SEISMIC QUALIFICATION OF SYSTEMS, STRUCTURES, EQUIPMENT AND COMPONENTS

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SUMMARY

The purpose of this paper is to give an overview of the various qualification procedures available to the vendors of nuclear power plants and equipment for hopefully achieving NRC (Nuclear Regulatory Commission) plant licensing and overall guaranteed safe operation. These procedures usually involve computer-aided analyses for large systems and structures, but trend toward shaking table tests for small equipments and components. For example, analysis is used to investigate primary piping loops where calculated stresses are the criteria for failure. On the other hand, testing of sensitive devices becomes necessary where the avoidance of conceivable malfunctions is the criterion for safe performance.

The seismic qualification of the safety systems for an entire power plant begins with an evaluation of the earthquake environment at the plant site. This consists of test borings and vibration measurements to establish local soil conditions and determine how stress waves can be transmitted to the site. Continuing the emphasis on dynamics, a modal analysis of the soil interaction with the subsequent foundation and buildings is made for specific earthquake occurrences. Vibration field tests are then useful to validate the computer modelling. Design response spectra are made available not only for the building foundations, but also for the building floor areas that support safety-related equipment and components. Finally, the shaking tables used to qualify devices mounted in cabinets must simulate earthquake dynamic effects in terms of reproducing seismic response spectra.

The dynamic analysis and testing required for seismic qualification can be covered in a practical manner by reference to several pertinent Regulatory Guides and Standards. They have been issued by the NRC on specific subjects, but often represent a consensus of more general standards prepared by ASME, IEEE, ASCE, ANSI and NEMA. These documents cover such diverse subjects as (a) reactor site criteria, (b) seismic design limits and loading combinations, (c) system damping values, and (d) recommended vibration test practices. Engineers have had to learn that their final designs are subject to review by the NRC, University advisors and environmentalists. Eventually, they must account for the legitimate concerns for safety raised by such groups, and this goal can be approached by learning what the guides and standards have to say.

The available documents on seismic qualification procedures, including the regulatory guides, are subject to change. In particular, some of the engineering society standards amount to discussions of recommended practices that represent the "state of the art". From the equipment vendors point-of-view, the early seismic specifications were both tentative and exploratory. However, they have proliferated in the form of specific regulations and standards that have become the basis for contractual obligations. There has been a continuing escalation of safety-related seismic requirements. This present overview indicates a need for R & D work and re-examination of published documents to counterbalance unwarranted conservatism.

1. Introduction

Starting in about 1969, the seismic specifications received by the equipment vendors have been tentative and exploratory. Originally, some electric utility customers asked for equipment that could withstand a 0.2g earthquake without damage, and in addition all devices were to remain operable. There was no mention of dynamic analysis or vibration testing, and it was assumed that ordinary "off-the-shelf" apparatus would survive a seismic environment. From the vendors' point of view, such equipment and devices were made lightweight to satisfy high-speed performance requirements, and also had been value-engineered for reduced-cost. Shock resistance had not been a design consideration.

With regard to nuclear power plant applications, the specifications were later accompanied by seismic design response spectra at conservative, low values of damping. Sometimes the latter data in the form of families of curves were prepared by University seismologists and actually represented the original "free-field" earthquake ground motions. On the other hand, they might have been prepared by architect-engineers and represented "filtered" building floor motions based upon dynamic analyses of structure-foundation-soil interaction. Since the spectra varied from broad-band to narrow-band and the accelerations escalated to over 10g, the equipment vendors had to initiate extensive seismic qualification programs to stay in the nuclear business.

Such early contractual specifications have since then proliferated in the form of specific NRC issued guides and more general standards written by ASME, IEEE, ASCE, ANSI, NEMA and even individual equipment vendors. For example, there is a Westinghouse Corporate Standard for Class 1E equipment in order that some 25 different apparatus divisions can agree on the interpretation of seismic specifications and subsequent contractual obligations. Engineers have had to learn that overall system designs can be subject to review by the NRC, University advisors and environmentalists.

This paper will give an overview of the various qualification procedures available to the vendors of nuclear power plant equipment for hopefully achieving NRC plant licensing and guaranteed safe operation. The compelling reason for developing improved system standards is to avoid having arbitrary procedures imposed by law. At the other extreme, the compelling reason for developing improved equipment components is that they are most sensitive and vulnerable to the seismic environment in the form of possible malfunction.

2. Outline of Qualification Procedure

Seismic qualification usually involves computer-aided analyses for large systems and trends toward shaking table tests for small equipments. However, "in situ" vibration testing of large systems can be used to validate computer modelling, whereas "substructuring" computer techniques are used to qualify combinations of small equipment components that are tested separately.

As a generalization, analysis is used to qualify large structures involving the primary loop of nuclear power systems, where calculated stresses are the criteria for failure. On the other hand, testing is used to qualify small, sensitive devices used in plant safeguards equipment, where measured acceleration g-levels and malfunction are the failure criteria.

Both mechanical and electrical engineers must ultimately recognize and take into account the legitimate concerns expressed by the regulatory guides and standards that pertain to the seismic environment for their specific applications. An overview of the entire spectrum of

analysis and test is needed and can appropriately be achieved by referring to some of the more pertinent documents [1] in the following discussion of systems, structures, equipment and components.

3. Systems

The seismic qualification of the overall power plant system begins with an evaluation of the local earthquake environment according to the following:

10 CF 100 (NRC-RG)	Reactor Site Criteria, Appendix A - Seismic and Geologic Siting Criteria for Nuclear Power Plants
N 18.4 (ANSI)	Guidelines for Determining the Operating Base Earthquake and Associated Vibratory Ground Motion
RG 1.60 (NRC-1973)	Design Response Spectra for Seismic Design of Nuclear Power Plants

These documents incorporate conservative design rules that emphasize the long-term safety objectives of the NRC. For example, their use of broad-band spectra is conservative because earthquake motion recordings are often narrow-band. Also, the amplification factors used in the specified design spectra at a particular plant site are greater by one standard deviation than the mean factors found in the spectra derived from earthquake time-histories. Finally, the damping assumed in the analysis may be considerably smaller than found by vibro-seismic testing on site, which means increased response values and larger factors of safety.

Eventually, it should become practical to establish safe reactor site criteria as "the probability of exceeding" the SSE (Safe Shutdown Earthquake) g-level value predictions. At present, because of limited historical data on seismic frequencies as a function of intensity, licensing decisions have not made use of damage-probability assessments.

Recent site studies include the mapping of all active faults within a 200 mile radius, with a determination of the earthquake magnitude that could occur at each fault. Also, test borings and vibration measurements establish local soil conditions and how stress waves can be transmitted to the site. Such information, when used for a new kind of evaluation not presently found in Appendix A of 10 CF 100, would emphasize the low probability of specific earthquake occurrences.

The equipment vendor is well-aware of the steady escalation in recent years of seismic design requirements and cannot reconcile what appear to be contrary opinions expressed in the literature. For example, Housner [2] has stated that "the earthquake design forces for a nuclear power plant might be from three to five times larger than would be used for a fossil fuel power plant". Also, "A common method of describing the intensity of ground shaking is by means of the maximum ground acceleration although this gives only an imprecise specification of intensity". On the other hand, Hudson [3] states that "It must be always kept in mind that consideration of long term average conditions may be of small comfort to the engineer whose building was destroyed by an earthquake which happened to depart from the average".

4. Structures—Main Coolant Loop

Computer-aided dynamic analyses are used to calculate stresses in large structures such as the reactor pressure vessel, including associated piping, pumps and valves in the main coolant loops. Seismic qualification is demonstrated in terms of:

10 CFR 50 (NRC)	General Design Criteria for Nuclear Power Plants, Appendix A - Design Bases for Protection Against Natural Phenomena
RG 1.48 (NRC-1973)	Design Limits and Loading Combinations for Seismic Category 1 Fluid System Components (Related to Section III of the ASME Boiler and Pressure Vessel Code)
RG 1.92 (NRC-1976)	Combining Modal Responses and Spatial Components in Seismic Response Analysis
RG 1.61 (NRC-1973)	Damping Values for Seismic Design of Nuclear Power Plants

To establish comprehensive plant design criteria, the most effective analysis would couple the main reactor structures with the building foundation and underlying soil or rock system. However, Hall [4] has stated that "The problem of structure to structure interaction to be adequately accounted for, should consider truly three-dimensional characteristics. There are few solutions available today to handle this problem". More hopefully, he adds that "Lumped parameter approaches (readily available in three dimensions) can do just as well as two-dimensional plain strain, in fact maybe a little better". Considering the uncertainties in our knowledge of the soil conditions, it is further suggested that "Finally, one of the most important things is to perform parametric studies using upper and lower bounds on soil properties".

Having derived and specified conservative seismic design spectra, it is appropriate to make use of the normal mode method for dynamic analysis of linearized structural systems. Once again, there are regulatory guides which specify appropriate combinations of loadings "associated with normal operation, postulated accidents and specified seismic events". Conservative procedures are required, this time for "combining model responses and spatial components".

The damping values tabulated for use in the response spectrum method of analysis are again made smaller than given by test results on structures, similar to the conservative interpretation of the previously mentioned vibro-seismic soil tests made at the plant site. To establish appropriate damping values for the dynamic analysis of the main reactor coolant loop, it was necessary to make vibration tests on a full-scale plant system [5]. It was found that at large amplitudes the internal damping of the material was supplemented by external structural damping associated with relative motion at connections, impacting of parts and vibration of entrained fluids.

5. Structures - Auxiliary Buildings

Design response spectra for floors in buildings that support relatively small secondary plant equipment are derived from a seismic time-history analysis of the building-structure

interaction with its underlying foundation-soil system. The original broad-band ground response spectra become filtered [6] to give narrow-band floor response spectra according to:

RG 1.122 (NRC-1976)	Development of Floor Design Response for Seismic Design of Floor-Supported Equipment or Components
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This type of shock response spectrum emphasizes the filtered motion effects of earthquake motions on floor-mounted equipment, especially when equipment natural frequencies coincide with building natural frequencies. The multi-mode, multi-frequency features of broad-band spectrum testing become less important than the possible quasi-resonance effects in the equipment, which correspond to the narrow-band region of seismic motion amplification.

The constant reference to design response spectra in published guides and standards makes it pertinent to recall that Biot [7] originated the shock response spectrum to evaluate the damaging effects of earthquakes on buildings (and equipment). Unless there are natural frequencies in the buildings or equipment that occur in the 1 to 33 Hz range of seismic shock and vibration, there should be no amplified ground motion effects to cause damage. The original acceleration-time histories from which the corresponding ground and building floor response spectra are derived give a more graphic illustration of the large-amplitude fatigue effects that can occur in a comparatively small number of cycles [8].

The concept of "instantaneous response spectrum" can be used to show that even when earthquake records appear to have damaging potential over a wide range of frequencies, they actually produce narrow-band spectra when examined for short time intervals. Consequently, when the building structure filters the original ground tremors, the floor motion has less frequency content and corresponding narrow-band response spectra. Sometimes floor response spectra are artificially broadened to account for various assumed soil conditions, but this situation has been recognized and should not work to the detriment of the seismic qualification of the equipment.

6. Equipment and Components

It is mandatory that safety-related equipment and components be designed to withstand the effects of earthquakes without loss of their intended functions both during and after a seismic event. Because of their complex nature, most equipment devices cannot be qualified by design analysis. Also, since they may be subject to deterioration in hostile environments (i.e., temperature, radiation, humidity and vibration), the criteria for malfunction must incorporate actual operating conditions. The need for testing is emphasized by the following:

STD 323 (IEEE-1974)	Qualifying Class 1E Equipment for Nuclear Power Generating Stations
STD 344 (IEEE-1975)	IEEE Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations

IEEE Std 323-1974 has been endorsed by the NRC, with exceptions, by Regulatory Guide 1.89. It requires that equipment be aged "to its expected end-of-qualified life" before seismic testing. Simulated aging must account for degradation caused by hostile

environments and also by normal loading, applied voltages and mechanical wear. R&D work is being done to establish "projected qualified life" so that engineers have guidelines for selecting materials that suffer "no degradation", meaning continuous maintenance of the intended design function. It follows that seismic testing without prior aging is justifiable. In some instances, however, prior operation and conditioning of mechanical linkages may be appropriate. Additional work by the equipment vendors on the meaning and application of the qualified life concept will be required.

IEEE Std 344-1975 has also been endorsed by the NRC, with exceptions, by Regulatory Guide 1.100. The NRC has hired Southwest Research to review Std 344 for technical adequacy. When the foregoing qualification procedures are performed, there should be an adequate basis for complying with the following:

10 CFR 50 (NRC-RG)	Design Verification Requirements of Criterion III of Appendix B on Seismic Adequacy of Electric Equipment
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7. Continuing IEEE Seismic Standards Activities

In general, the standards being developed for nuclear plant systems and all types of equipment are becoming more specific. This means that it becomes more difficult for both vendors and potential customers to arrive at a consensus. There is an increasing need for R&D work and practical field experience to overcome the present emphasis on extra conservatism in all specifications.

Within IEEE, standards are being prepared by special Working Groups (i.e., WG 2.5 Seismic) under various parent Subcommittees (i.e., SC-2, Equipment Qualification). Regarding seismic qualification of equipment, there are numerous groups concerned with specific items such as switchgear (WG 2.7), motor control centers (WG 2.14), transformers (WG 2.8), etc. Each group is developing its own seismic standard based upon the recommended practices in document Std 344-1975. The power relaying committee (WG P501) will be the first to issue their seismic qualification guidelines for industry-wide approval.

In particular, WG 2.5 on seismic activities has formed a Task Force to study recent industry concerns and has already recommended some 17 important changes in Std 344 to be reissued by 1979. Some of the more general topics to be revised are as follows:

7.1 Generic Testing

Narrow-band spectra testing leads to equipment qualification for only one power plant at a time. At the other extreme, broad-band qualification is difficult to achieve in terms of both present-day shaking table and Class 1E equipment capabilities. However, it is believed that a practical, economic compromise can be reached by testing in three (3) overlapping spectrum bands (1 through 33 Hz), and still comply with the specified multi-frequency content of simulated earthquake motions.

7.2 Spectra Damping Values

There is widespread misunderstanding of the use of damping values and often a reluctance to supply equipment RRS (Required Response Spectra) at more than two (2) percent of critical damping. It is evident that larger values mean less conservatism when qualifying equipment by use of the normal mode design method. However, for demonstrating that a TRS (Test Response Spectrum) envelops an RRS, the comparison can be made at virtually any value of

damping (usually 1 and 5 percent). In any case, the damping value is determined by the steady-state vibration response of the equipment (usually 5 percent or larger in typical electrical equipment cabinets) as recorded during a slow frequency-sweep search for resonances.

7.3 Multiaxis Test Machines

The 1975 version of IEEE Std 344 on seismic qualification tends to emphasize multi-frequency, multi-direction proof testing at the expense of the original (1971) single-frequency, single-direction fragility level testing at important equipment resonances. The development of complex wave motion excitation and the superposition of single frequency sine beats for generic testing establish an intermediate, alternative procedure. The questionable significance of vibration phase relationships, geometric positions on the shaking table, and triaxial motion input must be re-evaluated. Even the renewed use of sine sweep testing has been suggested and appears to have merit for more comprehensive qualification testing at the reduced OBE (Operating Base Earthquake) acceleration g-levels

7.4 Combined Test and Analysis

The proposed generic testing is limited to a few cabinets which contain typical devices, but the final equipment application may be composed of different combinations. However, by using the g-level acceleration test data obtained in the shaking table validation, it becomes possible to qualify each new assembly by means of normal mode analysis.

8. Development of Biaxial Shaking Table

The seismic qualification IEEE Std 344-1975 states "The minimum is biaxial testing with simultaneous inputs in a principal horizontal and the vertical axes". If the resulting motions along these two axes are multi-frequency (complex, phase incoherent), the equipment need be tested in only two (2) positions which are 90° apart in the horizontal plane.

A direct way to obtain such motions has been to support the shaking table on air bags and apply independent excitation in the horizontal and vertical axes. Since the table might twist about the vertical axis, it is necessary to provide some table guidance by means of two parallel, hinged-end rods that encourage translatory motions. However, unless the excitation systems are correctly controlled, there may still result undesirable "rock and roll" of the table, especially with tall equipment structures mounted on it.

In order to obtain translation without rotation, the shaking table can be guided at the corners by four (4) parallel (journal) rods and linear bearings. Only one driver is required along an inclined axis, and several angular positions can be provided to give a fixed ratio of horizontal to vertical components (i.e. 45°, 35° and 25°) for the inclined motion input. If single-frequency excitation is used, then the seismic standard requires that equipment be tested in four (4) positions which, again, are 90° apart in the horizontal plane. When multi-frequency excitation is used, it becomes necessary to show that the resulting component (horizontal vs vertical) motions are phase incoherent to justify testing the equipment in only two (2) positions.

9. Qualification of Multi-Cabinet Assemblies

The IEEE Std 323 appears to require "ongoing" seismic qualification of a wide variety of multi-cabinet assemblies of switchgear and motor control centers as installed in nuclear power plants. However, the proposed generic testing is limited to only a few cabinets at one

time, although they do incorporate many typical devices. Also, the latter may occupy quite different locations in the larger final assemblies, which are known to exceed both the weight and size limitations of available seismic shaking tables.

Computer analyses can be used to relate the individual cabinet seismic test data to multi-cabinet assemblies, where the normal mode design method will determine g-level response values at any device location in the computer model. However, it is essential to make use of simple static deflection and resonant vibration tests to establish that the computer model is valid. Also, to keep the model extrapolations within the limit of computer memory capabilities, the technique known as "substructuring" must be applied to individual cabinets and device packages. The earlier generic testing in terms of spectra enveloping and g-level recordings can then be used to qualify devices at new locations in different equipment assemblies.

10. Conclusions

Seismic qualification procedures start with geologic and seismologic considerations with regard to plant siting criteria. They apply to all sizes of structures and equipment. Ultimately, they delve into possible malfunction of every nuclear safeguard device. Meanwhile, engineers are confronted with numerous government regulatory guides, industry standards and customer contractual obligations. Some of the more pertinent of such documents have been tabulated and then discussed to give a brief overview of the latest developments involving both seismic analysis and test. There appears to be a continuing need for R&D work and re-examination of published documents to counterbalance unwarranted conservatism and thereby emphasize the low probability of specific earthquake occurrences.

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