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Preliminary evaluation of the influence of faulted isolators in the propagation of seismic loadings

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Sommario

That report has been issued in the frame of the second research programme of ENEA-MSE agreement and it is one of the deliverables of the task I "Seismic analyses" of the work-programme 2 "Evolutionary INTD reactors" of the research theme on "Nuovo Nucleare da Fissione".

The reports deals with the results of the study aimed at evaluating the behaviour of isolation bearings in the hypothesis of isolators damage equal to 1-2% and the effects of these failure conditions on the response of reactor components subjected to the transmitted seismic loadings.

Note

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Preliminary evaluation of the influence of faulted isolators in the propagation of seismic loadings

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1. INTRODUCTION

At presents there is a large worldwide interest in the development and application of advanced nuclear power plants (NPPs). Decisions on the construction of several NPPs with built evolutionary light water reactors have been taken (e.g. EPR in Finland and France, AP1000 in China, etc.) and more are under consideration for licensing in several countries.

Innovative NPPs are designed to be suitable for very broad siting conditions; therefore the safety aspects related to the external events should consider new scenarios and failure modes, different from those well known for the currently operated reactors.

Violent seismic activity not only in high seismic regions, is considered the most destructive external loads for the reason that the ground motion may determine dangerous consequences and/or damages in nuclear power plants with threats to the integrity, the tightness and the operability of structures and components.

Moreover it is important to note that structural damages (resulting from inelastic deformations) are induced by the propagation of the dynamic loads and represent, in a conventional earthquake resistance design, a consequence of the released seismic energy that should be dissipated preventing as well as reducing the probability of collapse of structures.

Many of early NPPs were designed and constructed according to seismic design procedures that at present are recognized to be in many cases less rigorous than the ones used for more recent plant design.

The safety of nuclear reactors has always been a very important issue; improving NPPs safety was and is a continuous process, related to both the development of reactor designs with improved safety and of new and more stringent safety objectives and requirements also for the seismic design during the past two decades.

In fact nuclear power plant must be designed, installed and maintained according to stringent international rules, like the NRC ones, taking into account not only the internal events but also the threats arising from external events and natural phenomena, such as flood, seismic event, etc., in order to ensure that the occurrence of one of these events will not compromise the reactor shutdown, the decay heat removal capabilities and containment functions that is the confinement of radioactive materials.

In this context the concept of seismic isolation offers a viable and effective approach that allows the reactor systems and structures to withstand in a better way the seismic dynamic loadings.

Seismic isolation may be considered as a practical approach for providing seismic protection to buildings, systems (Fig. 1) and components, especially in the case of structures for which it is essential to maintain/ ensure safety functions and structural integrity.

In recent years, base isolation technique attracted a great deal of interest.

Isolation technique has been already applied to various structures such as bridges, buildings and also in 2 LWR facilities.

Isolation approach differs from the conventional strategy based on the strengthening of structures and components, coupled to structures ductility, in order to cope with seismic loads.

Seismic isolation is especially attractive for the nuclear industry since it can reduce design loads, minimize the effect of specific site environments for the major components of the primary system.

Decoupling of the super-structure from the soil and consequently from the adverse effects of the earthquake motion by using base isolation systems, has become a very interesting method. It is important to note that all the base isolated structures performed well during two big earthquakes: Northridge, 1994 and Kobe, 1995.

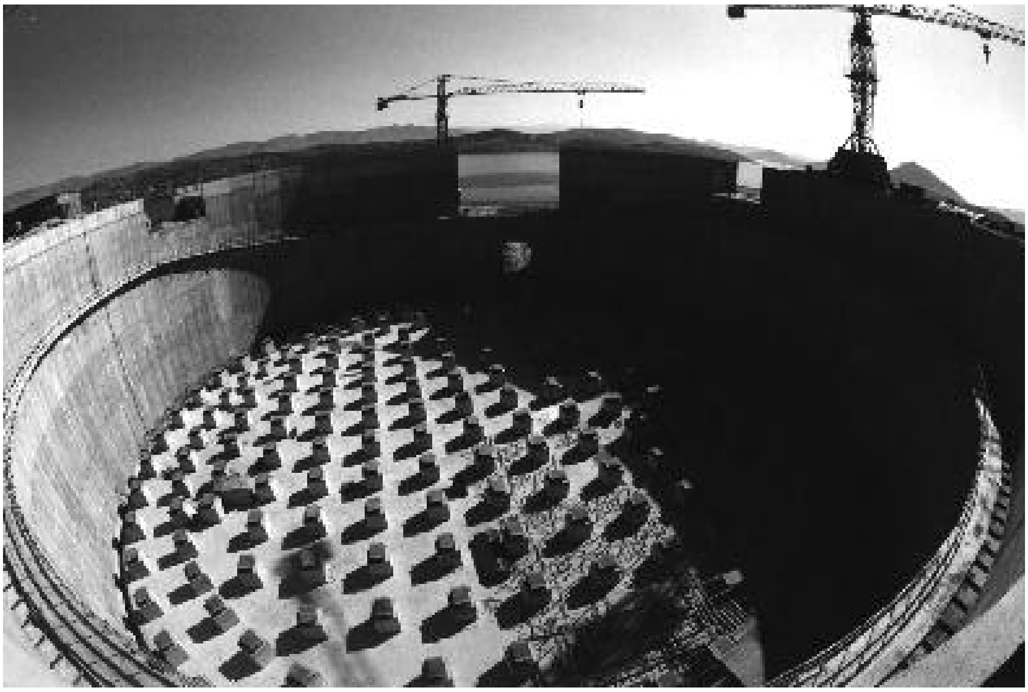


Fig.1 - LNG Tank in Revithoussa island in Greece during construction (Constantinou 1997)

Nagarajaiah and Sun (2000) analysed the performance of base isolated USC hospital building during the Northridge Earthquake on the base of the recorded data.

The seismic response and performance evaluation of the hospital building shows that base isolation was effective in reducing the response and providing seismic protection.

The peak roof acceleration was reduced to nearly 50% of the peak ground acceleration and the “super-structure” remained in the elastic range which would have not been the case if it were a fixed base structure.

On the basis of what already said, the present study is aimed at evaluating the behaviour of isolation bearings in the assumed hypothesis of damage of 1-2% of the isolators number, and the influence and effects of these failure conditions on the response of reactor components subjected to the transmitted seismic loadings. To the purpose the faulted isolators position are chosen randomly distributed in the foreseen array.

2. SYSTEM DESCRIPTION

The use of innovative anti-seismic techniques, such as seismic isolation (SI) and passive energy dissipation (ED), seems to able to ensure the full integrity and operability of important structures in very severe seismic conditions.

The main objective of this report is to verify the existence of possible relationships, if any, between the ground motion and the effects on the isolated relevant structure (in term of seismic demand parameter) and to compare the isolated to not isolated reference reactor behaviour in order to gain information/data on the isolation technique effectiveness as reference.

The nuclear power plant considered in this study is the near term deployment IRIS reactor. Among the LWR standard designs, IRIS is a smaller-scale advanced pressurized light water reactor (PWR), being developed through a strong international partnership for near-term deployment and provides a viable bridge to Generation IV reactors.

IRIS has been hence primarily focused on achieving a design with innovative safety characteristics. Diameter and height of IRIS reactor building are approximately 45 x 60 m (Fig. 2), respectively. In figure 2 it is represented a possible IRIS reactor auxiliary building (AB) configuration with some mutually interacting components like the containment system (CS) and reactor pressure vessel (RPV) etc.

This structure represents the main safety barrier against radioactive leakages, “missiles” impact or against any kind of external hazards.

The nuclear island, which consists of the reactor outer containment building and adjacent building, is supported on a common basement; the isolators are therefore inserted between the soil and reactor foundation.

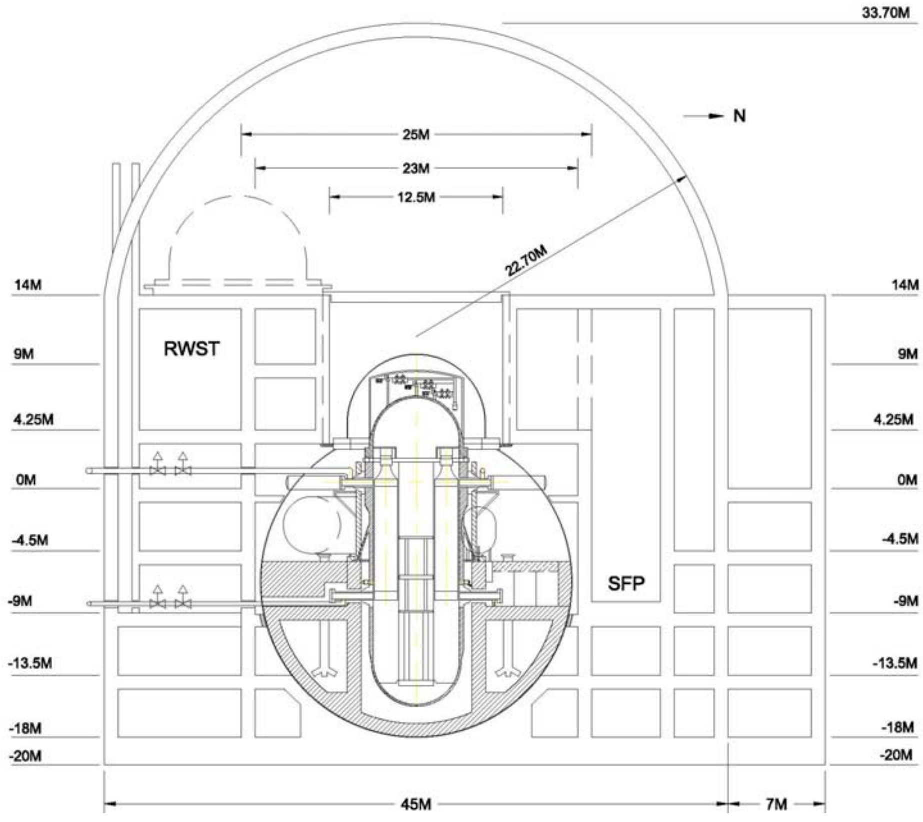


Fig. 2 - Near term deployment IRIS reactor scheme

3. SEISMIC ISOLATION

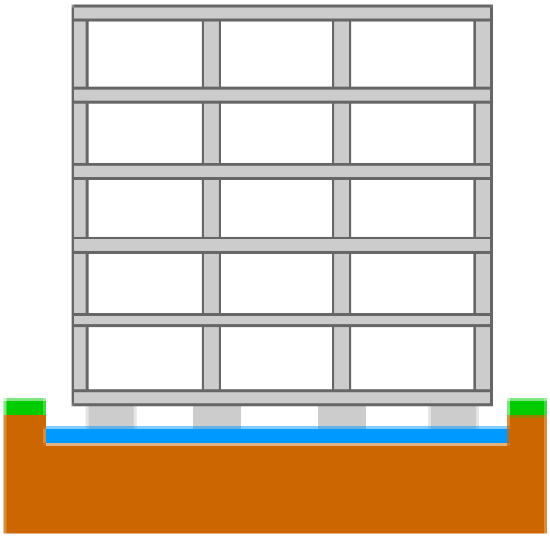
As already mentioned base isolation is an effective strategy to protect sensitive structures and buildings and particularly their components (or contents) during a seismic event.

At present, six large Pressurized Water Reactor (PWR) units have been considered for isolation; four unit at Cruas plant in France and two unit in South Africa.

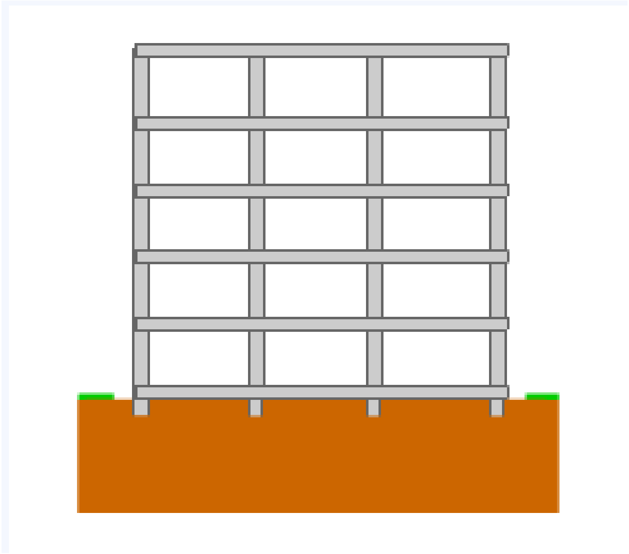
The Cruas operational units, having safe shutdown earthquake (SSE) acceleration equal to 0.2 g, are supported on 1800 neoprene pads (measuring 50 x 50 x 6.5 cm), whilst the Koeberg plant, where the site is characterized by higher seismicity (SSE acceleration equal to 0.3 g) is supported by a total of 2000 pads measuring 70x70x10 cm.

In seismically isolated systems, the superstructure is decoupled from the ground motion by introducing a flexible interface (isolators) between the foundation and the base of structure (Fig.2).

The isolation system, by introducing flexibility and energy absorption capacity, may be able to shift the fundamental time period of the superstructure to a large value and to dissipate the energy in damping, limiting the amount of transferred force, such that accelerations are drastically reduced.



(a)



(b)

Figs 2. Seismically Isolated and Conventional Structure

The use of seismic isolation devices as a means to guarantee the passive protection of critical facilities under moderate-to-major earthquake ground motions relies upon the following mechanical properties:

- Horizontal flexibility to increase structural period and reduce the transfer of seismic energy to the superstructure (except for very soft sites);

- Energy dissipation (due to relatively high viscous damping) to reduce lateral displacements;

- Sufficient stiffness at small displacements to provide adequate rigidity for service level environmental loads, e.g. wind and traffic-induced tremors.

Several countries have initiated programs to develop seismic isolation systems for advanced nuclear applications; the benefits of the adoption of seismic isolation in NPP re related to the possibility to standardize of the plant design regardless of the site seismic characteristics as well as to enhance the safety and reliability of nuclear power plants.

When applied to nuclear reactors, seismic isolation allows to minimize seismic effects on the reactor design which therefore may be less site dependent.

The dynamic response of a seismic-isolated structure depends mainly on the mechanical characteristics of the isolators and on the nature of the ground motion.

In any case the correct design of the base-isolation system is essential for a good behaviour of the structure undergoing earthquake event. Nowadays, a wide variety of isolators exist, differencing, one from each other, for the materials used and the design strategy adopted to disconnect the superstructure from the shaking under ground soil.

In the performed study seismic isolation is obtained by applying high damping rubber bearings (HDRBs) which are characterized by high dissipative capacity of the released earthquake energy by hysteretic damping.

The high damping rubber bearings (HDRBs), with or without lead plug, as represented in Figs. 3, are made of rubber and steel layers bonded together by means of vulcanization process.

The rubber is made of special mixtures of rubber and carbon providing high dissipation properties (high horizontal flexibility). The inner steel plates provide sufficient vertical rigidity to sustain vertical loads and stiffness to prevent the lateral bulge of the rubber layers while allowing the isolator to shear freely.

(a)

(b)

Figs. 4 – HDRB without (a) and with lead plug (b)

The rubber is made of special mixtures of rubber and carbon providing high dissipation properties (high horizontal flexibility). The inner steel plates provide sufficient vertical rigidity to sustain vertical loads and stiffness to prevent the lateral bulge of the rubber layers while allowing the isolator to shear freely.

The isolation system, by means of introducing flexibility and energy absorption capacity, may be able to shift (increase) the fundamental time period of the superstructure to a large value and to dissipate the energy in damping effects, limiting the amount of transferred force, so that accelerations are drastically reduced. The use of seismic isolation devices as a means to guarantee the passive protection of critical facilities under moderate-to-major earthquakes relies upon the following mechanical properties:

- High horizontal flexibility to increase structural period and reduce the transfer of seismic energy to the superstructure (except for very soft sites) (Fig.5);

- Energy dissipation (due to relatively high viscous damping) to reduce lateral displacements;

- Sufficient vertical stiffness at small displacements to provide adequate rigidity to sustain gravitational and vertical loads.

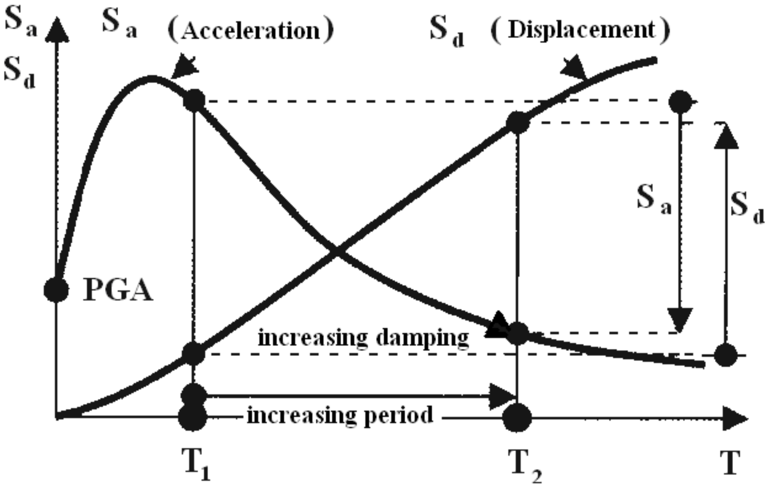


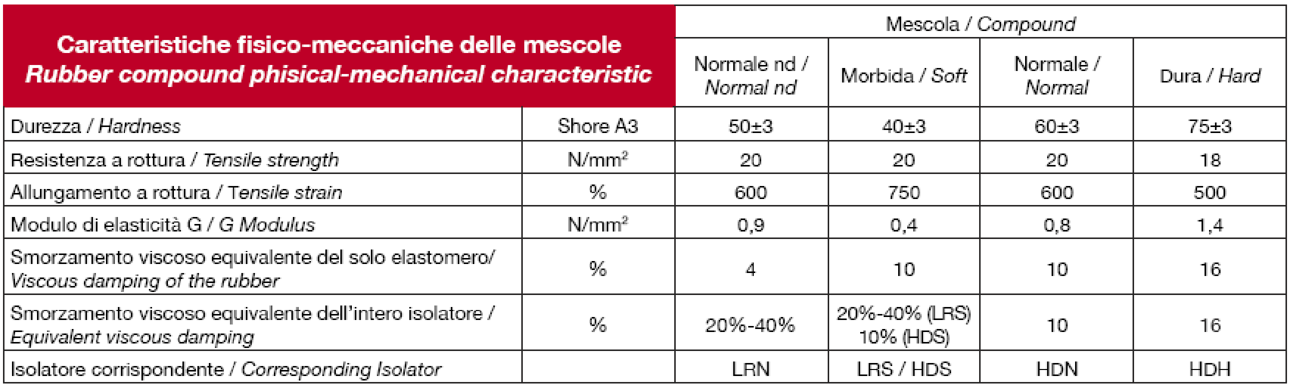
Fig. 5 - Isolation effects

It is important to highlight that the isolation of the structure complies with a proper selection of the horizontal stiffness of HDRBs which can dissipate energy up to 16% in damping.

Generally there are several types of rubber compounds in order to match different design needs. For HDRB isolators 3 high dissipating compounds are available:

- Soft compound, with modulus of elasticity G = 0,4 N/mm^2 and 10% equivalent viscous damping;
- Normal compound, with modulus of elasticity G = 0,8 N/mm^2 and 10% equivalent viscous damping;
- Hard compound, with modulus of elasticity G = 1,4 N/mm^2 and 16% equivalent viscous damping.

In table I are summarized some mechanical characteristics of a typical HDRB device [1].

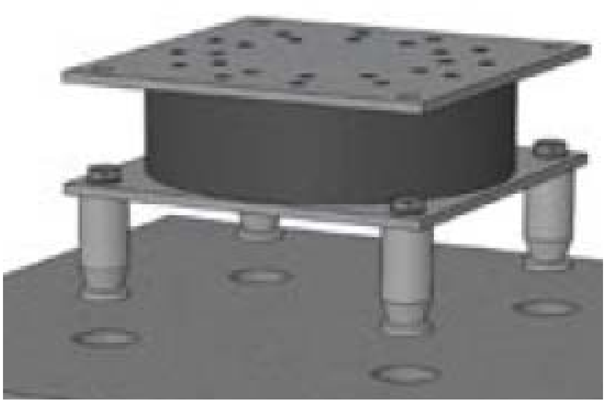


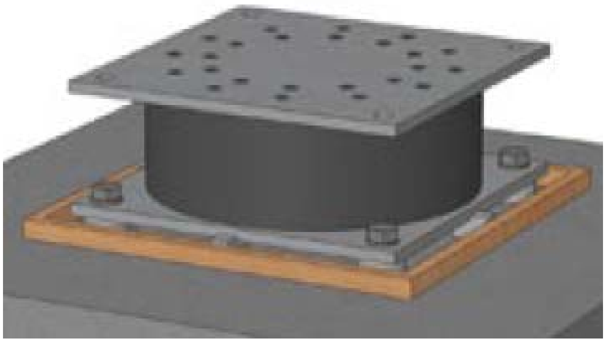
Caratteristiche fisico-meccaniche delle mescole ***Rubber compound phisical-mechanical characteristic***		Mescola / *Compound*			
		Normale nd / *Normal nd*	Morbida / *Soft*	Normale / *Normal*	Dura / *Hard*
Durezza / *Hardness*	Shore A3	50±3	40±3	60±3	75±3
Resistenza a rottura / *Tensile strength*	N/mm^2	20	20	20	18
Allungamento a rottura / *Tensile strain*	%	600	750	600	500
Modulo di elasticità G / *G Modulus*	N/mm^2	0,9	0,4	0,8	1,4
Smorzamento viscoso equivalente del solo elastomero/ *Viscous damping of the rubber*	%	4	10	10	16
Smorzamento viscoso equivalente dell'intero isolatore / *Equivalent viscous damping*	%	20%-40%	20%-40% (LRS) 10% (HDS)	10	16
Isolatore corrispondente / *Corresponding Isolator*		LRN	LRS / HDS	HDN	HDH

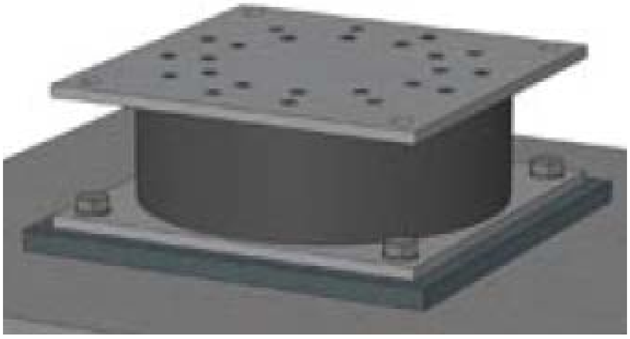
Because of the uncertainty of seismic action, the performed seismic analyses were carried out by using a deterministic approach and considering an isolated next generation reactor with 2% of faulted isolators.

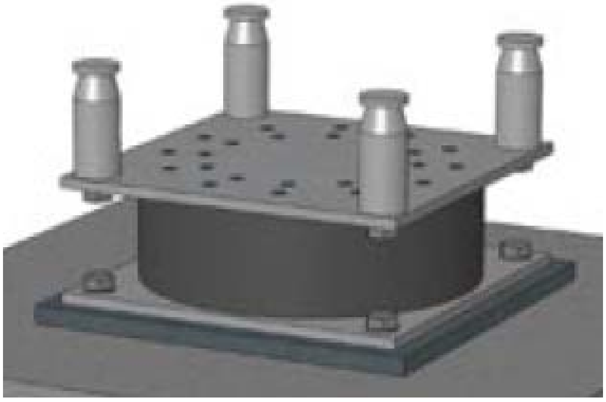
4. NUMERICAL ANALYSIS

To isolate the reactor building, against the assumed safe shutdown earthquake (SSE) with a very small probability of occurrence, a large number of seismic isolation bearings are located under the reactor foundation according to the installation scheme showed in Fig.6.


1) Casting of the isolator


2) Positioning of the isolators at the proper level


3) Casting of the joint in the non-shrink or epoxy mortar



4) Placing of the formwork of the superstructure

Fig.6- Installation scheme of isolators [1]

To establish the effects of earthquakes and proceed with design of earthquake resistant structures, as well as to analyze the existing structures, the first step is to develop a detailed representative model (Fig. 7) of the reference reactor structures to simulate closely their dynamic behaviour.

The modelling process has required the setting up of appropriate meshes assembled with suitable elements, as for example three-dimensional solid and/or shell isoparametric type elements, available in the used finite element modelling code, to represent the spatial discretization of the structure and thus the behaviour of each mentioned structure [2].

To simplify the analyses and reduce the calculation time some internal structures such as the reactor pressure vessel mass, the water inventory contained inside the suppression pools, the radioactive storage and spent fuel tanks, as well as the mass of the equipment that might be installed inside the AB, were assumed as masses distributed at their reference location.

In order to obtain a suitable three-dimensional base isolation system, a combination of horizontal and vertical isolators were considered assuming that the isolation devices were isoelastic and therefore suitable to be represented by means of springs and dashpots distributed in all directions.

Each isolator may be characterized by the horizontal and vertical stiffness and viscous damping; its behaviour is therefore defined by two parameters: the angular frequency ω and the damping ratio ξ_b [3-4].

In this study simplified isolators, constituted by springs and dashpots, are indicated in the previous Fig. 7 as an array of parallel red line segments under the AB foundation.

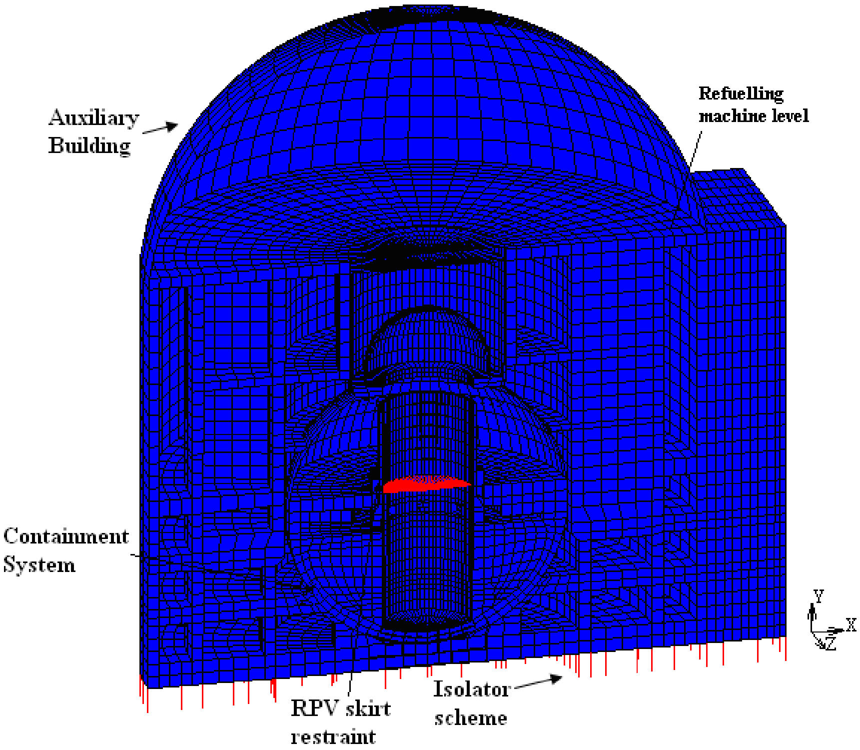


Fig. 7 - IRIS AB models with isolators

Before to perform seismic analyses the correct number of isolators that allowed to attain the horizontal isolation frequency of 0.7 Hz were calculated for the peak ground acceleration of the input SSE and the isolation bearing characteristics.

On the basis of the isolator characteristics, indicated in Tab.2, the number of isolators, assumed to be very stiff in the vertical direction, resulted to be 121, in the hypothesis that the fundamental frequency (isolation frequency) of the AB system was equal to 0.7 Hz.

Table 2- Isolator characteristics

Rubber diameter	1000 mm
Maximum vertical load during seismic event	≈ 14000 KN
Maximum horizontal load	≈ 22600 KN
Horizontal stiffness	13.09 KN/mm
Vertical stiffness	8508 KN/mm
Damping	15%

In Fig. 8 it is shown a distribution example of isolation devices.

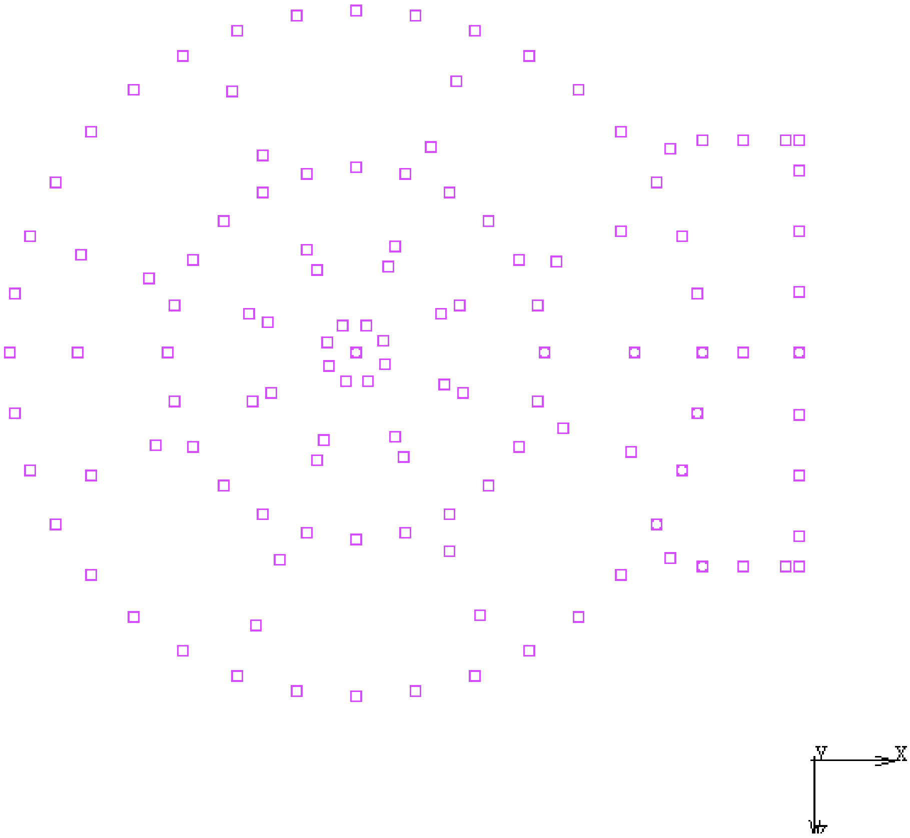


Fig.8 - Isolators distribution

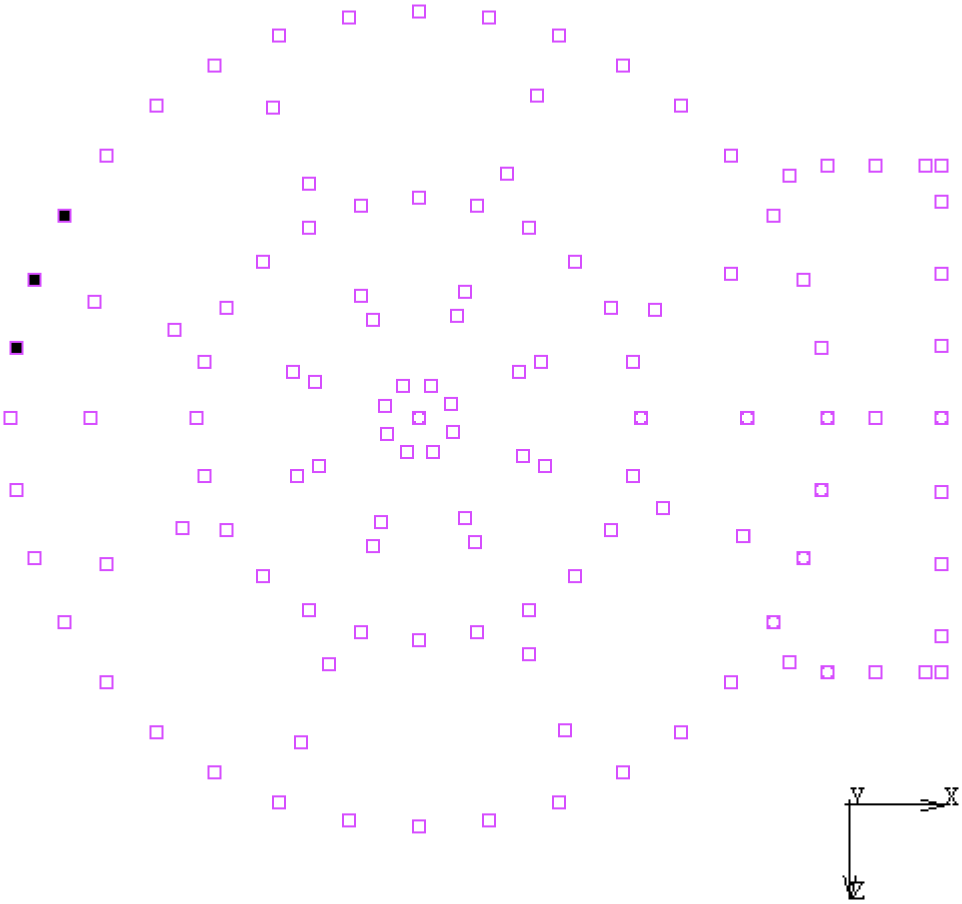
4.1 Analysis Method

The analysis method is based on a deterministic seismic assessment which is made possible by means of a numerical evaluation of the propagation of seismic waves along the considered AB structure. Therefore a numerical evaluation of the AB structural response is obtained by using a finite element model and suitable code, that allowed to represent all relevant reactor structural components with their real geometrical and material properties.

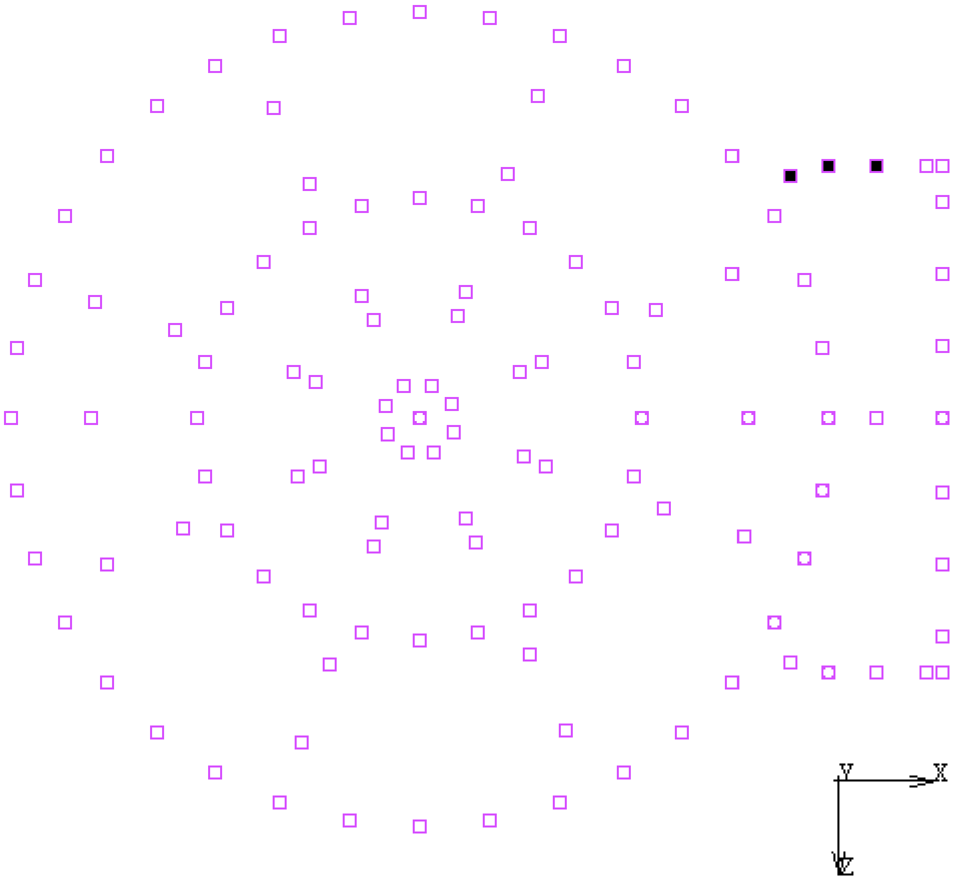
During the seismic event, the released energy is in some measure absorbed in the structure, in both the form of kinetic and strain energy, whilst the remaining part is dissipated through the damping and by the structural hysteresis behaviour of isolators.

Because of the uncertainty of seismic action effects , the performed seismic analyses on a possible isolated IRIS reactor configuration were carried out by considering also 2% of faulted isolators (indicated in the following figures with black box).

In this context, the failure of isolators is represented by the absence of isolators in respect to the original distribution (indicated in Fig.8). Moreover three different axisymmetric and random configurations, as shown in Figs. 9, were identified, analysed and discussed.



(a)



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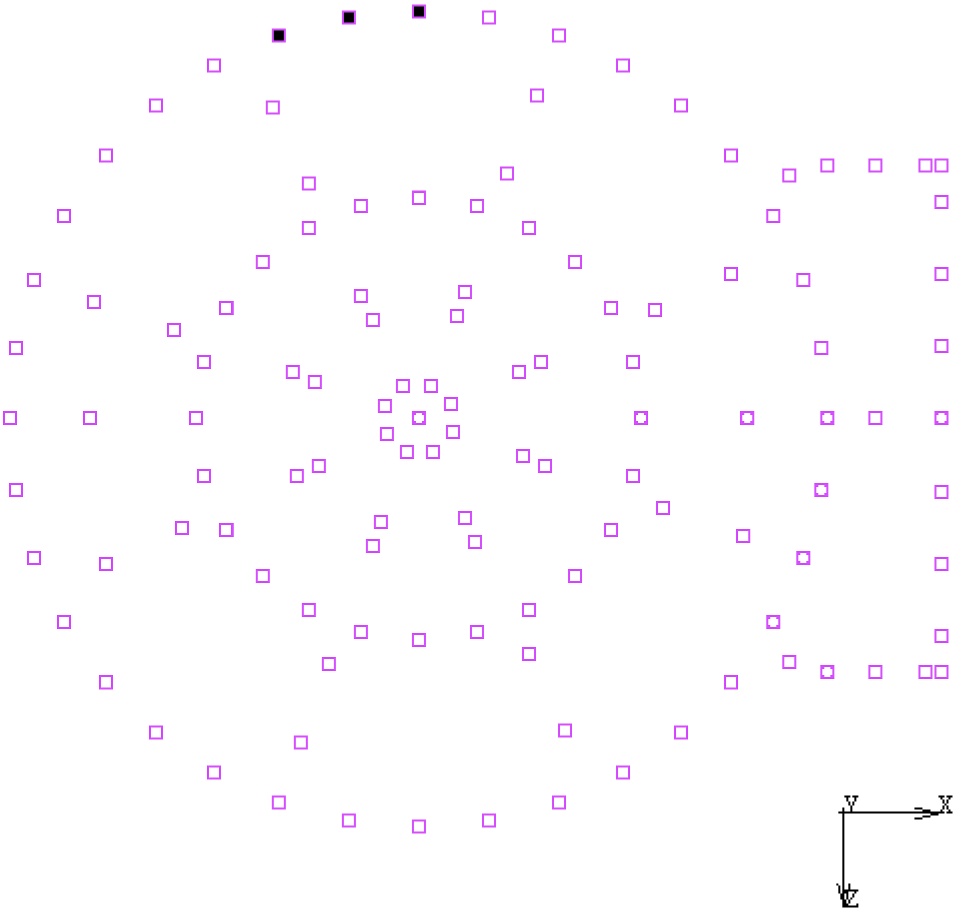


(c)

Figs. 9 - The three considered faulted isolators configurations: scheme 1 (a); scheme 2 (b); scheme 3 (c)

In order to understand the dynamic response of the building and to evaluate its dynamic characteristics, input Acceleration Time Histories (ATH) were applied, along the horizontal and vertical directions, at the base of the isolation system of the nuclear power plant structure.

The shaking ground motion in form of ATH, like the one shown in Fig. 10, characterized by a peak ground acceleration of 0.3 g, were derived from the response spectra, according to the Regulatory Guide US NRC 1.60, and applied at the base mat of the nuclear building assumed to be embedded in stiff rock soil.

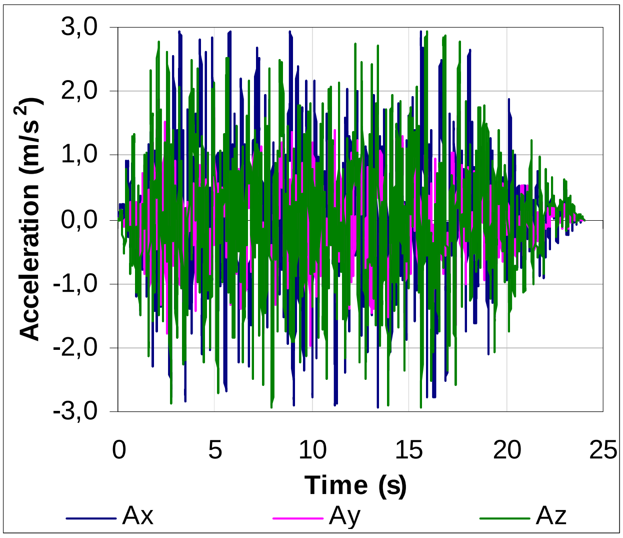


Fig. 10 - Shaking ground motion in form of ATH

The vertical acceleration was taken equal to 2/3 of the horizontal one in the entire frequency range.

5. NUMERICAL RESULTS

Before the development of the dynamic transient analysis, a modal analysis was carried out to evaluate the natural frequencies and modes of all the most relevant components of the considered system.

Three-dimensional dynamic analyses of AB structure has been done, with the available computational capability, in order to describe and analyze the main relevant structures of the reference IRIS system.

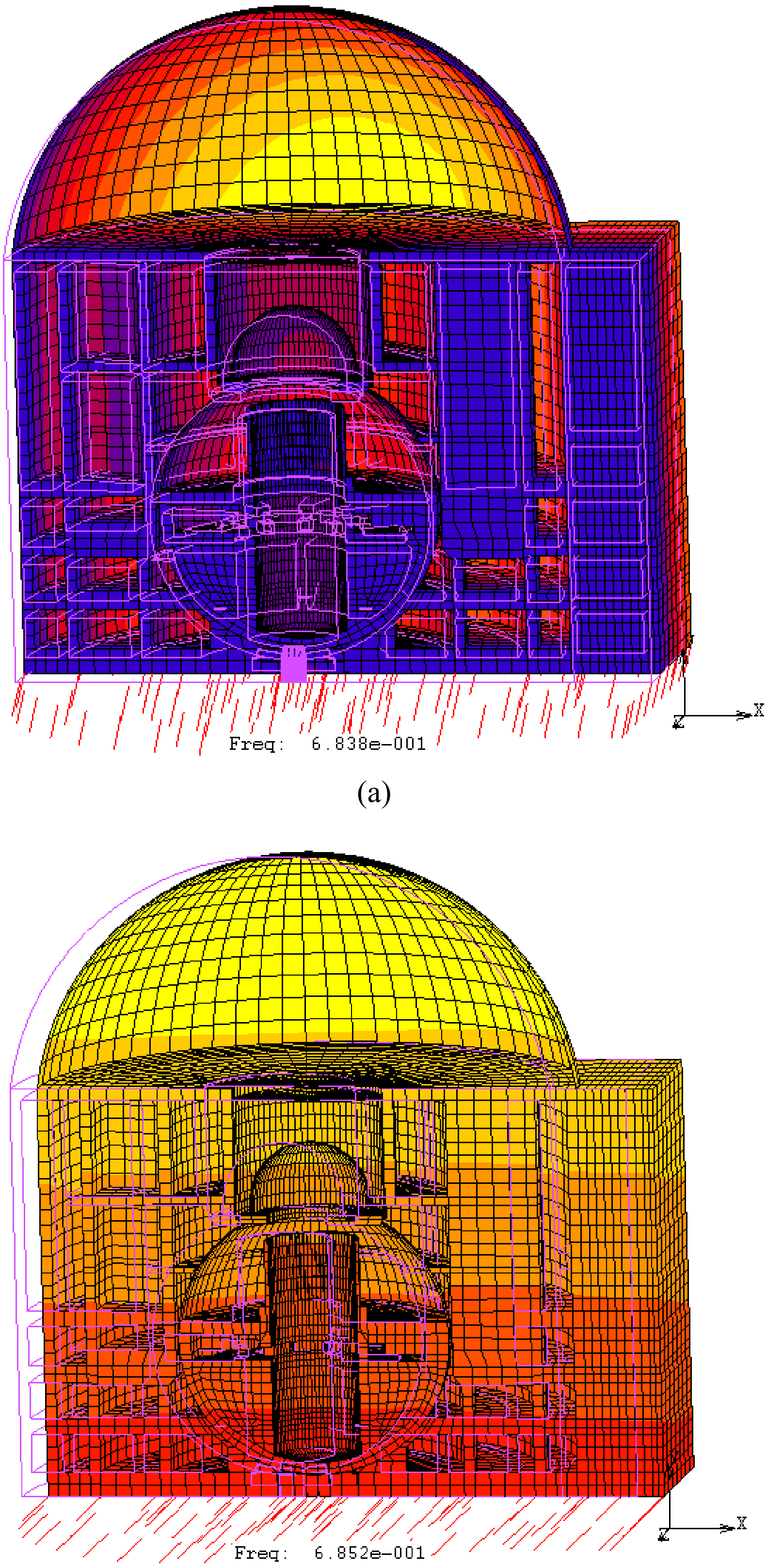
A preliminary modal analysis, that provided information on the total significant response modes of AB structure, was carried out in all the three faulted isolators configurations considered to determine the influence of the faulted isolation bearings on the natural dynamic behaviour of structures.

Afterwards seismic transient analyses were performed in the mentioned configurations assuming for isolators an horizontal and a vertical damping ratio respectively equal to 15 and 20%; while for the AB structures, according to the Equivalent Rayleigh damping, a damping ratio of 5 and 7 %, respectively for welded steel and reinforced concrete structures (NRC Regulatory Guide 1.61 (USNRC, 1973)) were assumed.

5.1 Modal Analyses Results

The natural frequency values and modal shapes provided information about the nuclear island seismic responses characteristics such as earthquake amplification factors, which are strictly related to the energy dissipation or damping effects of each material considered.

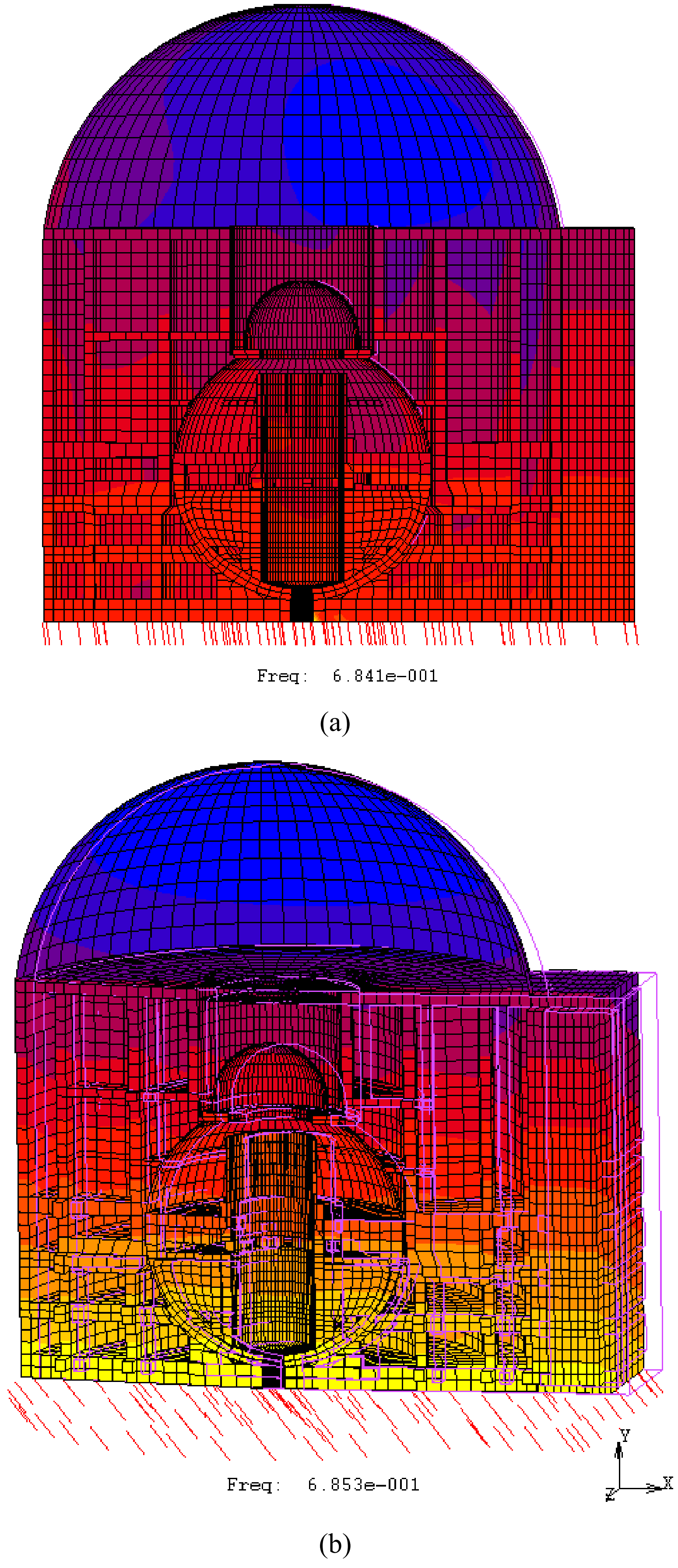
In the present study the 3-D finite element models were used to evaluate the main modes and frequencies of the auxiliary building and containment system structures, whose deformed shapes are shown in the following Figs. 11,12 and 13, corresponding respectively to the calculated 1st and 2nd modes in the translational horizontal directions (along z, x axis) and 3rd one is observed to be a torsional mode.



(a)

(b)

Figs. 11- Deformed dynamic behaviour of AB in the scheme 1 at 1st (a) and 2nd (b) frequencies



(a)

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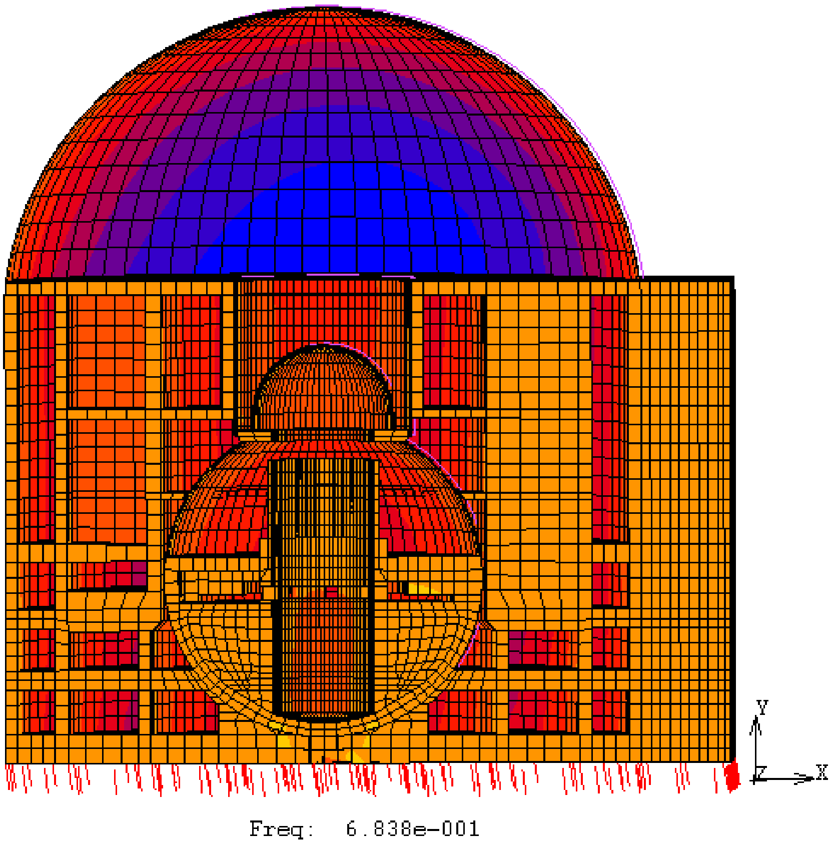
Figs. 12 - Deformed dynamic behaviour of AB in the scheme 2 at 1st (a) and 2nd (b) frequencies



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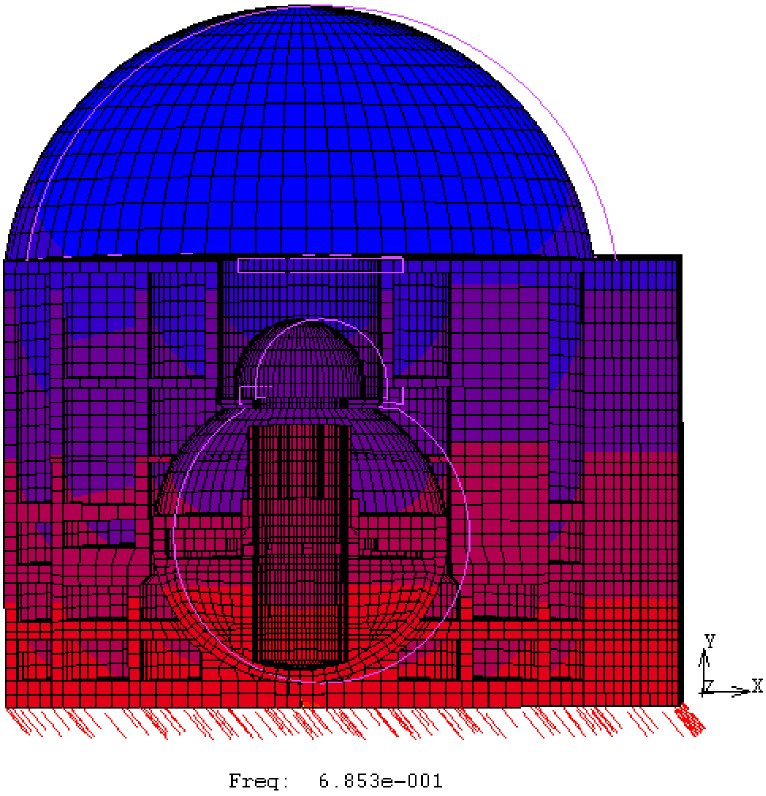


(b)

Figs. 13- Deformed dynamic behaviour of AB in the scheme 3 at 1st (a) and 2nd (b) frequencies

5.2 Transient Analyses Results

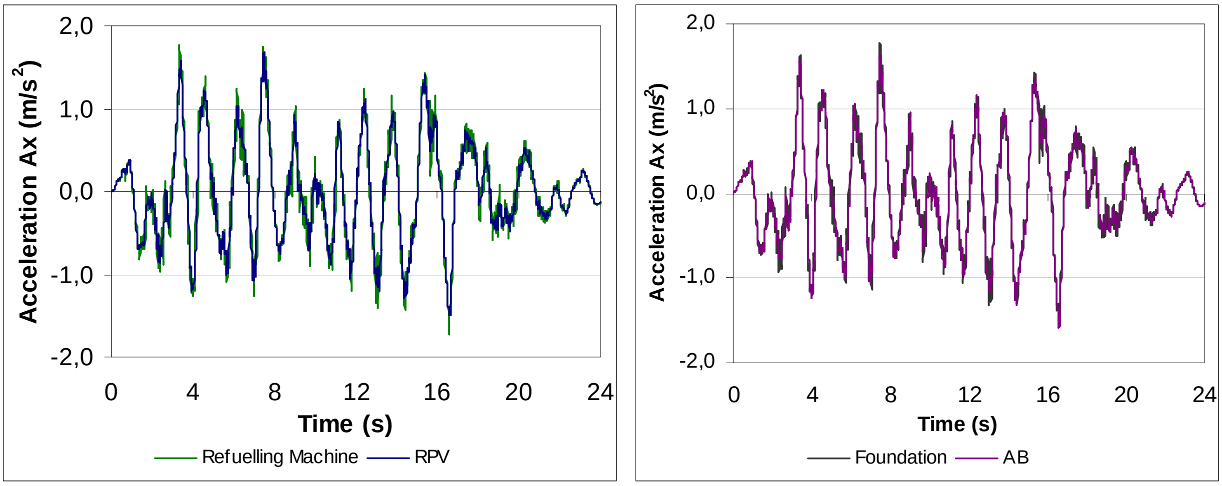
In order to analyze the effects of a SSE on the considered nuclear building type and obtain the amplification or decreasing factor which may influence the seismic response of IRIS AB accounting for the energy dissipated by structural damping systems (isolators), several analyses were carried out.

The isolated structural model was coupled with the free-field input motion (in time domain) by using the Time History approach in order to analyze the propagation of dynamic loads from the free field for a rather "severe" earthquake, characterized by peak ground accelerations of 0.3 g. Overviews of obtained displacement and acceleration values inside the auxiliary building are showed in the following graphs for each of the three faulted isolators configurations.

In Figs. 14, 15 and 16 the transmitted accelerations up to the most relevant AB internal components are indicated whilst in Figs. 17, 18 and 19 the relative displacements respectively in the some cases of scheme 1, scheme 2 and scheme 3 are presented.

The comparison of the obtained acceleration values highlighted a relevant "similarity" for all the points inside the auxiliary building, even if 2% of isolators are damaged (faulted).

Among the carried out acceleration values it was observed a discrepancy about 10% due to the influence of eccentricity and torsional effects deriving from the assumed failure conditions (the center-of gravity of the structure does not coincide with the elastic center of the isolation systems).



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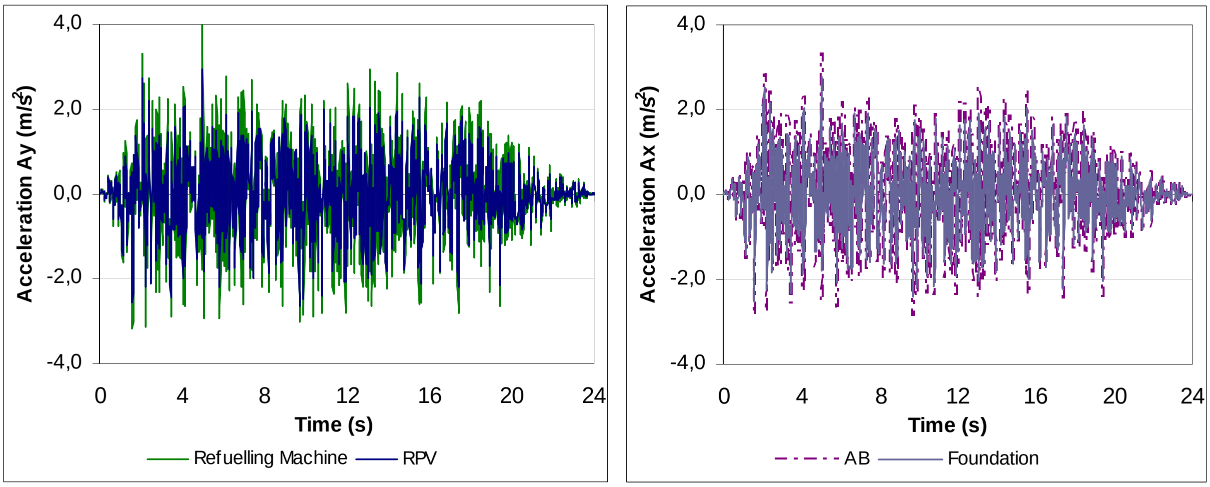

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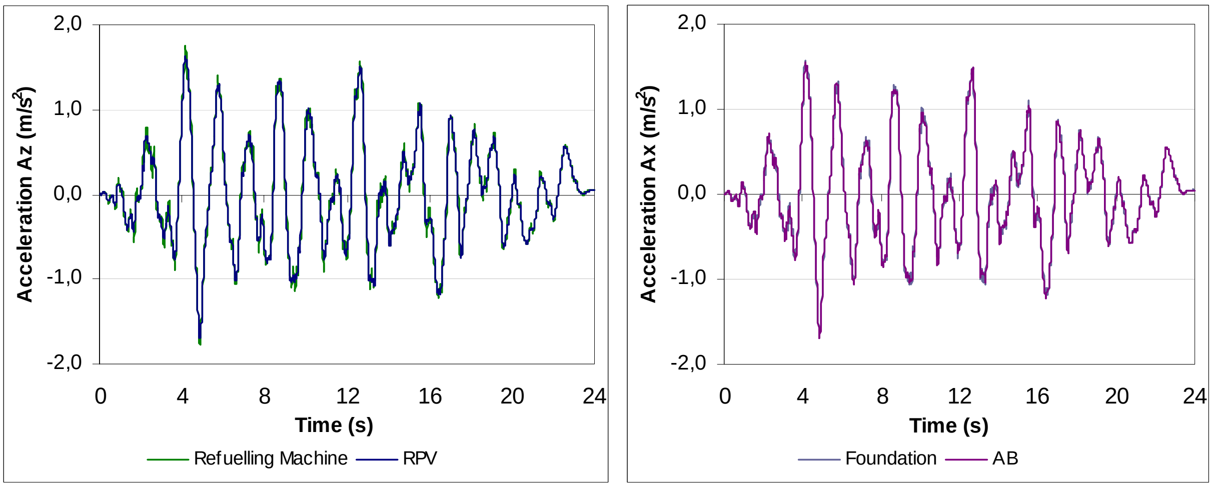
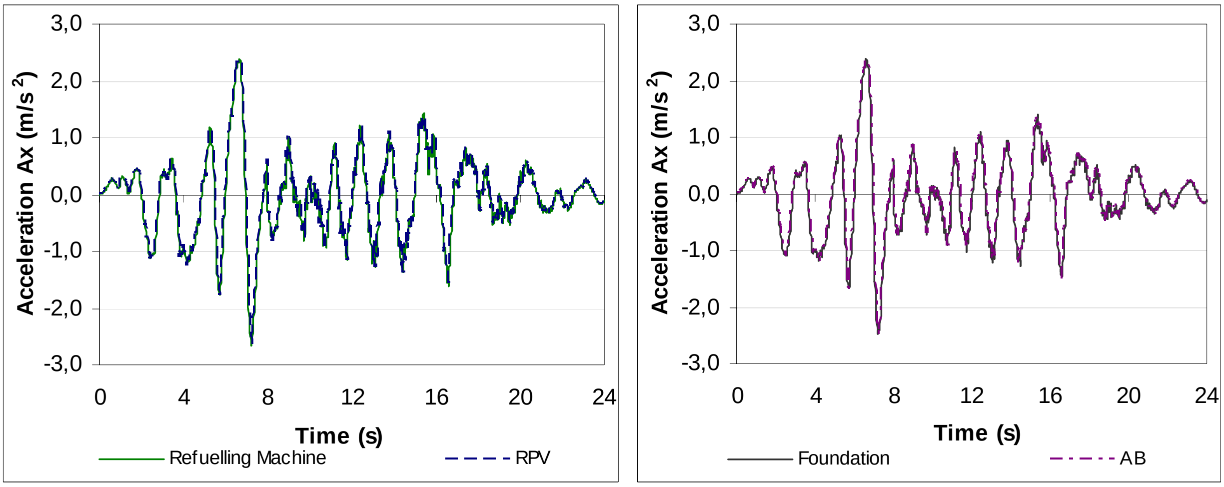
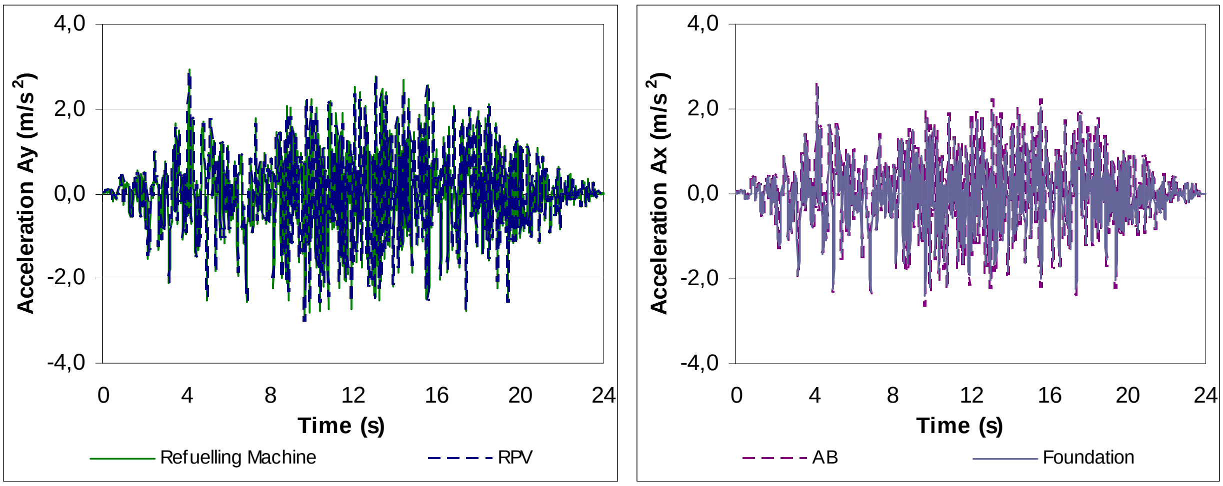


(c)

Figs. 14- Accelerations for the faulted isolators configuration: scheme 1



(a)



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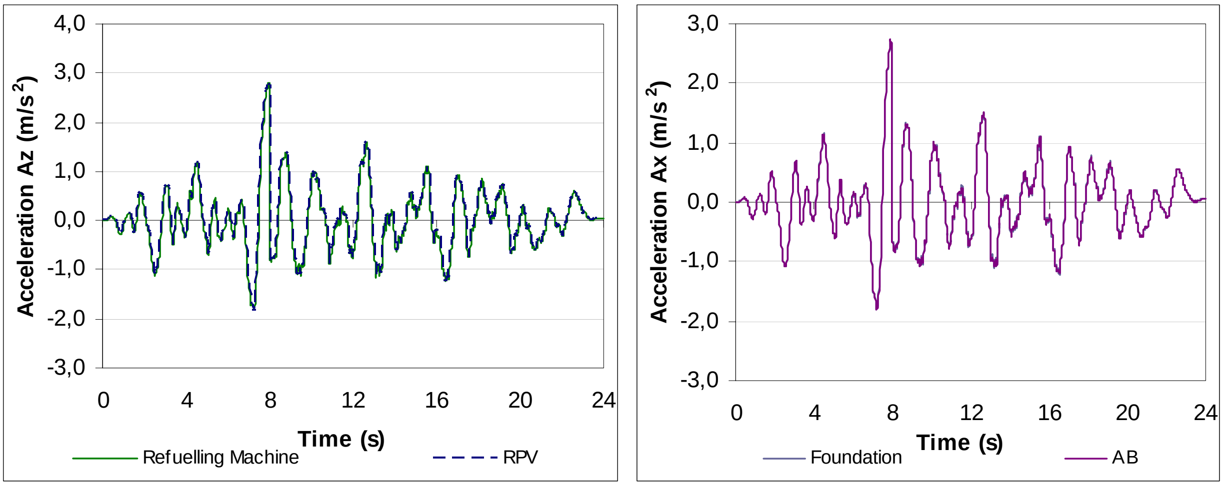
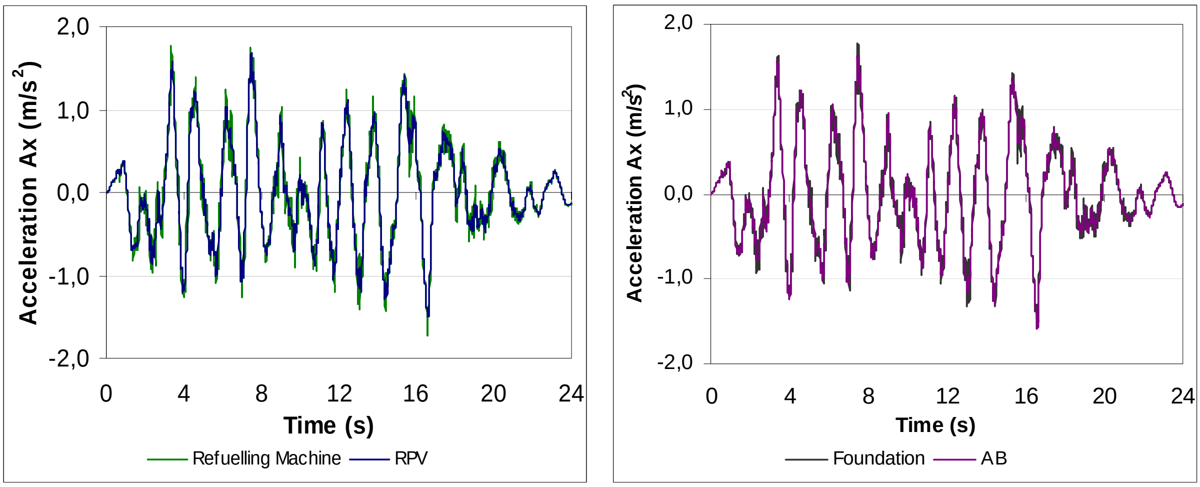
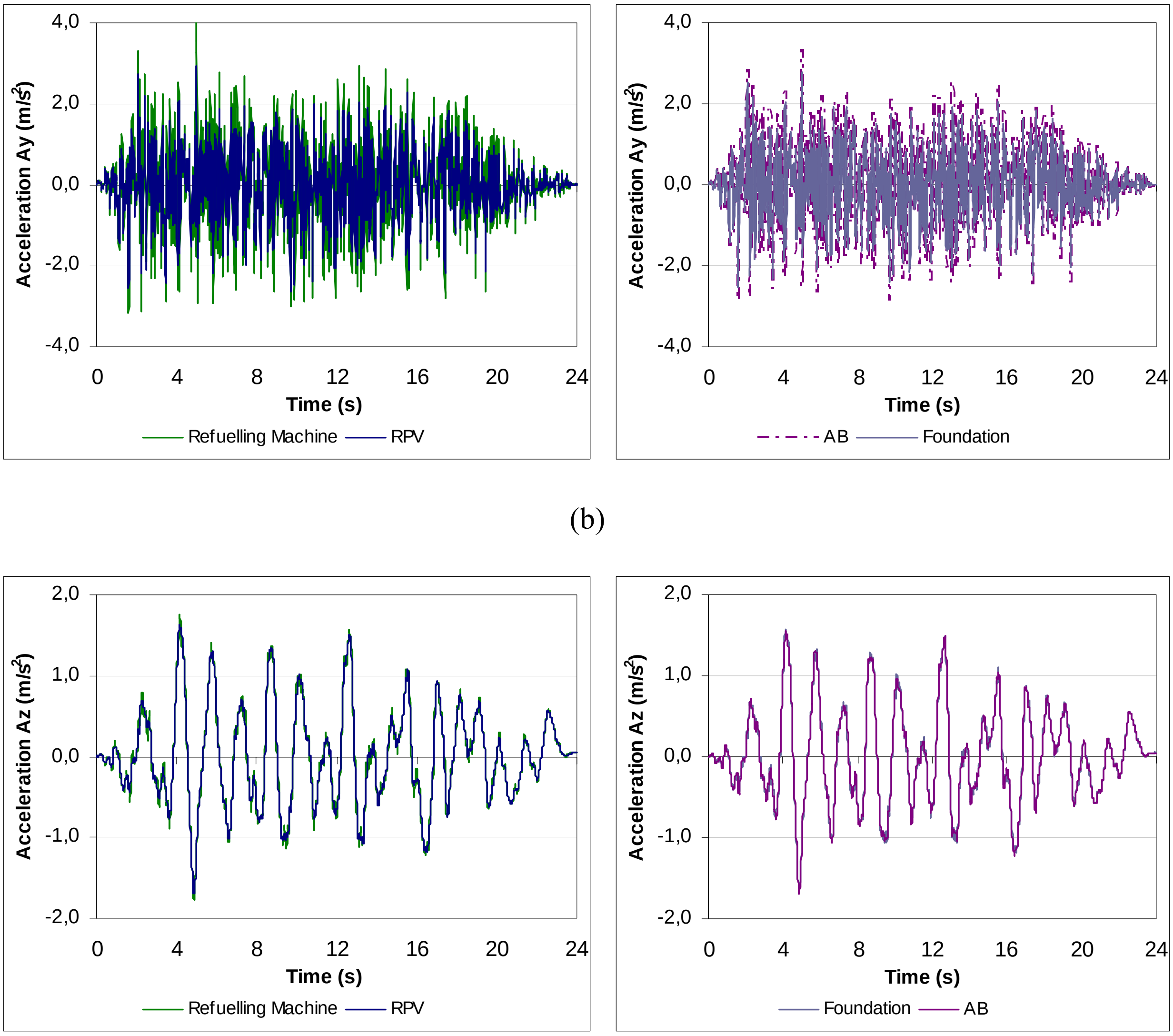


(c)

Figs. 15- Accelerations for the faulted isolators configuration: scheme 2



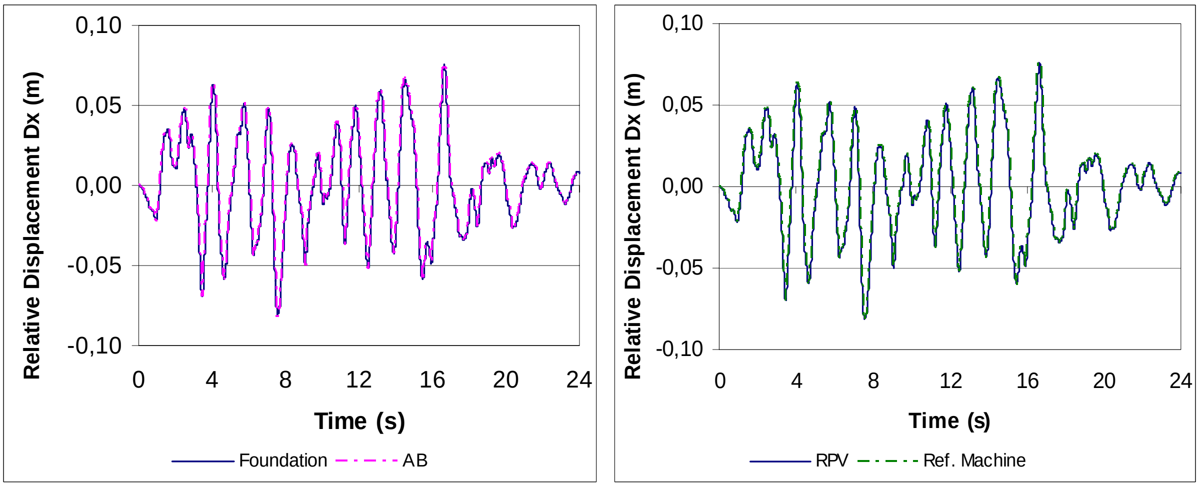
(a)



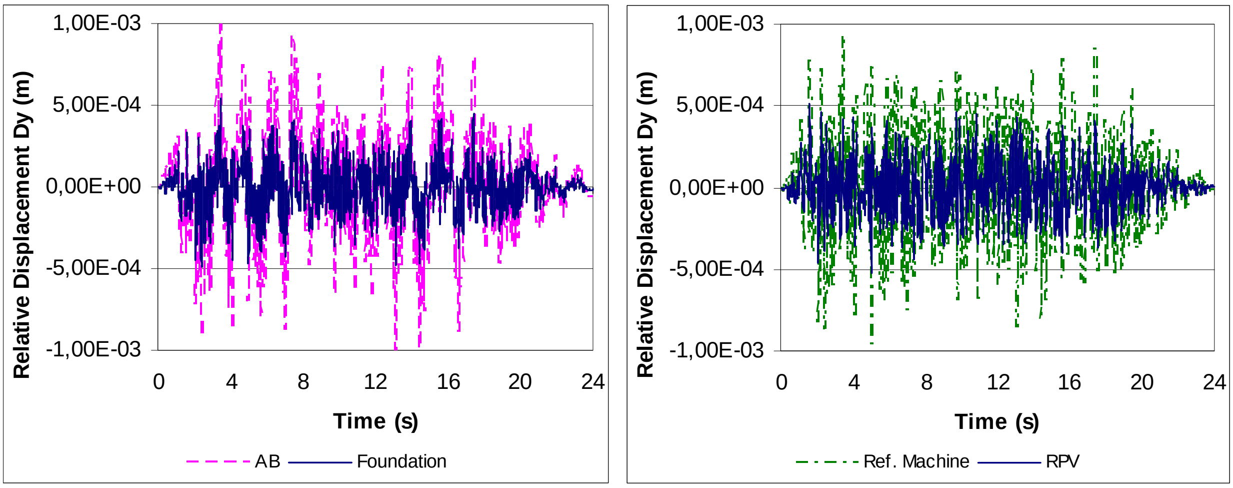
(b)

(c)

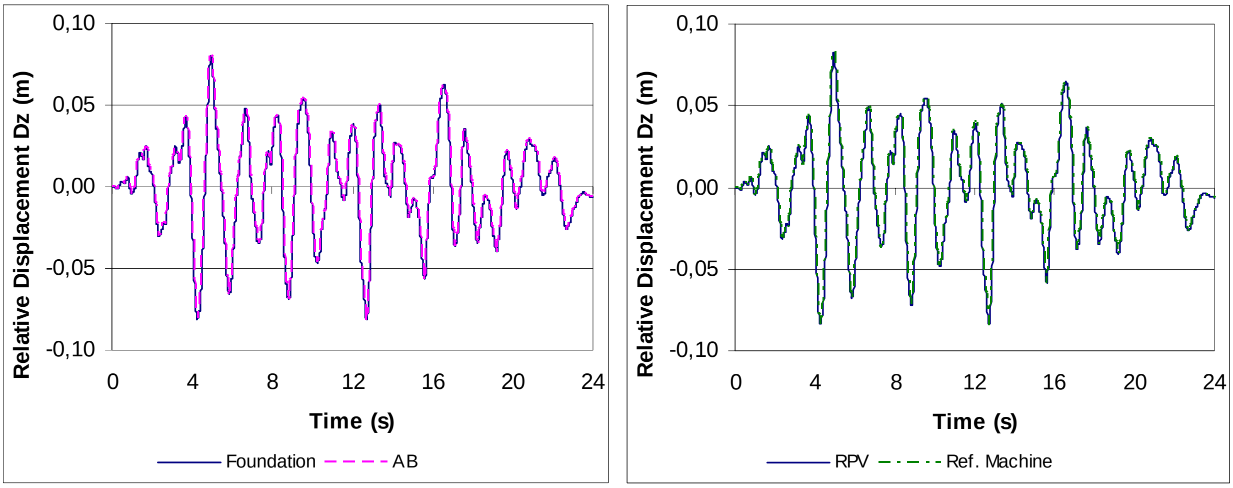
Figs. 16- Accelerations for the faulted isolators configuration: scheme 3



(a)

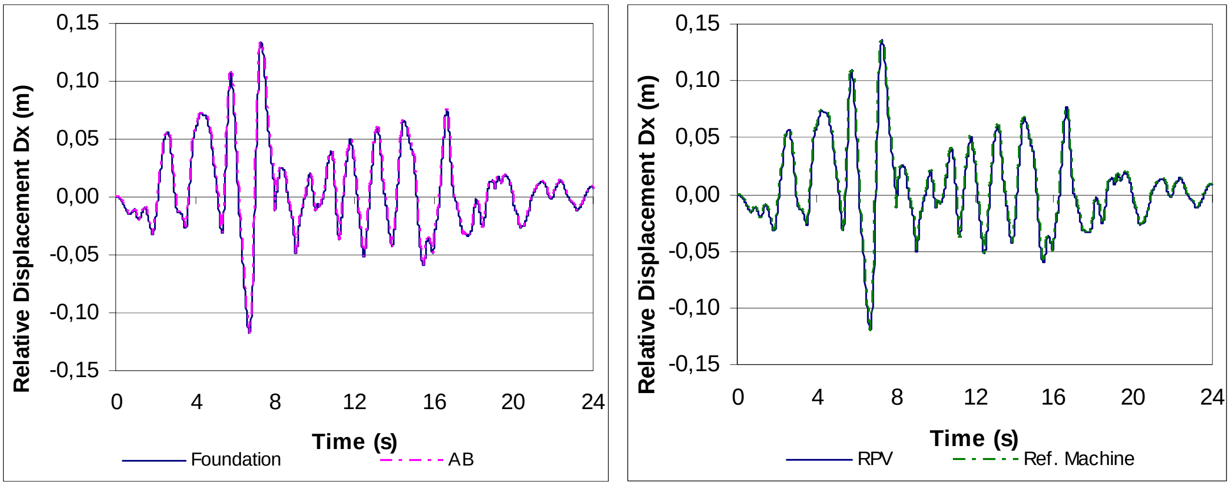


(b)

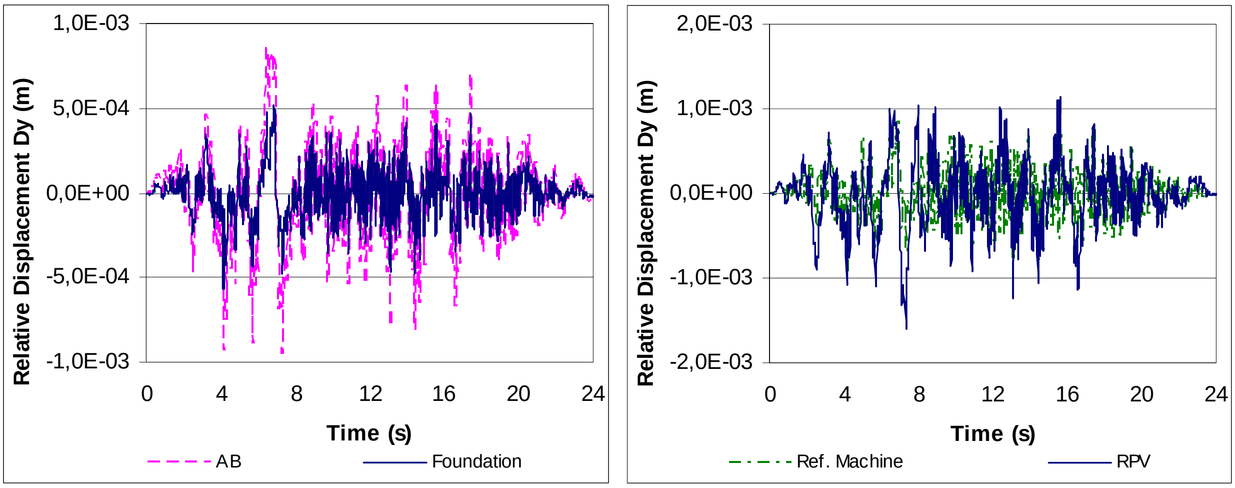


(c)

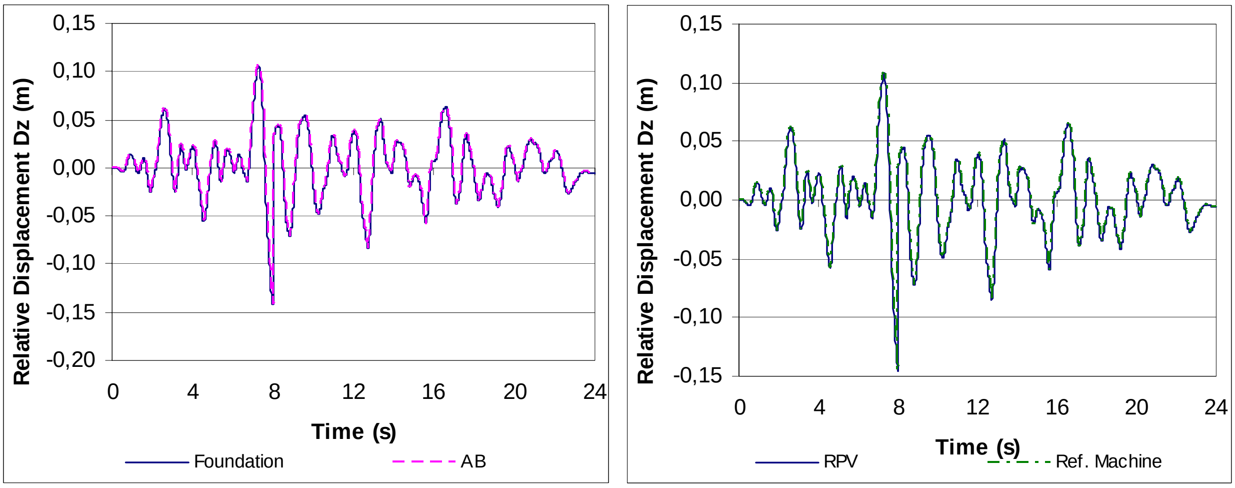
Figs. 17- Relative displacements for the faulted isolators configuration: scheme 1



(a)

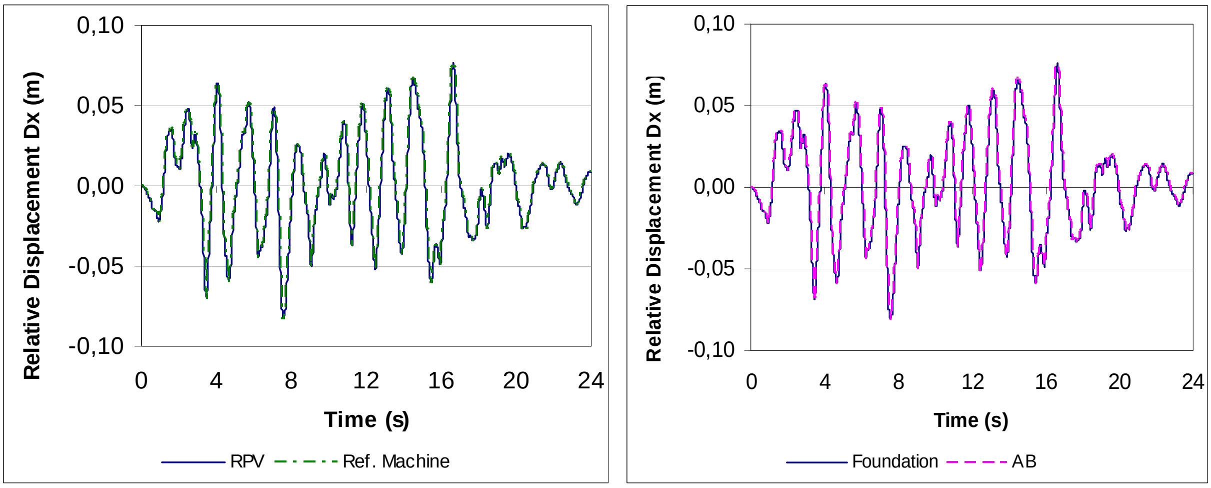


(b)

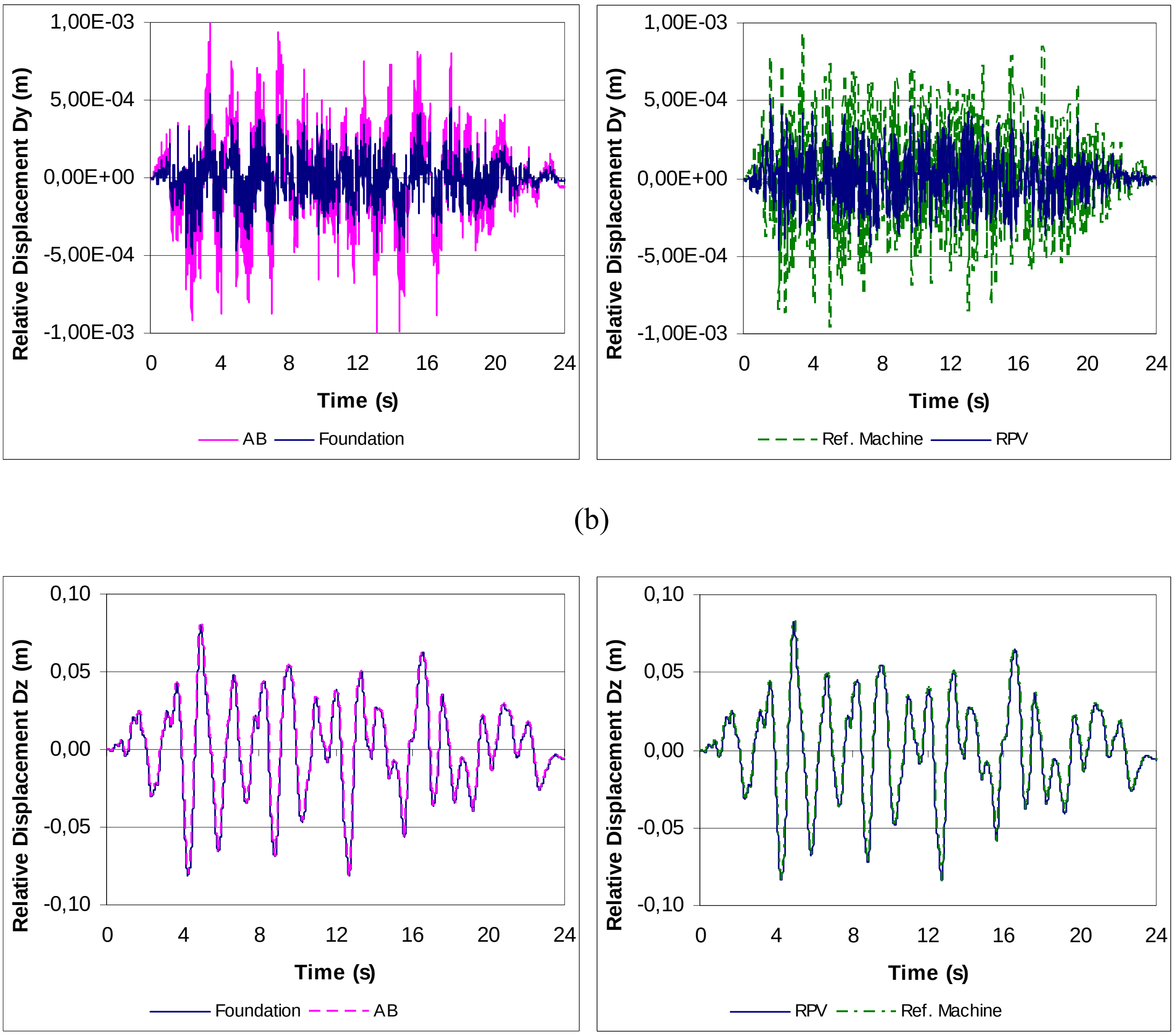


(c)

Figs. 18- Relative displacements for the faulted isolators configuration: scheme 2



(a)



(b)

(c)

Figs. 19- Relative displacements for the faulted isolators configuration: scheme 3

Besides that the effectiveness of isolators system seemed to be not influenced by the presence of some faulted isolators, randomly distributed, confirming the positive influence in damping the earthquake energy content up to about 30- 40 %.

As for the corresponding horizontal relative displacements it was observed that this values are quite similar in the three cases and limited below 10 cm.

The vertical acceleration behaviours highlighted an amplification along the AB height, reaching 3.5 m/s^2 (mean value) in correspondence roughly of the refuelling machine level.

6. CONCLUSION

The adoption of seismic isolation has being investigated for a Gen III+/IV reactor building in order to reduce the seismic induced residual risk.

Preliminary dynamic analyses for the a possible outer NPP containment building were performed adopting a deterministic approach, by means of FEM codes, assuming an isoelastic model, based on springs and dashpots, to represent the isolation system.

In order to understand the dynamic response of the building and to evaluate its dynamic characteristics, input Acceleration Time Histories (ATH) were applied, along the horizontal and vertical directions, at the base of the isolation system of the nuclear power plant structure.

In the present study the failure of isolators (represented by the absence of isolators, assumed 2 % of the overall isolators) was identified, analysed and discussed assuming three different axisymmetric and random configurations in respect to the original distribution.

The obtained results highlighted the effectiveness of isolation system that seemed to be not influenced by the presence of some faulted isolators, confirming therefore the positive influence in damping the earthquake energy content up to about 30- 40 %.

On the other hand, the vertical acceleration behaviours highlighted an amplification along the AB height, reaching 3.5 m/s^2 (mean value) in correspondence roughly of the refuelling machine level.

The carried out results highlighted that the safety and the performance of the considered isolation devices were ensured also when some randomly isolator device are faulted.

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