

Assessing the reliability of seismic base isolators for innovative power plant proposals

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Keywords: Seismic analysis, base isolation, NPP seismic safety.

1 ABSTRACT

The *safety-by-design*TM approach adopted for the IRIS reactor reduces the Core Damage Frequency (CDF) from at-power internal initiating events to the order of magnitude of $10^{-8}/\text{ry}$, thus making external events dominant. Among them, earthquakes play a significant role. A strategy presently considered to face their effects is base isolation: isolators dramatically reduce the excitation perceived by the reactor vessel, the containment structures and all the main Engineered Safety Features (ESF) components, thus virtually eliminating the seismically induced CDF. In this situation, however, the isolators become themselves the limiting components and an assessment of their reliability is mandatory. Such a study is presently undertaken at the Politecnico di Milano and the results so far obtained are summarized in this paper.

2 INTRODUCTION

Some innovative power plant proposals are conceived so as to enhance safety. In particular, the IRIS reactor, a small modular integral nuclear power plant developed by an international consortium coordinated by Westinghouse, is based on a *safety-by-design*TM approach, which eliminates by design most of the main accident scenarios associated to conventional Pressurized Water Reactors (PRW) and reduces the consequences of the remaining accident initiators significantly. As a result, the Code Damage Frequency (CDF) from internal initiated events was reduced to the order of $10^{-8}/\text{ry}$ (Carelli et al., 2004). In this situation external events, earthquakes above all, become dominant.

To face the consequences of seismic events, a strategy that is presently considered is base isolation. Base isolators, consisting of laminated rubber bearings capable of very large deformations, have been successfully employed for buildings, bridges or tanks operating in seismic areas and it is felt that similar benefits could be gained in the nuclear context as well. The IRIS reactor and its Nuclear Steam Supply System (NSSS) building, which includes all Engineered Safety Features (ESF), all the emergency heat sinks and all the required support systems, has a small footprint, which makes base isolation of the nuclear island an attractive solution. The adoption of seismic isolators decouples the seismic input perceived by the reactor vessel and by the ESF and significantly reduces the probability of failure (Forni et al., 2009). In this situation, however, isolators become the most critical components. The isolator system reliability is expected to be high due to the large number of isolating devices and their passive nature. Nevertheless, the issue deserves significant attention and this paper is intended as a step toward the definition of a feasible and reliable procedure to this end.

When a damage frequency of so low an order of magnitude is aimed at, a non trivial and still open problem is the definition of the earthquake to be considered, which is expected to be more severe than nowadays Safe Shutdown Earthquakes (SSE). Rather than facing this problem, in this paper a typical isolator is studied, with the goal of determining the maximum Peak Ground Acceleration (PGA), compatible with given design spectra, that can safely be undergone. The analysis goes through the following steps.

1. Definition of the stress state in the rubber layers induced by vertical and horizontal forces acting on the isolator. In this phase, rubber is considered as an incompressible hyperelastic material undergoing large strains and metal disks as rigid.

2. Definition of a limit stress state for the isolator, which is assumed to occur when stresses at the rubber-metal interface become strong enough to initiate detachment (delamination). A limit domain for horizontal and vertical stresses is constructed on this basis.
3. Computation of the vertical and horizontal forces induced on the isolators by given earthquakes, represented by suitable input time histories consistent with design spectra of increasing PGA. To this end the isolator is modelled according to Abe et al. (2004).
4. Comparison of the computed force histories with the strength limits and assessment of the isolator reliability. This study has just been initiated and this paper only provides an outline of the procedure that is envisaged.

The procedure entails a large number of computations and rapidly becomes extremely demanding unless suitable simplifying assumptions are introduced. They must ensure efficiency without jeopardizing accuracy and this aspect is an important part of this study. In particular, it is worth noting that in steps 1 and 3 two different models for the isolator are considered. In the first instance the goal is a precise definition of peak stresses; then, the stress-strain curve for the rubber must reproduce with good accuracy the reference (experimental) data, but hysteretic loops can be ignored. On the other hand, when the overall response of the isolated system is sought, dissipation is crucial, even if the rubber behaviour does not need to be represented to the same detail.

3 THE PROPOSED PROCEDURE

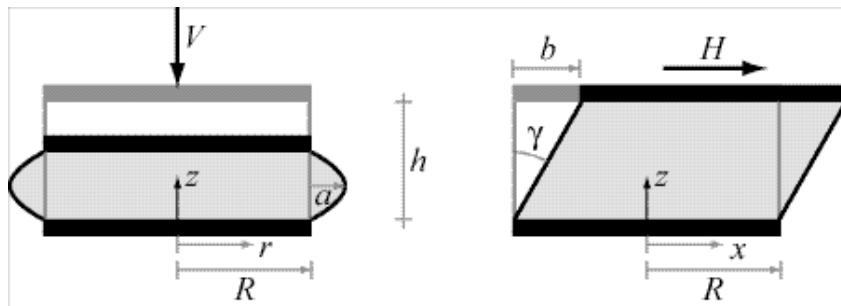


Figure 1. Displacement models for the rubber layer

3.1 Definition of stresses in the rubber layer

As anticipated, isolators consist of layers of rubber and metal. The latter are assumed to be rigid, while rubber is modelled as an incompressible, isotropic and hyperelastic material. Stresses in the rubber are computed separately for vertical and horizontal forces and results are superimposed. Computations are based on the assumption of suitable displacement models, which are depicted in Fig. 1.

According to Imbimbo and De Luca (1998), for vertical loads a small displacement assumption is adequate and the solution is independent of the material properties, except that for the initial tangent modulus G . In cylindrical coordinates, the displacement assumption is as follows

$$s_r = a \frac{r}{R} \sin \frac{\pi z}{h}, \quad s_\theta = 0, \quad s_z = g(z) \quad (1)$$

where the parameter a and the function $g(z)$ are determined by enforcing incompressibility and global equilibrium. After some algebra, omitted for brevity, the stress state in the layer is arrived at. In particular, at the interface with metal the normal and shear components are

$$\sigma_z = -2 \frac{V}{\pi R^2} \frac{R^2 - r^2}{R^2}, \quad \tau_{rz} = 2 \frac{V}{\pi R^2} \frac{hr}{R^2} \quad (2)$$

Such solution entails some approximation, as witnessed by the fact that shear stresses do not vanish on the boundary $r=R$, as equilibrium requires. However, finite element computations show that shear stresses agree with eqn (2)₂ almost everywhere, with the exception of sudden drop close the boundary.

The response to a horizontal force demands that large strains be considered. In this case rectangular coordinates are used and the displacement field is assumed as

$$s_x = kx, \quad s_y = s_z = 0 \quad (3)$$

Where $k = b/h$ is the horizontal displacement per unit height ($k = \tan \gamma$, γ being the shear angle). The field eqn (3) is incompressible and the deformations associated to it are represented by the left Cauchy-Green tensor, usually denoted by \mathbf{B} . Such tensor is coaxial with the Cauchy stress $\boldsymbol{\sigma}$ and the general form of the constitutive law of an incompressible, isotropic and hyperelastic material is expressed as (Holzapfel, 2000)

$$\boldsymbol{\sigma} = P\mathbf{I} + 2 \frac{\partial W}{\partial I_1} \mathbf{B} - 2 \frac{\partial W}{\partial I_2} \mathbf{B}^{-1} \quad (4)$$

Where $W(I_1, I_2)$ is the strain energy depending, because of isotropy, on the linear and quadratic strain invariants I_1, I_2 (incompressibility requires $I_3 = 1$), \mathbf{I} is the identity tensor and P the hydrostatic stress component, which is determined by boundary conditions.

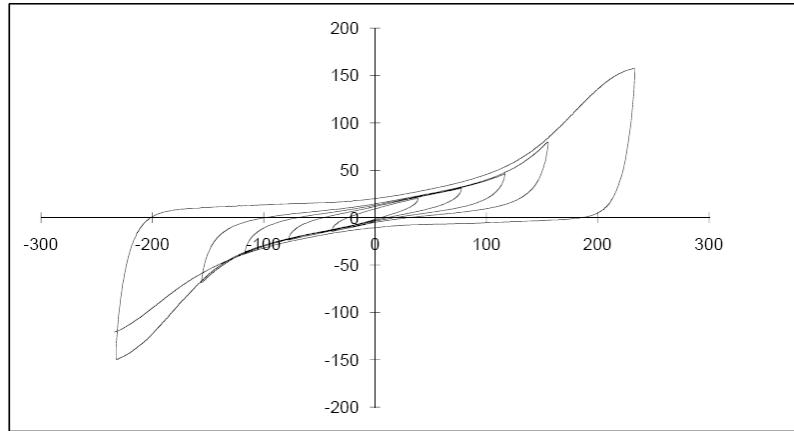


Figure 2. Experimental shear stress-shear strain curve (courtesy of M. Forni of ENEA, Bologna, Italy)

The problem is brought to the definition of a strain energy function capable of representing the actual behaviour. Reference data are depicted in Fig. 2, which reproduces the experimental results of a cyclic shear test on a model isolator. This is not suited for the IRIS NSSS building because of too small dimensions and a too low tangent modulus for rubber ($G = 0.8$ MPa instead of the required value of 1.4 MPa), which required that results be scaled so as to produce a feasible curve. Since to the purpose of defining peak stresses hysteresis loops are not crucial, only the most external plot was considered. After some arrangement, the blue curve Fig. 3 is arrived at and the definition of the rubber constitutive law is based on it. Obviously, such a definition is arbitrary to a significant extent, but the curve is qualitatively correct and the procedure can be applied without modifications to the actual experimental data, when available.

To reproduce the curve, a 9-parameter Mooney-Rivlin model is assumed, based on the strain energy function

$$W = c_{10}(I_1 - 3) + c_{01}(I_2 - 3) + c_{20}(I_1 - 3)^2 + \cdots + c_{12}(I_1 - 3)(I_2 - 3)^2 + c_{03}(I_2 - 3)^3 \quad (5)$$

which produces, through eqn (4) the stresses at the rubber-metal interface

$$\sigma_z = 2c_{10}k^2 + 2(2c_{20} + c_{11})k^4 + 2(3c_{03} + 2c_{12} + c_{21})k^6 \quad (6a)$$

$$\tau_{zx} = 2(c_{10} + c_{01})k + 4(c_{20} + c_{11} + c_{02})k^3 + 6(c_{30} + c_{21} + c_{12} + c_{03})k^5 \quad (6b)$$

(the hydrostatic pressure P was defined by imposing equilibrium conditions on the free vertical boundary). The values of the material parameters c_{ij} giving the best approximation to the reference curve were subsequently computed and the red curve in Fig. 2 was obtained, which shows an excellent agreement throughout.

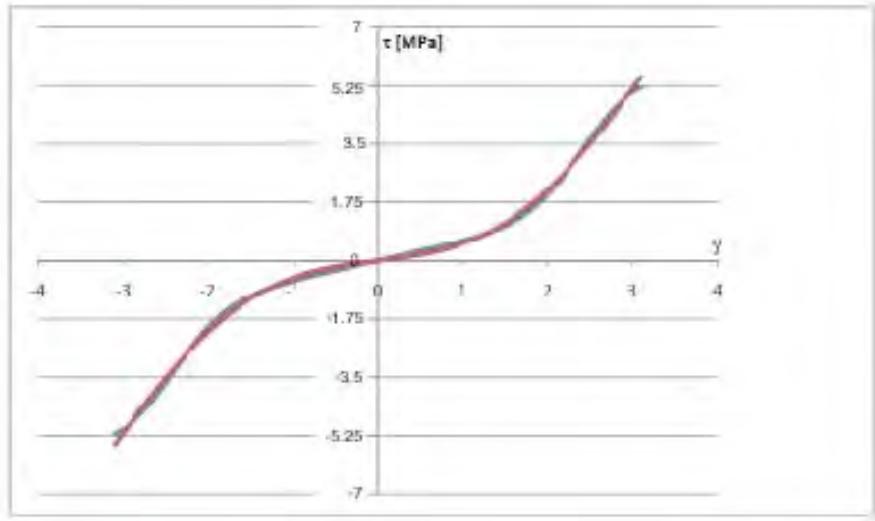


Figure 3. Shear stress-shear strain curve: reference curve (blue) and approximation (red)

3.2 Limit domain for the isolator

The serviceability limit for the isolator corresponds either to detachment of rubber from metal (delamination) or to tension failure of rubber. In the devices currently employed for civil engineering applications, the first occurrence is by far the most likely and will be considered as critical in what follows.

The onset of delamination is supposed to occur when shear stresses at the interface reach a given threshold, taken as a linear function of the normal stress, with the shear limit decreasing with increasing tension. Stresses at the interface are given by eqns (2) and (6) and are depicted in Fig. 4. It appears that the critical point is located on the boundary $r=R$, where shear stresses of equal sign sum up and tension induced by horizontal forces is not reduced by the presence of a vertical load.

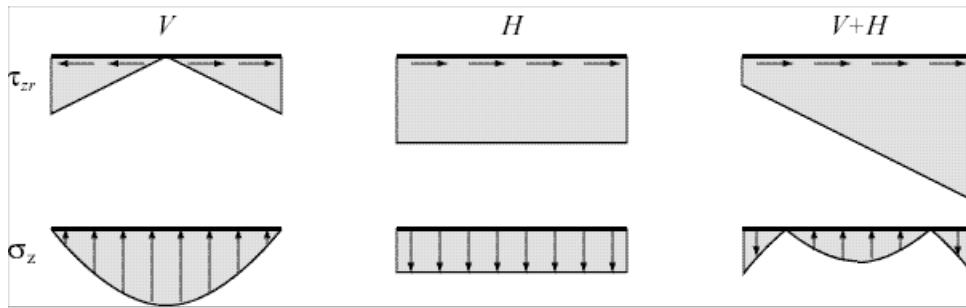


Figure 4. Stresses at the rubber-metal interface

The only piece of information available on the isolator limit state is that, under the static vertical load given by the weight of the NISS building, a value of 300% for k must not be exceeded. This is assumed to correspond to the onset of delamination and from eqns (2) and (6) the corresponding values of σ_z and τ_zr are computed. In addition, it is assumed that the effective (von Mises) stress in this situation represents the tensile limit. These rather drastic assumptions permit the definition of the limit domain in the σ_z - τ_zr plane depicted in Fig. 5a.

The domain is conveniently expressed in terms of the horizontal and vertical forces acting on the isolator (details on the procedure can be found in Guiducci (2009)) and the result is illustrated in Fig. 5b. The gap between the curve and the vertical axis is filled by horizontal lines.

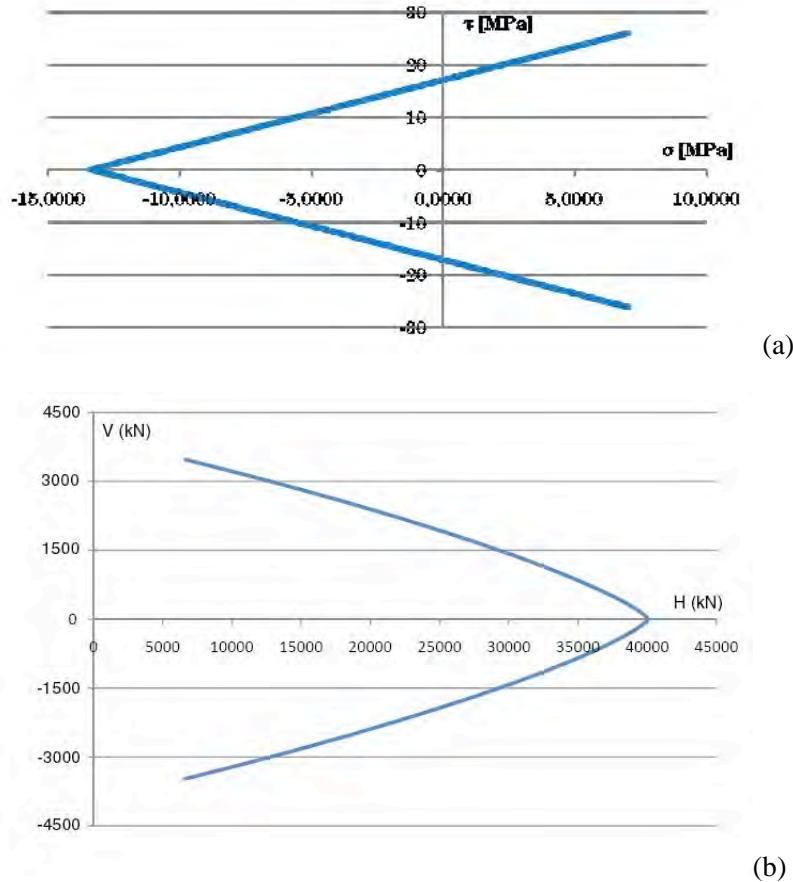


Figure 5. Limit domains for the isolator

3.3 Computation of forces on the isolators

The subsequent step is the evaluation of the horizontal and vertical forces induced by earthquakes on the isolators. This is a computationally demanding phase and some assumptions are required to ensure the feasibility of the procedure. First, it is assumed that the motion occurs in a plane. Secondly, it is considered that a properly designed isolator system is such that the NSSS building undergoes essentially rigid body motions under horizontal excitations. Therefore the building was modelled as a rigid block with three in-plane degrees of freedom, supported by a linear distribution of isolators. The first assumption is verified by small responses for the rotational lagrangian coordinate.

To represent the isolator behaviour, the model proposed by Abe et al. (2004) is employed. Such model incorporates the dissipation effects provided by the hysteresis loops, which is regarded as an essential feature for the description of the overall seismic response. The model also provides a qualitatively correct picture of the non linear shear stress-shear strain curve, but the search for a precise fitting of experimental data is abandoned in favour of a simpler expression.

The system was subjected to a number of ground acceleration time histories, partly “natural” (i.e., actually measured) and partly artificially built. The first set was chosen so as to agree with the design spectra required by *Eurocode 8* (type 1, ground C), while artificial histories were filtered from the *Regulatory Guide 1.60* spectra. First computations considered 9 natural and 10 artificial time histories, scaled so as to represent SSE’s with a PGA of 0.3 g.

Computations were performed by Barbaglia and Magli (2009) as part of their graduation thesis in civil engineering and produced as output the histories of the vertical and horizontal forces on the isolators (as well expected, the most severe situations are experienced in the isolators located close the boundary of the building). Typical results are illustrated in Fig. 6, referring to a natural time history (left) and to an artificial one (right). It appears that both histories can be accommodated within the isolator limit domain with a reasonable margin.

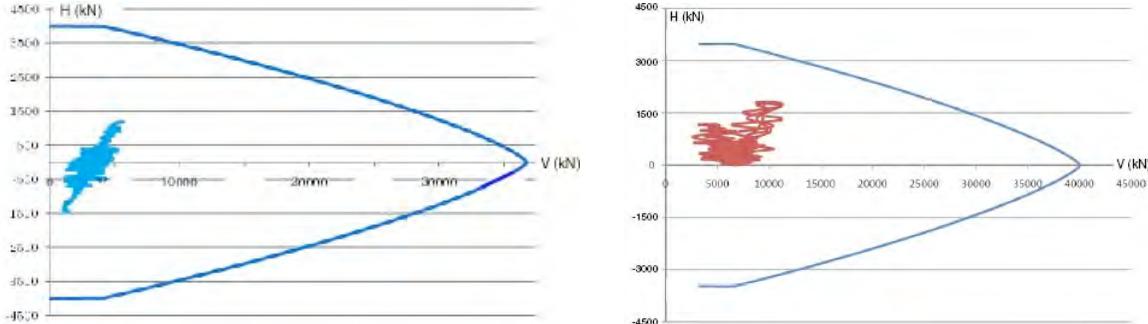


Figure 6. Typical force histories compared to the isolator limit boundary

3.4 Assessment of reliability

The ultimate goal of this study is to associate a probability of failure (or damage) of base isolators to earthquakes of given PGA's. This requires that earthquakes of increasing amplitude be considered (so far, computations only referred to PGA's of 0.3 g), which, however, does not entail any novelty. More relevant is the assessment of the uncertainties inherent to the problem and their modelling in probability terms. This aspect presently is still under study and only an outline of the procedure envisaged can be given at this stage.

The problem statement presented in Fig. 6 summarizes the two main characters of a reliability analysis, the strength and the capacity demand for the isolator device. The macro-system, which consists in the NPP reactor building, has been previously considered by the dynamic analysis of the three d.o.f. system (Section 3.3) and it is represented by the H - V forces variation. The limit state domain in the H - V plane can be assumed for the evaluation of the seismic fragility of the isolator, in which uncertainties associated to the dynamic properties of the macro-system (building) and the parameters defining the H - V interaction domain can be assumed as random variables.

In this light, in the parallel paper (Perotti et al., 2009) an overall procedure for defining the seismic fragility of the isolators is sketched. Within the proposal, the reliability problem is addressed by a refined procedure based on the representation of the dynamic behavior of the isolated building by a meta-model (response surface RS). Preliminary analyses on a the physical (finite element) model allow to define the coefficients of the RS polynomial equation so as to speed up the evaluation of the probability of failure (or damage), obtained via Monte Carlo computation of a multifold integral which manages several random variables. A risk based procedure for refining the RS is also proposed.

4 CONCLUSION

To reduce the seismic induced CDF, the use of base isolators beneath small size NPP's is envisaged and a study aiming at the evaluation of their reliability, which is presently undertaken at the Politecnico di Milano, is described in this paper. The study is under progress and several points are far from being assessed, but it is felt that the results obtained, though partial, show that the procedure is feasible and that proper answers to the questions raised can be obtained on its basis. The main points requiring additional investigation and the main results that can be regarded as conclusive are briefly summarized.

The first step of the procedure is the computation of local stresses in an isolator subjected to given forces. In this paper, the computation was based on simple displacement models, which certainly provide reliable mean values, but only a finite element, large displacement analysis on a complete isolator may

produce a detailed picture of local effects. Such analyses are going to be undertaken. Their results, however, must be related to some overall measures of the isolator loading and/or global response parameters, so as to establish an immediate connection between global and local effects. The 9 parameter Mooney-Rivlin model, which is both flexible and accurate, seems adequate to this purpose and may be considered as a suitable basis for the final version of the procedure as well.

The definition of the isolator limit domain requires experimental results that are not available presently. In this study, delamination was considered as the most critical event but, at the moment, this is more a reasonable opinion than an established fact, and limit states corresponding to rubber failure because of cavitation under excessive tension also might have to be considered. The only reliable piece of information so far available is that a 300% average shear strain is a limit state that can be taken as corresponding to the onset of delamination, but even a limit domain as simple as that in Fig. 5a requires a second point to be defined. In any case, such a domain is reasonable as long as delamination is the critical situation and corrections to account for possible rubber tension failure should not alter significantly the qualitative picture. Proper numerical values can be introduced on the basis of suitable experimental data, when available.

The assumptions used for the computation of the force histories induced by an earthquake on the isolator seem adequate. A number of refined finite element analyses confirm that the isolated NISSS building does in fact behave as a rigid body and the only improvement envisaged is to consider out of plane motions, with 6 degrees of freedom for the system. Also the isolator modelling appears satisfactory: the adopted proposal of Abe et al. (2004) maybe could be improved in view of a better agreement with some details of the stress-strain curve, but already represents well the dissipative behaviour, which is considered the essential aspect in this phase.

The fact that the limit domain is expressed in terms of such forces permits the computation of the isolator probability of failure, on which a Probability Risk Assessment of the isolation system can be based. To be effective, such an assessment requires that both loading and strength are expressed in simple form and what discussed in this paper shows that adequate simplifications can be achieved without jeopardizing accuracy.

As a final remark, it must be noted that the procedure suggested entails a significant amount of conservativeness. Failure is identified with the *onset* of delamination and, in dynamic situations above all, this does not imply that detachment will really occur. In addition, whether induced by delamination or by tension in the rubber, the isolator failure is not brittle and this fact, together with the redundancy connected with the large number of isolating devices employed, suggests that the isolation system will not lose its effectiveness when the limit state considered in this paper is attained. The study of further resources of the system appears as a formidable task but, despite this limitation, it is felt that the proposed procedure provides a significant piece of information on the behaviour of the isolated plant.

Acknowledgements. Authors wish to thank Gianluca Barbaglia and Marco Magli for having carried out the seismic computations used in this study.

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