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Seismic risk computation for the base-isolated reactor building of the IRIS NPP

M. Domaneschi, F. Perotti

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M. Domaneschi, F. Perotti - POLIMI

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SEISMIC RISK COMPUTATION FOR THE BASE-ISOLATED REACTOR BUILDING OF THE IRIS NPP

Autori

M. Domaneschi

F. Perotti

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1. Introduction

This report deals with the fragility assessment of the IRIS reactor building in its base-isolated version, following the previous configuration without any isolation system [1]. The aim of this step consists in the evaluation of the effectiveness of the base-isolation when applied to the IRIS NPP for the reduction of the seismic risk and in the comparison between the performance of the traditional and the isolated reactor building. Since the behavior of the isolators is markedly hysteretic, the hypothesis of linearity of the building response, typical of the traditional building, has been removed herein, and a suitable force-displacement literature model is adopted to represent the isolators inelastic response to horizontal loading.

The probabilistic assessment is based on the procedure described in [2], on a nonlinear analytical model, by performing sequential seismic analyses in the MATLAB framework [3], with the application of an explicit direct integration method. Previous studies [4] on an extensive finite element model of the isolated IRIS reactor building allow to introduce the rigid body condition for the structural equation of motion.

The most important requirement of the procedure remains to reduce as much as possible the uncertainties related to the incomplete knowledge and accuracy in defining models and methods; this reduction is here sought by refining analysis procedures and using consolidated analytical and numerical tools.

The characterization of the isolator devices has been preliminarily performed by testing scaled prototypes, in view of further full scale laboratory experimentations; the definition of the limit state domain for the reference device in terms of the total vertical and horizontal forces has been also evaluated.

The definition of the random variables and the generation of the seismic excitations are also key aspects of the analysis. They represent significant requisites for setting up the probabilistic assessment of the response of the structural system.

The exceedance probability of the control system limit state domain is here computed via Monte Carlo simulations; to reduce the computational effort, the response surface (RS) method is used to express the seismic response as a function of the variation of the adopted random parameters. The generation of the RSs is performed in terms of mean and standard deviation of the minimum distance from a specific limit domain. In such setting, the RS evaluation must be repeated for every value of peak ground acceleration; on the other hand, to evaluate the isolators' behavior, the seismic behavior of the isolated building can be captured by means of a very simple mechanical model which can be based on the hypothesis of rigid-body motion of the building.

Finally, the results of the fragility analysis are computed, also in view of a refinement of the response surfaces, within a complete risk assessment for a prototype site.

2. A literature review for a mathematical model of a base isolation system

Following the choice of implementing high damping rubber bearings (HDRB)for the IRIS NPP isolation system, a preliminary literature review has been developed for assessing the suitable numerical model. Some main features characterize the isolator devices are the strong nonlinear response, the *scragging* and *Mullins'* effects (stiffness and damping degradation), the horizontal stiffness variation (due to temperature and axial load), strain-rate dependence and ageing.

A first overview on this technology, including modeling and analysis options, can be found in the research report [5]. Even if it is oriented not specifically to NPP buildings, the report describes the main characteristics of a seismic isolation system, listing several models for the unidirectional numerical simulation. Finally, a bidirectional model is also proposed for representing the bearings response to bidirectional loading in terms of stiffness, damping and degradation. It consists in a decomposition of the bearing resisting force as the sum of elastic component (from Mooney-Rivlin strain energy function) and an hysteretic force.

Kikuchi and Aiken proposed a non-differential unidirectional model for elastomeric isolation bearings [6], developed from the Fujita one, in order to improve the performance into the large strain range. The Fujita model has the characteristic of including a procedure to update model parameters in contrary to other differential models as Ozdemir or Wen one. The proposed model neglects the effects of strain rate and variation of axial load on the bearing hysteresis.

Hwang et al [7] present a different analytical unidirectional model developed from a previous version by Pan and Yang for high damping elastomeric isolation devices. This model has been developed for describing the damping and the restoring force of a rubber material; the first component of the total resisting force is considered herein as a viscoelastic dissipation, that depends on the strain rate. The study investigates in particular the *Mullins'* and *scragging* effect, frequency and temperature dependence. Axial loads and rubber compounds are not considered. The model parameters identification is also not included in this study, which is mainly focused on the potential of the proposed approach in the prediction of the force-displacement hysteresis.

The differential unidirectional model for HDRB by Tsai et al [8] has been developed by modifying the Wen model to include rate-dependent effects under constant axial loads. The good correlation between experimental and numerical results does not show the stiffness and damping degradation, induced by *Mullins* and *scragging* effects, which is distinctive of such devices.

A nonlinear rate dependent unidirectional model for HDRB is proposed by Jankovsky in [9] under constant axial loads. It is a non-differential model developed from the Pan and Yang solution. The cyclic experimental tests are well reproduced by the model, even if it seems to loose its good performance when a seismic signal is applied.

Abe et al [10,11] propose differential hysteretic models of laminated rubber bearings (HDRB, rubber bearings (LRB), natural rubber bearings (NRB)) under biaxial and triaxial loading conditions on the basis of experimental results. Firstly, an unidirectional model is proposed by extending the Ozdemir elasto-plastic model; second, a bidirectional model of the bearing is derived. They result accurate in the simulation of the device response also under the seismic action.

The study proposed by Ryan et al [12] approaches the problem of the influence of the axial load variation in the isolator horizontal stiffness and yielding strength (in particular when the lead core is implemented or HDRB are considered). The following considerations has been underlined for both HDRB and lead LRB:

- the lateral stiffness decreases with the increasing axial load;
- the lateral yield strength decreases with decreasing axial load (LRB only);
- the vertical stiffness decreases with increasing lateral deformation.

Some considerations on the numerical modeling of HDRB and LRB devices are also included but the proposed solutions, although an improvement, are reported by the Authors as an incomplete representation of the experimental response.

Table 1. Main characteristics of the evaluated models

	Grant et al. [5]	Kikuchi et al. [6]	Hwang et al. [7]	Tsai et al. [8]	Jankovsky [9]
Dimension	Bidirectional	Unidirectional	Unidirectional	Unidirectional	Unidirectional
Formulation	Differential	Non-differential	Non-differential	Differential	Non-differential
Device	HDRB	LRB-HDRB	HDRB	HDRB	HDRB
Axial load	Constant	Constant	Constant	Constant	Constant
Modified version of	-	Fujita	Pan & Yang	Bouc-Wen	Pan & Yang
Degradation	Y	Y	Y	Y	Y
Hysteretic damping	Y	Y	N	Y	N
Viscoelastic damping	Y	N	Y	Y	Y
Rate-dependent effects	Y	N	Y	Y	Y
Temperature	N	N	Y	N	N
Parameters identification	Y	Y	N	Y	Y
Cyclic response	Y	Y	Y	Y	Y
Seismic response	N	Y	Y	N	N

	Abe et al. [10,11]	Ryan et al. [12]	Yamamoto et al. [13]	Kikuchi et al. [14]
Dimension	Uni & Bidirectional	Unidirectional	Unidirectional	Bidirectional (**)
Formulation	Differential	Non-differential	Non-differential	Non-differential
Device	NRB-LRB-HDRB	LRB-HDRB	LRB-HDRB	LRB-HDRB
Axial load	Constant	Variable (*)	Variable (*)	Variable (*)
Modified version of	Ozdemir	Kelly	Kikuchi & Aiken	Yamamoto et al. [13]
Degradation	Y	N	Y	Y
Hysteretic damping	Y	Y	Y	Y
Viscoelastic damping	N	N	N	N
Rate-dependent effects	N	N	N	N
Temperature	N	N	N	N
Parameters identification	Y	Y	Y	Y
Cyclic response	Y	N	Y	Y
Seismic response	Y	N	Y	N

(* the model properties vary with the applied axial load)
(** three dimensional loading paths have not been evaluated)

The study by Yamamoto et al. [13] proposes a two-dimensional analytical model the numerical simulation of seismic isolation bearings including the influence of axial load. Such model is an

Four independent random variables have been considered in the fragility analysis, namely

- x_1 device stiffness
- x_2 device damping
- x_3 limit domain quadratic coefficient
- x_3 limit domain constant term

6.1 Device random variables

The first two random variables (RV) account for the randomness of the dynamic properties of the isolator, represented via the model in [11]; according to this the restoring force is the sum of three contributions, i.e. an elastic-plastic model (F_2 contribution) and two elastic non-linear springs, namely a non-linear elastic spring (F_1) and an hardening spring (F_3); the model allows to reproduce analytically the experimental behavior of laminated rubber bearings. So, it results:

- RV x_1 - the stiffness of the isolator device has been varied by multiplying the stiffness parameters K_1 and a in eq. (1), K_2 in eq. (4) and dividing the initial yielding displacement U_0 in eq. (2) by the coefficients defined in the design of experiment. This random variable has lognormal distribution with 0.22 coefficient of variation (c.o.v.).
- RV x_2 - the damping of the isolator has been tuned by multiplying the initial yielding force Y_0 by the coefficients defined in the design of experiment. This random variable has lognormal distribution with 0.22 c.o.v.

A numerical sensitivity analysis has been performed by extensive cyclic simulations on the unidirectional model [11] for evaluating the variability of the original numerical stiffness and damping (Table 3 and Figure 7a) performed by the designed device prototype. Table 4 reports a brief example on the variability of the stiffness and the damping when a coefficient α has been employed in the numerical model for amplifying their intensity by using the procedure itemized above. Figure 9 depicts the hysteresis cycles resulting by the forth options considered in Table 4. It is shown how stiffness and damping into a hysteretic cycling are strictly correlated and it is impossible to vary one independently to the other one. However, the proposed procedure is able to emphasize the amplification of the selected mechanical parameter.

Table 4. Sensitivity analysis on the unidirectional model [11]

(αK_1, αK_2, U_0/α)

	α = 1.2		***α = 1.6***	
	EQUIVALENT VISCOUS DAMPING FACTOR [%]	*SECANT STIFFNESS [KN/mm]*	*EQUIVALENT VISCOUS DAMPING FACTOR [%]*	*SECANT STIFFNESS [KN/mm]*
1° CYCLE	10.6	13.1	9	16.5
2° CYCLE	8.1	10.7	6.6	13.6
3° CYCLE	7.7	9.7	6.3	12.4
4° CYCLE	7.8	9.5	6.4	12
5° CYCLE	8.2	9.8	6.7	12.3
6° CYCLE	8.5	10.6	7	13.3

(αY_0)

	α = 1.2		***α = 1.6***	
	EQUIVALENT VISCOUS DAMPING FACTOR [%]	*SECANT STIFFNESS [KN/mm]*	*EQUIVALENT VISCOUS DAMPING FACTOR [%]*	*SECANT STIFFNESS [KN/mm]*

1° CYCLE	13.2	12	16	13.1
2° CYCLE	10.4	9.5	13	10.3
3° CYCLE	10	8.7	12.2	9.4
4° CYCLE	10	8.6	12.2	9.5
5° CYCLE	10.4	9	12.5	10.1
6° CYCLE	10.4	9.9	12.7	11.2

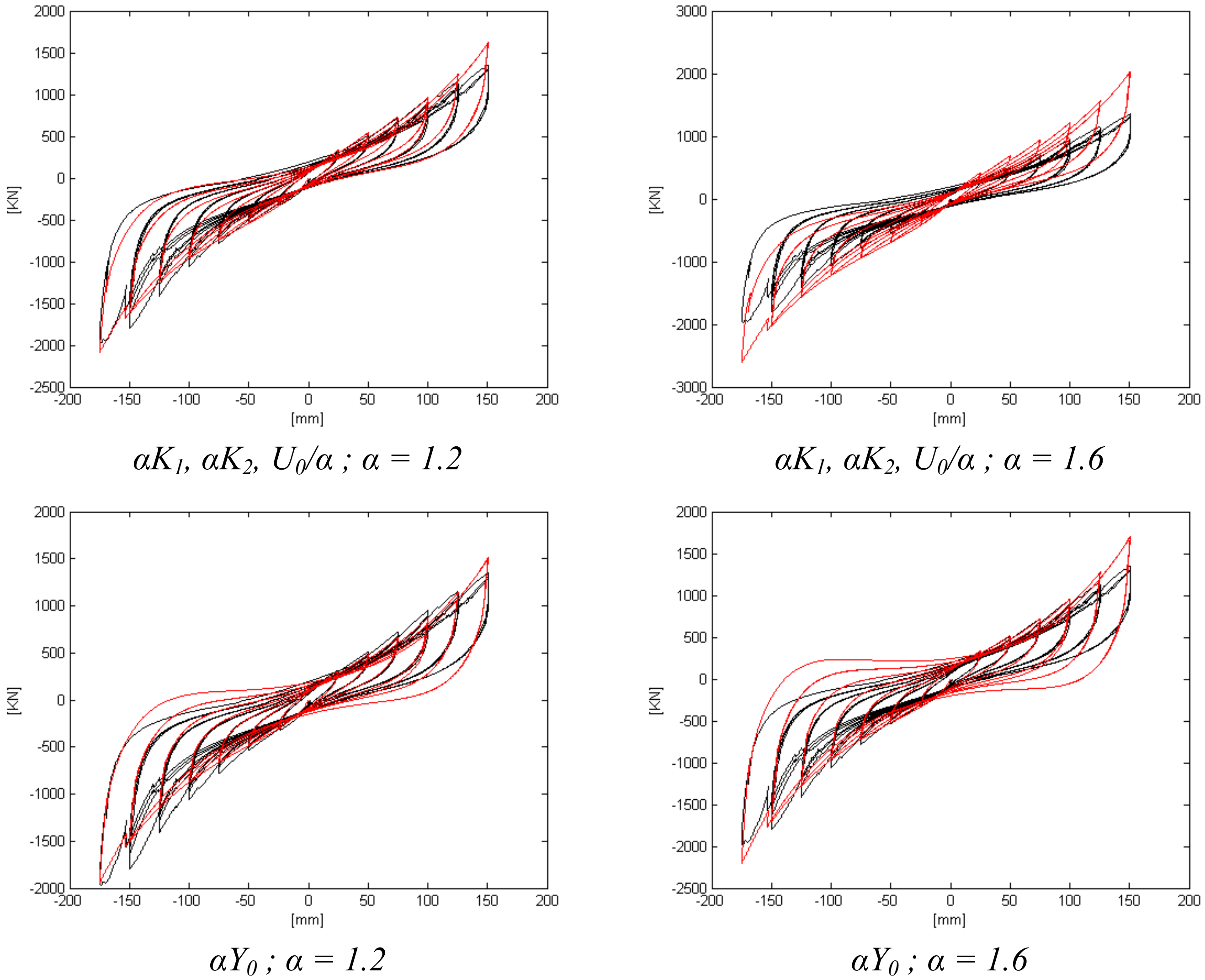
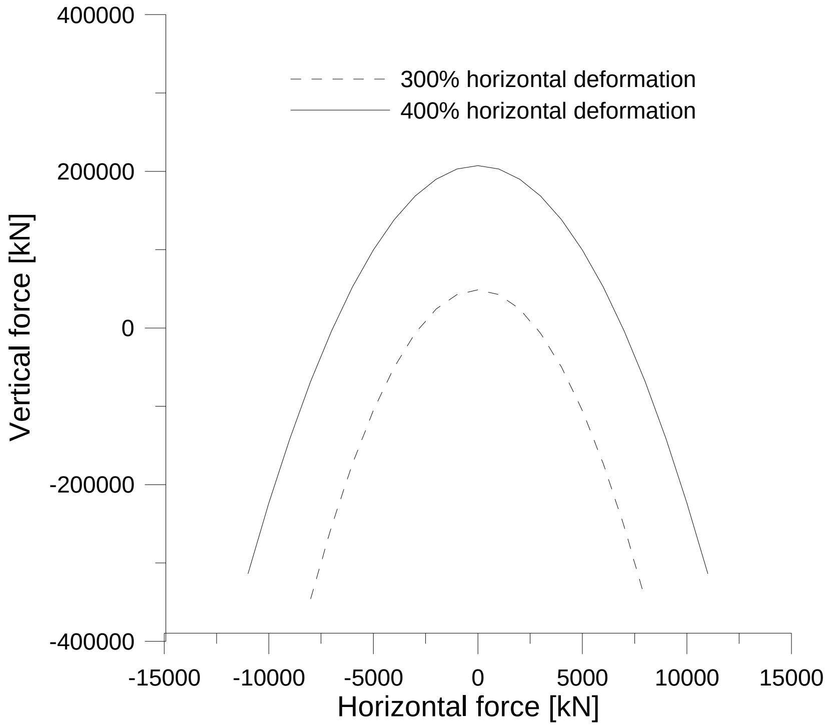


Figure 9. Hysteresis cycles resulting by the forth options considered in Table 4 (black line reference cycling test)

6.2 Limit domain random variables

The remaining two RV account for the uncertainty of the limit state function (Figure 8). A parabolic shape ($H=aV^2+c$, H horizontal reaction, V vertical reaction) has been assumed following the procedure in [19]. The coefficients of the quadratic (a) and the constant (c) terms have been taken respectively as x_3 and x_4 RVs with lognormal distribution, evaluating the reference mean value [19] and assuming the c.o.v. as 0.22. The resulting shape of the mean safety domain is depicted in Figure 10 for two reference horizontal strain levels: 300% and 400% of rubber height. The second one corresponds in particular to the first damage level evaluated in the laboratory tests and it has been adopted (a = -0.00431, c = 207230.6).



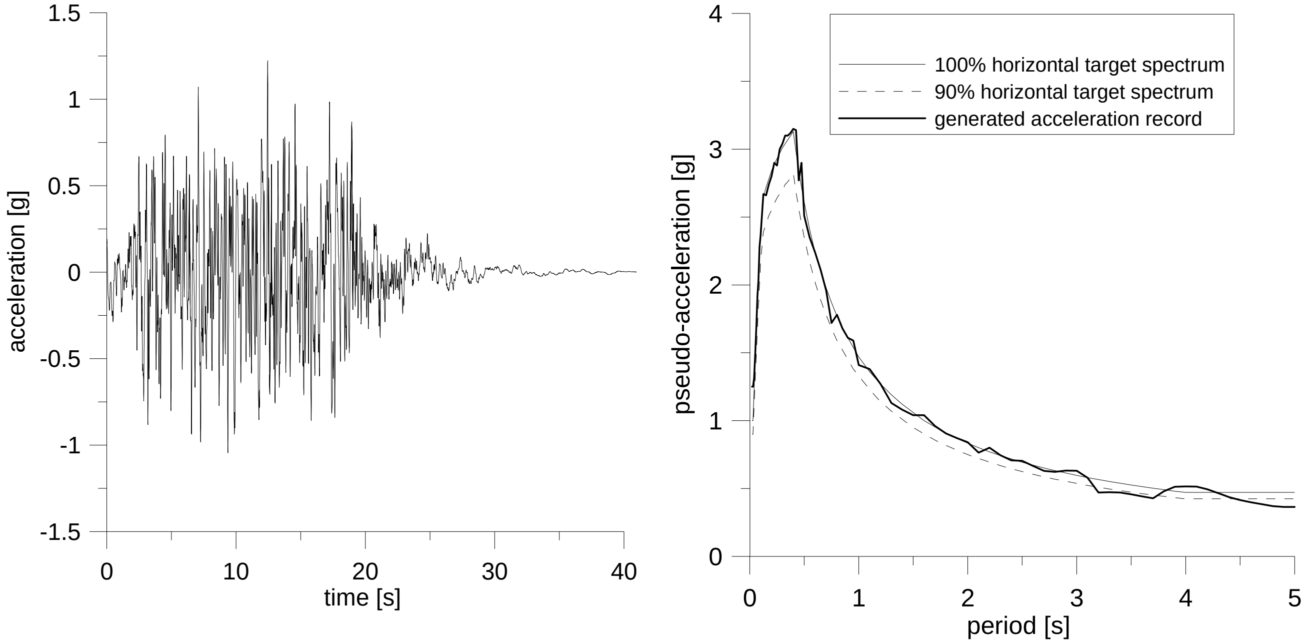
(Positive vertical forces: compressions)

Figure 10. Safety domain levels

7. The seismic excitation

The Response Spectra prescribed by the USNRC 1.60 (1973) [26] was adopted as seismic input. The spectral parameters where treated as deterministic, so that a single set of 20 input motions, each described by three components, has been generated and used at all experimental points. Generation was performed starting from white-noise accelerograms, modulated in the time domain, and iteratively correcting their Fourier Amplitude Spectra in order to match the USNRC 1.60 (1973) curve. An example of accelerograms is given in Figure 11.

The set of 20 input motions have been prepared by this procedure for being applied to the follow probabilistic assessment on the reactor building models: in particular the 3-DOFS option implements only two components (one horizontal and one vertical), the 6-DOFS option all the seismic components (two horizontal and one vertical).



a) b)

Figure 11. Example of an artificial accelerogram with the target spectra from USNRC 1.60 (1973) – damping 5%

8. Numerical simulations in Matlab

The 3- and 6-DOFS ordinary differential (ODE) equations of motions, accounting the isolation effects by the numerical model [11], are integrated directly by the explicit Runge-Kutta (2,3) pair of Bogacki and Shampine [27] by using the ODE23 function in Matlab. This function is useful for non stiff problems; remembering that a problem is stiff when the numerical solution has its step size limited more severely by the stability of the numerical technique than by the accuracy of the technique.

The 6-DOFS system is represented by larger computational efforts, so it has been decided to implement a greater time integration step (0.01s), with respect to the 3-DOFS system (0.005s), for limiting the time calculation of the procedure. This choice has been supported by considering the main natural frequencies of the system, efficiently captured by the selected integration step, and by testing the non linear solution accuracy.

From a quantitative point of view, if the differential system to be integrated is the following:

$$y' = f(t, y) \tag{36}$$

accounting y_n as the numerical solution at time t_n and h_n is the step size, defined by $h_n = t_{n+1} - t_n$, the one step of the Bogacki–Shampine method is given by:

$$k_1 = f(t_n, y_n)$$
$$k_2 = f(t_n + \frac{1}{2}h_n, y_n + \frac{1}{2}hk_1)$$
$$k_3 = f(t_n + \frac{3}{4}h_n, y_n + \frac{3}{4}hk_2)$$
$$y_{n+1} = y_n + \frac{2}{9}hk_1 + \frac{1}{3}hk_2 + \frac{4}{9}hk_3$$
$$k_4 = f(t_n + h_n, y_{n+1})$$
$$z_{n+1} = y_n + \frac{7}{24}hk_1 + \frac{1}{4}hk_2 + \frac{1}{3}hk_3 + \frac{1}{8}hk_4$$
(37a-f)

Here, y_{n+1} is a third-order approximation to the exact solution. On the other hand, z_{n+1} is a second-order approximation, so the difference between y_{n+1} and z_{n+1} can be also used to evaluate the suitable step size.

9. Design of experiments: Central Composite Design

For representing the isolated building response a second-order model can be used in the application of the Response Surface Method to the structural problem [2]. A full model (i.e. encompassing all quadratic terms) requires, for *k* random variables, the estimation of $p=1+k+k(k+1)/2$ coefficients. In this situation the most suitable experimental strategy is the "Central Composite Design" (CCD); once fixed a "center point", CCD is the combination of a classical "two-level factorial design", in which all the combinations of two levels (high/low) of the random variables are considered, with a "Star Design". In the latter *2k* points are considered in which one variable takes an intermediate value and the others are at the central value. Including the central point, a total number of experiments equal to $n=2k+2k+1$ is reached. Reasoning in terms of non-dimensional zero-mean random variables $\eta_i = (x_i - \mu_{xi})/\sigma_{xi}$ while for preserving the "rotatability" of the design the star points must be placed at $\alpha = \eta_i = \sqrt[4]{2^k}$ =2. In this study for $k=4$, it results $p=15$, $n=25$ and $\alpha = 2$.

Table 5 summarizes the design of experiments (DoE) for the selected random variables, normalized to the mean value.

Table 5. DoE with mean value normalization

	Abe et al. [11] model parameters		*Safety domain*	
Experiment	x_1 *(stiffness)*	x_2 *(damping)*	x_3 *(a)*	x_4 *(c)*
1	1.00	0.56	1.00	1.00
2	1.44	1.00	1.00	1.00
3	1.00	1.00	1.00	1.44
4	1.00	1.00	1.00	0.56
5	1.00	1.00	0.56	1.00
6	0.56	1.00	1.00	1.00
7	1.00	1.00	1.44	1.00
8	1.00	1.44	1.00	1.00
9	1.61	0.59	0.59	1.61
10	1.61	0.59	0.59	0.59
11	0.59	0.59	0.59	1.61
12	0.59	0.59	0.59	0.59
13	0.59	0.59	1.61	0.59

14	1.61	0.59	1.61	1.61
15	0.59	0.59	1.61	1.61
16	1.61	0.59	1.61	0.59
17	1.61	1.61	0.59	1.61
18	1.61	1.61	0.59	0.59
19	0.59	1.61	0.59	1.61
20	0.59	1.61	0.59	0.59
21	0.59	1.61	1.61	0.59
22	1.61	1.61	1.61	1.61
23	0.59	1.61	1.61	1.61
24	1.61	1.61	1.61	0.59
25	1.00	1.00	1.00	1.00

10. Application of the response surface method

Running the experiments detailed in Table 4, spanning from lower (0.3g) to higher (1.1g) values of seismic peak ground acceleration, it is possible to compute the extreme structural response in terms of mean and standard deviation of the ratio SC/SL (see Figure 8). In particular the most strained device in the whole isolation system has been selected step by step for each PGA. Tables 6 and 7 report the 25 experiments for the central composite design with the resulting mean and standard deviation, respectively for the 3-DOFS and 6-DOFS model option: the last one presents always higher mean and standard deviation levels due to the input characteristic: the horizontal resultant is generally more intense.

Table 6. 3-DOFS: mean and standard deviation of the ratio SC/SL for each PGA level

PGA [g]	0.3		0.4		0.5	
Experiment	E (SC/SL)	σ (SC/SL)	E (SC/SL)	σ (SC/SL)	E (SC/SL)	σ (SC/SL)
1	0.3548	0.0557	0.5624	0.1190	0.8485	0.1597
2	0.3346	0.0383	0.5068	0.0635	0.7171	0.1117
3	0.2365	0.0424	0.3663	0.0768	0.5273	0.1060
4	0.3910	0.0717	0.6040	0.1280	0.8650	0.1771
5	0.2160	0.0396	0.3337	0.0707	0.4780	0.0978
6	0.2406	0.0406	0.3750	0.0528	0.5471	0.1045
7	0.3424	0.0613	0.5301	0.1112	0.7632	0.1535
8	0.2646	0.0444	0.3994	0.0783	0.5542	0.1094
9	0.2678	0.0293	0.4071	0.0553	0.6111	0.1281
10	0.4576	0.0504	0.6948	0.0966	1.0553	0.2260
11	0.1697	0.0339	0.2681	0.0538	0.3905	0.0869
12	0.2865	0.0602	0.4547	0.0985	0.6657	0.1544
13	0.4713	0.0944	0.7449	0.1498	1.0851	0.2416
14	0.4394	0.0488	0.6702	0.0909	0.9971	0.2082
15	0.2806	0.0545	0.4416	0.0857	0.6422	0.1387
16	0.7441	0.0812	1.1312	0.1538	1.6986	0.3563
17	0.1731	0.0211	0.2613	0.0402	0.3620	0.0583
18	0.2948	0.0377	0.4451	0.0725	0.6191	0.1013
19	0.1366	0.0224	0.2098	0.0422	0.2938	0.0651
20	0.2301	0.0375	0.3587	0.0735	0.5027	0.1113
21	0.3794	0.0623	0.5830	0.1174	0.8165	0.1810
22	0.2855	0.0343	0.4307	0.0644	0.5959	0.0948
23	0.2259	0.0383	0.3443	0.0693	0.4822	0.1069
24	0.4809	0.0586	0.7259	0.1120	1.0061	0.1620
25	0.2862	0.0516	0.4429	0.0932	0.6368	0.1286

PGA [g]	0.6		0.7		0.8	
Experiment	E (SC/SL)	σ (SC/SL)	E (SC/SL)	σ (SC/SL)	E (SC/SL)	σ (SC/SL)
1	1.1204	0.2652	1.4273	0.2813	1.6693	0.4312
2	0.9312	0.1616	1.1623	0.2217	1.4642	0.3081
3	0.7030	0.1341	0.8966	0.1702	1.0925	0.2013
4	1.1535	0.2192	1.4794	0.2817	1.8142	0.3450
5	0.6374	0.1211	0.8173	0.1556	1.0021	0.1903
6	0.7140	0.1482	0.9277	0.1793	1.1462	0.2139
7	1.0175	0.1941	1.2977	0.2463	1.5813	0.2914
8	0.7388	0.1320	0.9465	0.1790	1.1668	0.2020
9	0.7732	0.1852	1.0398	0.3189	1.3705	0.3470
10	1.3308	0.3330	1.7718	0.5723	2.3545	0.6149
11	0.5427	0.1567	0.6756	0.1579	0.8711	0.1995
12	0.9225	0.2766	1.1545	0.2726	1.4879	0.3583
13	1.5079	0.4358	1.8772	0.4390	2.4204	0.5551
14	1.2639	0.2980	1.7101	0.5066	2.2433	0.5600
15	0.8920	0.2531	1.1116	0.2560	1.4330	0.3194
16	2.1490	0.5152	2.8891	0.8875	3.8092	0.9651
17	0.4772	0.0731	0.6091	0.0935	0.7567	0.1318
18	0.8150	0.1306	1.0513	0.1655	1.3064	0.2355
19	0.3804	0.0837	0.5023	0.0964	0.6239	0.1119
20	0.6462	0.1452	0.8561	0.1683	1.0635	0.1937
21	1.0569	0.2328	1.3958	0.2679	1.7337	0.3111
22	0.7818	0.1195	0.9950	0.1504	1.2333	0.2107
23	0.6261	0.1371	0.8242	0.1580	1.0256	0.1843
24	1.3261	0.2033	1.6930	0.2601	2.1033	0.3668
25	0.8489	0.1614	1.0843	0.2059	1.3241	0.2463

PGA [g]	0.9		1		1.1	
Experiment	E (SC/SL)	σ (SC/SL)	E (SC/SL)	σ (SC/SL)	E (SC/SL)	σ (SC/SL)
1	2.1410	0.6236	2.6760	0.5628	3.1225	0.7929
2	1.7690	0.3760	2.1489	0.4387	2.4379	0.5397
3	1.2510	0.1997	1.5016	0.2679	1.8105	0.3308
4	2.0788	0.3484	2.4836	0.4697	2.9983	0.5863
5	1.1482	0.1921	1.3720	0.2589	1.6562	0.3233
6	1.4095	0.2561	1.6832	0.2936	1.9133	0.3214
7	1.8107	0.2892	2.1733	0.3879	2.6205	0.4791
8	1.3855	0.2109	1.6390	0.2186	1.9139	0.3262
9	1.6360	0.2851	2.2373	0.7759	2.7612	0.9252
10	2.8195	0.5185	3.8364	1.3432	4.7705	1.6649
11	1.1193	0.2723	1.2761	0.2859	1.4919	0.4177
12	1.9278	0.5003	2.1908	0.5173	2.5840	0.7519
13	3.1109	0.7586	3.5468	0.7955	4.1474	1.1627
14	2.6826	0.4521	3.6676	1.2635	4.4988	1.4656
15	1.8320	0.4237	2.0884	0.4519	2.4296	0.6608
16	4.5467	0.7940	6.2179	2.1568	7.6756	2.5749
17	0.9166	0.1582	1.0930	0.1798	1.2892	0.2159
18	1.5776	0.2864	1.8841	0.3279	2.2215	0.3897
19	0.7160	0.1520	0.8284	0.1728	0.9750	0.1896
20	1.2184	0.2521	1.4100	0.2849	1.6525	0.3120
21	1.9895	0.4218	2.3017	0.4796	2.7089	0.5261
22	1.5000	0.2520	1.7907	0.2812	2.1070	0.3433
23	1.1774	0.2558	1.3654	0.2881	1.6045	0.3228
24	2.5476	0.4401	3.0379	0.5008	3.5831	0.6010
25	1.5172	0.2457	1.8184	0.3301	2.1918	0.4111

Table 7. 6-DOFS: mean and standard deviation of the ratio SC/SL for each PGA level

PGA [g]	0.3		0.4		0.5	
Experiment	E (SC/SL)	σ (SC/SL)	E (SC/SL)	σ (SC/SL)	E (SC/SL)	σ (SC/SL)
1	0.4158	0.0484	0.6775	0.0899	0.9907	0.1200
2	0.3939	0.0301	0.5908	0.0488	0.8347	0.0821
3	0.2833	0.0305	0.4387	0.0549	0.6231	0.0837
4	0.4763	0.0514	0.7375	0.0921	1.0472	0.1402
5	0.2630	0.0284	0.4072	0.0508	0.5782	0.0774
6	0.2999	0.0484	0.4447	0.0741	0.6477	0.1257
7	0.4101	0.0442	0.6351	0.0795	0.9020	0.1212
8	0.3164	0.0347	0.4766	0.0624	0.6655	0.0973
9	0.3094	0.0328	0.5075	0.0707	0.7778	0.1379
10	0.5401	0.0574	0.8856	0.1237	1.3566	0.2401
11	0.2075	0.0339	0.3350	0.0590	0.4877	0.0942
12	0.3624	0.0588	0.5852	0.1034	0.8516	0.1645
13	0.5771	0.0943	0.9316	0.1642	1.3562	0.2618
14	0.5003	0.0530	0.8207	0.1141	1.2580	0.2231
15	0.3356	0.0551	0.5415	0.0952	0.7884	0.1521
16	0.8604	0.0913	1.4113	0.1966	2.1627	0.3833
17	0.2120	0.0229	0.3194	0.0391	0.4460	0.0565
18	0.3699	0.0400	0.5570	0.0677	0.7778	0.0978
19	0.1662	0.0316	0.2540	0.0412	0.3541	0.0559
20	0.2905	0.0555	0.4446	0.0711	0.6192	0.0974
21	0.4621	0.0878	0.7065	0.1146	0.9846	0.1554
22	0.3430	0.0372	0.5167	0.0634	0.7216	0.0918
23	0.2686	0.0509	0.4104	0.0671	0.5718	0.0905
24	0.5895	0.0638	0.8882	0.1086	1.2403	0.1570
25	0.3449	0.0372	0.5341	0.0668	0.7586	0.1018

PGA [g]	0.7		0.8		0.9	
Experiment	E (SC/SL)	σ (SC/SL)	E (SC/SL)	σ (SC/SL)	E (SC/SL)	σ (SC/SL)
1	1.6405	0.2582	2.1153	0.4335	2.8542	0.7393
2	1.3859	0.1865	1.7293	0.1939	2.1599	0.3672
3	1.0446	0.1511	1.2861	0.1690	1.5163	0.1800
4	1.7542	0.2530	2.1596	0.2822	2.5464	0.3020
5	0.9686	0.1397	1.1925	0.1558	1.4060	0.1668
6	1.1238	0.2233	1.3504	0.2474	1.6245	0.2756
7	1.5122	0.2188	1.8618	0.2446	2.1949	0.2606
8	1.1611	0.1672	1.4261	0.2036	1.7210	0.2301
9	1.5032	0.3618	1.8630	0.6014	2.5985	0.7681
10	2.6238	0.6335	3.2538	1.0535	4.5404	1.3419
11	0.8443	0.1501	1.0978	0.1602	1.3229	0.2159
12	1.4725	0.2636	1.9169	0.2787	2.3108	0.3754
13	2.3475	0.4174	3.0526	0.4453	3.6785	0.6003
14	2.4300	0.5839	3.0108	0.9701	4.1983	1.2412
15	1.3656	0.2417	1.7744	0.2594	2.1377	0.3498
16	4.1798	1.0062	5.1804	1.6725	7.2258	2.1359
17	0.7386	0.0989	0.9209	0.1335	1.1299	0.1571
18	1.2886	0.1707	1.6067	0.2336	1.9724	0.2741
19	0.6169	0.1087	0.7672	0.1251	0.8975	0.1496
20	1.0771	0.1898	1.3395	0.2167	1.5663	0.2609
21	1.7155	0.3022	2.1332	0.3479	2.4956	0.4160
22	1.1943	0.1609	1.4894	0.2154	1.8265	0.2539
23	0.9975	0.1757	1.2400	0.2033	1.4511	0.2420
24	2.0537	0.2748	2.5607	0.3712	3.1417	0.4368
25	1.2714	0.1838	1.5653	0.2053	1.8454	0.2190

PGA [g]	1.1	
Experiment	E (SC/SL)	σ (SC/SL)
1	4.2553	0.9807
2	3.2456	0.5047
3	2.2643	0.3569
4	3.8062	0.6000
5	2.1016	0.3313
6	2.3182	0.4739
7	3.2778	0.5166
8	2.3911	0.3263
9	3.9414	1.6361
10	6.8933	2.8667
11	1.8406	0.3962
12	3.2143	0.6925
13	5.1181	1.1017
14	6.3645	2.6390
15	2.9748	0.6399
16	10.9603	4.5499
17	1.6397	0.1940
18	2.8630	0.3390
19	1.2521	0.2472
20	2.1854	0.4315
21	3.4818	0.6875
22	2.6502	0.3136
23	2.0243	0.3997
24	4.5594	0.5395
25	2.7567	0.4345

A specific RS must be computed for each considered PGA and it is a distinctive procedure of the non linear configuration. On the contrary, for the linear approach, typically applied to non isolated reactor buildings, it is sufficient evaluating one RS for a certain PGA level and deriving the other RSs by interpolation.
The so called “dual response surface” approach for solving the reliability problem under stochastic input is herein adopted. The analytical expression of the generic response surface has the following form for both the mean and the standard deviation surface:

$$g(\underline{x}) = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_1x_2 + a_6x_1x_3 + a_7x_1x_4 + a_8x_2x_3 + a_9x_2x_4 + a_{10}x_3x_4 + \\ + a_{11}x_1^2 + +a_{12}x_2^2 + a_{13}x_3^2 + a_{14}x_4^2 \quad (38)$$

In other words, the mean and the standard deviation value of the maximum ratio SC/SL (this last recorded in the most strained device of whole isolation system during each realization) over 20 time histories is evaluated for each design point. In light of these considerations several RSs, function of four random variables and the input PGA, have been processed by an ordinary least squares (OLS) method.
Tables 8 and 9 reports the RS coefficient calculated by OLS method for the 3-DOFS configuration, in the range of considered PGA, respectively for the mean and the standard deviation values. By the same, Tables 10 and 11 for the 6-DOFS structural model. This set of RSs allows to define a series of *meta-models* useful in the remaining of this report for performing fragility analyses on the isolated reactor building.

Table 8. 3-DOFS: mean RS coefficients for each PGA level

PGA [g]	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**
a_0	0.28032	0.47724	0.72932	1.09656	1.32180	1.92557	3.02343	3.19535	3.76347

a_1	0.22709	0.35670	0.54195	0.76059	0.99912	0.81540	0.24414	0.59017	1.45682
a_2	-0.18526	-0.35582	-0.64749	-0.96345	-1.06827	-0.91987	-2.44640	-2.84500	-2.93103
a_3	0.30590	0.48484	0.73519	0.93933	1.15024	1.14386	1.70307	2.10916	1.95177
a_4	-0.32813	-0.51581	-0.71650	-1.05396	-1.37089	-1.94875	-1.86445	-1.97857	-2.97467
a_5	0.00526	-0.01170	0.00036	-0.09570	-0.05600	0.20055	0.45075	0.80154	0.76475
a_6	-0.10517	-0.14974	-0.25913	-0.22878	-0.43208	-0.62704	-0.54405	-1.18576	-1.62165
a_7	0.05510	0.08110	0.11942	0.13324	0.20092	0.26014	0.30193	0.52355	0.66981
a_8	-0.06130	-0.08330	-0.13042	-0.15020	-0.20652	-0.28897	-0.32380	-0.54132	-0.70425
a_9	0.08420	0.15356	0.27650	0.36002	0.45894	0.38993	0.92616	1.24403	1.32124
a_{10}	-0.05160	-0.08400	-0.13672	-0.18370	-0.25165	-0.35691	-0.45346	-0.64959	-0.79319
a_{11}	0.05650	0.08880	0.15631	0.20500	0.25959	0.37128	0.49444	0.69547	0.88975
a_{12}	-0.03160	-0.05220	-0.08670	-0.08580	-0.08800	0.05150	-0.07180	-0.11750	0.10702
a_{13}	-0.07680	-0.11702	-0.16785	-0.22344	-0.28820	-0.36947	-0.44072	-0.54966	-0.66298
a_{14}	0.11407	0.17338	0.22623	0.34075	0.45139	0.65909	0.53339	0.54268	0.92265

Table 9. 3-DOFS: standard deviation RS coefficients for each PGA level

PGA [g]	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**
a_0	0.07540	0.10699	0.21899	0.57440	0.44030	0.62863	1.11669	1.04662	1.68766
a_1	0.08490	0.30835	0.18591	0.07250	0.15156	0.18983	-0.00313	0.04000	0.32844
a_2	-0.02580	-0.16409	-0.10060	-0.51858	-0.14401	-0.70216	-1.94466	-0.38383	-1.40198
a_3	0.03200	0.04990	0.06160	0.13586	0.08270	0.28731	0.65404	-0.03610	0.04960
a_4	-0.11829	-0.20141	-0.27412	-0.32097	-0.42995	-0.34309	-0.03270	-0.79562	-1.01646
a_5	-0.04430	-0.13991	-0.03080	0.01260	0.14397	0.09410	0.02880	0.59004	0.50572
a_6	0.00590	-0.00448	-0.08250	-0.06890	-0.28491	-0.21893	-0.01030	-0.82210	-0.83084
a_7	-0.00254	0.00084	0.01510	0.00503	0.05880	0.06740	0.00115	0.20864	0.20062
a_8	0.00281	0.00144	-0.01510	-0.01230	-0.07970	-0.07910	-0.01970	-0.22530	-0.26821
a_9	0.00021	0.06400	0.04690	0.19033	0.08970	0.29623	0.75443	0.29418	0.64303
a_{10}	-0.00751	-0.00982	-0.03450	-0.07060	-0.11264	-0.11503	-0.07300	-0.28235	-0.34783
a_{11}	0.00937	0.01320	0.04330	0.08590	0.13054	0.14119	0.13588	0.31610	0.44555
a_{12}	0.00557	0.00832	0.02940	0.03900	0.08180	-0.00042	-0.14927	0.25023	0.28656
a_{13}	-0.01000	-0.01780	-0.03350	-0.04700	-0.06640	-0.07430	-0.07940	-0.14277	-0.17044
a_{14}	0.04160	0.07250	0.09190	0.08040	0.13334	0.07800	-0.09850	0.24256	0.27428

Table 10. 6-DOFS: mean RS coefficients for each PGA level

PGA [g]	**0.3**	**0.4**	**0.5**	**0.7**	**0.8**	**0.9**	**1.1**
a_0	0.40947	0.73645	1.12704	2.05909	2.93084	3.66000	4.61979
a_1	0.19526	0.44836	0.56827	0.74296	1.00838	1.28657	2.66833
a_2	-0.19438	-0.48932	-0.73945	-0.95929	-1.89482	-3.59547	-4.59323
a_3	0.34331	0.48230	0.68554	0.94996	1.17029	1.75463	2.54247
a_4	-0.44047	-0.75502	-1.08094	-1.97164	-2.46494	-2.33104	-3.51244
a_5	0.01982	-0.01612	0.06228	0.42957	0.43303	0.90390	1.23460
a_6	-0.09580	-0.18293	-0.33754	-0.92048	-1.05011	-1.78545	-2.92272
a_7	0.06078	0.09883	0.16005	0.32740	0.38428	0.63256	1.03795
a_8	-0.06693	-0.10719	-0.17114	-0.35081	-0.41606	-0.67992	-1.12151
a_9	0.07752	0.20052	0.31022	0.49525	0.86877	1.75044	2.34515
a_{10}	-0.05465	-0.10640	-0.18485	-0.39991	-0.51077	-0.75559	-1.14532
a_{11}	0.06283	0.12134	0.20906	0.43861	0.56452	0.84350	1.29846
a_{12}	-0.03330	-0.01614	-0.00856	0.12587	0.18509	0.09462	0.10923
a_{13}	-0.08922	-0.14168	-0.20703	-0.37282	-0.46793	-0.59585	-0.86793
a_{14}	0.15205	0.25744	0.35832	0.65126	0.79420	0.65423	1.03373

Table 11. 6-DOFS: standard deviation RS coefficients for each PGA level

PGA [g]	**0.3**	**0.4**	**0.5**	**0.7**	**0.8**	**0.9**	**1.1**
a_0	0.12990	0.22297	0.35710	0.51338	0.59202	0.82298	1.53995
a_1	-0.05222	-0.02672	-0.16411	-0.20207	0.04326	0.08824	0.18166
a_2	-0.06211	-0.12990	-0.04847	-0.03600	-0.59002	-1.85794	-0.87744
a_3	0.02709	0.03429	0.02706	0.05648	0.10713	0.58251	-0.13196
a_4	-0.06580	-0.13606	-0.23353	-0.35015	-0.21576	0.26484	-0.93255

a_5	0.02540	0.02560	0.12540	0.35450	0.51323	0.63801	1.47036
a_6	-0.01276	-0.02321	-0.07414	-0.37919	-0.73557	-0.92778	-2.20988
a_7	-0.00337	0.00505	0.02086	0.08838	0.19313	0.23898	0.50552
a_8	0.00441	-0.00381	-0.01854	-0.08824	-0.19851	-0.24977	-0.52892
a_9	0.02960	0.05018	0.01313	0.08391	0.43247	1.02551	0.86188
a_{10}	-0.00483	-0.01927	-0.04914	-0.12202	-0.20121	-0.26682	-0.63950
a_{11}	0.00515	0.02233	0.05170	0.13475	0.22250	0.30306	0.70352
a_{12}	0.00877	0.02124	0.05065	0.09181	0.09652	-0.07591	0.47003
a_{13}	-0.01217	-0.02140	-0.03525	-0.07290	-0.10274	-0.12725	-0.25102
a_{14}	0.01863	0.04157	0.07190	0.09839	0.03284	-0.21660	0.21101

11. Fragility analysis

The fragility functions have been computed by the "hit or miss" Monte Carlo Method (MCM) [2,28]. The RSs support the computational procedures. In particular the application of the MCM consists in a sequential generation of samples of lognormal variables (x_1 x_2 x_3 x_4).

Taking into account the probabilistic parameters of a lognormal distributed random variable, one can evaluate the parameters of the variable's natural logarithm (by definition, the variable's logarithm is normally distributed) as

$$\overline{a} = \ln(\mathrm{M}(x) + 0.5\ln\left(1+\frac{\Sigma(x)}{\mathrm{M}(x)^2}\right) \tag{39}$$

$$\sigma^2 = \ln\left(1+\frac{\Sigma(x)}{\mathrm{M}(x)^2}\right) \tag{40}$$

where $\overline{a}$ and σ are the mean and standard deviation of the variable's natural logarithm. Table 12 reports the main normalized random variables statistic parameters where x is a generic random variable with a lognormal distribution, then $y = \ln(x)$ has a normal distribution.

Table 12. Normalized random variables statistic parameters

	Lognormal	Normal
x_1	$M(x)=1$ $\Sigma(x)=0.22$	$\bar{a}=-0.02363$ $\sigma=0.217406$ $\Sigma^2=0.047265$
x_2	$M(x)=1$ $\Sigma(x)=0.22$	$\bar{a}=-0.02363$ $\sigma=0.217406$ $\Sigma^2=0.047265$
x_3	$M(x)=1$ $\Sigma(x)=0.22$	$\bar{a}=-0.02363$ $\sigma=0.217406$ $\Sigma^2=0.047265$
x_4	$M(x)=1$ $\Sigma(x)=0.22$	$\bar{a}=-0.02363$ $\sigma=0.217406$ $\Sigma^2=0.047265$

For each sample extracted by the lognormal distributions it is possible to evaluate, by the mean and standard deviation response surfaces, the probability density function of the maximum ratio SC/SL (Figure 8). The mean and standard deviation computed via the RSs are subsequently used for extracting the extreme value from the Gumbel distribution. The extracted value is finally compared to the critical threshold. By this procedure the exceedance probability is evaluated and the MCM fragility curve is completed.

Figure 12 depicts the fragility functions processed by MCM for the 3-DOFS structural model. The fragility is represented as the probability of exceeding the limit state domain.
Figure 13 presents a comparison between the fragility curves respectively for 3- and 6-DOFS.

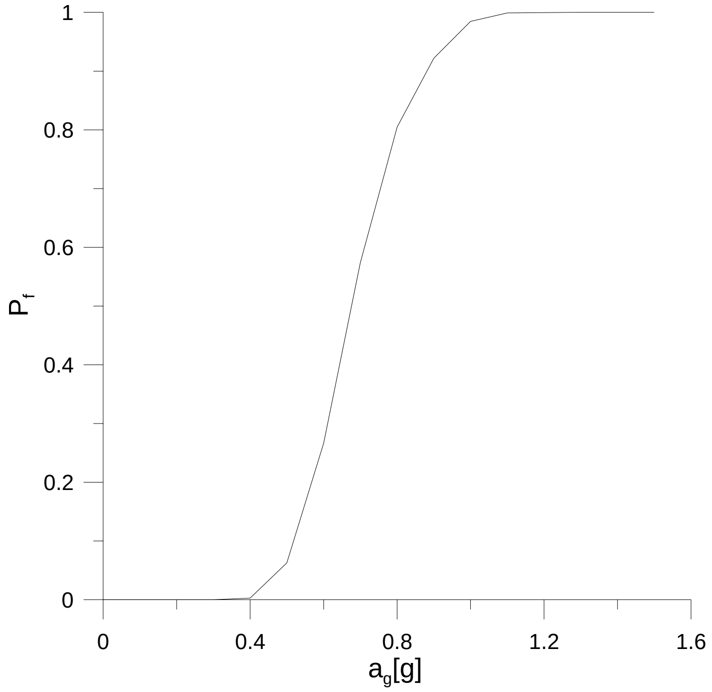


Figure 12. MCM fragility function for the 3-DOFS model

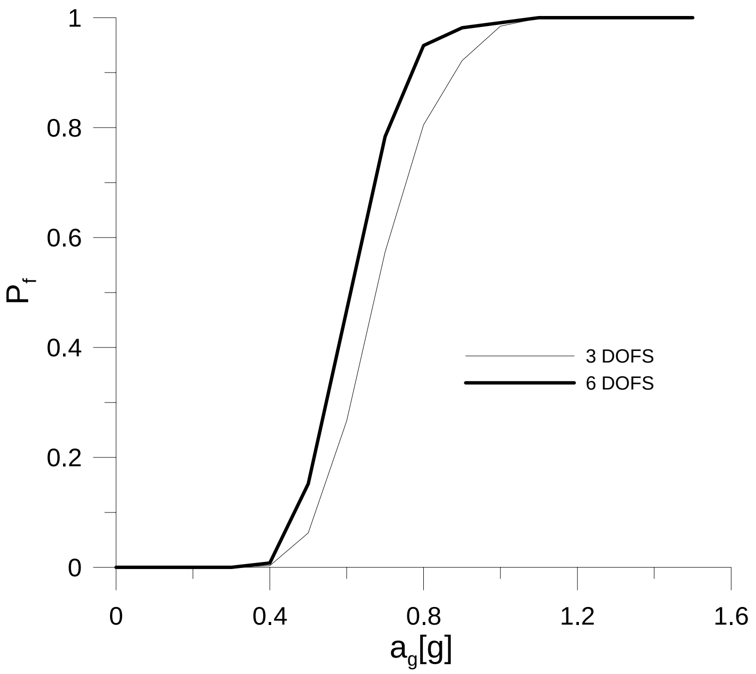


Figure 13. Comparison: MCM fragility functions for the 3- and 6-DOFS models

The 6-DOFS system emphasizes more fragility than the 3-DOFS due to the different weight of the seismic input. The 3-DOFS presents only one component in the horizontal direction;

instead, the 6-DOFS implements the resultant of both horizontal components. This last horizontal resulting force is in general more intense than the single component; even if, formally, both the inputs are characterized by the same PGA.

12. Application to the computation of seismic risk

The remaining of this report is devoted to the evaluation of the seismic risk by integrating the hazard and fragility evaluations. In particular both the fragility function of the maximum ratio SC/SL for 3- and 6-DOFS models are considered.

The problem of establishing the hazard curve is complex due to the fact the statistical parameters over a certain limit, in terms of return period, lacks of observable data. Therefore, some assumptions have been introduced. The hazard is related to a site described by return period vs ground acceleration in Figure 14.

In the estimation of the seismic risk two hypotheses has been introduced:

1) the PDF (probability density function, Figure 15) for the hazard is extended and truncated to 16m/s^2 (Figure 16);
2) the PDF is extended to 20m/s^2 and it is not truncated (Figure 17).

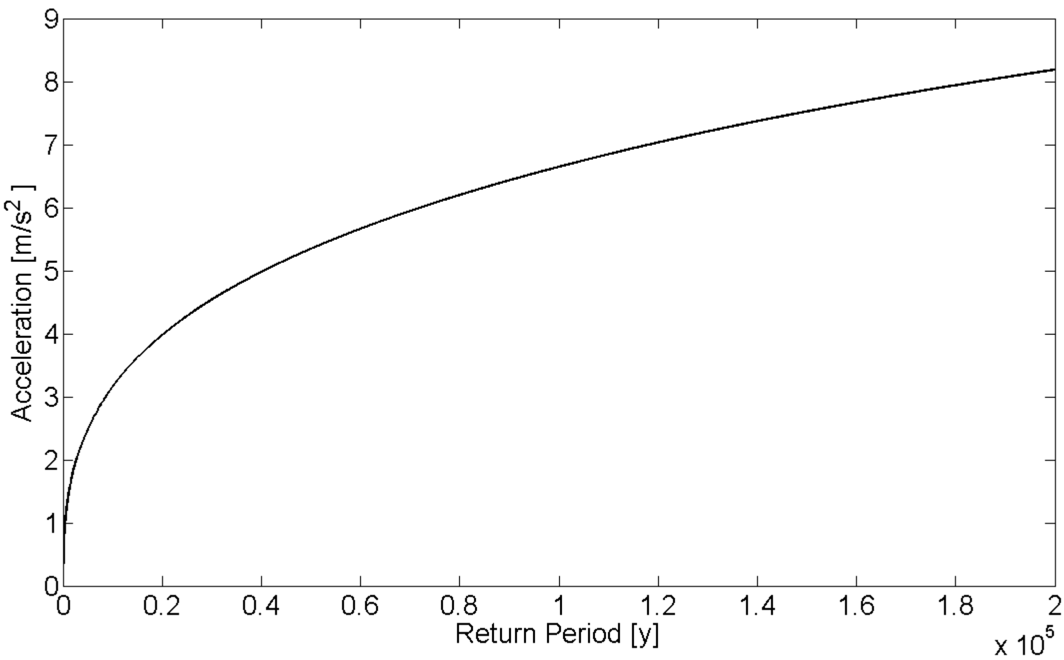


Figure 14. Seismic hazard

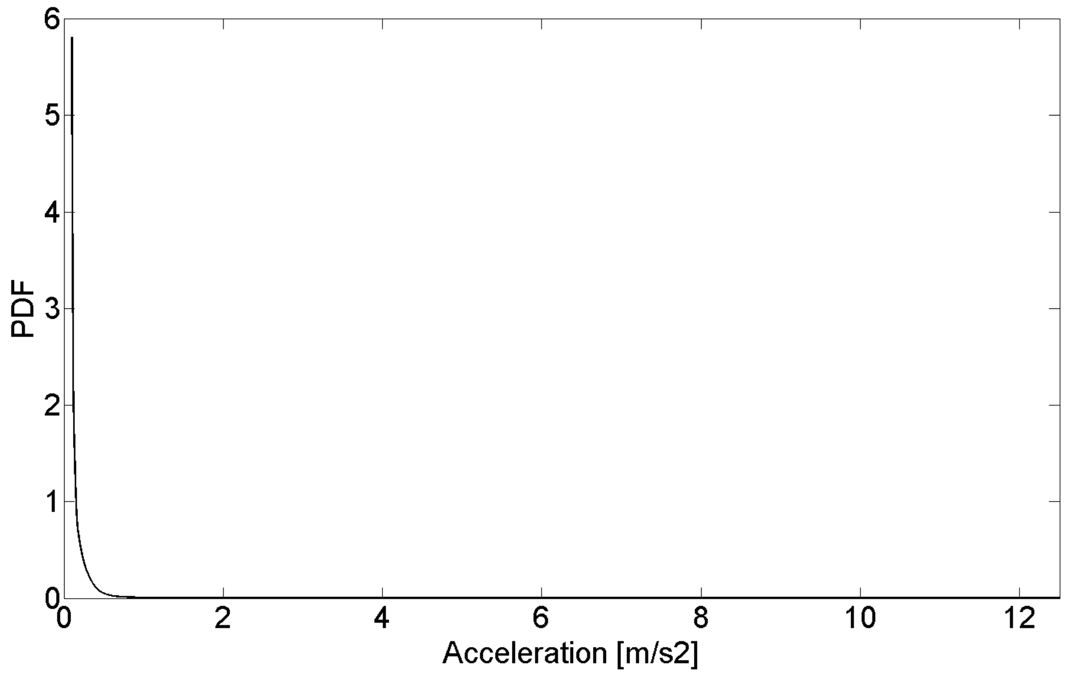


Figure 15. PDF

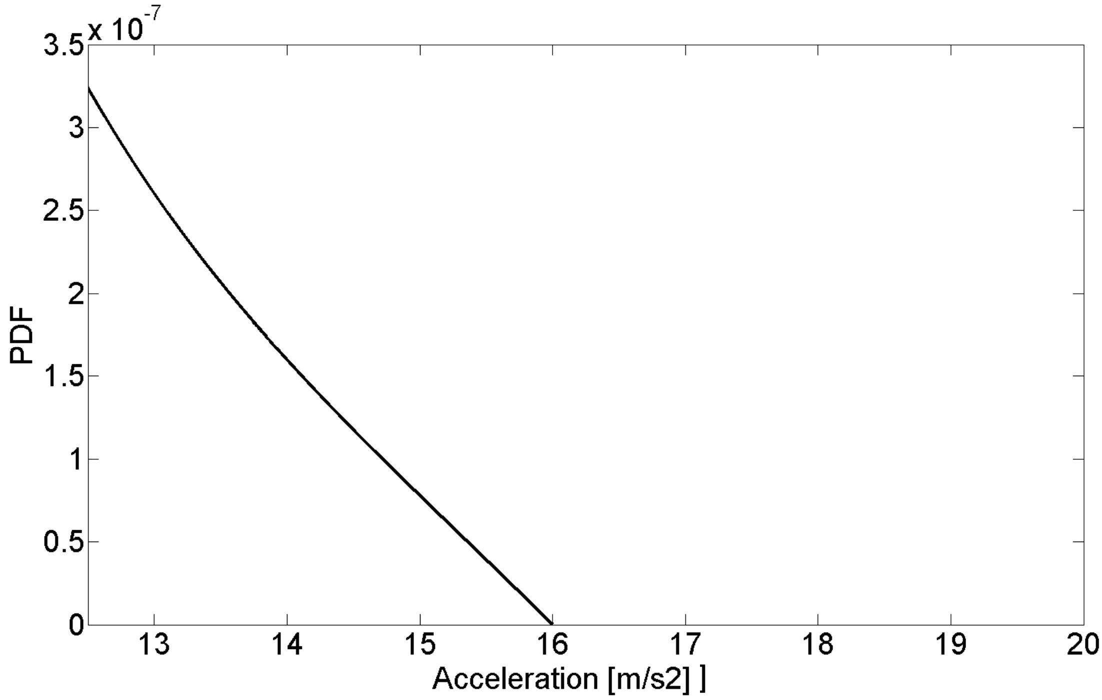


Figure 16. Detail: PDF extended and truncated to $16 m/s^2$

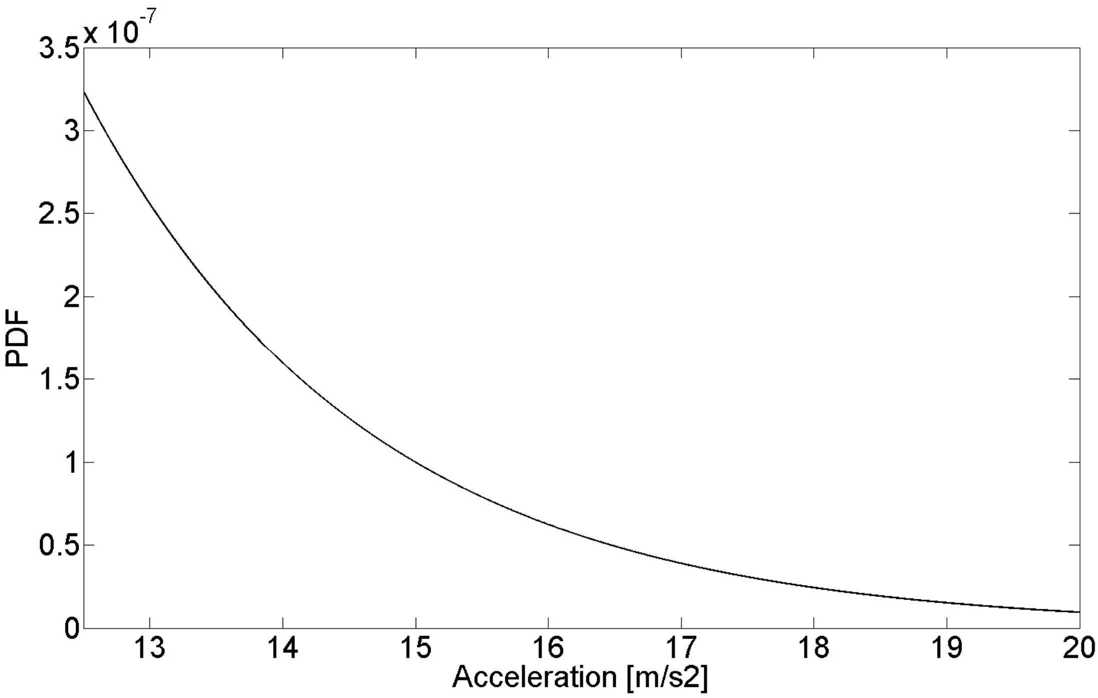
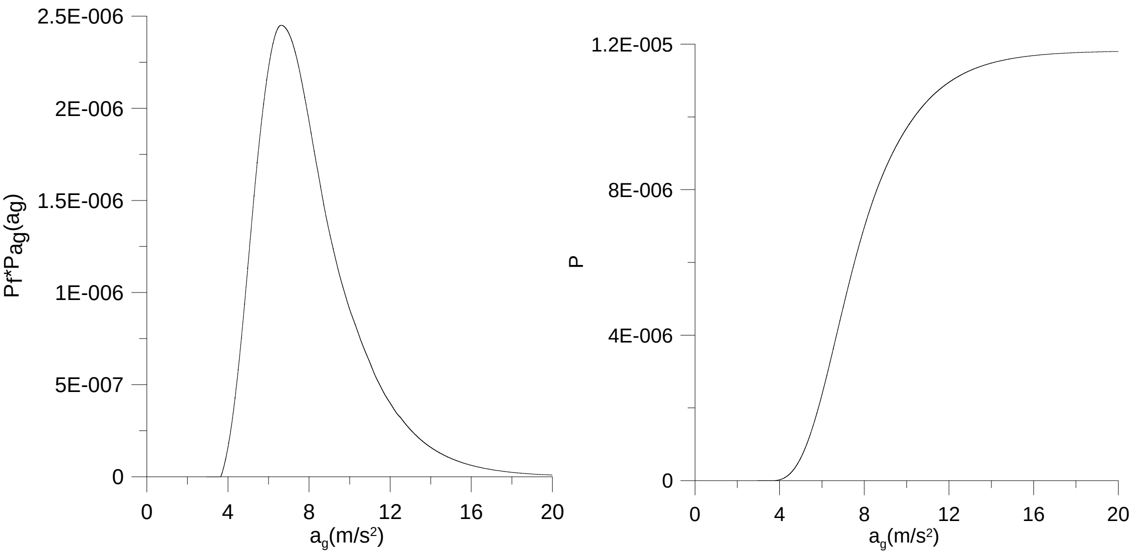


Figure 17**.** Detail: PDF extended to $20m/s^2$

Following these assumptions, the probability of failure has been computed for both the structural systems, plane and three-dimensional: Table 13 summarizes the total probabilities of failure for truncated and not truncated PDF. The 3-DOFS system presents a lower risk of failure due to the lower fragility feature; the truncated PDF also is a conservative assumptions for the total probability of failure.

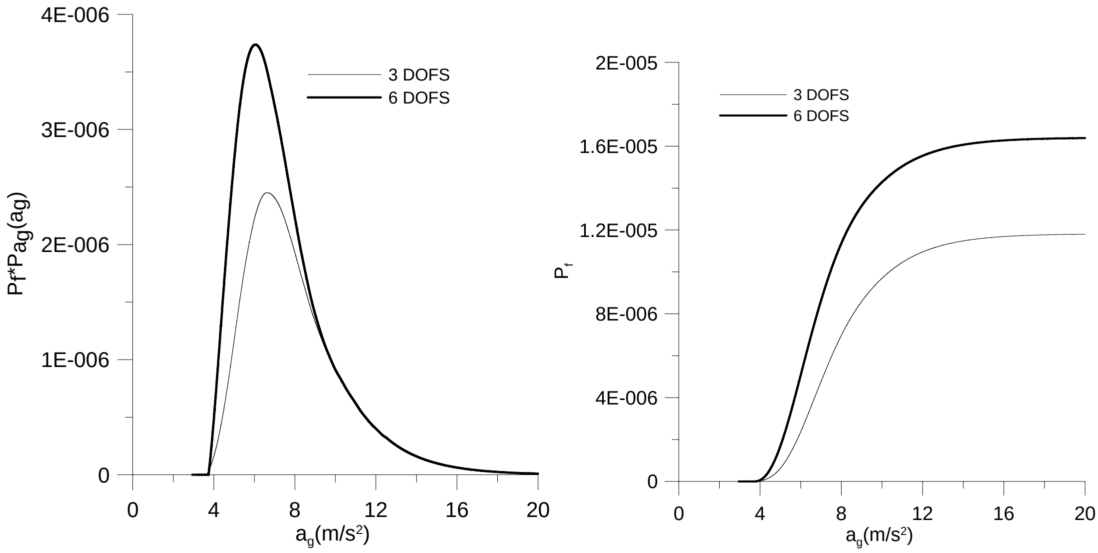
Table 13. Failure probabilities

	P_f ($16m/s^2$ extended and truncated PDF)	P_f ($20m/s^2$ extended PDF)
3-DOFS	1.1642e-005	1.1799e-005
6-DOFS	1.6542e-005	1.6699e-005



a) b)

Figure 18. 3-DOFS system: (a) integrand function (total probability theorem) with (b) probability of failure function



a) b)

Figure 19. 6-DOFS system compared to 3-DOFS one: (a) integrand function (total probability theorem) with (b) probability of failure function

Figure 18a reports the integrand function computed by combining the not truncated, less conservative, hazard and the fragility function with the total probability theorem for the 3-DOFS option. Figure 18 b depicts the total failure probability. Similarly, Figures 19a and 19b shown the 6-DOFS model results; a comparison is also proposed.

13. Conclusions

This study reports about the seismic risk computation of the isolated IRIS Reactor Building. When the base-isolation system based on HDRB is implemented, the acceleration values inside the building undergo a dramatic decrease. The isolation system itself becomes the weakest element in terms of seismic safety of the building.
MATLAB models of the Auxiliary Building are adopted with rigid body motion assumption by considering 3-and 6-DOFS approaches. The fragility analysis of the Reactor Building is then performed by consolidated analytical and numerical tools. The seismic risk is finally computed by considering an hazard function related to a medium seismicity site with two different extended PDFs (truncated and not truncated).
The proposed procedure, funded on consolidated numerical methods, results effective, though considering a limited number of random variables and a first tentative limit state domain for the devices.

14. Recommendations and future developments

The limit state domain definition for delamination behaviour plays a significant role in the final risk assessment and its definition remains under development by this research group, studying similar approaches in literature on composite structures.
The laboratory activity is also a key point of the procedure and full scale assessment of the control devices seems mandatory for characterizing their mechanical behaviour in quasi-static

and dynamic conditions. The influence of the vertical force on the isolator horizontal behaviour seems also to be an remarkable aspect to be deepen.

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