Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division IX (include assigned division number from I to X)

SEISMIC BASE ISOLATION FOR NPPS

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ABSTRACT

While the use of seismic base isolation for traditional structures and bridges are more common, this is not the case for NPP. However, several new projects are being designed and built with isolators. The purpose of this paper is to present the work carried out by NECS for EDF and CEA, to study and design NPPs equipped with different type of isolators. For this purpose several material constitutive models have be developed and implemented in Code_Aster, the finite element software created by EDF. The studies presented concern the ASTRID and EPR nuclear power plants, for which 3D models of the entire nuclear island were created. Soil structure interactions are taken into account, and floor response spectra estimated by time history analyses. In cases when the behavior of base isolation devices is not linear, nonlinear resolution algorithm is used. These results allowed well understanding the seismic behavior of superstructures, basemats, and soil pressure. For these two projects, results indicate complex phenomenon such as horizontal and vertical movement interactions, secondary peak floor response spectrum, and non-homogeneous base isolator loading in the presence of poor soil conditions. These were possible thanks to the use of more appropriate modeling techniques which are detailed in this paper.

INTRODUCTION

Seismic isolation is a widely used strategy of earthquake-resistant design in civil engineering applications (bridges, retrofitting of existing building). The fundamental idea behind seismic isolation is to position a horizontal flexible layer of isolation units between the structure and the foundation. With this isolation layer, the dynamic response of the structure is modified through the reduction of the natural frequency of the building. The forces transmitted to the structure (inertial forces and vibrations) are thus reduced.

The seismic isolation, developed in 1970's, has been applied first to the 2PWRs (Pressurized Water Reactor) nuclear plant of Koeberg (South Africa,1976) and to the 4PWRs of Cruas (France, 1978). In both cases, neoprene pads have been used. Several plants in construction or in design include seismic isolation units. The current study presents the case of the Astrid and EPR Italy projects. The interest for the seismic isolation for NPPs raise initially from the need for a standardized nuclear plant design applicable to site with stronger seismic demand (Coladant, 1991). With the new generation of fast reactors, more sensitive to earthquake loads (both in the horizontal and vertical directions), the interest in isolation has increased (Forni 2011).

The objective of this study is to present the up-to-date modeling techniques for isolation bearings used for NPPs: elastomer bearings, made of laminated rubber with low horizontal and high vertical stiffness, or sliding bearings, with contact surfaces with designed friction coefficients. The presentation of the various units is followed by the presentation of study cases of isolation of NPPs carried out with EDF and CEA.

METHODOLOGY AND MODELING

This section describes the numerical models developed in Code_Aster (EDF) for the finite element analysis of structures with isolation bearings (elastomer and friction bearings). Discrete 2D or 3D finite elements are used to represent these units, namely 'DIS_T' (Code_Aster EDF). They can be one-node elements if the base of the isolators is assumed fixed or it can be two-nodes elements if the bearing links a superstructure and a substructure (foundations, soil, …). These elements are equivalent to springs elements with 2 to 6 degrees of freedom in translation and/or rotation. For each type of bearings, a specific response law is implemented. The response between degrees of freedom can be coupled depending on the type of bearings.

Elastomer Bearings

For the elastomer bearings, the mechanical characteristics consist in horizontal and vertical stiffness. For the three types of elastomer presented here: LDRB, LRB and HDRB, the vertical response is assumed decoupled from the horizontal movements.

Low Damping Rubber bearings (LDRB)

The horizontal response of a LDRB is depicted in Figure 1. It is characterized by a horizontal stiffness K_h, function of the shear modulus G, the surface area of the elastomer A and the height of the elastomer T_r : $K_h = GA/T_r$ The shear modulus usually varies between 0.4 MPa and 1.4 MPa. The damping ratio of the bearing, characterized by the area under the Force/Displacement curve, is limited to 2 to 5%. This device is usually modeled with three uncoupled linear springs. The linear elastic response of the bearing is valid for shear strains lower than 200%.

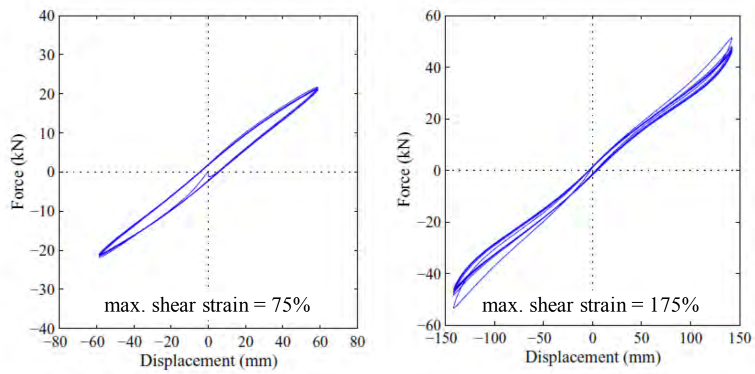


Figure 1. Typical force displacement response of an LDRB bearing (Constantinou 2007)

Lead Plug Rubber bearings (LRB)

The LRB is made of a low damping rubber bearing with lead plugs insertions. The experimental response of the LRB bearing is depicted in Figure 2. The lead core is considered as a perfectly plastic material: it has a high horizontal stiffness before yielding. After yielding, the horizontal stiffness is mainly provided by the elastomer.

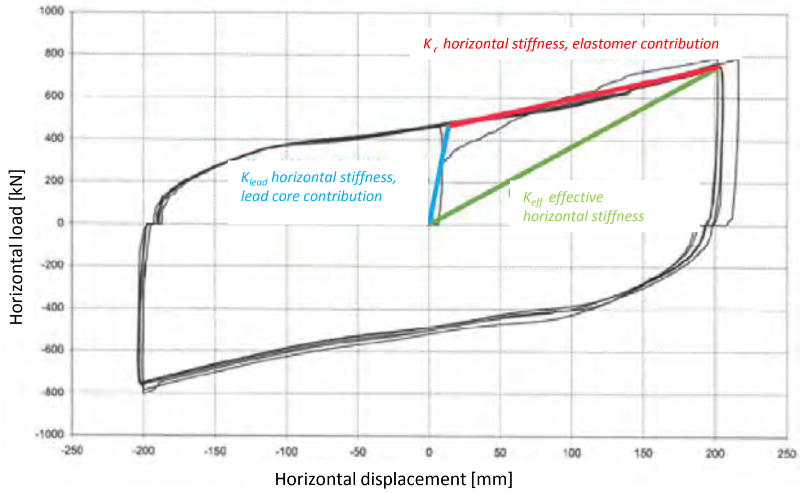
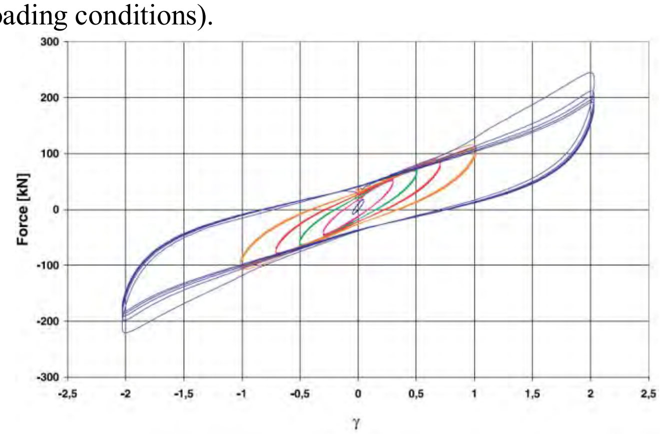


Figure 2. Typical hysteretic curve of an LRB isolator (ALGA)

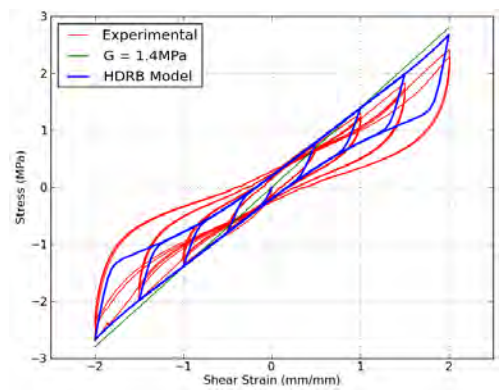
This response is modeled with a bilinear response law, as pictured in Figure 2. An alternative modeling consists of using a linear elastic response corresponding to the effective stiffness and an equivalent damping ratio corresponding to the area under the curve. The equivalent damping can be up to 30%.

<u>High Damping Rubber bearings (HDRB)</u>

HDRB bearings are made of elastomer with additives which modify its stiffness and hardness. A typical experimental response of an HDRB is presented in Figure 3. Compared to the previous case, its response is characterized by the scragging effects (degradation of the stiffness and damping under cyclic loading conditions).



(a) Typical hysteretic curve of an HDRB for increasing shear amplitudes (FIP)



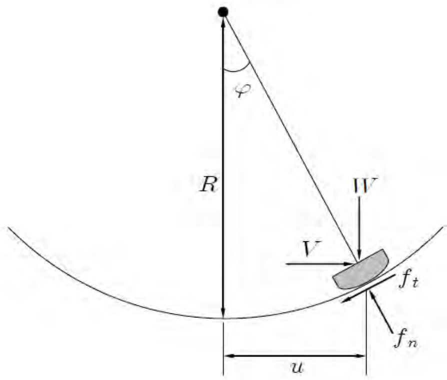
(b) Modelling of the HDRB response

Figure 3. Typical hysteretic curve of an HDRB isolator

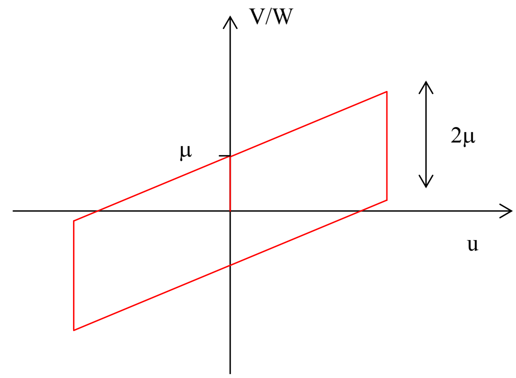
A specific model, based on the work done by D. Grant (Grant 2004) was developed and implemented to represent this specific behaviour. The model allows for the description of the bi-directional response of the element with the coupling of the two horizontal directions. The horizontal force vector F in the bearing is expressed in terms of the displacement vector and the velocity vector; the force is decomposed into a non-linear elastic and a hysteretic parts. Three parameters are needed to calibrate the response of these two components. In addition, four parameters are used to describe the degradation of the isolator response. An example of the calibration of the model, without the degradation effect, and its comparison with experiment is presented in Figure 3 (b). The model is also used and results compared for bidirectional tests (Grant 2004).

Friction pendulum Bearings

The friction pendulum bearing (FPB) is made of a single concave dish with an articulated slider. The response of the bearing is determined by the friction coefficient μ between the two surfaces and the radius R of the curved dish. The mechanics of the FPB is shown in Figure 4 (a). The model implemented is based on the model proposed by Zayas (1987) and Morgan (2007). In addition, second order effects in the vertical displacements due to the curb plate are taken in account. The responses in the three directions of translations are coupled.



(a) Equilibrium of slider in displaced configuration (Morgan 2007)



(b) Idealized hysteresis loop of single-concave FP bearing pad

Figure 4.Idealized response of a FPB

The response of the FBP bearing model is compared to experimental data. Figure 5 shows an example of the non-linear recordings from a six-story structure subjected to seismic excitation (Scheller 1999).

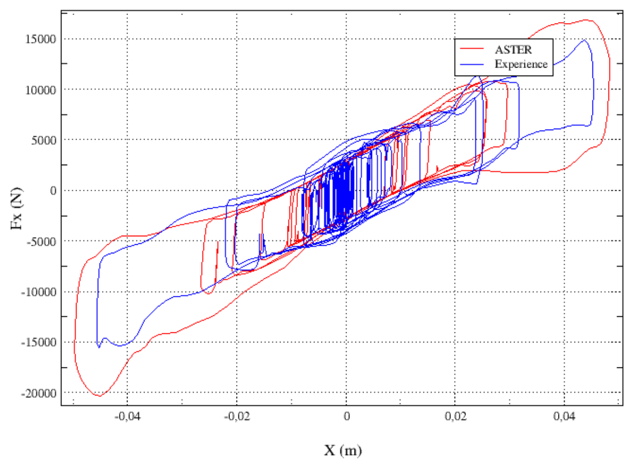


Figure 5. Comparison of the FBP model against experiment (Horizontal force versus horizontal displacement)

CASE APPLICATIONS

ASTRID Sodium Fast Reactor

ASTRID (*Advanced Sodium Technological Reactor for Industrial Demonstration*) is a French prototype project of Sodium Fast Reactor (SFR), conducted by CEA (Commissariat à l’Energie Atomique et aux Energies Alternatives, i.e. the French Atomic Energy Agency), in collaboration with industrial partners (notably AREVA, EDF, Toshiba, Alstom, Bouygues). The likely construction site is the Marcoule nuclear site, in south of France.

Regarding the earthquake resistance, SFR technology denotes sensitivity due to the specific characteristics of primary cooling system. Contrary to PWR technology, whose primary cooling system has an intrinsic robustness due to its design under severe temperature and pressure operating conditions, the SFR cooling system operates under atmospheric pressure, and so its structural strength is lower.

Therefore, the preliminary design of ASTRID nuclear island includes a seismic isolation in order to reduce the seismic demand in equipment. NECS was commissioned by CEA to design several solutions of seismic isolation, evaluate and compare their respective performances, and define the optimal solution. Two main performance criteria are considered:

- Building seismic response, and associated construction cost and optimization capabilities.
- Equipment seismic response, which is characterized by Floor Response Spectra (FRS) at different locations in building, in horizontal and vertical directions.

A particular attention is paid on vertical FRS. Indeed, contrary to horizontal motion which is filtered by seismic isolation, vertical motion is not filtered. Generally, the vertical effects of earthquake are not predominant in design. But some ASTRID components are sensitive to vertical earthquake, notably the main vessel cover. Furthermore, a coupling between vertical motion and horizontal response is known to occur in complex isolated structures, generating secondary peaks in horizontal FRS. Therefore, the ability to reduce the response to earthquake vertical motion, by means of a specific design of isolation, is analyzed.

The seismic isolation preliminary design is based on LDRB technology. This type of isolators provides enough performance with respect to the Marcoule site specific Safe Shutdown Earthquake spectrum (SSE), which is moderate, with a 0.22 g ZPA. And its reliability is recognized by several decades of application in bridge construction. The isolation Eigenfrequency is chosen at 0.55 Hz. Several alternative designs are analyzed, with variations in damping and vertical stiffness, in order to identify the eventual effects on the earthquake vertical motion response. Finally, 6 configurations are studied and compared (see Table 1). Type 1 LDRB has a 5% damping ratio instead of 15% for type 3 HDRB. Isolators with reduced vertical stiffness are 5 times less stiff than standard isolators. This reduced vertical stiffness may be reached by a reduction of elastomer layers shape factor (for instance: increase in layers' thickness, and use of annular shapes).

Structure configuration	Seismic isolation type			
	0: without	1: standard LDRB	2: LDRB with reduced vertical stiffness	3: HDRB with reduced vertical stiffness
A: without isolation	A	-	-	-
B: with isolation	-	B1	B2	B3
C with isolation and structure optimization	-	C1	C2	-

Table 1. Different design configurations for ASTRID nuclear island

A finite element model of the ASTRID nuclear island is created (see Figure 6) to study the dynamic earthquake response and the comparative performances of the different design configurations. The bearings distribution is designed in accordance with the building load distribution, in order to minimize the torsional effects and to optimize the forces distribution in the structure, in the isolators, and in base slab. Soil structure interaction is modeled with distributed springs and equivalent damping ratio. The dynamic response of the structure is performed by modal spectral analysis, while FRS are computed by transient modal analysis.

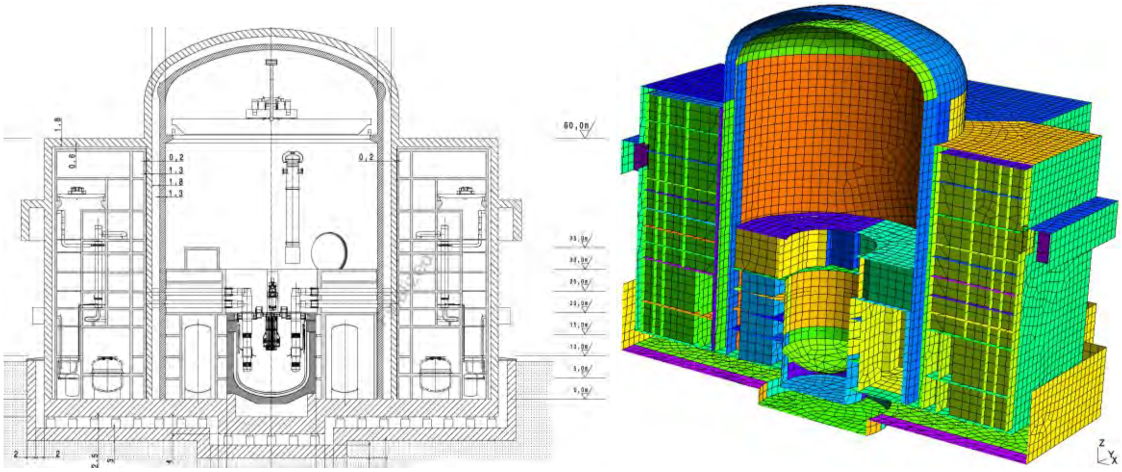


Figure 6. ASTRID nuclear island – General Layout and Finite Element Model

The main conclusions of this study are summarized hereafter:

- Base isolation provides a very significant reduction of horizontal seismic response and horizontal FRS in comparison with non-isolated structure.
- The building earthquake stability is verified for all studied configurations, with and without base isolation. However the isolation allows improving the seismic resistance margins and optimizing the structural design (reduction of raft thickness, number of shear walls, reinforcement ratios).
- For each configuration, resistance criteria of elastomeric bearings devices were examined and satisfactory (according to Euronorms EN 1337 and EN 15129), with significant margins allowing to withstand up to 2 x SSE.
- Furthermore, LDRB isolators with reduced vertical stiffness allow improving the building vertical dynamic earthquake behavior, reducing significantly the vertical response, vertical FRS, and also secondary peaks in horizontal response spectra (see Figure 7). Reduction of vertical FRS is particularly useful for some ASTRID components sensitive to vertical motion.
- The use of HDRB does not provide significant design improvement for this project.

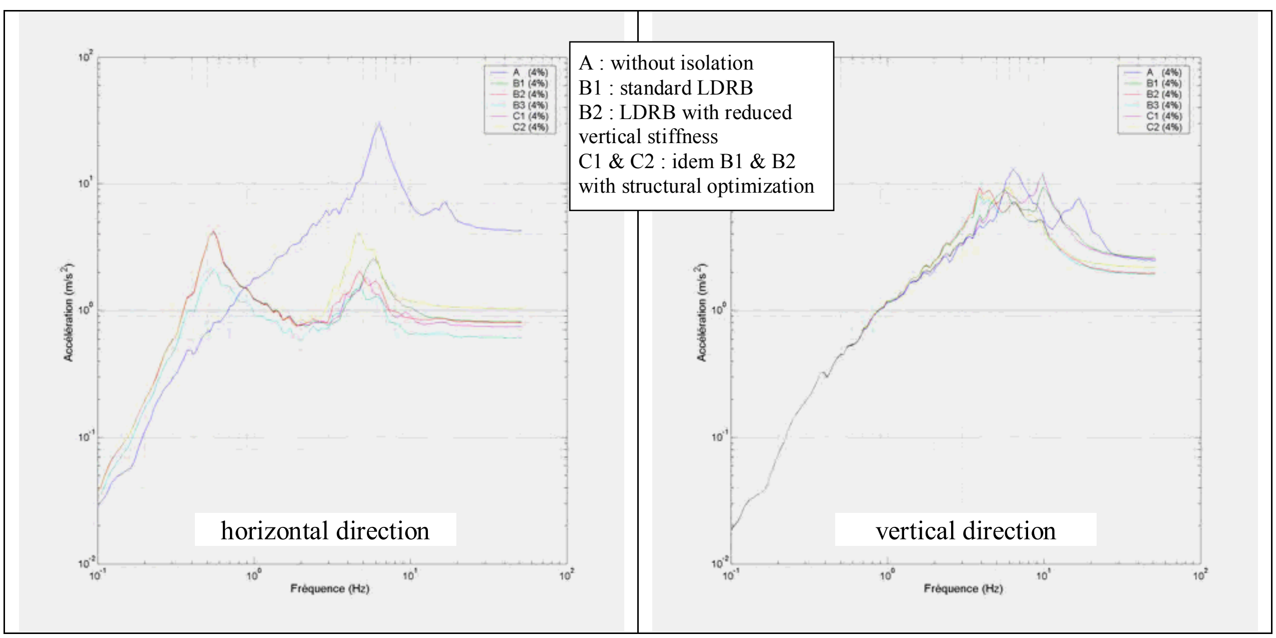


Figure 7. Comparison of floor response spectra for vessel cover, in each design configuration

Finally, the seismic isolation design with LDRB with reduced vertical stiffness seems to be a promising solution which allows reducing the vertical earthquake response.

EPR (European Pressurized Reactor) NPP

In 2009, Italian and French companies ENEL and EDF started to jointly develop a feasibility study, for the seismic isolation of the nuclear island of EPR Nuclear Power Plant.

The application field of this project aims at broadening the adaptability of EPR standard design to sites with high seismicity, typical of most sites of Italian territory, characterized by more severe values of seismic actions than those defined in the EPR standard project. The seismic protection of the nuclear buildings by means of seismic isolators has been chosen in order to minimize changes to the existing standard design of the civil works and internal components of the EPR Nuclear Power Plant.

The particularities of this pioneering study are threefold:

- Establishment of an overall project consisting in 8 studies (Table 2), shared between EDF and ENEL, with the contribution of design offices and consultants such as NECS and ENEA.
- Transposition of an existing standard design to higher seismicity sites (figure 8),
- Unfamiliar use of seismic isolation solutions with soft soil characteristics ($Vs_{30} < 300$m/s).

Task	Study
1	Expertise on feasibility of the project and definition of technical objectives
2	Analysis of existing technologies and applications
3	Collection of data for preliminary design
4	Preliminary design
5	Preliminary evaluation of associated costs and construction planning
6	**3D dynamic analyses: design, beyond design verifications, sensitivity studies**
7	Evaluation of modifications to the EPR standard - Re-evaluation of costs and construction planning
8	Conclusions of the project

Table 2. Steps of the overall project

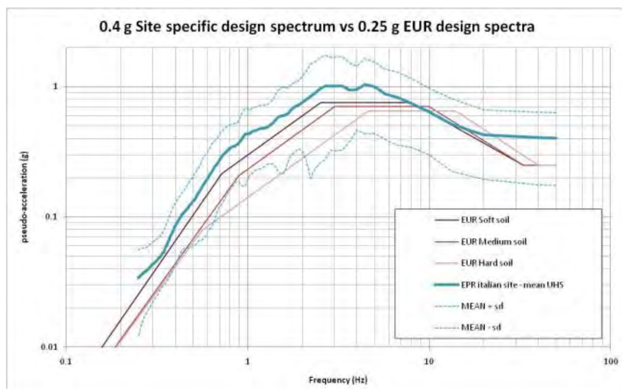


Figure 8. Site-specific spectrum and EPR design spectra

The objective of the project consists in the identification of an optimal design solution, in terms of type and location of seismic devices, to achieve compliance to the floor response acceleration spectra in horizontal and vertical direction as defined in the EPR standard project, with levels of horizontal displacements not exceeding the maximum acceptable values for structural and non-structural elements.

Moreover, the project explores the main issues that rise in case of application of seismic isolation systems to nuclear installations such as beyond design behavior, durability, inspection requirements, maintenance, replacement and qualification process.

NECS was commissioned by EDF to perform the numerical dynamic analyses (Task n°6 of Table 2). Results from previous tasks, such as type and number of bearings, are used as input data. An optimization procedure was used for the establishment of the bearings layout. The objective of the procedure is to minimize the dispersion of the compression value for each device under static loads, while minimizing the rotation effects under seismic loads. This is achieved with an iterative procedure that minimizes the distance between the center of rigidity of bearings and the vertical projection of the center of gravity of the EPR Nuclear Island, and provide a uniform load distribution on bearings.

Transient dynamic analyses, including soil-structure-interaction, are used to assess the behavior of the entire structure. 14 triplets of natural acceleration time histories (the mean value of their response spectra matches the site-specific design spectrum) were used for the linear and non linear assessments. The non-linearity is taken into account in the HDRB constitutive law presented above in this paper, implemented in *Code_Aster*. The following results are post-processed and compared to the EPRM standard values:

- Floor Response Spectra at each floor of each building,
- Maximum displacement of the isolated nuclear island,
- Relative displacements between buildings, top displacements, interstory drifts,
- Rocking and rotation effects,
- Stress state in concrete elements and in surrounding soil.

Bearing verification criteria are also verified according to NF EN 15129 and NF EN 1337-3: admissibility of the rubber shear strain, minimal thickness of the reinforcing plates, buckling stability, bearing decompression limit.

An equivalent linear modal analysis was also conducted. The results obtained with this method, currently used for the design of nuclear buildings, are compared to linear and non-linear transient results. Table 2 presents some key figures obtained from the preliminary design (fixed base) of the seismic isolation solution:

Horizontal cutting frequency (Hz)	0.5
Number of HDRB bearings	572
Diameter of a bearing (mm)	1 200
Dynamic shear modulus of rubber (MPa)	1.4
Total thickness of rubber layers (mm)	208
Maximum distortion under site specific earthquake	100%
Damping ratio	10%

Table 3. Isolation device key figures

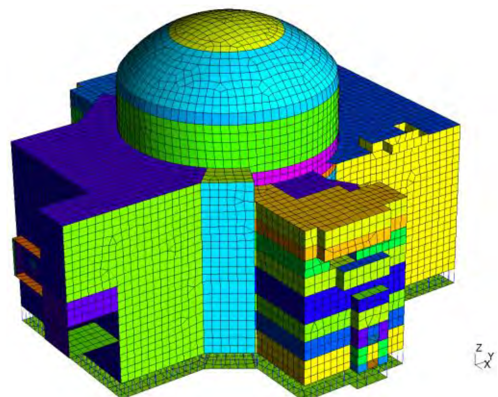


Figure 9. FEM meshing of the isolated EPRTM

Modal results indicate that the structure and the soil foundation behave simultaneously as coupled dynamic system. It reduces the horizontal cutting frequency to 0.43Hz, and adds a rocking movement of the nuclear island. Due to poor soil conditions, the significant deflection of the basemat under static loading requires special care in order to compensate for differential settlements affecting the well functioning of isolation devices. This also has an impact on the efficiency of shear walls of the building with high stress concentrations and strong demand in reinforcement closer to the edges of the structure.

The 3D modeling is useful for the identification of possible coupling of vertical excitation and horizontal responses. Some secondary peaks are observed on some of the horizontal FRS. However those peaks have low consequences since they are mostly covered by the EPR standard FRS (Figure 10).

The outputs were compared to the elements available from EPR standard design. The project, still ongoing, will use these comparisons for the determination of modifications needed for this application. A comparison of maximum top displacements (relative to basemat) of the Reactor building and BAS1 building was performed (Table 4). A reduction of 40% to 50% of the horizontal displacements is observed for the aseismic solution, and a reduction of 25% to 60% for the vertical displacements. Similar results are obtained for BAS23, BAS4 and Fuel buildings.

Top Displacement (mm)	HDRB model	BR & SI		BAS1	
		EPR with HDRB	standard	EPR with HDRB	standard
Horizontal direction	Linear	18.0	34	16.0	32
	Non linear	20.0		17.5	
Vertical direction	Linear	11.5	18	7.5	20
	Non linear	13.0		8.5	

Table 4. Comparison of top displacements with EPR standard values

The comparison of the Floor Response Spectra with the EPR standard values was carried out (Figure 10). It was observed for most buildings and floors:

- An important reduction of horizontal accelerations for frequencies higher than 0.8Hz,
- A horizontal peak response at 0.43Hz (coupled mode of bearing system and SSI),
- A second peak at 1.1Hz, due to a coupling of vertical motion and horizontal response,
- A reduction of most of the vertical response spectra, with a peak response at 1.4Hz that sometimes exceeds the EPR standard vertical FRS.
- A ZPA which is always lower than 0.2g for each FRS, of each building and within each direction (mean value of 14 time history analysis).

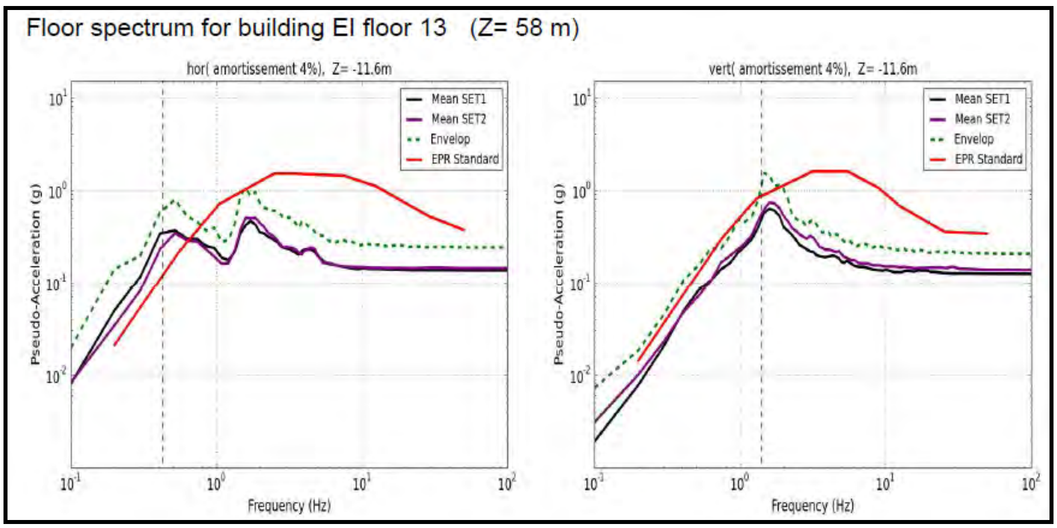


Figure 10. Comparison of FRS at top of internal containment

Given the available results, the majority of the Floor Response Spectra, seismic displacements and forces in structures are covered by the standard design. The major modifications will therefore be concentrated on the foundation raft design, flexibility of connected pipes, and probably improvement of soil bearing capacity.

CONCLUSION

With higher standard requirements, increasing population density and need of electrical energy in areas around the world with moderate to strong ground motions, the nuclear industry is more than ever considering base isolation of NPPs as an optimum design solution. While this technique has been extensively been used in non nuclear buildings and bridge constructions, very little knowledge exists today with NPPs equipped by base isolator. Therefore it is essential to study with great care in full detail the seismic behavior of base isolated structures. The purpose of this study is to show that with the progress in science to develop dedicated linear and nonlinear constitutive models capable to represent the response of various type of devices, and the capacity of structural analysis software using very powerful computers available to most engineering firms, it is now possible to carry out detailed analysis as the ones shown in this paper. The studies of ASTRID and EPR nuclear power plants are two examples of structures where thanks to numerical simulations, the complex behavior of structure are investigated. The use of appropriate modeling technique (isolation devices, 3D linear and nonlinear analysis, soil structure interaction, time history analysis) allowed detecting and quantifying phenomenon such as secondary peak floor response spectrum, soil-basemat strong interaction in presence of poor soil conditions, non uniform stress distribution in RC elements, etc. The conditions, in which these studies were carried out, are perfectly adapted for large scale industrial applications, in terms of reliable solutions, planning and budget constraints of the engineering projects.

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