Seismic Fragility Analysis Based On Vector-Valued Intensity Measures; Theory And Application To Fuel Assembly Grids

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ABSTRACT

Standard practice in seismic fragility analysis is to rely on a single (scalar) intensity measure (IM), typically horizontal peak ground acceleration (PGA). The present paper discusses the benefits of using alternative IM as well as fragility functions based on more than one IM, i.e. vector-valued IM.

A case study dealing with the seismic fragility of fuel assembly spacer grids is presented. The efficiency of various IM is compared. Uncertainties associated with scalar-IM fragility curves and vector-IM fragility functions are also compared and discussed.

The question whether vector-valued fragility functions lead to a reduction of uncertainty depends on the IM. In the present case study, a fragility surface based on PGA and PGA/PGV is associated with less uncertainties compared to the fragility curve based on PGA only.

1 INTRODUCTION

1.1 Context

Seismic Probabilistic Safety Analysis (PSA) and Seismic Margin Assessment have a long tradition in the nuclear industry, in order to quantify the seismic risk / margin of Nuclear Power Plants. This aspect of nuclear safety has received particular attention after the Fukushima accident, in the context of the so-called stress-tests [1].

As a crucial step of Seismic PSA and Seismic Margin Assessment, the vulnerability of the structures, systems and components (SSC) must be quantified with respect to a wide range of ground motion intensity. To this end, fragility curves, which express the probability of an SSC to reach or exceed a predefined damage state as a function of an intensity measure representing the hazard loading, are a well-established concept in the nuclear industry [2].

1.2 Seismic intensity measures

In the nuclear industry the standard practice is to **define** the seismic fragility curves in terms of a **single** (scalar) intensity measure (IM), typically the horizontal peak ground acceleration (PGA)[1]. In addition, the shape of the ground response spectra is taken into account by the so-called spectral shape factor. The bottom line is that – for a given SSC - the fragility curves make **explicit** use of two IM: namely the PGA and the spectral acceleration at the fundamental frequency of the respective building.

Numerous IM besides the two mentioned IM have been proposed. An important aspect of any IM is its correlation with the damage observed in real earthquakes. A more elaborated, alternative approach to fragility analysis is then to define – to begin with - the fragility in terms of more than one IM. In other words, the fragility is defined as a function of a vector-valued IM.

1.3 Seismic performance of fuel assemblies

Fuel assemblies (FA) in light water reactors are highly optimized towards efficient performance in normal reactor conditions. At the same time, FA are subject of stringent safety considerations regarding the capability to shut down the reactor under extreme loads. In particular, reactivity control by insertion of control rods needs to be ensured for extreme seismic events with low probability of occurrence during the lifetime of the plant.

FA row models are widely used for this purpose, i.e. to demonstrate adequate performance, as requested in the context of seismic design or beyond-design safety evaluations. The FA may experience impacts with neighbouring FA or with the core barrel. The seismic robustness of the FA depends on spacer grid buckling. Resulting permanent spacer grid deformations at control assembly positions could slow down or hinder the control rod insertion. Therefore, permanent spacer grid deformations should not exceed specific design limits or should be excluded by limiting impact forces to remain below the buckling strength.

Earlier studies on the seismic robustness of FA are [5], [6].

1.4 Structure of the paper

The present paper is strongly based on [3]. Sections 2 and 3 present the relevant concepts and formulations, while sections 4 and 5 present the application to FA spacer grids.

2 FRAGILITY ESTIMATION

2.1 Fragility curve

Fragility functions express the probability of reaching or exceeding a damage state (DS) given the level of seismic loading, represented by an intensity measure IM = im. Thus, they are written in the form of conditional probabilities. The damage state is defined by the engineering demand parameter (EDP) exceeding a given threshold: the EDP represent the physical demand that is subjected to the SSC, until its capacity is reached.

Depending on the type of SSC and the type of damage mechanism investigated, EDPs may be represented by a wide range of physical variables, such as the maximum deformation during the loading, the stress level reached by a structural element, or the ductility ratio.

See references [2], [8] for an introduction to fragility analysis.

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[1] See section 1 in Appendix A of [2].

Due to the statistical distribution of IMs and EDPs in practical applications, fragility curves are usually assumed in terms of the cumulative distribution function of the lognormal distribution, as follows:

$$P_f(im) = \mathrm{P}(ds \geq DS | IM = im) = \Phi\left(\frac{\ln im - \ln \alpha}{\beta}\right) \tag{1}$$

where P_f is the probability of failure, α represents the median and β the standard deviation, i.e. the fragility parameters. By definition, the parameter α is the value of im for which P_f is 50% and can thus be viewed as the median capacity (in terms of im).

2.2 Safety factor method

The standard approach for estimating the fragility parameters in Eq. (1) adopted in the nuclear industry is based on estimating the safety factor of individual SSC, with respect to a reference earthquake (RE).

$$PGA_{SSC} = F_{SSC} \cdot PGA_{RE} \tag{2}$$

The subscript "SSC" emphasizes that the safety factor is different for each individual SSC. The same applies to the fragility parameters and curves.

Typically, the RE is the safe shutdown earthquake (SSE) considered in the design. In some cases, the RE consists of a stronger earthquake, for which a seismic re-evaluation is performed, e.g. as a follow-up action of the Post-Fukushima stress tests (recall section 1.1).

This approach is pragmatic, in that it makes use of the design calculations, test reports and other pertinent documents prepared for the seismically classified SSC as part of the licensing. It is noted that a key assumption of the safety factor method is that seismic responses scale linearly with the PGA.

The safety factor method is not in the focus of this paper. Refer e.g. to [2].

2.3 Regression-based methods

For specific types of critical SSCs, alternative approaches to the safety factor method can be of interest. For instance, there are cases in which the definition of the DS takes credit of non-linear behavior of the SSC. The assumption of linear scalability in the safety factor method might be subject of scrutiny in this case.

One approach consists in performing non-linear time-history analyses with a suitable numerical model, for a set of ground motions with **varying IM**. This leads to a cloud of data points representing the IM on one hand and the corresponding EDP / DS indicators on the other. Regression can be used to estimate the fragility parameters, based on the data cloud. In the fragility context, two main types of statistical regression can be identified. In both cases, the log-normal model for the fragility function in Eq. (1) is assumed.

See references [7], [8] for a more detailed and instructive introduction, including other case studies than the one presented in this paper, such as a simplified model of the reactor coolant system.

The first type is the least-squares **regression on the IM-EDP** dataset. It is based on the lognormal assumption, where the following functional form is regressed from the data points:

$$\ln edp = a + b \ln im + \varepsilon \tag{3}$$

The error term ε is assumed to follow a normal distribution, of mean zero and standard deviation σ.

The second type is based on postprocessing the dataset so as to obtain – from the set of EDP - a set of binary damage variables Y: all points that exceed the damage state threshold take the value $y_i = 1$, and 0 otherwise. The variables Y follow the binomial distribution.

The dataset (im_i, y_i) can be fitted to the fragility function in Eq. (1) using **maximum likelihood estimation**. Given N data points, the likelihood function of the fragility parameters α and β, has the following form (Y is a binomial random variable):

$$L(\alpha,\beta) = \prod_{i=1}^{N} \left[P_f(im_i, \alpha, \beta)\right]^{y_i} \left[1 - P_f(im_i, \alpha, \beta)\right]^{1-y_i} \tag{4}$$

A maximization of L through a search algorithm leads to the best estimates of the fragility parameters α and β.

2.4 Vector-valued fragility function

The derivation of a vector-valued fragility function is described in [4]. A hybrid IM is formulated in terms of two IM (im_1 and im_2) as follows (α_1 and α_2 are regression coefficients):

$$\ln X = \frac{\alpha_1}{\alpha_1 + \alpha_2} \ln im_1 + \frac{\alpha_2}{\alpha_1 + \alpha_2} \ln im_2 \tag{5}$$

Assuming that the univariate fragility function in terms of X is compatible with the log-normal model in Equation (1), leads to the following **vector-valued fragility function**. The coefficients β_i can be estimated by maximum likelihood estimation, as in 2.3.

$$\mathrm{P}(ds \geq DS | im_1, im_2) = \frac{1}{2}[1 + \mathrm{erf}(\beta_1 \ln im_1 + \beta_2 \ln im_2 - \beta_0)] \tag{6}$$

3 ASSESSMENT OF IM

3.1 IM considered in this study

The following IM are considered in the case study presented in this paper.

Table 1: IM considered in the present case study

PGA	peak ground acceleration
PGV	peak ground velocity
PGD	peak ground displacement
I_A	Arias intensity
CAV	cumulative absolute velocity
SA_1	spectral acceleration at 1.3 Hz (close to the first frequency of the FA)
$SA_{1,avg}$	average of the spectral acceleration between 1.3 and 2.4 Hz
SVr_1	spectral relative velocity at 1.3 Hz
$SVr_{1,avg}$	average of the spectral relative velocity between 1.3 and 2.4 Hz
A_V	ratio PGA/PGV
SA_3	spectral acceleration at 4.9 Hz (close to the third frequency of the FA)
$SA_{B1,avg}$	average of the spectral acceleration between 3 and 4 Hz (first building frequency)
$T_{SM,F}$	duration of the strong motion (French definition, T_{95}-T_5)
$T_{SM,US}$	duration of the strong motion (US definition, T_{75}-T_5)

3.2 Efficiency and sufficiency of IM

The **efficiency** of an IM represents the ability of an IM to induce a low dispersion in the distribution of the structural response (i.e., fragility curve with a steep “slope”). The efficiency is measured by evaluating the standard deviation σ of the error term ε in the log-linear relation between IM and EDP, see Eq. (3): the lower the standard deviation, the more efficient the IM.

The **sufficiency** of an IM represents the ability of an IM to “carry” the characteristics of the earthquake that has generated the ground motion: a sufficient IM should render the distribution of EDP conditionally independent, given the IM, from the magnitude and the distance of the related earthquake events.

It is noted that the efficiency and sufficiency of IM are specific to the SSC considered (i.e., strong link with the vibration mode of the component) and to the studied site (i.e., location and characteristics of the seismic sources generating the ground-motion time histories).

The present paper deals with the efficiency of IM, while sufficiency is not in the scope.

3.3 IM efficiency analysis by ROC (Receiver-Operating characteristic)

ROC-curves are a tool for assessing the quality of classifier algorithms, when the classification is performed in terms of probability. Refer to [9] for a thorough explanation.

In the context of fragility analysis, the classes are “damage” and “no damage” and the probability is characterized by the fragility curve.

The ROC analysis is based on splitting the dataset into a training and test set. The training set is used to identify the fragility curve (section 2.3). The test set provides – for each element of the set - pairs of the type (I_F; P_F) where I_F is the Boolean expression of failure (true: failure; false: no failure) and P_F is the probability of failure, based on the identified fragility curve.

The basic idea is that P_F (and hence the fragility curve) is used to classify the test samples into “failure” or “no failure”. This requires the definition of a threshold level $P_{F,thresh}$.

A low value of $P_{F,thresh}$ is equivalent to a conservative (pessimistic) classification: a sample will be classified as a failure, even if P_F is low. The classification will correctly classify most of the true failures (high rate of “true positive” → high sensitivity). The downside is related to the “no failures”: most of them will be incorrectly classified as “failures (high rate of “false positives” → low specificity).

For high values of $P_{F,thresh}$, the above statements are reversed, the result is an optimistic classification.

For a given test set and classifier (i.e. one specific value of $P_{F,thresh}$), the quality of the classification is compactly visualized as a point in the ROC space by plotting the rate of true positive (sensitivity, ordinate) vs. the rate of false positive (1-specificity, abscissa). A classifier is good if it is in the northwest of the ROC space.

For a given test set, the ROC-curves are then the collection of points obtained by varying $P_{F,thresh}$: the trajectory of the curve goes from the North-East corner ($P_{F,thresh} = 0$) to the South-West corner ($P_{F,thresh} = 1$).

4 APPLICATION

4.1 Seismic analysis of fuel assembly

The virtual reactor as defined in NARSIS project contains 241 closely spaced FA, which are slender structures supported at both ends. FA geometry and core pattern are illustrated in the following Figure 1. Colored positions are positions equipped with rod cluster control assemblies, i.e. the so-called control rod positions.

During an earthquake, FA are likely to impact to each other or to the core baffles at the grid level. Impact loads should not lead to an excessive inelastic grid deformation, which would prevent regular insertion of the control rods in case of a reactor trip.

In order to estimate the impact loads, 2D models of rows of FA are built, see [6]. The FA are modelled by linear beams coupled at the top and at the bottom to the motions of the grid plate and the lower core plate, respectively.

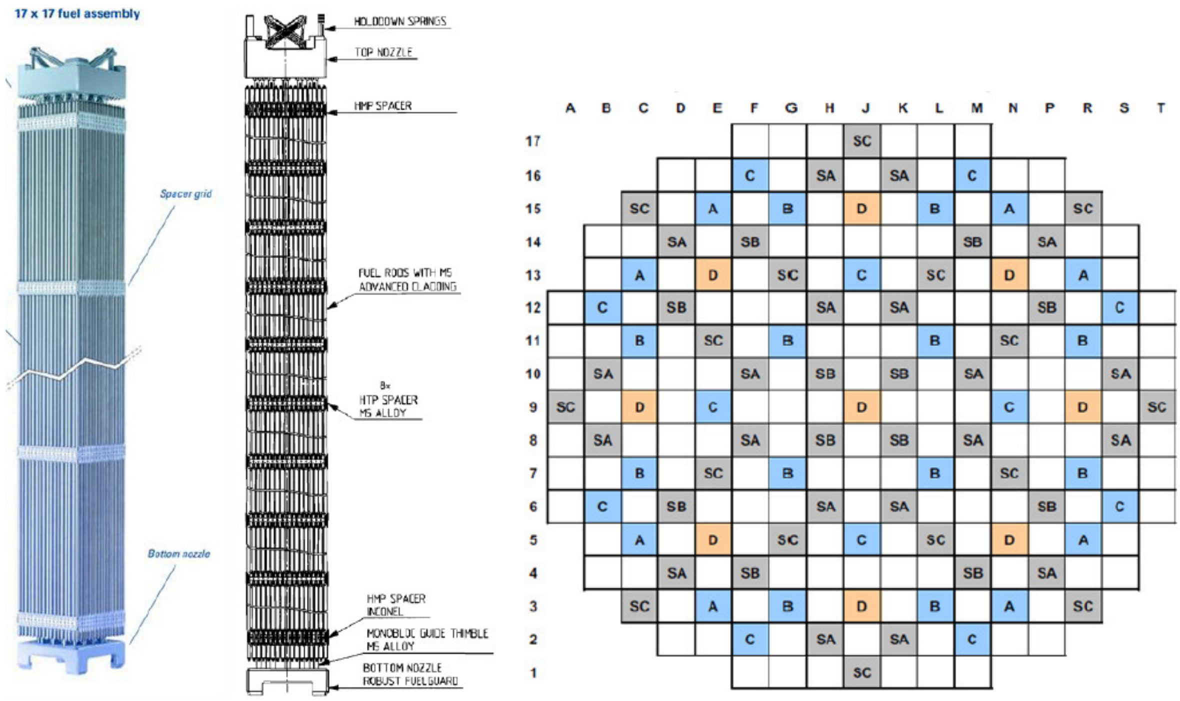

Figure 1: 17x17 fuel assembly and core pattern

FA are rather flexible structures. Their first eigenfrequency is lower than 3 Hz. Interaction of adjacent FA is modelled by nonlinear elastoplastic impact couplings between the spacer grid impact nodes attached to the beams.

Failure is defined to occur when the residual deformations induced by the seismic ground motion exceed the acceptable grid deformations with regard to control rod insertion.

4.2 Seismic loading

The dataset is based on 6 bins of 30 ground motion time histories, each bin corresponding to a different annual probability of exceedance at the reference site. The mean horizontal PGA range from ≈0.1 g (bin 1) to ≈1.5 g (bin 6). The time histories are applied to a building model of the reference plant. The building time histories at the core level are applied directly (without considering the dynamic behavior of the RPV internals) to the 2D model of the FA rows.

5 RESULTS

5.1 Univariate fragility curves

In a first step, univariate fragility curves are built for several IM. The parameters of the classical lognormal fragility model are identified using maximum likelihood estimation, on the basis of 90 time histories randomly chosen within the initial set of 180 time histories. Then, in order to identify which IM performs best for this test case, a Receiver Operating Characteristics (ROC) analysis is performed on the basis of another set of 90 time histories.

The operation is repeated several times with different sets of 90 time histories in order to check the robustness of the results. This step permits to identify, without a-priori assumptions, the best performing IM for this given test case.

The following figure shows the results obtained for the most efficient IM. According to the ROC curves (b), the most efficient IM are $SA_{1,avg}$ and $SVr_{1,avg}$. This is also indicated by the fact that the corresponding fragility curves (a) are steeper than the ones based on other IM; a steeper fragility curve implies less uncertainty about the capacity, i.e. the level of the IM at which failure occurs.

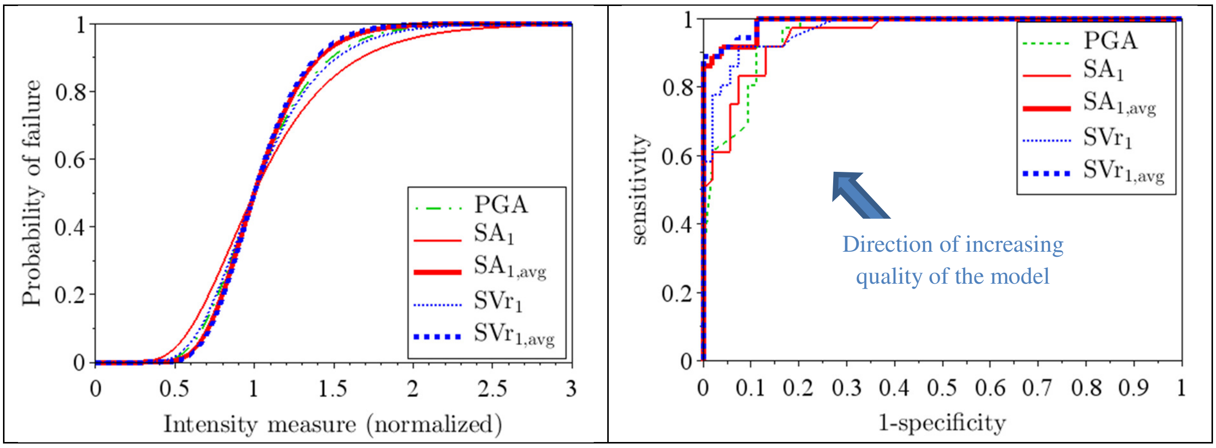

Figure 2: Univariate fragility curves (normalized, left); ROC analysis (right)

5.2 Vector-valued fragility surfaces

In a second step, it is studied whether uncertainties can be reduced by building a bivariate fragility surface based on two uncorrelated (or little correlated) IM. No pair of IM including $SA_{1,avg}$ or $SVr_{1,avg}$ has led to a reduction of uncertainty in comparison with $SA_{1,avg}$ or $SVr_{1,avg}$ alone.

However, it was found that it is possible to reduce uncertainties regarding the capacity in terms of PGA alone by building a vector valued fragility surface which combines PGA and the ratio PGA/PGV (peak ground velocity). These two parameters are little correlated, and PGA/PGV is a good indicator of spectral shape.

The following Figure 3 shows the effect of the second IM, PGA/PGV, by plotting fragility curves keeping the second IM constant and comparing with the univariate fragility curve based on PGA.

6 CONCLUSIONS

The ROC analysis of the IM considered in the present study indicates that the most efficient IM for the fragility of fuel assembly spacer grids are the average spectral acceleration ($SA_{1,avg}$) and the average spectral relative velocity ($SVr_{1,avg}$), where the average is taken over a 1-Hz-interval starting at the fundamental frequency of the fuel assemblies.

The use of a vector-valued fragility function with either of these highly efficient IM could not be shown to lead to a reduction of uncertainty, compared to the respective univariate fragility curves. However, a fragility surface based on PGA and PGA/PGV tends to reduce uncertainties in comparison to the fragility curve representing ground motion only by PGA.

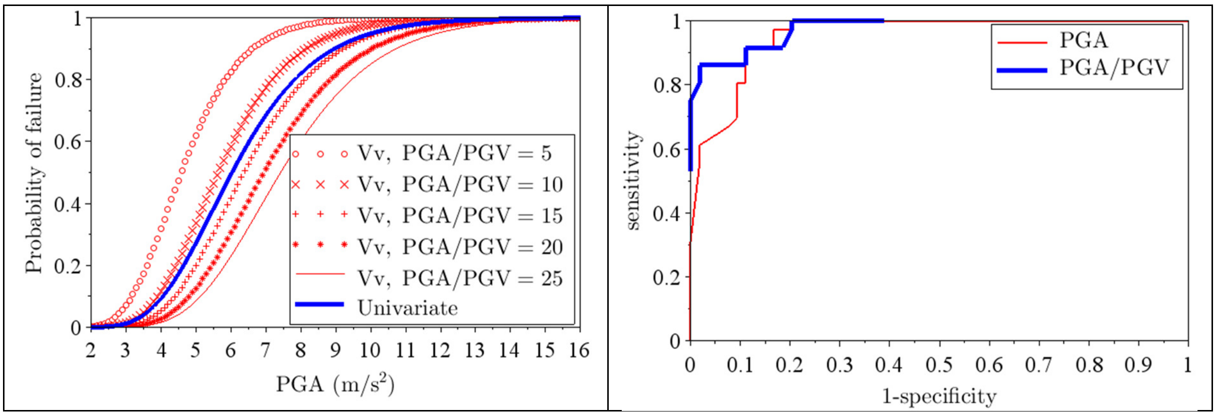

Figure 3: Univariate fragility curve vs. slices of fragility surface of vector-valued (Vv) fragility (left); ROC analysis (right)

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REFERENCES

[1] ENSREG, Peer review report – Stress tests performed on European nuclear power plants, 2012.

[2] Seismic Fragility Applications Guide Update. EPRI, Palo Alto, CA: 2009. Product ID Number 1019200.

[3] New Approach to Reactor Safety ImprovementS (NARSIS). Del2.6 – Methodology to derive vector-based fragility functions I: theoretical aspects. Euratom research and training programme 2014-2018, Grant Agreement No. 755439.

[4] P. Gehl, D. M. Seyedi, J. Douglas, "Vector-valued fragility functions for seismic risk evaluation", Bull. Earthquake Eng., DOI 10.1007/s10518-012-9402-7, 2012.

[5] M. Pellissetti, H. Kessler, J. Schmidl, A. Nykyforchyn, S. Staeuble-Akcay, "Seismic performance of fuel assemblies and impact force correlations with intensity-compatible sets of recorded ground motion time histories", Nucl. Eng. & Design, 375, 111052, 2021.

[6] D. Altieri, M.C. Robin-Boudaoud, H. Kessler, M. Pellissetti, E. Patelli, "Machine Learning Approaches for Performance Assessment of Nuclear Fuel Assemblies Subject to Seismic-Induced Impacts", ASCE-ASME J. Risk & Uncertainty in Eng. Systems, Part B: Mech. Engineering, Vol.6, 041002, 2020.

[7] I. Zentner, "Numerical computation of fragility curves for NPP equipment", Nucl. Eng. & Design, 240:1614-1621, 2010.

[8] I. Zentner, M. Gündel, N. Bonfils, "Fragility analysis methods: Review of existing approaches and application", Nucl. Eng. & Design, 323:245-258, 2017.

[9] T. Fawcett, "An introduction to ROC analysis", Pattern Recognit. Lett. 27:861–874, 2006.

ACRONYMS

DS → Damage state, EDP → Engineering demand parameter, FA → Fuel assembly, IM → Intensity measure, PGA → Table 1, PGV → Table 1, RE → Reference earthquake, ROC → Receiver operating characteristic, SA → Table 1, SSC → Systems, structures & components, SSE → Safe shutdown earthquake, SV → Table 1