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Seismic Isolation of the IRIS NSSS Building

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1 ABSTRACT

The safety-by-design^{TM} approach adopted for the design of IRIS resulted in the elimination of some of the main accident scenarios classically applicable to PWRs and to the reduction of consequences of the remaining classical at-power accident initiators. As a result the Core Damage Frequency (CDF) from at-power internal initiating events was reduced to the 10^{-8}/ry order of magnitude, thus elevating CDF from external events (seismic above all) to an extremely significant contributor.

The safety-by-design^{TM} approach was exported to the design of the IRIS Nuclear Steam Supply System (NSSS) building for reducing the impact of seismically induced scenarios. The small footprint of the IRIS building makes the isolation of the entire nuclear island relatively easy and economically competitive. The isolated NSSS building dramatically reduces the excitation perceived by all the main IRIS components. This solution is also contributing to standardization, leading to a single design compatible with a variety of seismic conditions.

The conceptual IRIS seismic isolation system is herein presented, along with a selection of the results of preliminary analyses. The approach adopted for the computation of the fragility analysis of the components is also briefly summarized, focused on the analysis of the isolators themselves.

2 INTRODUCTION

IRIS is a small (335 MWe) modular integral nuclear power plant being developed by an international team coordinated by Westinghouse and involving 24 organizations from 10 countries around the World, spanning from industries to universities and from utilities to national laboratories.

The design philosophy that has been driving the development of the IRIS reactor from its very beginning is the "safety-by-design^{TM}", which is aimed, when possible, at designing out potential hazardous scenario. Those hazardous scenarios that cannot be completely designed out are tackled with the aim of minimizing the frequency of occurrence, see Carelli et al (2004), and then with the adoption of simple passive systems, thus maximizing the safety and reliability of the entire plant.

Within the IRIS safety-by-design^{TM}, a risk-informed approach to the design phase of the reactor has been adopted as a quantitative way to rank and select different design solutions. In this framework a Probabilistic Risk Assessment (PRA) model of the IRIS has been developed in the very early phase of the design as one of the main ranking and supporting tool. The IRIS PRA model is used to evaluate the impact of each design solution in terms of both reduction of the Initiating Event Frequency (IEF) and of the conditional core damage probability. As reported by Maioli et al (2005), the structured deterministic/probabilistic approach to the design phase of the IRIS has so far resulted in outstanding safety metrics for internal initiating events at power, with an estimated CDF of the order of 2E-08/ry.

The very low internal events CDF resulted in a re-distribution of the classical PWR leading risk contributors with a subsequent significant rise in importance of accident scenarios induced by external events: seismic-induced accident scenarios were by large becoming the main contribution to risk. The same safety-by-design^{TM} approach that performed so well for protection from internal events was therefore exported from the design of the IRIS reactor and of its safety systems to the design of the IRIS NSSS building, with the goal of reducing the impact of seismically induced scenarios to the overall plant risk.

When dealing with seismic risk, two main parameters need to be considered: the first is the hazard, i.e., a measure of the frequency of a seismic event as a function of its magnitude. Seismic hazard can be represented through hazard curves, which report the frequency of exceeding a specific magnitude as a function of either the Peak Ground Acceleration (PGA) or the Spectral Acceleration (SA). Figure 1 shows an example of a seismic hazard curve as a function of PGA.

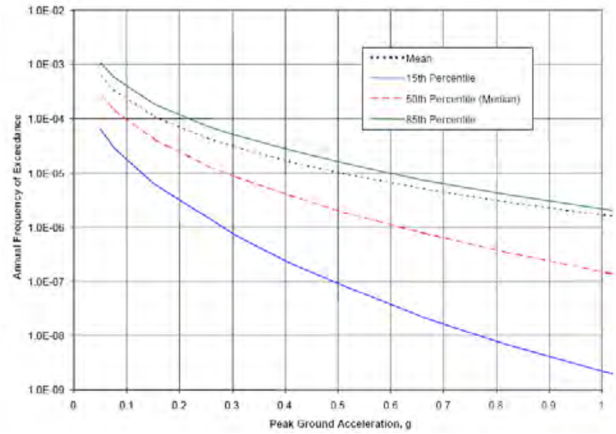

Figure 1. Seismic hazard curve as a function of PGA

The second parameter involved in the evaluation of seismic risk is the fragility of single components or structures, which measures the conditional failure probability of a component as a function of the severity of the seismic input (again measured in terms of PGA or SA). Figure 2 shows a typical fragility curve.

Seismic risk is then calculated, as shown by Nusbaumer (2005), through a combination of hazard and fragilities for significant components. A PRA assisted design approach to the layout of the IRIS NSSS building can in principle result in a lower seismic induced CDF. Obviously, while dealing with external events, reduction of the initiating event frequency is beyond the area of influence of the designer, thus the main focus needs to be on the fragility of the most significant components and structures.

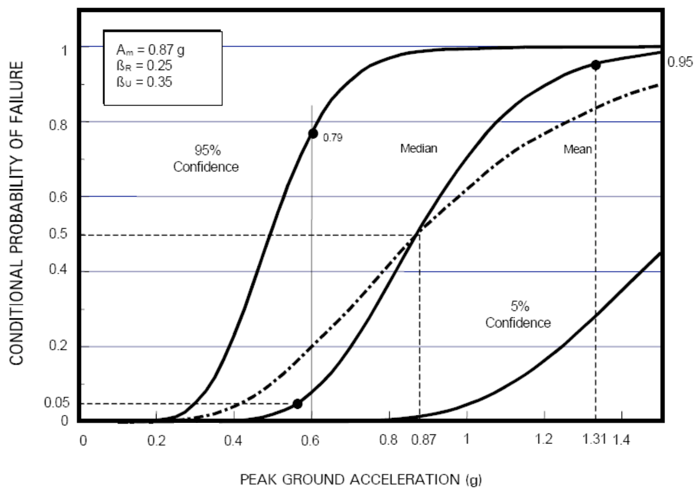

Figure 2. Fragility curve as a function of PGA

The extremely compact IRIS NSSS building (see figure 3), which includes all the structures usually included in the reactor building, the auxiliary building and the control building of a currently operated PWR, thus including all the Emergence Safety Features (ESF), all the emergency heat sink and all the required support systems, makes the idea of seismic isolation of the entire nuclear island a relatively easy and economically competitive solution.

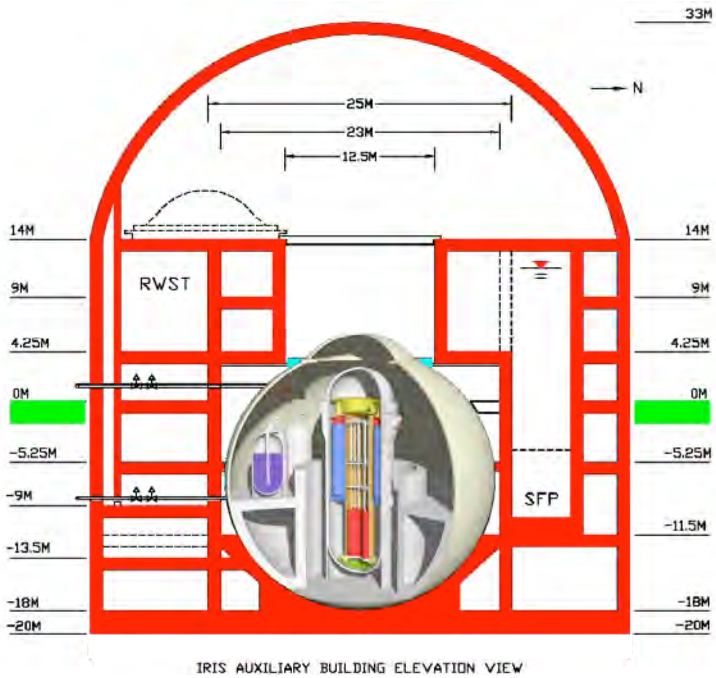

Figure 3. IRIS conceptual NSSS building: elevation view

The adoption of seismic isolators, by decoupling the seismic input perceived by the IRIS NSSS and the seismic excitation actually perceived by the IRIS reactor vessel and ESF Structures Systems and Components (SSCs), is effectively shifting all fragilities towards the right end side, thus significantly reducing the conditional probability of seismic induced failures. The combination with the hazard curves is now non-trivial only in those portions of the hazard curve (i.e., with extremely high accelerations), which are associated with extremely long return periods. Obviously, the treatment of such portions of the hazard curve represents a critical point, due to the high uncertainties associated to the lack of statistical data.

The seismic isolator system is now understandably the most critical component, and significant attention needs to be devoted to its reliability, which is expected to be high given the significant number of isolating devices and their passive nature; practically speaking, however, the adoption of seismic isolators has the capability of virtually eliminating the seismic-induced CDF.

3 SEISMIC ISOLATION SYSTEM DESIGN

IRIS seismic isolation system is made by High Damping Rubber Bearings (HDRBs), which are the most diffused and reliable isolators currently used all over the world. At present, over 7000 buildings are seismically isolated and most of them are provided with HDRBs. Seismic isolation technique is also used for bridges and viaducts and for industrial plants. However, only two nuclear facilities are currently provided with base isolation, both equipped with PWRs: the first at Cruas (France) isolated with 3600 PTFE (Polytetrafluoroethylene, better known as Teflon) pads and the second at Koeberg (South Africa) isolated with 1830 rubber bearings coupled with friction plates. These isolation systems, designed and manufactured in the early 70s, are quite ‘rough’. Nowadays, HDRBs have better characteristics, such as the re-centring capability and a more reliable damping factor, and can provide better performances. Notwithstanding that only two power plants have been isolated up to now, the most recent and innovative nuclear plants under design or development foresee the seismic isolation. Two of them, the Jules Horowitz Reactor and the International Thermonuclear Experimental Reactor are under construction at Cadarache, France; they both use HDRBs.

In the IRIS plant, HDRBs are installed between the foundation slab and the base of the NSSS building (figure 4). They are made of alternated rubber layers and steel plates, bonded together. The high-damping rubber can give a damping factor ranging from 10% to 20% and can have a shear modulus (G) ranging from 0.8 to 1.4 MPa.

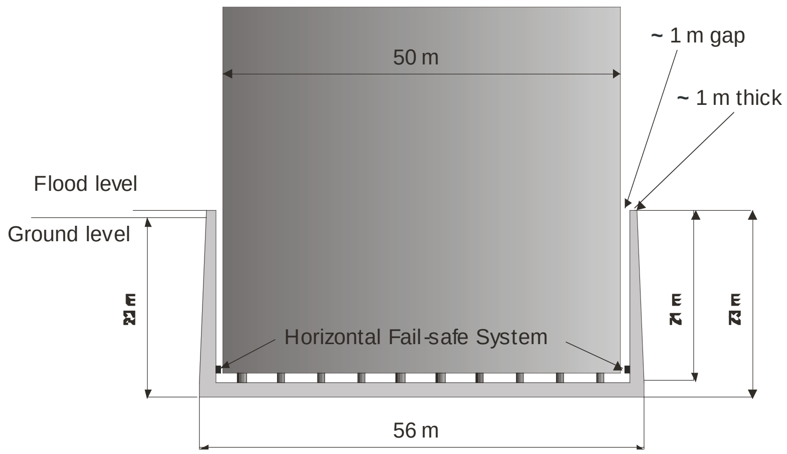

Figure 4. Sketch of the isolation system layout under the IRIS NSSS building

Steel plates give a high vertical stiffness to the isolator, which must continuously and safely carry the dead load of the superstructure, but easily allow horizontal relative displacements. Thus, the isolated building assumes a quite low natural frequency in the horizontal direction, typically in the range 0.5 - 0.7 Hz, where the earthquake has generally quite low energy. During the seismic attack the isolated building moves like a rigid body over the isolators, which are strained in shear (continuing to carry the dead load). The absolute acceleration of the building can be 2-3 times lower than the peak ground acceleration and is the same for each component at any level. On the contrary, in a conventionally founded building, the acceleration amplifies, especially at the highest floors, where it can be 3-4 times higher than the peak of the ground. Thus, a component located at the top of a conventionally founded building, could be subjected to an acceleration one order of magnitude higher with respect to the case of isolated building. The lower the isolation frequency is, the lower the absolute acceleration of the building (and then the inertial forces and stresses in the structure and components), but also the higher the relative displacement between the building and the ground. The isolation system design must therefore be optimized to have the lowest acceleration values in the building which are as low as necessary to protect the inner components, compatibly with the need to have a low relative displacement between building and ground, to reduce the difficulties in designing the expansion joints and the connections of all the pipelines and service networks which cross the joint between the isolated and non isolated buildings. If the isolated building contains critical components with a quite low natural frequency, it is necessary to adopt a low isolation frequency (say 0.5 Hz). In this case, the relative displacement between the building and the ground could be quite high (30 - 40 cm or even more, depending on the seismicity of the site). If, on the other hand, the superstructure is quite stiff, the isolation frequency can be higher. The IRIS isolation system envisions a horizontal fail-safe system (made of suitable rubber dampers installed all around the base of NSSS building, see figure 4) that limits the maximum deformation of the isolators and allows to exactly know the maximum deformation of the expansion joints on the pipelines and service networks crossing the gap between isolated and conventional buildings.

The most critical expansion joints are those to be installed on the steam pipelines; they are ‘*3-pins*’ systems made of one angular and two gimbals joints (figure 5), allowing for total release of internal forces. Very similar joints, designed for liquefied natural gas storage tanks in petrochemical plants, have already been tested on a shaking table in the framework of the INDEPTHS European Project (Forni, 2006). They are capable of supporting relative displacements up to 80 cm.

A preliminary cost analysis of the application of the seismic isolation to the IRIS NSSS building has been done by ENEA. Manufacturers of isolators and expansion joints, as well as construction companies, have been contacted and the various aspects analyzed in detail. Most of the total cost (3-4 M€) is due to the need to build an additional sub-foundation slab and a lateral containment wall for the part of the building underground (see again figure 4). The cost of the isolators ranges between 1.2 and 1.6 M€, while that of the expansion joints for the 4 steam pipelines is 0.5 M€. The horizontal fail-safe system is still under development and its cost estimation is not yet available. No significant costs are expected for maintenance and inspection of the isolation system. It is worth noting that the life of the isolators is the same of that of the plant and there is no need for replacing them even after a SSE event (still, their replacement is taken into account in the design phase).

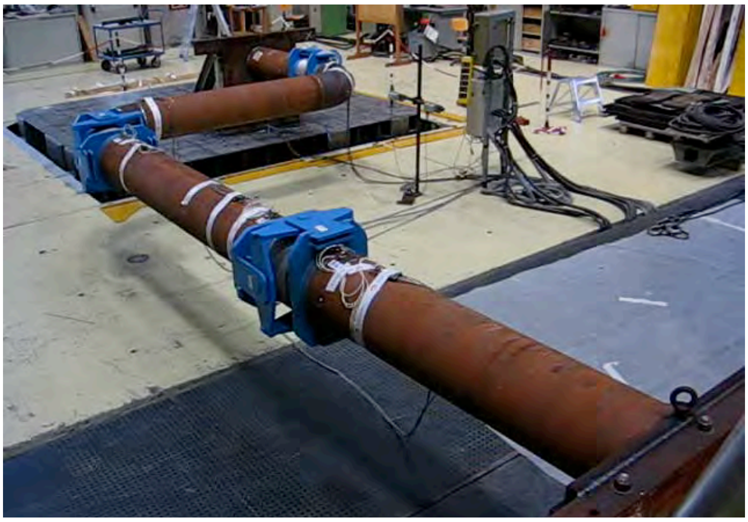

Figure 5. Shaking table testing of expansion joints for petrochemical applications

4 DETERMINISTIC DYNAMIC ANALYSIS ASSESSMENT

To evaluate the seismic risk and define the response of the nuclear structures, realistic and physically accurate numerical models are necessary. In this study the analysis methodology is based on a deterministic assessment, made possible by a numerical finite element evaluation of the dynamic response of the considered structure.

4.1 Seismic excitation and structural models

For the above quoted purpose, a strong Safe Shutdown Earthquake (SSE, which has a very small probability of occurrence) is postulated. Consistent with the classical approach (USNRC, 1973), the floor response spectrum method is applied and spectra are determined in correspondence of pre-defined support points related to the main components. Seismic isolation was then taken into account in order to gain a further decrease in the spectral values along the height of the structure and to ensure the full integrity and operability of IRIS important structures in the postulated very severe seismic conditions.

To attain the mentioned intent the preliminary IRIS NSSS and associated components (figure 3) were modelled through mutually interacting components, such as the NSSS building itself, the containment system and the Pressure Vessel (RPV).

To ensure adequate treatment of interaction effects and account for an adequate representation of the favourable isolation effects, the 3D Finite Element Model (FEM) of the structure (figure 6a) was used to provide the in-structure response spectra at the same reference locations or subsystem supports. Effects of the non-structural components, such as interior partitions or the water inventory, did not add any significant contribution to the mentioned structure modes/frequencies, but they were retained since they would add some initial mass and stiffness to the building.

A simplified FEM was initially used for sensitivity evaluations and as a quick supporting tool for the investigation of the impact of different parameters of the seismic isolator systems (e.g., number of isolators), while a more refined FEM model (figure 6b) was used to perform more refined analysis on the selected configuration of the seismic isolation system.

In the preliminary analyses, isolation devices were used in combination of base horizontal and vertical components and placed on a common underground surface level (i.e., under the NSSS building foundations) that can independently move under the effect of seismic external loads.

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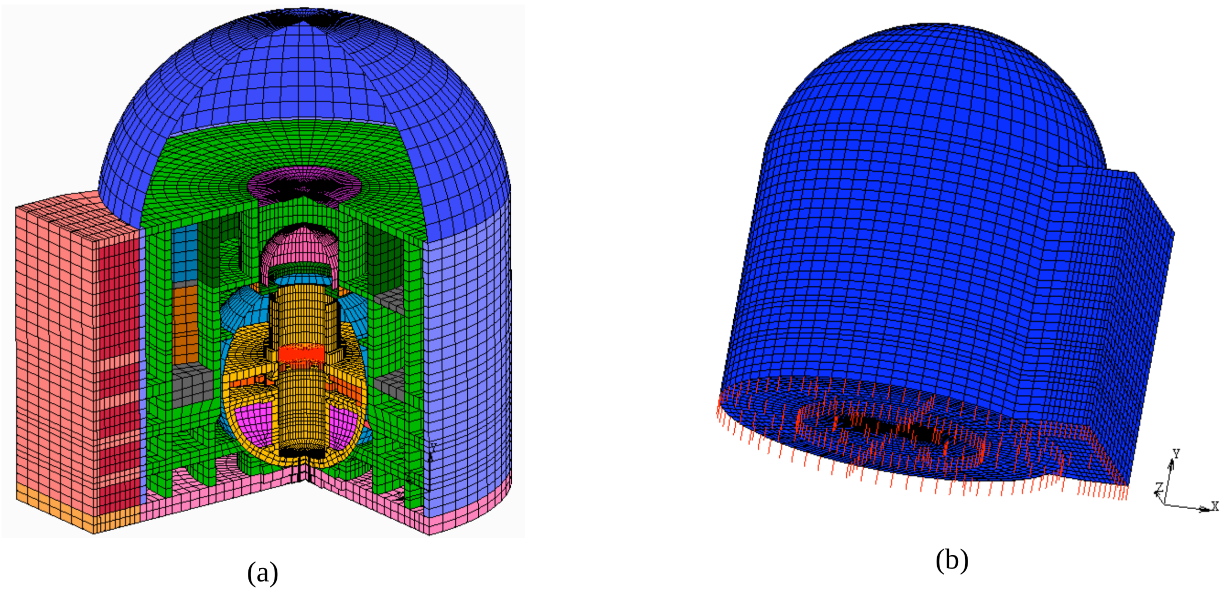


Figure 6. IRIS NSSS FE model: (a) section view, (b) layout of isolation system

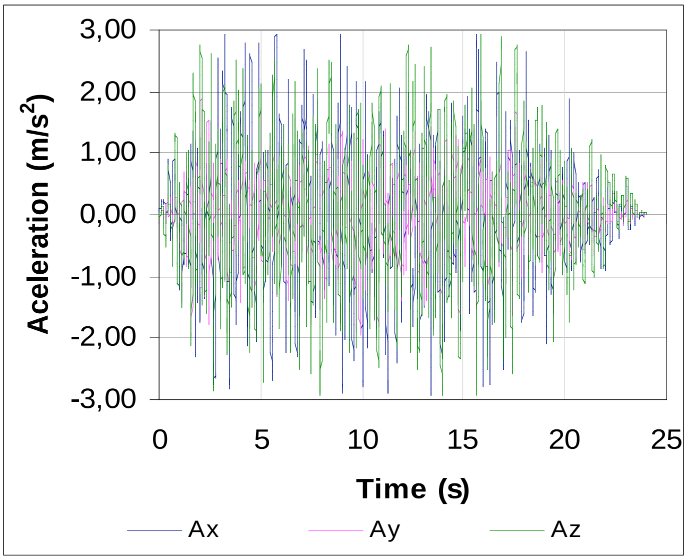


Figure 7. Seismic artificial time histories with PGA = 0.3 g

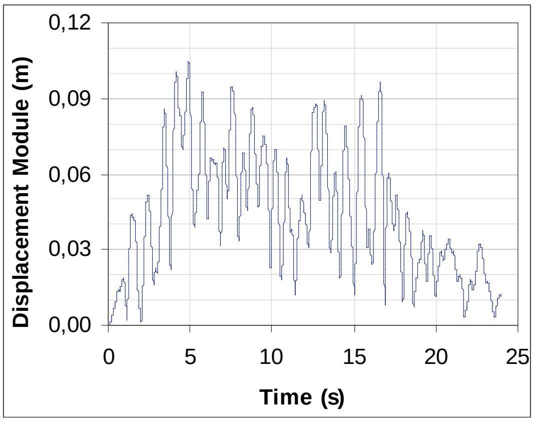
The preliminary seismic analysis of the isolated IRIS NSSS structures subject to a SSE investigated the isolation 'efficiency', in term of maximum acceleration ratio between the system with and without isolators. The applied methodological approach may be characterized by the following main three steps:

1. definition of the peak ground acceleration (PGA) of the input design earthquake (i.e., SSE), which was set to 0.3 g;
2. preliminary definition of type and number of isolators (represented in figure 6b as red arrows) on the basis of a fixed frequency (Ibrahim, 2008);
3. determination of dynamic response of the isolated system (see again figure 6), in term of acceleration and displacement components.

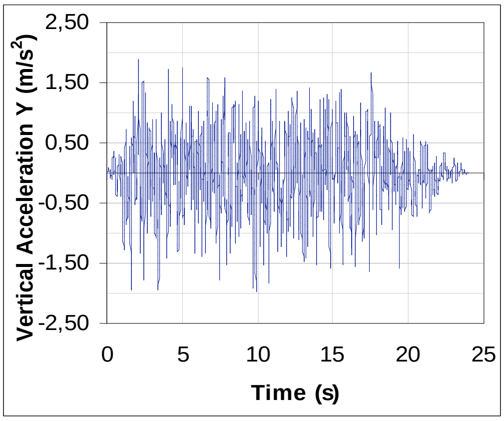
As aforementioned, to understand the dynamic response of the building and to evaluate its dynamic characteristics an input Acceleration Time History (ATH) was applied at the base of the isolation system of the nuclear power plant structure. The artificial time history (figure 7) used to model the seismic excitation was chosen to be compatible with the given free-field spectra applied at the base of the nuclear island as an excitation: the components in figure 7 represents the ATH of a SSE for an embedment in stiff rock. These components, aligned to three mutually orthogonal directions, are supposed to be statistically independent; the vertical acceleration component (A_z in figure 7) was taken equal to 2/3 of the horizontal one in the entire frequency range.

4.2 Dynamic analysis results

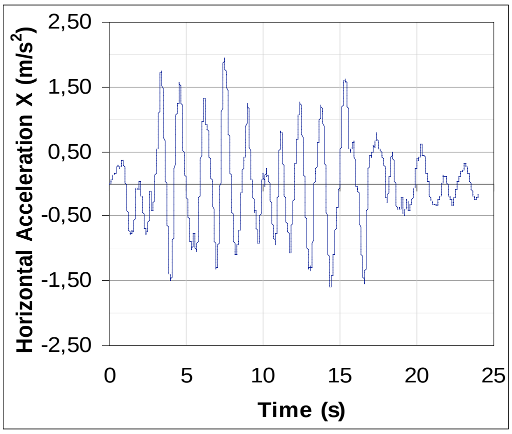
The chosen methodology was to analyze the seismic behaviour of the IRIS NSSS building in the isolated conditions by means of two widely used finite element codes: MSC.MARC (adopted at University of Pisa) and ABAQUS (analyses performed by ENEA). Both codes allow for assembling complex structures and components, with their different geometrical and material behaviours, in a unique system and solve the dynamic equilibrium equations at each point and time step.



(a)



(b)



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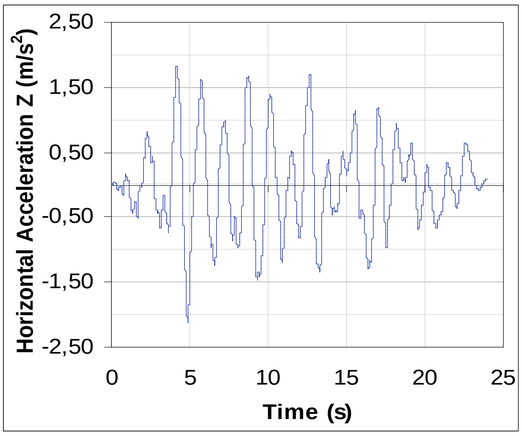

(d)

Figure 8. Dynamic response: amplitude of relative displacement (a), acceleration components at RV supports in vertical (b), and horizontal (c,d) directions.

The first step in the seismic analyses, performed by the substructure approach, corresponds to the extraction of modal properties, which have to be considered also in defining the structural damping model. To study the effectiveness of the isolation system in mitigating the effects of the SSE loadings, the maximum accelerations and displacements at chosen reference points were subsequently computed, either via modal superposition or direct integration, and used for comparison with the not isolated analyses results.

After several preliminary analyses the isolation frequency was set to 0.7 Hz. This gives a reduction of the absolute acceleration of the building from 0.3 g (PGA) to 0.23 g; at the same time the peak relative displacement between the building and the ground are limited is 10 cm (figure 8a). The isolation system yielding these performances is made of 120 HDRBs with 1 m diameter and 84 mm total rubber height.

The displacement and acceleration values at the RV skirt restraints, computed by the MARC code, are shown in figure 8(b,c,d). The ABAQUS results for the vessel base and roof levels are reported in figures 9 and 10; there are no appreciable differences between the two codes results. Furthermore these two FEM codes results demonstrated how the dynamic behaviour of the NSSS building, subjected to the three-directional SSE load, is a *rigid body* motion, i.e., a pure translation in the horizontal direction over the isolation system.

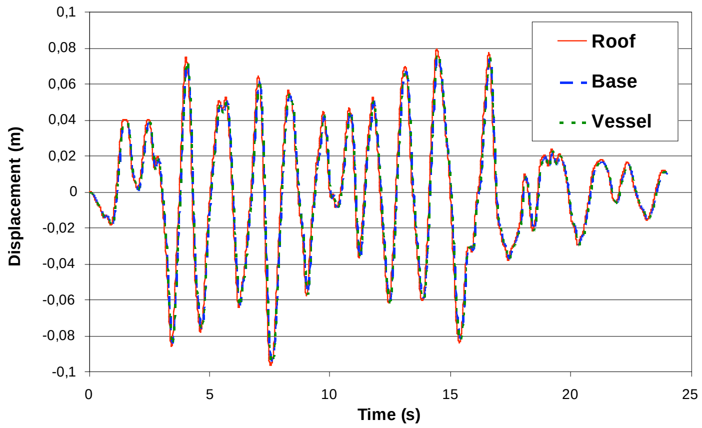

Figure 9. Horizontal displacement time-histories at the base (top of isolators), vessel and roof levels.

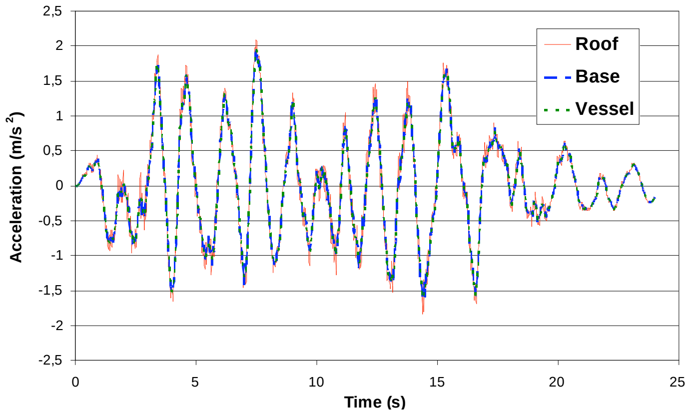

Figure 10. Horizontal acceleration time-histories at the base (top of isolators), vessel and roof levels.

In general the preliminary results have highlighted an evident “similarity” for the motion at all the points inside the IRIS NSSS building, due to the mentioned almost “rigid” behaviour (accelerations and displacements are practically the same at the base, vessel and roof levels), even though the vertical component of acceleration is undergoing some amplification along the building height.

Figure 11 shows the absolute acceleration of the isolated and non isolated building at the roof level as well as at the ground. It is worth noting that, in the case of the conventional building, the acceleration at the vessel level is practically equal to that of the ground, due to the high stiffness of the lower part of the building. It is evident that the acceleration reduction resulting from isolation, already significant at the base and vessel level, becomes dramatic at the roof level, where values 5 - 6 times lower are detected.

Finally, a comparison in terms of response spectra was performed for the same FEM model, with and without isolators, and SSE earthquake excitation (PGA = 0.3 g) in order to evaluate the effectiveness of the isolator system (0.7 Hz isolation reference frequency) in mitigating the seismic response of the equipments (figure 12). The calculated floor response spectra confirm the aforementioned favourable effects of the isolation system in terms of reduction of the seismic acceleration inside the building. The obtained results, in terms of acceleration and displacement time histories, might be used as design loads for further detailed structural analyses, as well as necessary data to determine the fragility curves for the considered PGA.

It is also worth stressing that the deformation of the isolators under the SSE is slightly higher than 100% average shear strain. This means that there is a safety factor significantly higher than 3 against the isolators’ failure, according to the results of many experimental campaigns performed at ENEA in the last 20 years on similar HDRB devices.

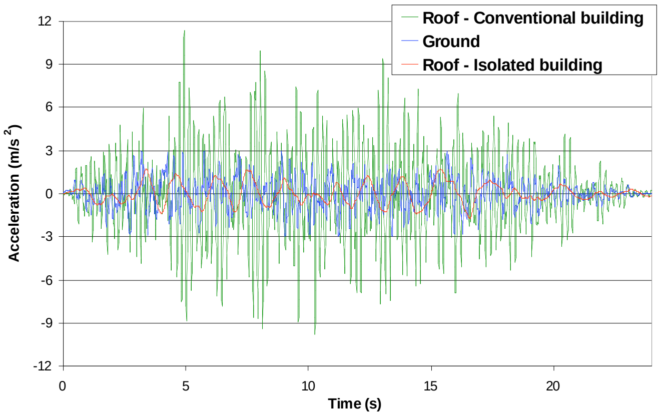

Figure 11. Ground acceleration vs. roof acceleration in the conventional and isolated NSSS building

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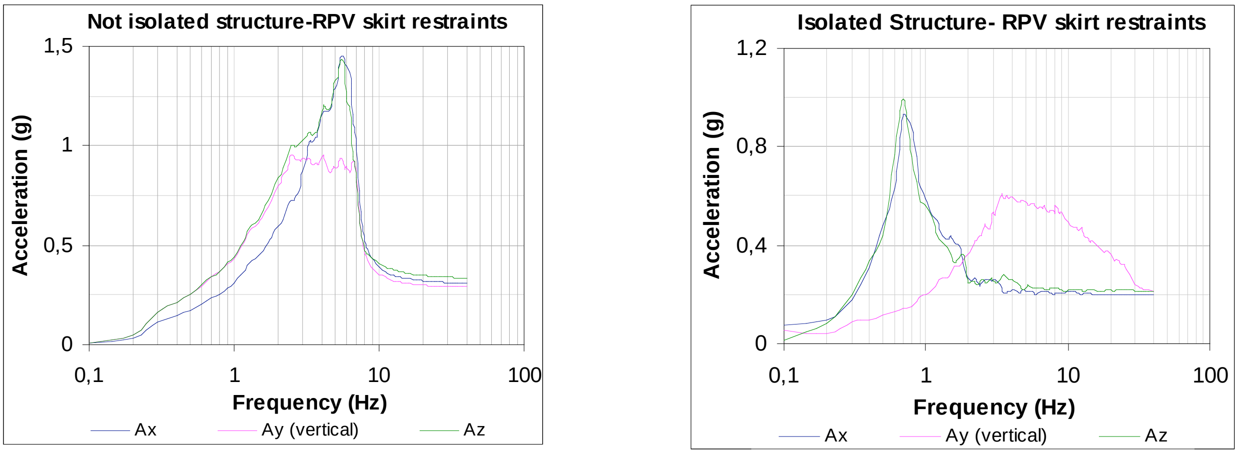

(a) (b)

Figure 12. Response spectra at RPV skirt restraints: not isolated (a) vs isolated (b)

5 FRAGILITY ANALYSIS

Once the seismic input to the base of the building and the seismic input perceived by the critical safety SSCs have been decoupled by means of the isolators, the isolators become the critical components in terms of ensuring adequate protection from seismic risk. A numerical procedure is being developed at Politecnico di Milano for computing seismic fragilities of critical equipment components. The procedure is based on the hypothesis, which is typical when seismic excitation of components is addressed, of linear behavior of the building (De Grandis et al 2008). Given the large size of the FEMs adopted for the dynamic analysis, which makes direct Monte Carlo Simulation impossible, the Response Surface Methodology is used to model the influence of the random variables on the seismic response. To account for stochastic loading the latter is estimated by means of a simulation procedure. Once the Response Surfaces defining the statistical properties of the response are available, the Monte Carlo method is used to compute the failure probability. A procedure for refining the Response Surface estimation has been also proposed based on the First Order Reliability Method (FORM) and on the evaluation of risk for a prototype site.

For the non-isolated NSSS building the procedure is applied to assess the failure probabilities associated to the occurrence of high acceleration values at the reactor vessel supports; on the other hand, when the isolation system is introduced, the resistance of the isolators is likely to govern the seismic risk and will therefore be the main focus of the mentioned methodology. Present research activity at Politecnico di Milano is thus also addressing the definition of the limit condition of the isolators under combined time-varying horizontal and vertical loading. Even though the horizontal fail-safe system, made of suitable rubber dampers installed all around the base of the building on the soil containing wall, will avoid the isolator failure in any seismic conditions, the mechanical behaviour of the isolators selected for the IRIS isolation system will be experimentally tested up to failure on scaled prototypes, consistently with the applicable European and Japanese standards; parallel refined FE analysis will support testing.

Data collected will be used for a validation of a linear spring-dashpot modelling of isolators. To this purpose a more refined model (Abe et al 2004), taking into account non linear hysteretic behaviour, has also been adopted and further developed at Politecnico di Milano. The model is currently used within a simplified preliminary dynamic analysis of the isolated NSSS building, aiming at the above validation and the optimization of the horizontal fail-safe system.

6 CONCLUSIONS

The adoption of seismic isolation is being investigated for the IRIS NSSS building in order to reduce the seismic induced residual risk. Preliminary dynamic analyses for the IRIS NSSS building were performed by means of two widely used FEM codes, assuming a simplified model of the isolation system, based on springs and dashpots.

The main benefit given by the seismic isolation is a significant reduction of the acceleration in the NSSS building, which becomes uniform for all the components at any level. This leads to a standardization of the design of the plant, which becomes almost independent of the site. Different seismicity or soil conditions will be ‘adapted to’ by slightly modifying the isolation system and won’t affect other critical components. This leads to significant advantages in both design and construction phases. Additional costs and difficulties due to the introduction of the isolators system can be considered as negligible.

To assess the seismic risk of the isolated building the resistance of the HDRB devices must be carefully considered, both in terms of experimental characterization and by means of adequately checked numerical models; to this aim both refined FE models and simpler approaches will be developed in parallel to testing.

Our studies show how a well balanced design solution has been achieved for the isolation system, in the sense that a major reduction in the building’s response has been obtained without an excessive increase in relative displacements. The adoption of seismic isolators has thus the potential for a significant improvement in the seismic-induced CDF.

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