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Guidelines for beyond design assessments (DEE/BEPU) and fragility evaluation (Technical report)

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Summary

Ensuring the safety and integrity of nuclear facilities is paramount in a world increasingly reliant on nuclear energy. A key aspect of nuclear power plant (NPP) safety assessment is evaluating the plants resilience against seismic events. This involves understanding both the likelihood of seismic hazards and the potential for plant structures, systems, and components (SSCs) to fail under seismic loading. Seismic fragility analysis links seismic hazard characterization to overall risk assessment. It quantifies the conditional probability of failure of SSCs as a function of seismic intensity measures. Assessing NPP performance under severe conditions, especially those beyond the design basis?requires robust methodologies. Approaches such as Seismic Margin Assessment (SMA), Best Estimate Plus Uncertainty (BEPU) analysis, and Conservative Deterministic Failure Margin (CDFM) are widely applied to explore these be-yond-design scenarios. The METIS project, a Research and Innovation Action funded by the European Commission, aims to develop advanced methodologies and tools for seismic risk assessment of NPPs. Within this framework, Work Package 6 (WP6) Beyond Design Assessments and Fragility Analysis focuses on evaluating the potential for failure of SSCs at the Zaporizhzhia nuclear power plant (ZNPP), under specified seismic scenarios. WP6 also supports the development of efficient fragility analysis methodologies and provides guidance for BEPU practices. This document, Deliverable D6.9, presents a synthesis of the key methodologies, findings, and lessons learned from the technical activities undertaken in WP6. Building upon the work documented in Deliverables D6.1 through D6.8, it provides practical guidance for conducting Beyond Design Assessments and Seismic Fragility Evaluation for NPPs.

Approval

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Seismic Risk Assessment
for Nuclear Safety

Research & Innovation Action

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Overview and lessons learned from WP6: beyond design and fragility analysis

Deliverable D6.9

Version N°1

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Abbreviations and Acronyms

Acronym	Description
NPP	Nuclear Power Plant
SSC	System, Structure, Component
FEM	Finite Element Model
SSI	Soil Structure Interaction
RB	Reactor Building
DGB	Diesel Generator Building
FCVs	Filter Containment Venting System
CMC	Control Monitor Cabinet
SWP	Service Water Pump
LHS	Latin Hypercube Sampling
IM	Intensity Measure
PGA	Peak Ground Acceleration
EDP	Engineering Demand Parameter
BE	Best Estimate
BEU	Best Estimate and Uncertainties
FEMA	Federal Emergency Management Agency
EPRI	Electric Power Research Institute
HCLPF	High Confidence Low Probability of Failure
IDA	Incremental Dynamic Analysis
MSA	Multiple Stripe Analysis

1 Introduction

Ensuring the safety and integrity of nuclear facilities is paramount in a world increasingly reliant on nuclear energy. A key aspect of nuclear power plant (NPP) safety assessment is evaluating the plant's resilience against seismic events. This involves understanding both the likelihood of seismic hazards and the potential for plant structures, systems, and components (SSCs) to fail under seismic loading.

Seismic fragility analysis links seismic hazard characterization to overall risk assessment. It quantifies the conditional probability of failure of SSCs as a function of seismic intensity measures. Assessing NPP performance under severe conditions, especially those beyond the design basis—requires robust methodologies. Approaches such as Seismic Margin Assessment (SMA), Best Estimate Plus Uncertainty (BEPU) analysis, and Conservative Deterministic Failure Margin (CDFM) are widely applied to explore these beyond-design scenarios.

The METIS project, a Research and Innovation Action funded by the European Commission, aims to develop advanced methodologies and tools for seismic risk assessment of NPPs. Within this framework, Work Package 6 (WP6)—Beyond Design Assessments and Fragility Analysis—focuses on evaluating the potential for failure of SSCs at the Zaporizhzhia nuclear power plant (ZNPP), under specified seismic scenarios. WP6 also supports the development of efficient fragility analysis methodologies and provides guidance for BEPU practices.

This document, Deliverable D6.9, presents a synthesis of the key methodologies, findings, and lessons learned from the technical activities undertaken in WP6. Building upon the work documented in Deliverables D6.1 through D6.8, it provides practical guidance for conducting Beyond Design Assessments and Seismic Fragility Evaluation for NPPs.

1.1 Scope of the Document

The scope of this deliverable encompasses the entire fragility assessment process as conducted in WP6, including:

- **SSC Definition, Classification, and Screening**: Development of procedures and criteria for selecting and categorizing SSCs for seismic fragility analysis, separating them into Tier 1 (detailed analysis) and Tier 2 (generic) based on important measures such as FV and RAW. *Referenced in D6.1.*
- **Mechanical Modelling and Validation**: Construction of reliable mechanical models, including multi-fidelity and reduced-order approaches. Verification and validation (V&V) procedures were developed using experimental data (e.g., SMART2013) and analytical benchmarks. *Modelling in D6.1; V&V in D6.2.*
- **Seismic Input Characterization**: Identification of appropriate scalar and vector-valued Intensity Measures (IMs) based on efficiency and sufficiency. Techniques for hazard-consistent ground motion selection and site response considerations were explored. *Documented in D6.3.*
- **Uncertainty Quantification and Propagation**: Comprehensive treatment of aleatory and epistemic uncertainties in fragility analysis, spanning modeling, structural response, and soil-structure interaction. Efficient propagation techniques such as Latin Hypercube Sampling (LHS), Sobol sequences, and FOSM were applied. *Detailed in D6.4.*
- **Seismic Fragility Evaluation Methods**: Comparative assessment of scalar and vector-based fragility methods, including Incremental Dynamic Analysis (IDA), Cloud Analysis (MLH, MLR),

and evaluation under linear/nonlinear response conditions.
Presented in D6.5.

- **Bayesian Updating**: Application of Bayesian techniques to reduce epistemic uncertainty in models and fragility curves by incorporating experimental or high-fidelity simulation data. *Covered in D6.6.*
- **Influence of Aftershocks and Clustered Seismicity**: Development of fragility models accounting for damage-state dependency due to aftershocks and seismic clustering. The impact of mainshock–aftershock sequences (MS-AS) on component capacity was analyzed. *Reported in D6.7.*
- **Application to Case Study**: Implementation of the developed methodologies on selected ZNPP SSCs assumed to be located in Tuscany, Italy, including the Reactor Building, Diesel Generator Building, Filter Containment Venting System, Transformer, and Service Water Pump. This case study supported result verification and benchmarking against existing methodologies (e.g., EPRI).
Described in D6.8.

2 Definition and Classification Scheme of SSCs

(Based on Deliverable D6.1)

2.1 Description and Aim

This chapter summarizes the content and contributions of Deliverable D6.1 of the METIS project, which serves as the foundational step in the seismic fragility analysis of Nuclear Power Plant (NPP) Systems, Structures, and Components (SSCs) within Work Package 6 (WP6). The main objective of this work is to establish a systematic methodology for the definition, screening, and classification of SSCs, enabling the identification of components that are critical for maintaining safety functions during and after seismic events.

The classification scheme introduced in D6.1 distinguishes SSCs into two main categories:

- Tier 1 SSCs, which require detailed, system-specific modelling and analysis,
- Tier 2 SSCs, which can be assessed using generic, class-level approaches.

The classification results support all subsequent WP6 tasks, including mechanical model development (Task 6.1), model verification and validation (Task 6.2), and seismic fragility evaluation (Task 6.5). Ultimately, this chapter ensures that fragility analysis efforts are risk-informed and resource-efficient.

2.2 Methodology

The methodology developed in Deliverable D6.1 outlines a structured approach for identifying, screening, and classifying SSCs for seismic fragility evaluation. The process begins with the development of a Seismic Equipment List (SEL), which includes both safety-related systems, structures, and components as well as non-safety items whose seismic failure could indirectly compromise key safety functions. The SEL is compiled using plant-specific documentation and existing equipment lists. Following this, an initial screening is conducted to exclude components that are either inherently seismically rugged or judged not to contribute significantly to seismic risk. For the remaining SSCs, a quantitative classification is applied based on important measures derived from a Seismic Probabilistic Safety Assessment (SPSA) model. Specifically, Fussell-Vesely (FV) and Risk Achievement Worth (RAW) metrics are recalculated to evaluate the relative contribution of each SSC to seismic risk. SSCs that show high or very high importance based on these metrics are categorized as Tier 1, indicating the need for detailed analysis, while the remaining SSCs are classified as Tier 2 and considered suitable for more generic, class-level fragility treatment. For the Tier 1 SSCs, the methodology proposes the development of both detailed nonlinear mechanical models and simplified surrogate models, depending on the complexity and objective of the analysis. This tiered classification serves as the foundation for subsequent tasks in the METIS project, including model development, validation, and fragility analysis.

2.3 Findings

- D6.1 defines a clear and replicable methodology for SSC identification, screening, and classification, aligning with PSA-informed fragility assessment principles.
- The classification process was applied to the METIS case study, Zaporizhzhia NPP Unit 1, using existing SPSA models to recalculate importance measures.
- Results show that:
    - Many SSCs are of low seismic safety significance and may be excluded from detailed analysis.
    - Approximately 20 SSCs were ranked as high or very high significance, forming candidates for Tier 1.
    - Around 50 SSCs were ranked as medium significance, potentially warranting further attention based on modeling feasibility.
- The analysis led to the identification of 16 SSC groups critical to reactor core damage prevention and 9 groups relevant to spent fuel pool safety.
- Examples of proposed Tier 1 SSCs include essential service water components, such as filters, strainers, valves, and pumps.

2.4 Concluding Remarks

- The methodology presented in D6.1 is recommended as a baseline procedure for SSC classification in seismic fragility assessment and should be applied in future projects requiring risk-informed prioritization.
- The Tier 1 candidate list derived from ZNPP should guide the selection of SSCs for detailed modeling (Task 6.1) and fragility evaluation (Task 6.5).
- The final selection of SSCs for detailed analysis should be contingent on the availability of sufficient plant-specific data to enable reliable mechanical modeling.
- The Tier 1/Tier 2 classification scheme should be applied across other NPPs and adapted as necessary to reflect their specific design and risk characteristics.
- It is further recommended that cross-disciplinary collaboration (civil, mechanical, PSA experts) be maintained throughout SSC classification and modelling to ensure consistent and complete coverage of relevant failure modes.

Deliverable D6.1 describes how to identify and classify SSCs for seismic fragility evaluation. The authors applied methods from existing guidelines and their PSA experience. The report includes screening rules to select SSCs for further analysis. It proposes a risk-informed approach to exclude SSCs with low-risk importance and focus on those with higher significance. Both qualitative and quantitative screening criteria are provided. The report also notes factors that may affect the seismic equipment list.

For the METIS case study (Zaporizhzhia NPP Unit 1), the team evaluated importance measures. They proposed 16 SSC groups related to core damage prevention and 9 related to fuel damage prevention for Tier 1. These groups will guide the next steps in the fragility evaluation, based on the available plant data.

3 Verification and Validation of Nonlinear Mechanical Models

(Based on Deliverable D6.2)

Following the classification of critical SSCs and development of mechanical models in Task 6.1, Deliverable D6.2—titled *"Verification & Validation of Nonlinear Mechanical Models on SMART2013 Campaign"*—represents the next key step within WP6. It addresses Task 6.2, which is dedicated to verifying and validating the numerical models and associated failure criteria, thereby ensuring their suitability for seismic fragility assessment.

3.1 Description and Aim

The primary objective of D6.2 is to establish and implement a comprehensive methodology for verification and validation (V&V) of both detailed and reduced-order nonlinear mechanical models developed in the context of WP6. The focus lies on confirming that the selected models for Tier 1 SSCs, as identified in D6.1, can accurately reproduce structural responses under seismic loading, using experimental results as the validation benchmark.

To this end, D6.2 provides a structured V&V framework supported by mathematical tools and engineering judgment, enabling robust comparison between numerical simulations and experimental data. The methodology also supports a multi-fidelity modelling strategy, essential for balancing accuracy and computational efficiency in seismic fragility applications.

3.2 Methodology

Deliverable D6.2 presents a stepwise Verification and Validation (V&V) procedure, drawing inspiration from the structured framework proposed by Roy and Oberkampf (2011). This methodology is organized into four main stages. It begins with the analysis of experimental tests, where relevant test data are characterized and suitable Engineering Demand Parameters (EDPs) are defined to support model validation. Following this, numerical analyses are conducted using mechanical models. These include both high-fidelity finite element models and simplified surrogate models, allowing for a comprehensive simulation campaign that captures a broad spectrum of system behavior.

After generating simulation results, the next stage involves calculating validation metrics that quantitatively compare numerical predictions with experimental data. A range of indicators is used, including mismatch indices and error measures. Particular attention is given to assessing model performance in a statistically meaningful way, which leads to the use of advanced metrics such as the modified area metric (d_0), errors evaluated at specified quantiles (err), and corrective metrics for drift capacity such as d_m and d_p.

The final stage of the methodology focuses on extrapolation and uncertainty propagation. This includes the evaluation of model behavior beyond the range of available test data and a comprehensive treatment of uncertainties. These uncertainties stem from numerical discretization aspects (e.g., mesh sensitivity), uncertain input parameters (UINP), and assumptions in the model formulation itself (UFORM). All identified sources of uncertainty are systematically quantified, propagated, and combined to ensure that the final validation results reflect the full scope of variability influencing model predictions.

3.3 Application to SMART2013 Experimental Campaign

The validation framework is applied to the SMART2013 experimental campaign, which involved shake-table tests on a scaled reinforced concrete building mock-up. Numerical simulations were conducted using the Cast3M platform, encompassing both linear and nonlinear mechanical analyses.

Results from these simulations were compared against experimental data in terms of relevant EDPs, such as displacements and strains at critical locations. The deliverable demonstrates how the proposed validation process effectively identifies discrepancies, quantifies model accuracy, and guides potential improvements.

This application served to:

- Validate the performance of nonlinear models in replicating seismic response,
- Assess the effect of model simplifications on reduced-order models,
- Demonstrate the role of surrogate models within a multi-fidelity context.

3.4 Findings

The main findings from D6.2 include:

- A systematic V&V methodology was established, integrating uncertainty quantification, validation metrics, and model evaluation criteria.
- The methodology supports both detailed and surrogate models, promoting a bias/variance reduction strategy.
- The SMART2013 campaign served as a successful testbed for evaluating the methodology, revealing insights into model capabilities and limitations.
- Several validation metrics were tested and improved to better capture model-to-test agreement, particularly in the context of cumulative distribution functions.
- The study emphasizes the importance of uncertainty characterization for ensuring robust validation conclusions.
- There is no single validation method universally applicable to all structural models; a tailored, case-specific approach can be useful.
- The availability and quality of experimental data are critical for the depth and reliability of the V&V process proposed here which means that it cannot be applied in the general case.
- The definition of validation criteria (including thresholds for key metrics) should be decided in advance by model owners or safety authorities, tailored to the specific objectives and critical EDPs.

3.5 Concluding Remarks

Based on the analysis and findings, D6.2 outlines several remarks:

- Select validation metrics based on the required level of precision. This report (D6.2) presents four metrics (d_0, d_m & d_p, $err(\alpha_\mathrm{err})$, and error per input combination). A graded approach, depending on the importance of the outcome and the desired precision, is recommended.
- Adjust the number of propagated samples according to the application context, available computational resources, and time. Justify these choices through sensitivity analysis and EDP–IM correlation studies, where possible, to eliminate low-influence variables and reduce computational cost.
- Incorporate relevant physical data and constraints to improve the quality of regression and prediction intervals.
- Include physical relationships between input variables or between EDPs when such relations are supported by known phenomena.

- Fit the regression according to the observed shape and distribution of the validation metrics within the domain.
- Where feasible, account for experimental uncertainties by considering confidence intervals to any computed quantity.

4 Damage/Failure Relevant Ground Motion Intensity Measures and Record Selection Schemes

(Based on Deliverable D6.3)

4.1 Description and Aim

This chapter builds upon the work conducted in Deliverable D6.3, focusing on the identification of appropriate ground motion intensity measures (IMs) and the development of efficient ground motion record selection schemes tailored for seismic fragility analysis of nuclear power plant (NPP) systems, structures, and components (SSCs). The primary objective is to identify scalar and vector-based IMs that are most relevant to damage and failure, and to propose record selection approaches that can reduce the epistemic and aleatory uncertainty in predicted structural responses. This work is part of Task 6.3 within Work Package 6 of the METIS project and addresses a key aspect of seismic risk assessment, as the choice of IMs and ground motion records has a direct and significant influence on the shape and reliability of fragility curves. Ultimately, the chapter aims to offer practical guidance for selecting ground motions and IMs that improve the robustness and efficiency of seismic performance evaluations of NPP SSCs. Additionally, this chapter includes considerations of site response analysis methodologies to ensure accurate representation of surface-level ground motions.

4.2 Methodology

The methodological approach began with an extensive literature review on both scalar and vector intensity measures, aiming to understand their theoretical basis and practical application in seismic analysis. A central focus was placed on assessing the response of NPP-relevant structures under different record selection schemes. Specifically, the study compared methods that enforce hazard consistency—such as Conditional Spectrum (CS) and Multiple Stripe Analysis (MSA), which build upon methodologies from WP5—with more conventional approaches like standard Incremental Dynamic Analysis (IDA), where hazard consistency is not enforced. These approaches were applied to a range of case studies, including both simple equipment models such as a service water pump and more complex structural systems such as the reactor building and the diesel generator building.

To evaluate the performance of various IMs, both scalar and vector-based fragility assessment techniques were employed. This typically involved conducting nonlinear time history analyses (NLTHAs) through either IDA or Cloud Analysis frameworks. Site response analysis methodologies were also implemented to translate bedrock motions to surface motions, with special consideration given to the uncertainty in soil properties and the necessity of deconvolution for achieving consistency between input and output motions. Transfer function analysis was used to investigate the dynamic characteristics of SSCs and to identify structural locations susceptible to high seismic demands. Regression techniques, particularly multiple linear regression, were applied to model the relationship between IMs and Engineering Demand Parameters (EDPs). The sensitivity of these IM-EDP relationships to variations in the ground motion dataset was also explored. For vector IMs, the estimation of EDPs relied on combining cloud analysis with regression-based approaches, scaling of records to dominant IMs, or fitting conditional distributions to IDA data—an aspect that is more extensively reported in Deliverable D6.5.

4.3 Findings

- Numerous IMs were identified in literature, broadly categorized into structure-specific and non-structure-specific measures.
- Scalar IMs remain the most commonly used in NPP applications due to the availability of seismic hazard curves.
- However, scalar IMs alone may not adequately represent complex failure mechanisms or the effects of vertical ground motion components.
- Vector IMs, which incorporate multiple ground motion parameters, offer a more comprehensive representation of seismic demand but require more advanced modeling and data handling. However, considering vector IMs requires the development of vector fragility curves for all SSCs which would be very time consuming. In addition, it required the consideration of vector-hazard and benefit in a seismic PRA study with realistic accident sequences that still need to be demonstrated.
- Based on our case study, CS-MSA produced more stable and hazard-consistent results than standard IDA, which showed greater sensitivity to the choice of IM and led to unconservative outcomes in this case.
- As expected, the choice of IMs had a notable impact on the resulting fragility curves, especially when component periods varied across structural elements.
- Site response analysis was found to be necessary for generating realistic surface-level input motions, particularly for regions with deep or variable soil profiles.

4.4 Concluding Remarks

- Scalar IMs should continue to be used for general fragility analysis tasks.
- For SSCs with complex behavior or sensitivity to specific motion components, incorporating additional IMs or moving to vector IMs can be useful. However, the use of several IMs is not compatible with current practice in risk assessment and would require substantial additional research and engineering work. Possible benefit needs to be related to this effort.
- Site response analyses should be integrated into the ground motion selection process, with attention to deconvolution for bedrock input motions.
- The methodologies developed in this task should be carried forward into detailed fragility assessments under Task 6.5.
- Further studies are encouraged to explore IM and record selection applicability across a wider range of SSC types, site conditions, and hazard scenarios.

5 Efficient Uncertainty Quantification and Propagation Techniques

(Based on Deliverable D6.4)

5.1 Description and Aim

In seismic fragility analysis of NPP SSCs, the accurate and efficient quantification and propagation of uncertainties is crucial to obtaining reliable risk estimates. Due to the complex interaction of structural, geotechnical, and ground motion variability, traditional Monte Carlo-based approaches can become computationally expensive and inefficient. Hence, there is a growing need for techniques that optimize sampling, capture key uncertainties, and enable scalable analysis. This chapter addresses these challenges by presenting methods developed within Deliverable D6.4 (WP6) to improve the computational efficiency of UQ&P in seismic fragility assessments. Additionally, the study explores uncertainty-robust Intensity Measures (IMs) that can improve the stability and generality of fragility models across varying SSC types.

5.2 Methodology

The study began with a comprehensive review of literature to identify and categorize the main sources of uncertainty relevant to seismic fragility analysis of SSCs in NPPs. These included variability in ground motion records, structural damping, modeling assumptions, structure and soil-structure interaction (SSI) phasing, among others. For each source, representative logarithmic standard deviation values were compiled to be used in probabilistic analysis. To propagate these uncertainties efficiently, various sampling techniques were evaluated and implemented. These included Latin Hypercube Sampling (LHS), Sobol sequences, and the First Order Second Moment (FOSM) method. Progressive or Hierarchical Latin Hypercube Sampling (PLHS), in particular, was employed as an iterative approach that allows sample sets to be progressively enriched, making it suitable for analysis where computational resources or convergence monitoring is a concern.

The developed methodology was applied to two case studies. The first involved a simple nonlinear Single Degree of Freedom (SDOF) system, serving as a benchmark to evaluate sensitivity to different uncertainty propagation schemes. The second and more detailed case study focused on a 3D finite element model of a service water pump located in the reactor building of a nuclear power plant. Incremental Dynamic Analysis (IDA) was performed on this model, and uncertainties in structural properties were modeled using log-normal distributions. Three structural parameters were randomly sampled according to an LHS design, and the displacement responses in the X and Y directions were extracted as Engineering Demand Parameters (EDPs). Various Intensity Measures (IMs) were tested, including Peak Ground Acceleration (PGA), Spectral Acceleration (Sa) at the pump's fundamental period ($T_{pump} = 0.101$ s), and Average Spectral Acceleration (AvgSa) over selected period ranges (0.10–0.40 s, 0.10–0.20 s, and 0.05–0.15 s). Fragility curves were then constructed for each uncertainty propagation approach and IM and compared in terms of their estimated median capacity and dispersion.

5.3 Findings

- **Sampling Methods**:
  - All proposed UQ&P methods produced similar fragility estimates in terms of median capacity and dispersion when compared to the R2R-only approach.
  - PLHS offers a practical advantage by allowing incremental sample refinement, useful for time-constrained studies or adaptive analyses.
- **Convergence behavior**:
  - LHS results illustrated convergence of fragility estimates (Am, β) as a function of sample size.
- **IM performance**:
  - Using Sa at a single period was found to be less robust for systems with a wide distribution of natural periods.
  - AvgSa over a defined range of periods provides better representation for a group of components with variable dynamic characteristics.

    - The choice of IM had a greater impact on fragility curve stability than the selection of UQ&P method.

- A **compiled list of β values** for different uncertainty sources (e.g., damping, SSI, modeling) is provided, serving as input for probabilistic assessments in WP6.

5.4 Concluding Remarks

Based on the analyses, the following conclusions and remarks are drawn:

- Efficient UQ&P methods such as LHS and Sobol are suitable for seismic fragility assessment of NPP SSCs and are computationally comparable to traditional methods.
- The results of this work will support WP6 by providing:
    - Guidelines for uncertainty modeling
    - Recommendations for efficient sampling techniques
    - Insight into uncertainty-robust IMs

Further investigations into AvgSa metrics and advanced UQ techniques are encouraged to enhance reliability in fragility modeling for NPP safety evaluations.

6 Scalar and Multi-Dimensional (Vector-Based) Fragility Evaluation Methods

(Based on Deliverable D6.5)

6.1 Description and Aim

This chapter is based on Deliverable D6.5 of Work Package 6 (WP6). It focuses on the evaluation of scalar and multi-dimensional (vector-based) fragility methodologies. The primary aim is to evaluate the effectiveness of different combinations of intensity measures (IMs) through scalar and vector-based fragility methodologies, covering both linear and nonlinear structural responses.

The report investigates the advantages of vector-based approaches in reducing uncertainties and improving the reliability of fragility assessments. A comprehensive comparison is conducted between scalar and vector-based IMs, with a particular focus on their correlation with engineering demand parameters (EDPs), namely drift and acceleration. The Diesel Generator Building (DGB) of the Zaporizhzhia Nuclear Power Plant (NPP) serves as the case study structure.

6.2 Methodology

The study evaluates scalar and vector-based fragility methodologies using two main approaches: Cloud Analysis and Incremental Dynamic Analysis (IDA). Cloud analysis involves subjecting the structural models to a suite of unscaled natural ground motion records, whereas IDA scales each record to multiple intensity levels to assess response under increasing levels of seismic demand. For both approaches, fragility functions are derived using two statistical techniques: Multiple Linear Regression (MLR) and Maximum Likelihood Estimation (MLH). These methods are used to quantify the probability of exceeding specific demand thresholds as a function of selected IMs.

The Diesel Generator Building (DGB) and its simplified structural model are used as case studies to represent the performance of typical NPP structures. Engineering Demand Parameters (EDPs) include interstory drift and floor acceleration, selected to capture structural and equipment-level seismic performance. These EDPs are correlated with various scalar IMs (e.g., PGA, Sa(T_1)) and vector combinations (e.g., pairs of IMs) to examine which combinations result in lower dispersion and better predictive capacity.

Ground motions were selected from WP5 datasets, covering Intensity Measure Levels (IMLs 5 through 9) under both Best Estimate (BE) and Best Estimate with Uncertainties (BEU) scenarios. A total of 30 ground motion records were used per IML. Site response analyses were conducted to obtain surface-level ground motions, and variability in site conditions was incorporated into the BEU cases. Uncertainties in structural properties were also included, with three key parameters sampled from log-normal distributions using a Latin Hypercube Sampling (LHS) scheme.

The performance of different IMs and their combinations was evaluated using statistical indicators such as dispersion, Akaike Information Criterion (AIC), and the Area Under the Curve (AUC) from receiver operating characteristic analysis. Scalar and vector-based fragility models were compared based on these metrics to assess which approach offers lower uncertainty in the fragility estimates.

6.3 Findings

The scalar fragility analysis showed that spectral acceleration at the fundamental period (Sa(T1)) consistently outperformed other scalar IMs for both linear and nonlinear responses. It exhibited the lowest dispersion and AIC and the highest AUC, indicating strong correlation with structural response and good model fit.

The vector-based analysis demonstrated that using pairs of IMs can further reduce fragility dispersion compared to scalar IMs. The optimal vector IM pair in Cloud-MLH analysis was (Sa(T1), Np). Across all methods and response types, Sa(T1) consistently appeared as a component in the best-performing IM or IM pair.

The benefits of vector IMs were more evident in nonlinear structural responses, where dispersion was generally higher due to the complex nature of structural behavior. While the improvement over scalar IMs was minor in linear cases, it became more substantial in nonlinear analyses.

6.4 Concluding Remarks

The findings support the selection of Sa(T1) as a reliable scalar IM for fragility analysis, due to its consistently strong performance across structural response types and statistical indicators. Drift is recommended as a more stable EDP than acceleration, particularly in Cloud and nonlinear IDA analyses.

Vector IMs should be considered when dealing with structures expected to undergo significant nonlinear behavior, as they offer improved predictive performance and reduced uncertainty. For such cases, including Sa(T1) in IM combinations (e.g., with Np) is particularly beneficial.

7 Application of Bayesian Updating Techniques

(Based on Deliverable D6.6)

This chapter presents the findings from Deliverable D6.6 of the METIS project, which falls under Task 6.6 of Work Package 6 (WP6). The focus is on the application of Bayesian updating techniques to improve the seismic fragility assessment of nuclear structures. The methodology is illustrated using the SMART2013 mock-up as a case study.

7.1 Description and Aim

The main objective of this task is to develop a methodology for Bayesian updating to enhance the seismic fragility assessment of nuclear structures. The case study focuses on the SMART2013 mock-up, a ¼ scale reinforced concrete model representing a building adjacent to a reactor building.

The aim of the methodology is to reduce epistemic uncertainties in fragility assessment by updating uncertain input parameters—specifically mechanical properties such as Young’s modulus and damping ratios—using Bayesian updating techniques based on experimental data from shaking table tests. These updates are expected to improve the predictions of structural response (e.g., acceleration response spectra, displacements) and to refine fragility curves by shifting them to more accurate probability-of-failure levels.

7.2 Methodology

The methodology couples numerical modeling, metamodeling, and Bayesian updating in a two-step process:

- The SMART2013 mock-up was modeled using the Cast3m finite element software, representing concrete structures with shell and solid elements and using Rayleigh damping based on calibrated frequencies.
- Seismic input was applied using measured shaking table accelerations, and boundary conditions were set to reflect the actuator constraints and foundation flexibility.

To reduce computational cost, Polynomial Chaos Expansion (PCE) metamodels were created to approximate the relationship between model inputs and outputs (e.g., eigenfrequencies, acceleration response spectra). Then, Bayesian updating using a Markov Chain Monte Carlo (MCMC) algorithm was applied to these metamodels, using experimental observations to infer the posterior distributions of uncertain parameters.

The two-step updating process was as follows:

1. Updating Young’s Modulus:
   Parameters for concrete elements were updated based on observed global eigenfrequencies, separately for elastic runs (#7, #9, #11) and nonlinear runs (#15, #17, #19). Metamodels were used to relate Young's modulus to modal properties.
2. Updating Damping Ratios:
   Based on updated stiffnesses from Step 1, Rayleigh damping ratios (ξ_1, ξ_2) were updated by comparing numerical and experimental acceleration response spectra at dominant frequencies.

Fragility curves were developed using a statistical regression between Peak Ground Acceleration (PGA) and selected Engineering Demand Parameters (EDPs):

- Spectral acceleration at the first eigenfrequency peak at control point D (Sa,N)
- Nominal inter-storey drift at point D (δ_n)

Uncertainty in the model-to-measurement relation was represented by a normal error term, and Monte Carlo simulations were used to evaluate fragility curves at various confidence levels (5%, 50%, 95%).

7.3 Findings

The two-step Bayesian updating method led to significant improvements in matching experimental observations:

- Updated Young's Modulus:
  Posterior distributions of Young's modulus showed substantial reductions for cracked elements in nonlinear runs, with reduction ratios greater than 2 in many cases, particularly for first-floor wall elements. For elastic cases, updates to the foundation stiffness helped match observed eigenfrequencies more closely.
- Updated Damping Ratios:
  Posterior damping values increased with PGA level and were significantly higher than prior assumptions, particularly in nonlinear cases. This enabled the numerical model to better reproduce the peak amplitudes of acceleration response spectra.
- Improved Model Predictions:
  Comparison of updated model responses with measurements at a secondary location (point B) demonstrated that improvements were not overfitted to the calibration point (point D) but reflected genuine enhancements in predictive accuracy.
- Reduced Epistemic Uncertainty:
  The Bayesian updating procedure led to a notable reduction in uncertainty—posterior fragility curves had narrower confidence intervals and were shifted to the right, reflecting decreased failure probabilities due to more accurate input estimates (especially damping).

7.4 Concluding Remarks

The study shows that coupling metamodeling (PCE) with Bayesian updating (MCMC) is an effective strategy for:

- Reducing model uncertainty,
- Improving the accuracy of fragility curves,
- Achieving this at a reasonable computational cost even within an equivalent linear framework.

Remarks and future directions include:

- Using nonlinear models for direct updating, despite the higher computational burden, with adapted experimental design plans.
- Updating fragility curves directly, bypassing intermediate parameter updates.
- Industrial-scale application, provided that sufficient experimental or in-situ measurements are available.
- Leveraging non-destructive testing (NDT) or advanced nonlinear simulations as surrogate "measurement" data.
- Using post-seismic databases (e.g., SQUG) to inform posterior fragility assessments when experimental data are lacking.

These avenues align with ongoing research and development goals within the METIS project and broader nuclear safety assessment efforts.

8 Influence of Aftershocks and Clustered Seismicity on Seismic Fragility

(Based on Deliverable D6.7)

8.1 Description and Aim

This paragraph refers to Deliverable D6.7 of the Methods and Tools Innovations for Seismic Risk Assessment (METIS) project, the report corresponds to Work Package 6 (WP6) and addresses Task 6.7: Influence of aftershocks and clustered seismicity on seismic fragility.

The report investigates how aftershocks and clustered seismicity affect the seismic fragility of Structures, Systems and Components (SSCs). Traditional seismic risk assessments typically neglect the cumulative impact of aftershocks, which can lead to an underestimation of seismic risk. The primary aim is to present a methodology for developing damage-state-dependent fragility curves, reflecting the reduced capacity of structures already damaged by a mainshock (MS). These curves are made hazard-consistent via a detailed MS–Aftershock (AS) record selection process that generates MS-AS sequences selected based on spectral shape.

Additionally, the report provides practical remarks for MS-only fragility assessments, such as the appropriate number of ground motions per stripe and the use of Bayesian updating to minimize the number of required analyses.

8.2 Methodology

The methodology is centered on creating damage-state-dependent fragility curves for SSCs affected by MS-AS sequences. It begins with a hazard-consistent MS-AS record selection, using the Conditional Spectrum (CS) approach to select MS ground motions. AS records are then selected using the MSAS-CS method, conditioned on the MS properties (magnitude, distance) and incorporating ETAS modeling for realistic aftershock occurrence.

For the METIS case study site, 10 IMLs were defined, spanning return periods from 40 to 100,000 years. The average spectral acceleration (AvgSa) was used as the intensity measure. 50 MS records per IML were selected. Aftershock (AS) records were filtered based on the following criteria: occurrence within one year after the MS, epicentral distance within 100 km of the MS, magnitude ≥ 3.5, and AvgSa > 0.2g. MS and AS records were assembled with a 10-second gap for structural recovery.

Although aftershocks can occur seconds, minutes, days, or even years after the mainshock, it is important to note that for longer time spans between MS and AS events, in real scenarios, damaged SSCs (Structures, Systems, and Components) could potentially be repaired. However, in this study, the effect of repair between MS and AS was not considered.

Nonlinear response simulations (NLRHA) were then performed on two case studies:

- A service water pump modeled as a single-degree-of-freedom (SDOF) system with three damage states: DS0 (undamaged), DS1 (malfunctioning, displacement ≥ 2.3mm), and DS2 (collapse, ductility $\mu = 2.5$).
- The Diesel Generator Building (DGB) at ZNPP, simplified as a 3D MDOF stick model with SSI, using displacement thresholds of 0.006 m (DS0), 0.020 m (DS1), and 0.034 m (DS2).

Fragility functions were developed as lognormal cumulative distributions. MS-only fragility curves used Maximum Likelihood Estimation (MLE) on MSA results. AS fragilities were conditioned on MS-induced damage states (e.g., DS1), with cloud analysis applied using log-space regression to determine medians and dispersions.

The study also investigated the impact of number of records per stripe on spectral matching and uncertainty in fragility parameters. A Bayesian updating approach, using MCMC and Metropolis-Hastings algorithms, was developed to minimize the number of required analysis stripes. Stripes were selected iteratively based on their influence on fragility (via the Kolmogorov–Smirnov statistic), applied to the water pump case study.

8.3 Findings

- For the service water pump, post-MS fragility curves showed reduced capacity compared to MS-only fragilities. The capacity loss was influenced by the defined thresholds for DS1 and DS2:

higher ductility thresholds reduced the median capacity loss (This analysis was conducted without considering any repair of the SSCs following the mainshock).

- For the DGB, using low-intensity MS-AS sequences, structural response remained mostly linear, and the system returned to its undamaged state. However, floor accelerations were higher for MS-AS than MS alone, which can be critical for non-structural equipment performance.
- When higher intensity GMs were used, the DGB experienced non-negligible effects from AS, though the annual collapse probability remained low.
- Ground motions per stripe: At least 7 records per stripe are needed for acceptable spectral matching. To obtain stable fragility estimates, 11–16 records are recommended. These results only apply to SDOF considered. For real-world structures a much larger sample size is generally required. Current practice consists in performing 30 time history analyses for the chosen intensity level. In addition, the SDOF results have been obtained by neglecting site response. METIS studies required 100 analyses to propagate soil uncertainty.
- The Bayesian updating method proved effective in reducing the number of analyses while maintaining accuracy. It enabled rapid convergence to target fragility curves and identified influential stripes efficiently.

8.4 Concluding Remarks

- The developed MS-AS fragility methodology is statistically sound but can be computationally expensive. Preliminary simplified analyses are recommended to assess the necessity of full-scale MS-AS evaluations.
- For MS-only fragility assessments for SDOF and neglecting site response:
    - Use >7 records per stripe to match the conditional spectrum.
    - Use 11–16 records per stripe for reliable median and dispersion estimates.
- Adopt the Bayesian updating procedure to reduce computational demand and improve analysis efficiency.
- Future improvements may focus on:
    - Refining damage metrics and thresholds for intermediate states.
    - Including more detailed damage states and varying records per stripe.
    - Adjusting Bayesian stopping criteria, particularly prioritizing lower IM levels due to higher hazard rates.
- The current findings on aftershocks' limited risk impact should be revisited with broader case studies and modeling strategies.

9 Fragility computations for METIS case study

(Based on Deliverable D6.8)

9.1 Description and Aim

Deliverable D6.8, part of WP6 of the METIS project, aims to develop fragility curves for a set of representative Structures, Systems, and Components (SSCs) from a nuclear power plant (NPP), using nonlinear time-history analysis. The goal is to quantify the probability of seismic failure of SSCs as a function of ground motion intensity, supporting seismic probabilistic safety assessment (SPSA) and enhancing decision-making under uncertainty.

The case study is based on the Zaporizhzhia NPP, with additional component data from other European NPPs due to confidentiality constraints. The site location for seismic input was assumed in Tuscany, Italy, to make use of the regionally specific seismic hazard and ground motion data from METIS WP5.

9.2 Methodology

- **SSCs Selected**:
  - Reactor Building (RB)
  - Diesel Generator Building (DGB)
  - Filter Containment Venting System (FCVs)
  - Transformer (6kV–380V)
  - Control Monitor Cabinet (CMC)
  - Service Water Pump (SWP)
- **Modeling Approach**:
  - Used OpenSees for all structural and component models.
  - Applied nonlinear finite element modeling for RB and DGB with shell and fiber elements.
  - Simplified dynamic models were used for components, focusing on modal response and anchorage conditions.
- **Ground Motions**:
  - To reduce computational cost, 250 ground motions from METIS WP5 were used from the BEU (Best Estimate with Uncertainty) site response scenario.
  - PGA was the chosen Intensity Measure (IM) for all SSCs.
- **Fragility Method**:
  - Used the Cloud Regression Method to relate the probability of failure to the IM.
  - Included uncertainty quantification via Latin Hypercube Sampling (LHS) for parameters like material properties, damping, and SSI.
  - Failure thresholds were defined using Engineering Demand Parameters (EDPs) such as drift, strain, or displacement depending on SSC type.

9.3 Findings

Structures:

- Reactor Building (RB) showed the highest seismic capacity (Median PGA: 2.23 g, HCLPF: 0.79 g).
- Diesel Generator Building (DGB) had a slightly lower capacity (Median PGA: 1.68 g, HCLPF: 0.69 g).
- Both exhibited low to moderate dispersion ($\beta c \approx 0.4$–0.45).

Components:

- Control Monitor Cabinet (CMC) and transformers also showed higher fragility, especially when installed in buildings with high-frequency vibration.
- Filter Containment Venting System (FCVs) showed high variability ($\beta c = 0.80$) due to uncertainty in support conditions and strain limits.

Influence of SSI and Floor Response:

- Dynamic interaction between building response and component location (e.g., RB vs DGB) significantly affected fragility.
- Multi-support excitation and component anchorage details were critical to performance.

9.4 Concluding Remarks

- Improve Data on Support and Anchorage Conditions: High variability in component fragility (e.g., FCVs) arises from uncertain support conditions. More accurate anchorage data can significantly reduce uncertainty.
- Use Cloud Method for Future Fragility Work: The cloud approach, combined with nonlinear modeling and uncertainty propagation, provides a more realistic picture of seismic behavior than simplified traditional methods.
- Consider Multi-Support and Nonlinear Effects in All relevant SSC Evaluations: This is especially important for components mounted across flexible structures or systems with complex support interactions.

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