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Proposal for design guidelines for isolated nuclear facilities

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ABSTRACT: A proposal for design guidelines for seismically isolated nuclear reactors and other nuclear facilities has been developed in the framework of a study sponsored by the European Commission. This proposal updates a previous document which focused on the high damping rubber bearings and extends it to most of the other isolation system types of interest.

1 INTRODUCTION, SCOPE AND APPLICABILITY

A proposal for guidelines for seismically isolated nuclear plants was prepared by Forni et al. (1995a) in the framework of a European Commission (EC) study contract, taking into account the most recent information on seismic analysis of nuclear plants in general and the state-of-the-art of engineering design of isolated structures (see, for instance, Martelli and Forni, eds., 1994), and taking advantage of considerable R&D and guidelines development work performed in Italy for seismic isolation (SI) of civil structures (Martelli et al. 1993 & 1995; Forni et al. 1995b).

The document of Forni et al. (1995a) was published in a tentative form to allow for broad review from experts. The qualification procedure specified for the SI devices may lead to a definition of a standard and use of a standardized product for SI design. The document updates and extends that of Martelli et al. (1990). It applies not only to isolated reactors, but also to other nuclear facilities (e.g. spent fuel storage pools) and concerns the horizontal SI systems that - according to the technologies developed in the EC countries, Japan, New Zealand and the USA - may be suitable for application to nuclear structures, namely those formed by high damping rubber bearings (HDRBs), lead rubber bearings (LRBs), low damping natural or synthetic (e.g. neoprene) rubber bearings (LDRBs) with separate elastic-plastic dampers (EPDs) or viscous dampers (VDs), and sliding devices (SDs). Remarks are also provided on simultaneous horizontal and vertical SI systems (3D systems), although the development of such systems or related information available to the authors were insufficient as to enable them to propose detailed guidelines (in particular, no details were available on the 3D pneumocord system which has been developed by Russians and is being considered for application to the VVER-500 reactor project, see Martelli and Forni, eds., 1994).

2 CONTENTS OF THE PROPOSAL

Similar to the proposal of Martelli et al. (1990), that of Forni et al. (1995a) mainly deals with items different from non-isolated systems. Focus is on requirements, analysis methods and qualification procedures of SI system and devices; proposals for design requirements and analysis methods for isolated structures, systems and components are also included. More details are provided for horizontal SI systems using rubber bearings than for horizontal systems formed by other SI devices, or especially, 3D systems, according to the larger application and experimental experiences of the authors on the former. Areas in which experimental data or design experience are not available have been marked (TBD) (To Be Determined). A list of still TBD items is summarized in appendix. When needed, the document provides comments to clarify the guidelines. Information on the SI systems considered in also provided in appendix.

The main structure of the previous proposal of Martelli et al. (1990) has not been modified. Some remarks are reported below on the technical sections of the document, by stressing some modifications and extensions with respect to the previous document.

Sect. 5: Definition of ground motions. Only analysis at Safe-Shutdown Earthquake (SSE) remains mandatory, while that at Operational Basis Earthquake (OBE) is now mandatory only when significant changes of isolator stiffness are expected from OBE to SSE, and the requirement that the minimum OBE value shall be half the SSE has been deleted. The need for special attention to the low-frequency range 0.1-1 Hz (because of the effects on isolated structures) is still stressed, but the requirement that design response spectra in the frequency range to 1 Hz shall be equal at least to that specified by R.G. 1.60 has been changed to a suggestion. Specific requirements concerning the features of design time-histories (t.hs.) have been moved to this section from Sect. 6 and better precised. The need for a characterization of ground motion rotational components, if relevant, has been specified.

Sect. 6: Design requirements and analysis methods for isolated building and isolation support structure. Somewhat improved definitions have been given for the horizontal Reference Displacement D_R, Calculated Displacement D_C, and Design Displacement D: in particular, reference shall be now made to 90% D_R (instead of D_R) for calculating D_C, and account for accidental eccentricity due rotational ground motion component is suggested to determine D_R. Residual Displacement D_F (which is relevant for some sliding systems) has also been defined. While the requirements concerning the stiffness of structural elements located above and below the SI interface and that no resultant tensile loads nor isolator uplift are permitted up to SSE remain unchanged, the safety factors agaist overturning at SSE has been increased from 1.1 to 2. The functions of ultimate vertical and horizontal fail-safe systems have been better pointed out, by also precising the related (previously TBD) values: it has been specified that the vertical system (for which a maximum clearance of 3-5 cm with respect to the structure is now required) and horizontal system shall be used unless it is demonstrated that the isolators can support the structure to 5 and 3 times the SSE, respectively; as regards the horizontal system it has been also specified that - if present - it shall not act until horizontal displacement is lower than 0.85 SF (where SF is a safety factor for which a value larger than 2 is now required) and shall hinder displacements larger than SF times the design value. A somewhat less conservative approach is now required for the definition of the gaps between adjacent isolated and non- or independently isolated structures (according to that mentioned above for D_C), and a specific requirement that they shall remain free in every design condition (e.g. flood) has been added. No major changes have been made as regards the rules concerning inspectability and replacement capability of isolators, and recentring of the structure if necessary. For soil-structure interaction analysis the maximum damping ratio which can be assumed at SSE has been increased from 5% to 15%. For design analysis (use of t.hs., applicability of simplified methods, features of parametric calculations) some requirements have been implemented, namely the need for taking into account the contribution of input motion rotational components if they are larger than 10% of that due to translational components, need for at least 4 t.hs. (6 to 8 for sliding systems) when using t.h. analysis, and that for also considering damping (or friction) of the SI devices - in addition to soil, device and structure stiffnesses - when performing parametric analysis.

Sect. 7: Design and performance requirements of overall seismic isolation system. The horizontal design force has been defined, consistent with the design displacement, for sliding systems also. Maximum and minimum vertical loads V_{max} and V_{min} (resulting from the combination of vertical design load with the vertical earthquake component) have also been defined. The values concerning some previously TBD safety factors to be used in the design have been specified, by requiring that systems shall have a safety factor 1.7 for V_{max} and for 1.7 of D applied statically and simultaneously, and a safety factor 1.7 for D at 0.6 V_{min} (the minimum safety factor 3 was kept unchaged for V in the laterally underformed state of SI system). For SI systems using rubber bearings with or without separate EPDs the permissible range for horizontal isolation frequency has been extended to 0.33-1 Hz, and the requirement that vertical stiffness shall be sufficiently high to reduce any tendency of amplification refers now not only to vertical motion, but also to rocking. For such systems the minimum equivalent viscous damping ratio has been lowered from 10% to 8%, variations of +/- 30% and +/- 15% of the mean values have been specified as permissible for stiffness and damping, respectively (considering the external and environmental conditions and ageing - these ranges were TBD), and the need for investigating the effects of minor earthquakes has been specified, while requirements concerning self-centring with a minimum offset of 10% of the design displacement and wind resistance remain unchanged. Similar requirements have been specified separately, where applicable, for the sliding systems and systems including VDs. For the former a permissible range of +/- 30% of the mean value has been specified for friction coefficient; for the latter the need for accounting in the design for the dependance of damping on vibration velocity and internal fluid temperature resulting from ambient temperature and the number of applied vibration cycles has been specified; for both systems the presence of recentring devices in the SI system has been required, should not the devices be self-centring.

Sect. 8: Design requirements and analysis methods for isolated structures, systems and components. Should the OBE analysis be performed, the minimum number of OBEs to be accounted for in the analysis (in addition to one SSE) has been increased to 5 for components remaining in the plant during the entire life, although a minimum of 2 OBEs is frequently recommended. The rules previously provided for the analysis of secondary components, evaluation of floor response spectra and static analysis remain unchanged. As to sloshing, reference to simplified rules has been added in comments, and the requirement that the loss of liquid shall be prevented has been specified.

Sect. 9: Design requirements and analysis methods for interface components. Besides defining the displacements to be accomodated by both safety and non-safety related components and systems which cross the isolation interface (piping, cables, etc.), prescribing the effects to be considered and pointing out the need for experimental qualification (accounting for the multidirectional nature of seismic motion, and the actual values of pressure and temperature when relevant), the present document includes more specific requirements concerning interface piping. These were derived from those applicable to usual nuclear piping, and concern design prescription, design analysis, the supports and their location, bellows, expansion joints, fittings and flanged joints. In particular, it has been stated that bellows should be avoided in all safety-related piping until their reliability has not been fully demonstrated.

Sect. 10: Design requirements for individual isolation devices. The use of previous experimental experience, instead of performing specific tests on prototypes, has been permitted to evaluate the basic parameters for the design (stiffnesses, damping, friction coefficient). The requirements concerning the vertical load capacity and design load, maximum horizontal displacement capacity, design displacement D and stability, and damping have been made consistent with those related to the overall SI system (Sect. 7). In addition, it has been specified that vertical load capacity and safety factors shall account for buckling effects and respectively, for roll-over if relevant. The definitions and requirements concerning vertical and horizontal stiffnesses, stiffness-strain relationship, dependence of horizontal stiffness on vertical load and maximum scatterings of stiffness and damping (+/- 10% from the mean value) have been confirmed, together with the need for specifying maximum and minimum stiffness, friction and damping values within the ranges mentioned in Sects. 7 and 12 and the possibility of using simplified formulas for estimating stiffnesses for rubber and steel devices. For damping the requirement that it shall be calculated as an average of the last 5 cycles has been removed, although conditionning before tests is still recommended for rubber bearings (it is suggested that 2 cycles are sufficient for them). Specific requirements have been added for LRBs (sufficiently high shape factor as to confine the lead plug, vertical load to be supported only by the rubber), for SDs (need for tests to evaluate friction coefficient dependence on sliding velocity, vertical load and temperature) and for VDs (evaluation of their stiffness contribution depending on frequency and temperature). As regards the effects of cycling and related degradation (fatigue), it has been specified that the characteristics of SI devices shall not vary more than 15% between the 2nd the the 10th cycle performed at the isolation frequency and at the displacement D after 50 cycles at OBE (all these items were TBD). Requirements concerning the environmental effects have been also much better precised, in particular by including the need for SI devices of withstanding chemical and biological attacks, by requiring that adequate engineering solutions are adopted to prevent and mitigate the various attacks, by providing information on radiation effects, by limiting temperature effect to +/-15%, and by requiring resistance to exposition to a temperature of 150°C for 2 hours, direct exposition to fire for a TBD time, and replacement after a fire. The limit value for creep vertical deformation has been increased from 20% of the dead load deflection during the isolator life (which shall be equal to at least that of the plant) to 30%. It is now specified that SI devices shall survive the faulted conditions at the end of their design life and that periodic (TBD) replacement is permitted for internal fluid of VDs. Experiments have been required to evaluate maximum offset unless previuos experience is available. The requirements concerning absence of resultant tensile loads, limit tensile capacity of isolators and absence of disengagement of monolateral bearing connections to SF times D have been confirmed. Finally. the requirements concerning design tolerances have been extended to SI devices other than the HDRBs.

Sect. 11: Qualification of seismic isolation device and isolation system. It has been specified that seismic qualification by test is mandatory unless finite-elements (f.e.)

models are available which have been previously qualified for the relevant test conditions (see Forni et al. 1995b). Reference to IEC standards has been introduced as regards non seismic aspects, together with the requirement that the manufacturing process of SI devices shall be qualified. The static and dynamic tests required on materials, complete bearings and SI system proposed by Martelli et al. (1990) have been updated and specified for all horizontal SI systems considered, taking into account subsequent experience and the requirements mentioned in previous sections (see also Martelli et al., 1995a). The minimum number of each device type to be manufactured for qualification tests has been specified (4 for isolators and 2 for dissipators). As regards SI device tests, the concept has been introduced that qualification is necessary every time that devices with new features are used; accordingly, criteria for keeping previous tests valid, in spite of somewhat different values of some parameters have been specified, together with those allowing for tests on scaled devices. Repetition of some tests on ageed bearings at the maximum and minimum design temperatures has been required. As regards the SI system the shake table tests which are required (unless previous detailed experience is available) have been somewhat simplified according to test experience, by permitting two- or even one-dimensional shake table tests if they aim at simply evaluating the self-centring or re-centring capability of SI system (to this purpose free-vibration tests are generally not adequate). The usefulness and limits of in-situ dynamic tests on actual structures have been outlined.

Sect. 12: Acceptance testing of isolation devices. Similar to qualification tests, those required to provide the quality control of SI devices have also been updated and extended to the various systems considered. As regards rubber bearings, while the compression tests to confirm vertical stiffness and sustained compression tests shall be still performed for all isolators, the destructive tests have been limited to 2% of those to be installed (minimum 2 isolators) and combined shear and compression tests shall be carried out for a minimum between 20 and 20% of isolators. With regard to sustained compression tests the duration of 24 hours has been specified, and the limit of 20% of the dead load deflection has been confirmed for total height variation (taking into account temperature and ageing effects as evaluated during qualification). The criteria to be adopted for rejecting bearings in the case that controls are out of tolerances have been better precised. Finally, the importance of reliable bearing identification has been better stressed and the required documentation concerning acceptance tests has been specified.

Sect. 13: Seismic isolation reliability. No major changes have been made as to the Quality Assurance program and bearing life-time (only the reference to f.e. analysis as to the evaluation of phenomena affecting the bearing reliability has been deleted). On the contrary, in-service inspection tests have been updated and extended to all SI devices considered, based on criteria consistent with those adopted for qualification and acceptance tests, and the requirement concerning submission of the in-service inspection program to the Licensing Authorities has been deleted. The previously TBD numbers of devices to be tested, time intervals between subsequent testing and related procedures have been precised (3 full-scale or scaled devices per each outage, kept in actual vertical compression load and environmental conditions, every 6 months; 10 or 10% of full-scale devices every two years; 10 or 10% of actual devices, temporarily removed at random from the plant, after an OBE).

Sect. 14: Seismic safety margins. This section has been considerably shortened, because it was unnecessarily too detailed. Reference is now made to relevant documents as regards the description of Probabilistic Risk Assesment (PRA) and Seismic Margin

Evaluation (SME) procedures (which are alternative options), and requirements have been limited to specific issues related to the adoption of SI, namely to the definition of seismic input (earthquake level for SME, maximum displacement at the ground and spectral content) and SI effects on the response to beyond SSE earthquakes (scaling issues, possible closure of gaps, evaluation of the seismic capacity/fragility of the SI system taking into account various non-linear effects).

Sect. 15: Seismic safety and monitoring systems. No significant changes were made for the requirements concerning these systems. The document still specifies the need for a detailed monitoring system, capable of recording seismic motions during time in the free-field and on the structure, partly in short time, and points out that dispacements between the structure base and SI system support base must be recorded, besides acceleration at various elevations.

4 CONCLUSIONS

This paper has summarized the main features of an updated proposal for design guidelines for seismically isolated nuclear plants, applicable to most horizontal isolation systems of interest, by stressing the improvements with respect to a previous document, which was limited to the use of HDRBs and for which several issues were still unresolved. The document will be periodically updated by ENEA to include comments and to reflect the advances in seismic isolation technology development. Future R&D work shall focus on establishing a data base which will support the development of specific rules for items which are still "To Be Determined" (TBD).

REFERENCES

Martelli, A., Carpani, B., Forni, M., Di Pasquale, G., Sanò, T., Bonacina, G., Olivieri, M., Marioni, A. & G.F. Cesari 1993. Extension of guidelines to seismically isolated reactors. *Proc. 12th Int. SMiRT Conf., Stuttgart, 15-20 August 1993.* K2: 333-338. Amsterdam: North Holland.

Forni, M., Martelli, A., Bergamo, G., Bonacina, G., Cesari G.F., Di Pasquale, Marioni, A. & M. Olivieri 1995a. *Proposal for design guidelines for seismically isolated nuclear plants. EC-ENEA Contract ETNU-0031-IT.* Bologna: ENEA for EC.

Forni, M., Martelli, A., Dusi, A. & G. Castellano 1995b. F.E. models of steel-laminated rubber bearings for seismic isolation of nuclear facilities. *Proc. 13th Int. SMiRT Conf., Porto Alegre, 13-18 August 1995.* Rotterdam: Balkema.

Martelli, A., Masoni, P., Di Pasquale, G., Lucarelli, V., Sanò, T., Bonacina, G., Gluekler, E.L. and F.F. Tajirian 1990. Proposal for Guidelines for Seismically Isolated Nuclear Power Plants - Horizontal Isolation Systems Using High Damping Steel-Laminated Elastomer Bearings. *Energia Nucleare.* 1: 67-95.

Martelli, A. & M. Forni, eds., 1994. *Isolation, energy dissipation and control of vibrations of structures. Proc. of the Post-SMiRT Conf. Seminar, Capri, 23-25 August 1993.* Bologna: ENEA for GLIS.

Martelli, A., Forni, M., Spadoni, B., Marioni, A., Bonacina, G. & G. Pucci 1995. Progress of Italian experimental activities on seismic isolation. *Proc. 13th Int. SMiRT Conf., Porto Alegre, 13-18 August 1995.* Rotterdam: Balkema.