modeling uncertainties. *Earthquake Engineering & Structural Dynamics, 38*(6), 805-825.

Eads, L., Miranda, E., & Lignos, D. G. (2015). Average spectral acceleration as an intensity measure for collapse risk assessment. *Earthquake Engineering & Structural Dynamics, 44*(12), 2057-2073.

EPRI (2007). Program on Technology Innovation: *Validation of CLASSI and SASSI Codes to Treat Seismic Wave Incoherence in Soil-Structure Interaction (SSI) Analysis of Nuclear Power Plant Structures*. EPRI, Palo Alto, CA.

EPRI (2018). Program on Technology Innovation: *Seismic Fragility and Seismic Margin Guidance for Seismic Probabilistic Risk Assessments*. EPRI, Palo Alto, CA.

GitHub. (2021). mvbin. [Online] Available at: https://github.com/shz9/mvbin

Jayaram, N., Lin, T., and Baker, J. W. (2011). A Computationally Efficient Ground-Motion Selection Algorithm for Matching a Target Response Spectrum Mean and Variance. *Earthquake Spectra, 27*(3), 797-815.

Kazantzi, A.K. and Vamvatsikos, D. (2015). Intensity measure selection for vulnerability studies of building classes. *Earthquake Engineering & Structural Dynamics, 44*(15), 2677–2694.

Kohrangi, M., Bazzurro, P., Vamvatsikos, D. (2016). Vector and Scalar IMs in Structural Response Estimation, Part II: Building Demand Assessment. *Earthquake Spectra*, *32*(3), 1525–1543.

Kohrangi, M., Bazzurro, P., Vamvatsikos, D., & Spillatura, A. (2017). Conditional spectrum-based ground motion record selection using average spectral acceleration. *Earthquake Engineering & Structural Dynamics, 46*(10), 1667-1685.

Lanzano, G., Sgobba, S., Luzi, L., *et al.* (2019). The pan-European Engineering Strong Motion (ESM) flatfile: compilation criteria and data statistics. *Bulletin of Earthquake Engineering, 17*(2), 561-582.

Lee, W. S., Grosh, D. L., Tillman, F. A., and Lie, C. H. (1985). Fault Tree Analysis, Methods, and Applications - A Review. *Reliability Engineering & System Safety, 34*(3), 194–203. DOI: 10.1109/tr.1985.5222114

Leisch, F., Weingessel, A., and Hornik, K. (1998). On the generation of correlated artificial binary data. SFB Adaptive information systems and modelling in economics and management science, Working paper series, WU Vienna University of Economics and Business, Vienna.

Lin, T., Haselton, C. B., & Baker, J. W. (2013). Conditional spectrum-based ground motion selection. Part I: hazard consistency for risk-based assessments. *Earthquake Engineering & Structural Dynamics, 42*(12), 1847-1865.

METIS (2021). Case study for implementation and application of METIS results. Deliverable D3.1, The METIS Consortium.
URL: D3_1_description_of_case_study_and_collection_of_data_and_reports_V1.pdf (metis-h2020.eu)

METIS (2023). Preparation of the METIS study case (WP4) and application. Deliverable D4.6, The METIS Consortium.
URL: METIS_D4_6_Application_to_METIS_study_case_submitted_20_03_2023_V1.pdf (metis-h2020.eu)

OpenSees (2006). Open System for Earthquake Engineering Simulation, Pacific Earthquake Engineering Research Center, University of California, Berkeley. Retrieved from http://opensees.berkeley.edu/

Python Software Foundation (2008). Python (version 3.0), retrieved from https://www.python.org/

Spillatura, A., Kohrangi, M., Bazzurro, P., and Vamvatsikos, D., (2021). Conditional spectrum record selection faithful to causative earthquake parameter distributions. *Earthquake Engineering & Structural Dynamics, 50*(10), 2653–2671.

Vamvatsikos, D., & Cornell, C. A. (2005). Developing efficient scalar and vector intensity measures for IDA capacity estimation by incorporating elastic spectral shape information. *Earthquake Engineering & Structural Dynamics*, *34*(13), 1573-1600.

Vamvatsikos, D., & Fragiadakis, M. (2010). Incremental dynamic analysis for estimating seismic performance sensitivity and uncertainty. *Earthquake Engineering & Structural Dynamics*, *39*(2), 141-163.

Vamvatsikos, D. (2014). Seismic Performance Uncertainty Estimation via IDA with Progressive Accelerogram-wise Latin Hypercube Sampling. *ASCE Journal of Structural Engineering, 140*(8), A4014015.

Van Houtte, C., Bannister, S., Holden, C., Bourguignon, S., & McVerry, G. (2017). The New Zealand strong motion database. *Bulletin of the New Zealand Society for Earthquake Engineering*, *50*(1).

Willaume, P., & Noret, E. (2011). Présentation du modèle brochette (Report No. DT-PMPE-00234-002-B). Électricité de France (EDF). [Confidential].

Wolf, J.P. (1998). Simple physical models for foundation dynamics. *Developments in Geotechnical Engineering*, *83*, 1-70.