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Overview of a global methodology to assess the seismic fragility curves of structures, systems, and components in nuclear power plants

David Bouhjiti[1], Marine Marcilhac Fradin[2], Nadia Rahni[2], Benjamin Richard[1]

[1] IRSN/PSN-EXP/SES/LMAPS, B.P. 17 - 92262 Fontenay-aux-Roses Cedex, France (david.bouhjiti@irsn.fr)
[2] IRSN/PSN-EXP/SCEPS/BEPAM, B.P. 17 - 92262 Fontenay-aux-Roses Cedex, France

ABSTRACT

The primary aim of this paper is to present a global methodology to assess the seismic fragility curves of Structures Systems and Components (SSC) based on uncertainties propagation through a representative and physical finite elements model. The fragility curves are computed based on the principle of metamodeling of the structural responses as a function of the considered intensity measures (PGA, CAV, etc.). On the one hand, such fitting results into the definition of an explicit function making dependent the Engineering Demand Parameters (EDP) of interest on the intensity measure considered. And, on the other hand, the fitting is achieved according to a certain precision leading to the definition of an error function that should be ideally following a centered normal distribution. As an example of application, the methodology is applied to the case of the SMART2013 mock-up (3-story reinforced concrete structure at the scale 1/4). It is shown that thanks to few hundred calculations, one can obtain a representative fragility curve which is a considerable advantage compared to crude (with no optimization) Monte Carlo based approaches.

INTRODUCTION

Probability safety assessment (PSA) achieved by the French Technical Safety Organization (TSO) covers mainly pressurized water reactors (PWR) and aims at estimating the risk level of core meltdown associated with this type of reactor for the surrounding population and the environment. During this process, all plausible accidental configurations are analyzed extensively to quantify their probabilities of occurrence and the associated consequences within the facility (in this case core meltdown is assumed) and outside (radioactive waste spreading). Three PSA levels are foreseen: Level 1 focusing on the consequences of reactor core meltdown, Level 2 focusing on the consequences of radioactive waste disposal outside the defense barriers and Level 3 dealing with the consequences on the neighboring population and on the environment.

During PSA studies, several aspects are tackled: identification of sources of hazards and uncertainties, characterization of plausible accidental scenarios, identifying the Structures Systems and Components (SSC) ensuring the core reactor safety, establishing comprehensive failure event trees, quantifying the probabilities of failure of each SSC using adapted physical-based approaches, accounting for human actions and possible errors, quantification of radioactive waste emissions in the environment, etc.

In this work, the interest is geared towards the Level 1 PSA, more precisely the consequences of seismic hazard on the integrity of SSCs accounting for inherent uncertainties of the soil and the structure and their interaction under seismic loading. Accordingly, the aim of this paper is to present a global methodology to assess the seismic fragility curves of SSCs based on uncertainties propagation through a representative finite elements model. The retained strategy consists of five main steps:

- Step 1: defining simplified assumptions yet representative and sufficiently conservative allowing the realizations of an important number of calculations (several hundreds). With that regard, the equivalent linear based methods are of interest (impedance-based modelling of soil-structure-interaction, stiffness modulus reduction for cracked elements, definition of an equivalent reduced and structural damping ratio, etc.).

- Step 2: identification and quantification of uncertain parameters affecting the seismic load, the behaviour of, of reinforced concrete, of soil-structure-interaction and of equipment.

- Step 3: identification of the most critical failure modes and estimation of the seismic margins for structural elements and anchorages and equipment (accounting for the ductile behaviour when possible).

- Step 4: after running the minimum number of calculations (few hundreds), a scatter graph is obtained relating the seismic margins to the applied seismic load represented by its PGA. To simplify data analysis, such scatter is fitted into an explicit formula using a Box-Cox transformation (given a certain confidence level of fitting).

- Step 5: given a certain threshold of seismic margin, the fragility curve can then be computed assuming a normal distribution of the fitting error (box-cox transformation vs. scatter).

In this paper, after presenting shortly the SMART2013 experimental campaign, each one of the five previous steps is detailed and illustrated through the SMART2013 case study.

SMART2013 EXPERIMENTAL CAMPAIGN

The SMART2013 experimental campaign is based on a ¼ scaled mock-up of a building that is attached to the reactor building with a strong sensitivity to the torsional behaviour under seismic loads. This mock-up is bolted to the shaking table through 34 thread stalks at the foundation level (Figure 1 - left). The mock-up consists of walls (with a thickness of 10 cm); slabs (with a thickness of 10 cm); beams (with a section of15 cm x 32 cm); shallow foundation (with a section of 25 cm x 65 cm) and column (with a section of 20 cm x 20 cm) to assure the stability during the tests. Masses are added to each floor (around 11 tons) to meet the scaling effects criteria.

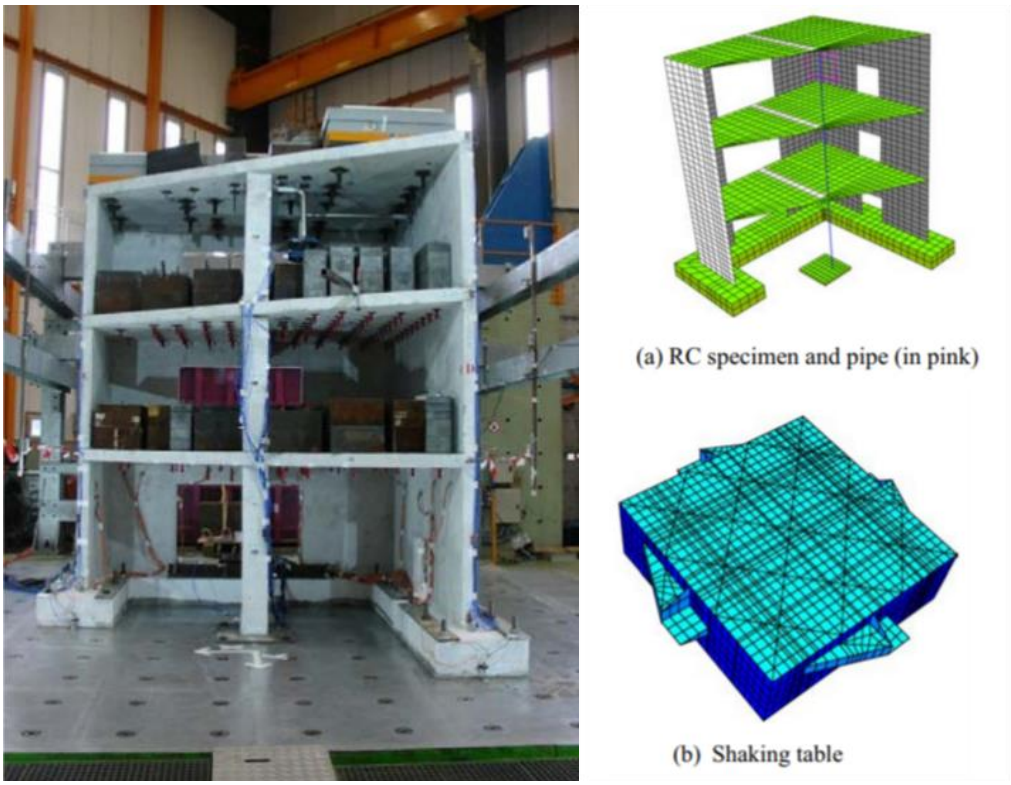

Figure 1: SMART mock-up: (left) Experimental set up and(right) FE mesh of the mock-up and of the shaking table (from Richard B. M., 2015)

As for the seismic loads, three seismic sequences are considered: the design level (0.2g), Northridge main-shock (1.78g) and Northridge after-shock (0.37g). These loads are applied in an increasing way through several runs (Table 1). The seismic tests were realized through the shaking table AZALEE installed at CEA. The shaking table is a 6x6m aluminium plate with a maximum capacity load of 100 tons. It is equipped with eight hydraulic actuators, 4 horizontal actuators at the sides and 4 vertical actuators at the bottom of the table. Each actuator can provide at maximum of 1 MN.

Table 1: Peak ground acceleration measured at the center of the shaking table level

# run	PGAx (g)	PGAy (g)	Description
7	0.13	0.13	Design level
9	0.21	0.24	
11	0.21	0.15	Northridge main shock
15	0.38	0.22	
17	0.56	0.39	
19	1.08	0.9	

During each run, the mock-up is monitored to measure the eigenfrequencies and modal deformations, displacements, the accelerations, crack openings, strains within concrete, uplift at the foundation level.

ADAPTED MODELING STRATEGY

The numerical simulation is done using the Cast3m software (version 2022). The structural elements such as walls; floors and beams are modelled using multi-layered shell elements (5 layers for concrete). The foundation is modelled by the solid elements (Figure 1 – right). The rebars are modelled using 4 additional layers (1 layer for each reinforcement direction). The mesh density is globally set at about 20 cm. The shaking table is also modelled by shell elements and is calibrated to obtain the relevant eigenfrequencies of the shaking table.

The damping of the structure is modelled through the Rayleigh model (Figure 2) where the damping matrix is a linear combination of the mass and stiffens matrix. Such model is well defined using two frequencies defining the range of interest (here we consider the first f1 and third f3 main eigenfrequencies) and a target damping value for each frequency. Based on experimental measurements, the damping ratios for these two frequencies are of 2.2% and 5.5% respectively (case of elastic behaviour – no damage). As for the connection between the mock-up and the shaking table, the model does not include any bolts and the nodes of the foundation and of the shaking table are fully merged (perfect kinematic bond). The interaction between the table and the mock-up is modelled by modifying the Young's modulus value of the massive foundations in the model.

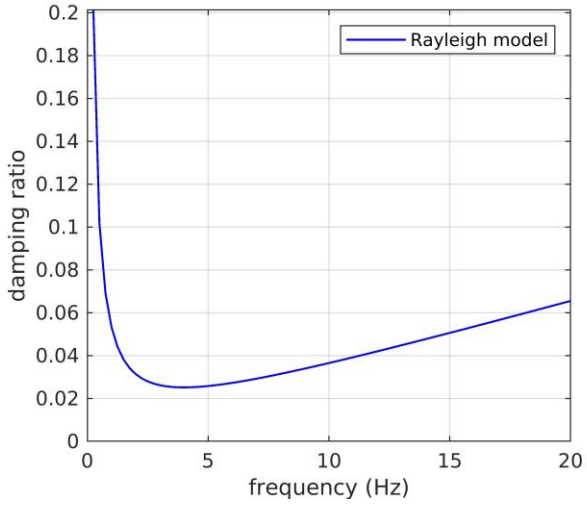

Figure 2: Damping based on Rayleigh model

The calibration of the Rayleigh model is not obvious since both the frequencies and the damping values evolve with the damage state. The boundary conditions (stiffness of the shaking table – mock-up interaction) are not easy to define precisely neither in the model.

The modal analysis of the mock-up takes about 2 minutes whereas a full transient analysis requires about 6 minutes when elastic behaviour is considered and around 3 days when nonlinear behaviour is considered. To keep the numerical cost reasonable, we consider in this work, an equivalent linear based analysis allowing us to have a linear and elastic solving framework but also account for nonlinearities by reducing the Young's modulus of cracked elements and by increasing the general damping ratios as the damage increases with the applied seismic loads.

IDENTIFICATION AND QUANTIFICATION OF UNCERTAINTIES

In this part, we distinguish two types of uncertainties.

The first type is of an aleatoric nature that can be quantified thanks to sufficient experimental tests mainly at the specimen scale. If we consider the case of the Young's modulus, tests at the specimen scale show a mean value of 27 GPa and a coefficient of variation around 10%. When we move to the structural scale, values of the Young's modulus vary from one wall and one slab to the other (different concrete batches). Given the small number of specimen tests (few dozens), we assume in this work a lognormal distribution of this parameter. In addition to that, we can also consider, according to our expert's judgement, an aleatoric variation of the damping ratio for a given damaged state with a supposed variation of 50%. The values of damping ratios vary between 2% (for elastic run #7 in Table 1) and 30% (for nonlinear run #19 in Table 1). This random input is supposed hereafter to follow a uniform distribution.

The second type of uncertainties is of an epistemic nature that is due to our modelling limitations compared to the experimental or in situ complexity. A representative example would be the modelling of the mock-up's interaction with the shaking table: in the real structure, the mock-up is bolted down to the shaking table whereas in our model the bottom nodes of the foundation are merged with the ones of the shaking table (perfect bond). Naturally, the stiffness of the shaking table and the mock-up interaction is overestimated numerically. One way of reducing such effect would be to define smaller Young's modulus values for the first range of finite elements at the interface. These Young's modulus values can be calibrated to get the same eigenfrequencies as the ones measured experimentally. A second source of epistemic uncertainty would be the use of surrogate models to limit the computational cost. In this case, the uncertainty refers simply to the error function defining the gap between the finite elements model's response and the surrogate model itself.

FAILURE MODES OF INTEREST

In the following sections, the goal is to quantify the effect of such uncertainties on the risk of failure at a given seismic level described by the PGA. For the sake of illustration, we consider hereafter two outputs of interest. The first engineering demand parameter (EDP) to be considered is the spectral acceleration amplitude ($S_{a,N}$) at the top edge of the mock-up corresponding to the first peak at the 1st eigen frequency. The second EDP is the maximal nominal inter-storey drift (δ_n).

$$S_{a,N} = \sqrt{S_{a,X}^2 + S_{a,Y}^2} \qquad \delta_n = \sqrt{\delta_{X,max}^2 + \delta_{Y,max}^2}$$

The risk of failure refers to the probability of exceeding a certain drift threshold or a certain limit of the spectral acceleration.

UNCERTAINTIES PROPAGATION AND METAMODELLING

In this work, we achieve random inputs sampling using Latin Hypercube Sampling. The number of realizations is limited to 400 and concerns Young's modulus values and damping ratios. That means that for each seismic signal in Table 1, we achieve 400 calculations and each time we post process the spectral accelerations and the drifts at the top of the structure. Eventually, we obtain 400 values of these outputs per PGA. One can note that these calculations require about 40 hours in total.

To go further, one gets an empirical Cumulative Density Function of each quantity of interest and at each PGA level. If one selects a fractile of interest (usually at 5%, 50% and 95%), one will get a list of single values of either the spectral acceleration or the drift associated with the PGA levels.

For SMART2013 mock-up, we obtain scattered points as depicted in Figures 3 and 4. From this scatter, one can try to fit a curve to achieve interpolation and extrapolation beyond the computed PGAs if necessary. In the present case, a linear fit seems enough though its validity beyond the last run #19 is not straightforward. Ideally, the calculations should cover all the PGA range of interest so as not to extrapolate the fitted curves way beyond the computed domain.

So now one has a law f_{fit} relating the drift or the spectral acceleration (Engineering Demand Parameters EDP of interest) to the PGA given an error function f_{err} (gap between the computed points and their estimate using the fitted curve) for a given fractile α. Such function is supposed to follow a centred normal distribution with a standard deviation $\sigma_{\varepsilon,\alpha}$:

$$EDP_\alpha = f_{fit,\alpha}(PGA) + f_{err,\alpha}(0, \sigma_{\varepsilon,\alpha})$$

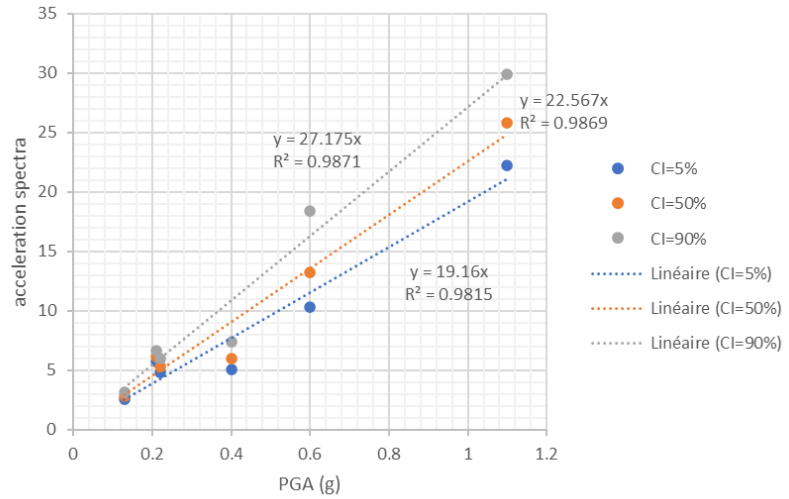

Figure 3: Linear fit of the spectral acceleration vs. PGA at 5%, 50% and 95% fractiles

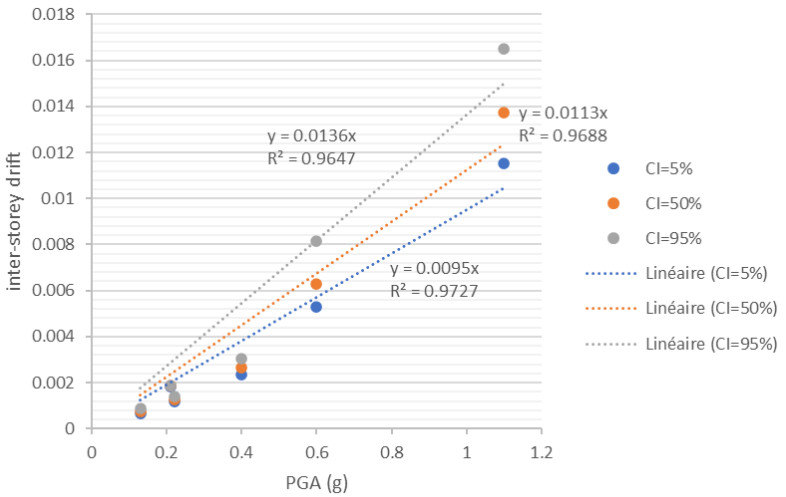

Figure 4: Linear fit of the drift vs. PGA at 5%, 50% and 95% fractiles

FRAGILITY QUANTIFICATION

Now that we have an analytical model relating the EDPs of interest (referring to the failure modes of interest), the fragility curve can be written analytically for each PGA value as following:

$$P_\alpha(EDP \geq EDP_{lim}|PGA) = P\left(f_{err,\alpha} \geq \left(EDP_{lim} - f_{fit,\alpha}(PGA)\right)|PGA\right)$$

The standard deviation of the error function $f_{err,\alpha}$ represents the uncertainties coming from the variation of the Young's modulus and damping ratio values. The higher this standard deviation is, the more sloped the fragility curve is. One can note that according to this formulation no prior hypothesis concerning the fragility curve is imposed (not necessarily lognormal) and that this includes an estimation of the fragility curves given a confidence level (epistemic part of uncertainties).

The application of this formulation to the case of SMART2013 and by considering thresholds at 15g for the spectral acceleration and limit drift values at 4‰ and 6‰ lead to the following fragility curves:

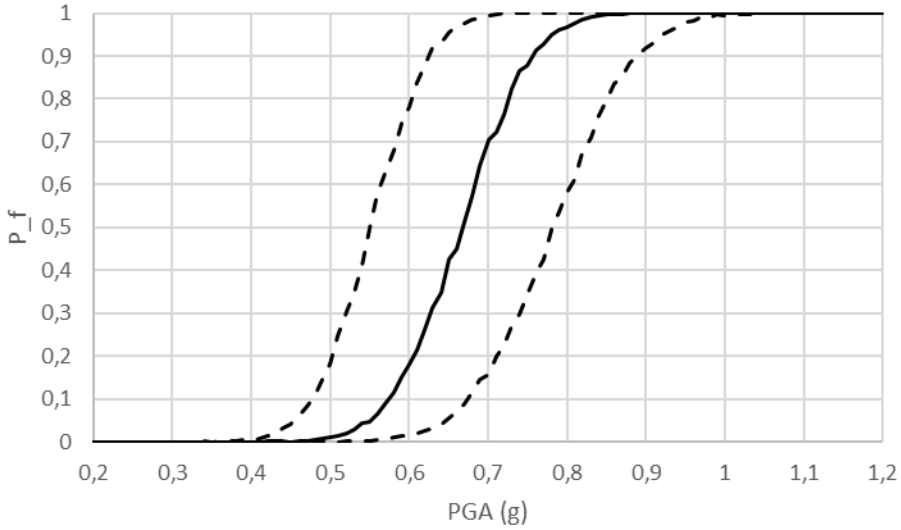

Figure 5: Fragility curve regarding the spectral acceleration criterion (5%-95% confidence interval in dotted lines)

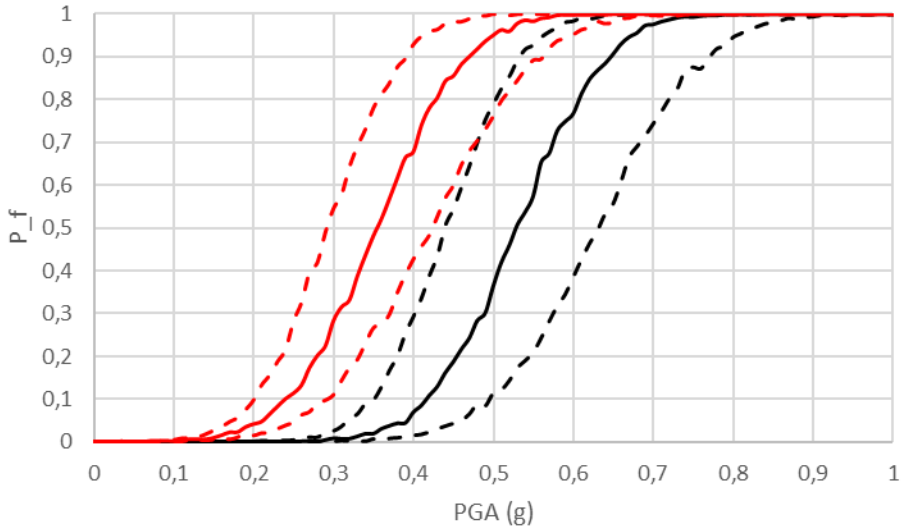

Figure 6: Fragility curve regarding the drift criterion (5%-95% confidence interval in dotted lines) – in red threshold at 4‰ – in black threshold at 6‰

CONCLUDING REMARKS

In this paper, a practical and cost wise efficient methodology is provided to quantify seismic fragility curves of SSCs. The approach is based on five steps: (1) definition of the finite elements model; (2) identification and quantification of inputs uncertainties; (3) identification of failure modes of interest; (4) uncertainty propagation and (5) fragility estimation. The originality here is due to the use of metamodeling to relate the EDPs of interest to the seismic intensity measure (PGA) along with the quantification of an approximation error associated with the surrogate model.

The case study (SMART2013 mock-up) shown here before is a particular case of application that can be generalized to all cases regardless of the used model, the considered random inputs and the failure modes of interest. However, one needs to bear in mind that:

- the use of the LHS method can also be applied to seismic loads if enough samples are available;
- the regression function relating EDPs to PGAs does not have to be linear as it depends on the scatter of points (a cox-box log-log fitting, the usage of Polynomial Chaos Expansion or kriging techniques can also be considered – see Ghanem, 1991);
- the error function can be characterized in an empirical way so as not to impose the normal distribution and limit the bias in the fragility curve calculation phase.

This methodology has been successfully implemented using an inhouse software named (GOFACS, 2021) developed by IRSN for the purpose of fragility curve quantification (Figure 7).

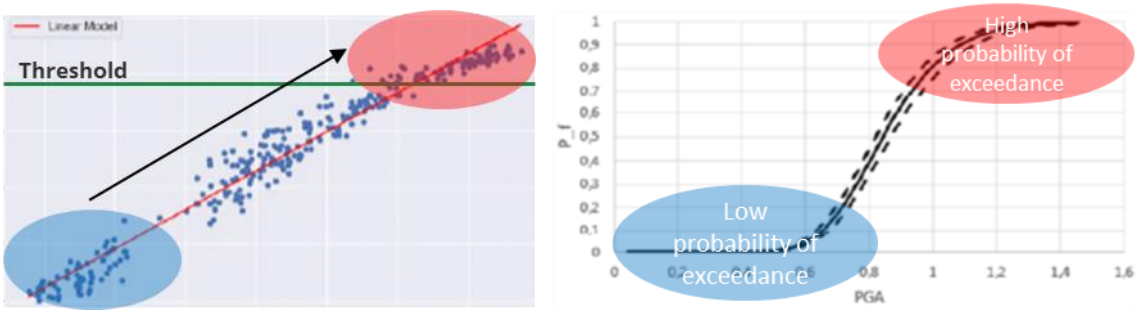

Figure 7: Illustration of fragility curves with GOFACS (from log-log cox-box fitting to fragility curve generation)

The industrial applications covered six different buildings as part of the nuclear island with a wide range of uncertainties (concrete, equipment, soil structure interaction, anchorages, etc.) and of failure modes (shear failure of walls and floors, sliding failure at wall-floor junctions, anchorage failure of equipment, functional failure of equipment, etc.). Equivalent linear based modelling approaches according to (ASN, 2006) guidelines were used to limit the computational time and the considered seismic return periods vary from 1000 up to 10 000 000 years with PGAs between 0.04g and 2.25g (this range of return periods is considered to cover extreme probabilities).

REFERENCES

ASN (2006). Guide 2/01. Accounting for the seismic risk during the design of civil engineering works of basic nuclear installations except those for the long-term storage of nuclear waste.

Marcilhac M., Rahni N., Raimond E., Moussi E., Macocco K., Blondet G. 2021. GOFACS: Generator of Fragility Assessment for Coupled Systems, Structures and Components. Proc. International Topical Meeting on Probabilistic Safety Assessment and Analysis. Pp: 1106-1113

Richard, B. M. (2015). Smart 2008: Shaking table tests on an asymmetrical reinforced concrete structure and seismic margins assessment. Engineering Structures, 48-61.

Cast3m. (2022). http://www-cast3m.cea.fr/

Ghanem R., Spanos P. Stochastic Finite Elements – A Spectral Approach, Springer Verlag, 1991.