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IEEE Std 344™-2004
(Revision of
IEEE Std 344-1987)

344™

IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations

IEEE Power Engineering Society

Sponsored by the
Nuclear Power Engineering Committee

IEEE

3 Park Avenue, New York, NY 10016-5997, USA

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IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations

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Nuclear Power Engineering Committee
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Approved 8 December 2004

IEEE-SA Standards Board

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Abstract: Recommended practices are provided for establishing procedures that will yield data to demonstrate that the Class 1E equipment can meet its performance requirements during and/or following one safe shutdown earthquake event preceded by a number of operating basis earthquake events. This recommended practice may be used to establish tests, analyses, or experienced-based evaluations that will yield data to demonstrate Class 1E equipment performance claims or to evaluate and verify performance of devices and assemblies as part of an overall qualification effort. Common methods currently in use for seismic qualification by test are presented. Two approaches to seismic analysis are described, one based on dynamic analysis and the other on static coefficient analysis. Two approaches to experienced-based seismic evaluation are described, one based on earthquake experience and the other based on test experience.
Keywords: Class 1E, earthquake, earthquake experience, equipment qualification, inclusion rules, nuclear, operating basis earthquake, prohibited features, qualification methods, required response spectrum, response spectra, safe shutdown earthquake, safety function, seismic, seismic analysis, test response spectrum, test experience, type testing

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Introduction

This introduction is not part of IEEE Std 344-2004, IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations.

This revision of IEEE Std 344-1987 was developed to expand and clarify guidance for developing programs to seismically qualify Class 1E equipment for nuclear power generating stations. Specific areas of amplification included are based on experience gained since 1987.

The Class 1E equipment to be qualified by procedures or standards based upon this revised recommended practice can be of many forms; therefore, this recommended practice presents the guidelines for many acceptable seismic qualification methods with the intent of permitting the user to make a judicious selection from the options offered. This revised recommended practice attempts to define more fully the procedures by which Class 1E equipment can be seismically qualified. It presents the methods that are known by the working group to be practices that are acceptable to the nuclear power generation industry, its equipment suppliers, and the industrial test and analysis facilities utilized by the industry. The clarification and update of methods in this recommended practice reflect an effort to recommend state-of-the-art techniques at the time of publication.

The methods and definitions presented in this revision are not intended to limit other seismic qualification techniques. Exceptions to these recommended practices may be made at any time where it can be shown that the substituted procedure verifies that the equipment can perform its safety function with justifiable methodology. The basis for a technical justification may be, but is not limited to, partial analysis, tests on similar equipment, experience data, or a combination thereof. Engineering judgment may be used in conjunction with these methods. Exceptions to these guidelines, which are founded on a broad base of actual test, analysis, and earthquake experience, supplemented by engineering judgment, may be used to meet the intent of this standard, provided the methods are justified.

The Foreword of the 1987 revision of this standard noted that experience-based methods for seismic qualification of equipment were under development, and Clause 9 of the 1987 revision contained interim guidance for the use of experience data for this purpose. Since then, development of the experience-based approach has been furthered by the Seismic Qualification Utility Group (SQUG). The SQUG approach was used at many nuclear power plants to resolve USI A-46. It has also been adopted, in part, and used by other governmental and industrial organizations. Accordingly, Clause 10 and relevant parts of Clause 11 of this revision of the standard have been rewritten to incorporate the results of this development. Use of the experience-based approach in this recommended practice is acceptable for use in nuclear plants if it is consistent with the plant's licensing/regulatory design basis.

Issues related to use of median-centered in-structure response spectra for the earthquake experience-based method, operating basis earthquake (OBE) requirements associated with the test experience method, and generation of a test-experience spectrum were considered at length by the working group in the preparation of this document.

Further guidance for qualification of replacement components and devices within an existing, previously qualified larger equipment assembly by the earthquake experience-based method is deferred to the next revision of the standard. Special consideration could be added to determine how to extend earthquake experience data to replacement of components and devices in a previously qualified equipment assembly so that there is sufficient detail and traceability in the areas of equipment performance (physical configuration, operational, and dynamic), installation, excitation, and demonstration of safety function.

Adherence to this recommended practice to obtain equipment seismic qualification alone will not suffice for assurance of public health and safety since it is the integrated performance of structures, fluid systems,

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instrumentation systems, electrical systems, and man/machine interface systems of a nuclear power generating station that establishes totally safe operating conditions.

This standard was prepared by Subcommittee 2 Working Group 2.5 (Seismic) of the Nuclear Power Engineering Committee of the IEEE Power Engineering Society.

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IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations

1. Overview

This recommended practice is divided into 11 clauses. Clause 1 provides the scope of this recommended practice. Clause 2 lists normative references to other standards that are useful in applying this recommended practice. Clause 3 provides definitions that are either not found in other standards or have been modified for use with this recommended practice. Clause 4 provides background information on earthquake behavior and on the performance of equipment during simulated seismic events. Clause 5 defines the most commonly used methods for seismic qualification of equipment contained in this recommended practice. Clause 6 provides guidance on the measurement and application of damping in the seismic qualification of equipment. Clause 7 provides procedures for two approaches most commonly used to seismically qualify equipment by analysis. Clause 8 provides procedures for the commonly used methods for seismic qualification of equipment by test. Clause 9 provides guidelines for seismic qualification of equipment that cannot be practically qualified by analysis or testing alone. Clause 10 provides guidelines for two approaches to seismically qualify equipment using experience data for a reference equipment class. Clause 11 provides documentation guidelines for the seismic qualification of equipment.

This recommended practice also contains six annexes. Annex A explains how to measure the zero period acceleration (ZPA) from seismic test data. Annex B explains frequency content and stationarity of the input waveform. Annex C provides guidance on fragility testing. Annex D explains the use of test duration and response cycles in ensuring adequate equipment response relative to low-cycle fatigue capability. Annex E provides guidance in establishing statistically independent simulated simultaneous multiaxis motions for seismic testing and analysis. Annex F provides bibliographic references.

1.1 Scope

This document describes recommended practices for establishing seismic qualification procedures that will yield quantitative data to demonstrate that the Class 1E equipment can meet its performance requirements during and/or following one safe shutdown earthquake (SSE) event preceded by a number of operating basis earthquake (OBE) events. The test, analysis, or experienced-based evaluation methods described herein may be used to yield data to demonstrate Class 1E equipment performance claims or to evaluate and verify performance of devices and assemblies as part of an overall qualification effort.

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1.2 Purpose

The purpose of this document is to provide recommended practices and documentation requirements for seismic qualification of Class 1E equipment to verify the equipment's ability to perform its safety function during and/or after the specified seismic motions.

2. Normative references

This recommended practice shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

IEEE Std 323™-2003, IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations.[1,2]

IEEE Std 382™-1996, IEEE Standard for Qualification of Actuators for Power-Operated Valve Assemblies with Safety-Related Functions for Nuclear Power Plants.

MIL-S-901C-1963, Requirements for Shock Tests, H. I. (High Impact); Shipboard Machinery, Equipment and Systems.[3]

10 CFR, Energy—Chapter 1, Nuclear Regulatory Commission.[4]

3. Definitions

For the purpose of this recommended practice, the following terms and conditions apply. IEEE 100, *The Authoritative Dictionary of IEEE Standards Terms,* Seventh Edition [B1],[5] should be referenced for terms not defined in this clause.

3.1 broadband response spectrum: A response spectrum that describes motion in which amplified response occurs over a wide (broad) range of frequencies.

3.2 coherence function: A comparative relationship between two time histories. It provides a statistical estimate of how much two motions are related, as a function of frequency. The numerical range is from zero for unrelated, to +1.0 for related motions.

3.3 correlation coefficient function: A comparative relationship between two time histories. It provides a statistical estimate of how much two motions are related, as a function of time delay. The numerical range is from zero for unrelated, to +1.0 for related motions.

3.4 critical seismic characteristics: Those design, material, and performance characteristics of an equipment item that provide assurance that the item will perform its required function under seismic loads.

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3.5 cutoff frequency: The frequency in the response spectrum where the ZPA asymptote begins. This is the frequency beyond which the single-degree-of-freedom (SDOF) oscillators exhibit no amplification of motion and indicate the upper limit of the frequency content of the waveform being analyzed.

3.6 damping: An energy dissipation mechanism that reduces the amplification and broadens the vibratory response in the region of resonance. It is usually expressed as a percentage of critical damping. Critical damping is defined as the least amount of viscous damping that causes a SDOF system to return to its original position without oscillation after initial disturbance.

3.7 earthquake experience spectrum (EES): The response spectrum that defines the seismic capacity of a reference equipment class based on earthquake experience data.

3.8 flexible equipment: Equipment, structures, and components whose lowest resonant frequency is less than the cutoff frequency on the response spectrum.

3.9 floor acceleration: The acceleration of a particular building floor (or equipment mounting) resulting from the motion of a given earthquake. The maximum floor acceleration is the ZPA of the floor response spectrum.

3.10 Fourier spectrum: A complex valued function that provides amplitude and phase information as a function of frequency for a time domain waveform.

3.11 ground acceleration: The acceleration of the ground resulting from the motion of a given earthquake. The maximum ground acceleration is the ZPA of the ground response spectrum.

3.12 inclusion rules: The rules that define the bounds of equipment included in a reference equipment class based on an acceptable range of equipment physical characteristics, dynamic characteristics, and functions for which seismic ruggedness has been demonstrated by experience data.

NOTE—See 10.2.3.1 and 10.3.3.1.[6]

3.13 independent items: Components and equipment that (a) have different physical characteristics or (b) experienced different seismic motion characteristics, e.g., different earthquakes, different sites, different buildings, or different orientations/locations in the same building.

3.14 median-centered in-structure response spectrum: In-structure response spectrum developed using realistic damping and best estimate modeling parameters to obtain the most probable structural amplification that could realistically occur for the level of the specified earthquake ground motion.

3.15 narrowband response spectrum: A response spectrum that describes the motion in which amplified response occurs over a limited (narrow) range of frequencies.

3.16 natural frequency: The frequency(s) at which a body vibrates due to its own physical characteristics (mass and stiffness) when the body is distorted in a specific direction and then released.

3.17 operating basis earthquake (OBE): An earthquake that could reasonably be expected to occur at the plant site during the operating life of the plant considering the regional and local geology and seismology and specific characteristics of local subsurface material. It is that earthquake that produces the vibratory ground motion for which those features of the nuclear power plant, necessary for continued operation without undue risk to the health and safety of the public, are designed to remain functional.

[6]Notes in text, tables, and figures are given for information only, and do not contain requirements needed to implement the standard.

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3.18 power spectral density (PSD): The mean squared amplitude per unit frequency of a waveform. PSD is expressed in g^2/Hz versus frequency for acceleration waveforms.

3.19 prohibited features: Design details, materials, construction features, or installation characteristics that have resulted in seismic induced failure or malfunction of the equipment to maintain its structural integrity and perform its specified function at earthquake or test excitations up to and including the defined seismic capacity level.

3.20 qualified life: The period of time, prior to the start of a design basis event (DBE), for which the equipment was demonstrated to meet the design requirements for the specified service conditions.

3.21 reference equipment: The equipment used to establish a reference equipment class.

3.22 reference equipment class: A group of equipment sharing common attributes as defined by a set of inclusion rules and prohibited features.

3.23 reference site: A site containing equipment or items used to establish a reference equipment class.

3.24 required response spectrum (RRS): The response spectrum issued by the user or the user's agent as part of the specifications for qualification or artificially created to cover future applications. The RRS constitutes a requirement to be met.

3.25 resonant frequency: A frequency at which a response peak occurs in a system subjected to forced vibration. This frequency is accompanied by a phase shift of response relative to the excitation.

3.26 response spectrum: A plot of the maximum response, as a function of oscillator frequency, of an array of SDOF damped oscillators subjected to the same base excitation.

3.27 rigid equipment: Equipment, structures, and components whose lowest resonant frequency is greater than the cutoff frequency on the response spectrum.

3.28 safe shutdown earthquake (SSE): An earthquake that is based upon an evaluation of the maximum earthquake potential considering the regional and local geology and seismology and specific characteristics of local subsurface material. It is that earthquake that produces the maximum vibratory ground motion for which certain structures, systems, and components are designed to remain functional. These structures, systems, and components are those necessary to ensure the following:

a) Integrity of the reactor coolant pressure boundary
b) Capability to shut down the reactor and maintain it in a safe shutdown condition
c) Capability to prevent or mitigate the consequences of accidents that could result in potential off-site exposures comparable to the guideline exposures of 10 CFR—Chapter 1, Part 100[7]

3.29 seismic capacity: The highest seismic level for which required adequacy has been verified.

3.30 seismic ruggedness: The ability to resist the damaging effects of an earthquake imparted by robust design and manufacture.

3.31 seismic vulnerability: A physical and/or electrical characteristic that renders an equipment item susceptible to structural damage or malfunction from the effects of an earthquake.

3.32 sine beats: A continuous sinusoid of one frequency, amplitude modulated by a sinusoid of a lower frequency.

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[7]Information on references can be found in Clause 2.

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3.33 stationarity: A condition that exists when a waveform is stationary and when its amplitude distribution, frequency content, and other descriptive parameters are statistically constant with time.

3.34 structure diameter: The diameter of a circle having the equivalent area of the facility's foundation.

3.35 test experience spectra (TES): The test-based response spectra that define the seismic capacity of a reference equipment class.

3.36 test response spectrum (TRS): The response spectrum that is developed from the actual time history of the motion of the shake table.

3.37 transfer function: A complex frequency response function that defines the dynamic characteristics of a constant parameter linear system. For an ideal system, the transfer function is the ratio of the Fourier transform of the output to that of a given input.

3.38 zero period acceleration (ZPA): The acceleration level of the high-frequency, nonamplified portion of the response spectrum. This acceleration corresponds to the maximum peak acceleration of the time history used to derive the spectrum.

4. General discussion of earthquake environment and equipment response

This clause provides background information on earthquake behavior and on the performance of equipment during simulated seismic events. Numerical values provided are typical and illustrative and should not be considered as standards.

4.1 Earthquake environment

Earthquakes produce three-dimensional (3D) random ground motions that are characterized by simultaneous but statistically independent horizontal and vertical components. The strong motion portion of the earthquake may last from 10 s to 15 s, although the complete event may be considerably longer. The ground motion is typically broadband random and produces potentially damaging effects over a frequency range of 1 Hz to 33 Hz.

4.2 Equipment on foundations

The vibratory nature of the ground motion (both horizontal and vertical) can be amplified or attenuated in foundation-mounted equipment. For any given ground motion, the alteration depends on the system's natural frequencies of vibration (soil, foundation, and equipment) and the damping mechanisms. The typical broadband response spectra that describe the ground motion indicate that multiple-frequency excitation predominates.

4.3 Equipment on structures

The ground motion (horizontal and vertical) may be filtered by intervening building structures to produce amplified or attenuated narrowband motions within the structure. The dynamic response of equipment on structures may be further amplified or attenuated to an acceleration level many times more or less than that of the maximum ground acceleration, depending upon the equipment damping and natural frequencies. The narrowband response spectra that typically describe a building floor motion indicate that single-frequency excitation of equipment subcomponents can predominate. Similar filtering of in-structure motion may occur in flexible piping systems. For components mounted away from supports, the resultant motion may be predominantly single frequency in nature and centered near or at the resonant frequency of the piping

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system. This resonance condition may produce the most critical seismic load on components mounted on the line.

4.4 Simulating the earthquake

The goal of seismic simulation is to reproduce the postulated earthquake environment in a realistic manner. The form of the simulated seismic motion used for the qualification of equipment by analysis or testing can be described by one of the following functions:

a) Response spectrum

b) Time history

c) Power spectral density (PSD)

The simulated seismic motion may be generated for the foundation, floor of the building, or substructure upon which the equipment is to be mounted. It is supplied by the user or the user's agent as a part of the specifications for that equipment (see Clause 11) or generated by others for generic applications.

Because of the directional nature of seismic motion and the filtered output motion of building and equipment structures, the directional components of the motion and their application to the equipment should be specified or accounted for in some other appropriate manner.

4.4.1 Response spectrum

The response spectrum provides information on the maximum response of single-degree-of-freedom (SDOF) oscillators as a function of oscillator frequency and damping when subjected to an input motion. The frequency content and the peak value of the input motion, that is, the ZPA, are indicated.

It is important to recognize that the response spectrum does not supply the following information:

a) The waveform or time history of the excitation that produced it

b) The duration of motion (this must be defined in the qualification specification)

c) The dynamic response of any particular equipment

4.4.2 Time history

A time history displays the earthquake-induced motion (usually in terms of acceleration) as a function of time. The simulated motion is derived from existing or artificially generated earthquake records. For application at any floor, the time history record generated includes the dynamic filtering and amplification effects of the building and other intervening support structures.

4.4.3 PSD function

The mean squared amplitude per unit frequency of the vibratory motion is characterized in terms of the PSD as a function of frequency.

NOTE—Although the response spectrum and the PSD function do not define the exact waveform or duration of the excitation, they are valuable tools. They enable significant frequency-dependent properties of the motion to be seen at a glance from one curve. The PSD provides information regarding the excitation directly without including the effects on an array of SDOF oscillators as is done for the response spectrum. As a result, the PSD allows application of relationships between excitation and response by way of the transfer functions for linear systems.

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4.5 Support structure and interactions

Seismic qualification of equipment requires consideration of installation features, such as (a) the seismic adequacy of the supporting structure (support assembly, structure, anchorage, floors, walls, or foundation), and (b) the potential for adverse seismic interactions (such as falling of overhead components, proximity impacts, differential displacements, spray, flood, or fire).

5. Seismic qualification approach

The seismic qualification of equipment should demonstrate an equipment's ability to perform its safety function during and/or after the time it is subjected to the forces resulting from one SSE. In addition, the equipment must withstand the effects of a number of OBEs [see 7.6, 8.1.5.2, item b) in 10.2.3.1, and 10.3] prior to the application of an SSE. The most commonly used methods for seismic qualification are contained in this recommended practice. The methods are grouped into four general categories that

a) Predict the equipment's performance by analysis.

b) Test the equipment under simulated seismic conditions.

c) Qualify the equipment by a combination of test and analysis.

d) Qualify the equipment through the use of experience data.

Each of the preceding methods, or other justifiable methods, may be adequate to verify the ability of the equipment to meet the seismic qualification requirements. The choice should be based on the practicality of the method for the type, size, shape, and complexity of the equipment configuration, whether the safety function can be assessed in terms of operability or structural integrity alone, and the reliability of the conclusions.

Equipment being qualified must demonstrate that it can perform its safety function during and/or after an earthquake. The required safety function depends not only on the equipment itself but also on the system and plant in which it is to function. The safety function during the earthquake may be the same, but is often different from the safety function required after the earthquake. For example, an electrical device may be required to have no spurious operations during the earthquake or to perform an active function both during and/or after the earthquake, or it may be required to survive during the earthquake and perform an active function after the earthquake, or any combinations of these. Another device may only be required to maintain structural integrity during and/or after the earthquake. Throughout this recommended practice, it is assumed that the requirements given here are understood and that the definition of the safety function is provided as part of the equipment qualification specification. It is the responsibility of the user to verify that the qualification approach selected complies with the requirements.

When the safety function of equipment requires a demonstration of operability during the earthquake, it shall be demonstrated during the strong motion portion of the qualification simulation.

The seismic testing, when part of an overall qualification program, should be performed in its proper sequence as indicated in IEEE Std 323-2003 and care should be taken to identify and account for significant aging mechanisms with test margins as discussed therein. Within these guidelines, it must be demonstrated that the equipment is capable of performing its safety function throughout its qualified life, including its functional operability during and/or after an SSE at the end of that qualified life.

Earthquake experience data will result in seismic capacities that are significantly less than those obtained from seismic testing. This is because earthquake ground motions, which form the basis for establishing capacities in 10.2, are significantly less than the seismic accelerations typically obtained during shake-table testing.

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6. Damping

6.1 Introduction

Damping is the generic name ascribed to the numerous energy dissipation mechanisms in a system. In practice, damping depends on many parameters, such as the structural system, mode of vibration, strain, normal force, velocity, materials, joint, and slippage. In linear vibration theory, the simplifying assumption is made that damping is purely viscous or proportional to the relative velocity of moving parts. Therefore, when a value of damping is associated with a practical system, it is usually assumed to be equivalent to viscous or linear. This is a convenient simplification relating real-world hardware behavior, which may be nonlinear to some degree, with theoretical concepts that normally utilize linear methods of analysis.

For equipment composed of an assembly of components, there is usually no single value of damping. Damping is associated with every part of the equipment, ranging from bolted or welded construction to uniform material. The value of damping may vary from place to place, depending on numerous factors. Therefore, when a value of damping is ascribed to equipment, it is common to give a range of typical values. Since each mode of vibration of a structure can, and most often does, have a different value of damping, a useful practice in analysis is to associate a value of damping to each mode of vibration of the equipment that is in the frequency range of interest.

6.2 Measurement of damping

Linear vibration theory indicates that there are numerous methods for measuring damping. Considerable care must be exercised in making the correlation between an idealized model and a practical system. For example, it is rarely possible to locate precise points in equipment that have exact correspondence with the lumped mass elements in a model. Some methods of calculating modal damping, such as the Q method, rely purely on SDOF assumptions.

Damping calculated directly from the maximum response at the resonance peak measured at any point in the equipment and the magnitude of the sine-sweep input excitation is not generally acceptable since the response of points in equipment is usually determined by the mode shape vector and the participation factor for each vibration mode. The following methods for evaluating damping are commonly used but other justifiable methods may be used. They assume that a single mode of vibration can be excited in the equipment and that motion transducers are mounted at positions other than at a point of zero motion. In all cases, care should be exercised to determine whether damping nonlinearity with response amplitude is significant.

6.2.1 Damping by measuring the decay rate

The equivalent viscous damping can be calculated by recording the decay rate of the particular vibration mode. This procedure is often referred to as the *logarithmic decrement method.*

6.2.2 Damping by measuring the half-power bandwidth

The equipment should be excited with a slowly swept sinusoidal vibration. The response of any desired location in the equipment is measured and plotted as a function of frequency. From these response plots, the damping associated with each mode can be calculated by measurements of the width of the respective resonance peak at the half-power point. This procedure is often referred to as the *half-power bandwidth method.*

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6.2.3 Damping by curve fitting methods

The equipment is excited by swept sine, random, or transient excitation, and a response transfer function is developed. The modal damping is obtained by fitting a mathematical model to the actual frequency response data (transfer function). This curve fitting will smooth out any noise or small experimental errors.

6.3 Application of damping

Ranges of damping, measured as described in 6.2, are valuable data for the equipment designer. Damping is used differently in equipment qualification analysis and testing as described in 6.3.1 and 6.3.2.

6.3.1 Application of damping in analysis

In analysis, a mathematical model is made of the equipment so as to predict the response to the seismic motion. The value of damping used in this model should correspond to the actual energy dissipation in the equipment to enable the response to be accurately predicted. An alternative approach is to use a conservative value of linear damping to obtain a conservative estimate of response. In any case, there is a need to know the ranges of damping for the specific equipment and the nature of nonlinearities and their effect on the response. Appropriate values of damping may be obtained from tests or other justifiable sources.

It is reasonable to state that actual damping is nonlinear by nature. In most equipment, it is a function of response amplitude owing to such factors as internal friction within material, or at connections between components, or Coulomb-type sliding friction. For analytical purposes, these energy dissipation damping mechanisms may often be treated in terms of linear damping approximations if proper consideration is given to the fact that these approximations vary, sometimes significantly, with increasing response. As an example, the use of low-impedance testing to determine damping must be exercised with caution since at strong motion shaking, indicative of significant earthquakes, the aforementioned factors may cause the real damping to be quite different and higher than that measured at low levels.

Generally, most treatment of structural systems assumes viscous damping; however, certain cabinets or housings may exhibit nonviscous damping. The treatment of such a problem is analytically complex and should be performed using appropriate techniques.

6.3.2 Application of damping in testing

In testing, the equipment may be qualified by subjecting it to a simulated seismic motion as defined by the required response spectrum (RRS). The response spectrum defines the seismic motion by way of the peak response of an array of SDOF damped oscillators. Since the oscillators are hypothetical, any practical value of damping, for example 5%, may be employed in the RRS for testing, and it need not correspond to the actual equipment damping (note the distinction from the use of the RRS in analysis where the value of damping must be related to the actual equipment). The application of the RRS and the test response spectrum (TRS) in selecting acceptable test motions is given in 8.6.1. The following relationships exist for the values of damping in the response spectra:

a) In comparing the RRS and the TRS, it is preferred that the damping in the two be the same.

b) In comparing the RRS and TRS when the damping is not the same, the following circumstances apply:

   1) When the damping for the TRS is greater than that for the RRS and the criteria in 8.6.1 are satisfied, then the qualification is acceptable, since under this circumstance it is conservative.

   2) When the damping in the TRS is less than that in the RRS, a conclusive statement is not possible without further evaluation. One possibility is to reanalyze the test motions to produce a TRS for an acceptable damping value and apply the criteria given in either item a) or item b1).

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7. Analysis

NOTE—The analysis method is not recommended for complex equipment that cannot be modeled to adequately predict its response. Analysis without testing may be acceptable only if structural integrity alone can ensure the design-intended function.

7.1 Introduction

Procedures are presented in Clause 7 that can be used to seismically qualify equipment by analysis for a number of OBEs followed by an SSE. Two approaches to seismic analysis are described. One approach is based on dynamic analysis, the other on static coefficient analysis. The methods described are most commonly used, but others may be used if they are justifiable. Figure 1 is a flowchart of the recommended analytical process. The general procedure is as follows:

a) Review the equipment to assess the dynamic characteristics.

b) Determine the response using one or more of several methods described in 7.2 through 7.7.

c) Determine the stresses and displacements that result from the response.

d) Compare the calculated responses with those that ensure compliance with design requirements.

The review stage should take into account the complexity of the equipment and the adequacy of analytical techniques to properly predict the equipment's safety functions while under seismic excitation. The review should determine which method will most accurately represent the equipment's performance under seismic conditions. The response determination phase of the analysis can take several paths, the first of which is determined by the choice between the dynamic analysis method (see 7.2) and the static coefficient method (see 7.3). In general, the choice is based on the perceived margin of strength of the equipment since the static coefficient method, while easier and more economical to perform, is generally more conservative.

Dynamic analysis or tests may indicate that the equipment is either rigid or flexible. Rigid equipment may be analyzed using static analysis and the seismic acceleration associated with the mounting location. Flexible equipment may be analyzed using the *static coefficient method* (see 7.3), or using its dynamic response computed from a response spectrum, time history, or other analysis methods.

The mathematical models used for analysis can be based on calculated structural parameters, on those established by test, or by a combination of these. Where complex mathematical models are based solely on calculated structural parameters, the use of verification testing is recommended (see Clause 9). The damping used in the analysis should have a reference basis such as the safety analysis report, the specification, or testing. When a damping value has not been defined, one can be established by any means when it is justified in the qualification report.

An evaluation of the effects of the calculated stresses and strains on mechanical strength, and where possible, function, may be performed using the calculated dynamic response. To check for any interference, maximum displacements should be computed for the component as installed. The seismic stress must be added to the equipment operating stresses to determine if the strength of the equipment is adequate.

7.2 Dynamic analysis

The equipment and any secondary structural supports must be modeled to adequately represent their mass distribution and stiffness characteristics. This model may be used to perform a modal (eigenvalue) analysis to determine whether the equipment is rigid or flexible.

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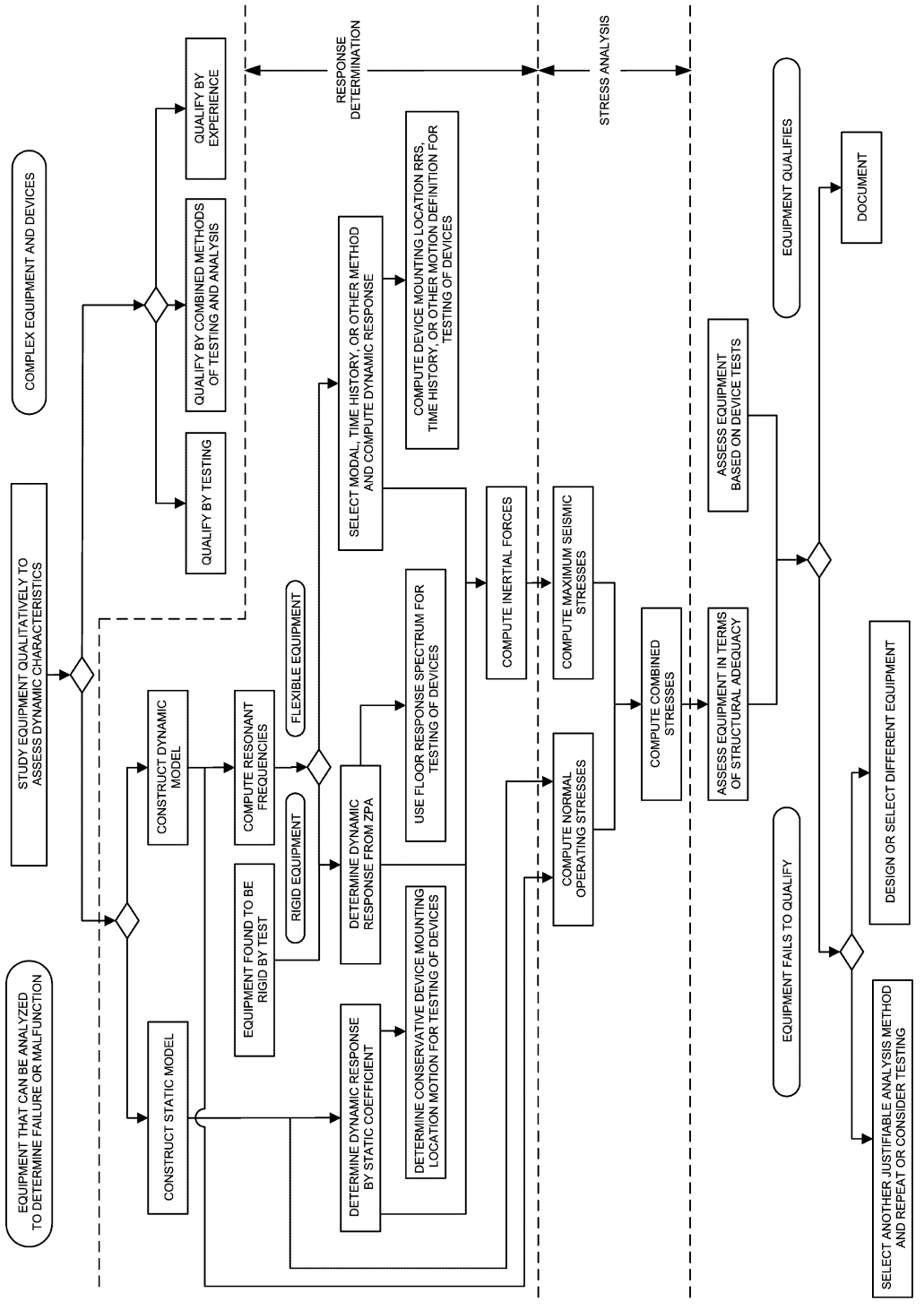

Figure 1—Seismic analysis flowchart

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The equipment is considered rigid when the model has no resonances in the frequency range below the cutoff frequency of the RRS and may be analyzed statically. The seismic forces on each equipment component are obtained by multiplying the distributed mass by the appropriate maximum floor acceleration (ZPA).

For flexible equipment, the model can be analyzed using a response spectrum analysis or a time history analysis. Using response spectrum analysis allows the response of interest, be it deflection, stress, or acceleration, to be determined by combining each modal response considering all significant modes. Sufficient modes (modal mass) should be included to ensure an adequate representation of the equipment dynamic response and constraint forces at supports. An acceptable criterion for sufficiency is that the inclusion of additional modes does not result in more than a 10% increase in response. The response is determined by combining each modal response by the square root of the sum of the squares (SRSS), except where closely spaced modes apply. Closely spaced modes shall be considered in the response evaluation. Closely spaced modes are those with frequencies differing by 10% or less of the next lower frequency. In the analysis using 3D individual earthquake components, the responses (acceleration, displacement, force, moment) due to two horizontal and one vertical component input should be combined at the last step by the SRSS method. When 3D statistically independent time histories are input simultaneously for a time history analysis, the responses can be combined algebraically at each time increment. To ensure statistical independence, artificially generated time histories should have coherence values of less than 0.5 when computed with at least 12 data samples. Alternatively, an absolute value for the correlation coefficient of less than 0.3 for all time delays may be used (see Annex E for further explanation).

7.3 Static coefficient analysis

This is an alternate method of analysis that allows a simpler technique in return for added conservatism. A determination of natural frequencies is not required. The acceleration response of the equipment is assumed to be the maximum acceleration in the amplified region peak of the RRS at a conservative and justifiable value of damping. A static coefficient of 1.5 has been established from experience to take into account the effects of multifrequency excitation and multimode response for linear frame-type structures, such as members physically similar to beams and columns, which can be represented by a simple model. A lower static coefficient may be used when it can be shown to yield conservative results. In a static coefficient analysis, the seismic forces on each component of the equipment are obtained by multiplying the values of the mass times the maximum peak of the RRS times the static coefficient. The resulting force should be distributed over the component in a manner proportional to its mass distribution. The stress at any point in the equipment can then be determined by combining the stress at that point due to the earthquake loading in each direction using the SRSS method.

7.4 Nonlinear equipment response

Nonlinearities may exist in addition to those associated with damping. These effects may be of a geometric nature, such as the closing of gaps, working of connections and rattling of components, or of a material source such as localized yielding. These effects may result in changing stiffness with increasing load. As frequency is also a function of stiffness, the frequencies may also change under increasing load. If a system exhibits significant nonlinearity, such behavior must be recognized and accounted for in any subsequent analysis so as to accurately predict the system response. If the nonlinearities cannot be adequately modeled, an alternative qualification method, such as those described in Clauses 8, 9, and 10, should be considered.

Nonlinearity may also occur as a result of local vibrations of equipment structure. One example has been the high-frequency rattling of electrical cabinet doors that are not solidly secured in place. When such a condition exists and the operability of the mounted devices is deemed sensitive to this type of equipment nonlinear behavior, the analytic procedure must account for the behavior and must be properly validated.

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7.5 Other dynamic loads

The analytical methodology described in 7.3 and 7.4 for seismic loading is equally applicable to other dynamic loadings, such as hydrodynamic. For further guidance on hydrodynamic loads, see 8.1.6.1.

7.6 OBE and SSE analysis

An analysis should be performed using one of the previously described methods, with an assumed number of OBE events (the number shall be not less than one and shall be justified for each site or five OBEs shall be used). Each OBE should contain a fatigue-inducing potential that is similar to the earthquake response motion at the mounting of the equipment. For floor-level excitation, this should be approximated by demonstrating that each excitation waveform will produce a response that includes the equivalent of at least ten maximum peak-stress cycles. For ground-level excitation, the number of equivalent peak-stress cycles may be different (see Annex D). The number of OBEs and the fatigue-inducing potential per OBE is important only for low-cycle fatigue-sensitive equipment. The analysis should determine that the structural integrity of the equipment is maintained in combination with other applicable loads during the OBE. The analysis must show that OBE events followed by an SSE will not result in failure of the equipment to perform its safety function. This may be particularly difficult to show for complex electrical equipment, in which case alternative qualification methods, such as those described in Clauses 8, 9, and 10, should be considered.

7.7 Documentation of analysis

The demonstration of qualification shall be documented and shall include the requirements of the equipment application or specifications, the results of the qualification, and the justification that the methods used are capable of demonstrating that the equipment can perform its safety function (see Clause 11).

8. Testing

8.1 Introduction

Procedures are presented in this clause that can be used to seismically qualify equipment by test. Seismic tests should be performed by subjecting equipment to vibratory motion that conservatively simulates that postulated at the equipment mounting during an earthquake. The details of the test procedures given herein constitute the more common methods currently in use but do not preclude other justifiable methods. It is outside the scope of this recommended practice to give the theoretical basis for the test procedures. These may be found in the literature on dynamics. One practical problem that arises when attempting to establish the tests to be used to qualify equipment is the choice of the earthquake environment. Many factors must be considered (see Clause 4). These involve the location of the equipment, the nature of the equipment, the nature of expected earthquakes, and others. An additional consideration is whether the equipment is to be used in one application or many. When the equipment is used in only one application, the seismic motion can be specified and the qualification test can be chosen to meet the specification (proof testing). When the equipment is used in many applications, the test should be designed to qualify the equipment for future undefined applications (generic testing). Proof testing and generic testing are discussed further in 8.2. Fragility testing, conducted to determine the limit of the equipment's capabilities, is discussed in 8.3. Another factor to be considered is the multidirectional nature of earthquakes. Equipment should be tested to conservatively account for these multidirectional effects. These are discussed in greater detail in 8.6.6.

Another practical problem arises in attempting to describe tests for devices (relays, motors, sensors, etc.) and for complex assemblies such as control panels. In the first case, it is reasonable to assume that the device can be subjected to seismic tests while simulating the operating condition and monitoring its performance during

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the test; however, in the case of complex equipment such as control panels, this may not be true. Such panels usually contain many devices that are part of several systems extending over many other panels located in various parts of the power generating station. To test such panels while in an operating condition may be impractical, and in such cases, the following alternate approach is recommended. Apply the appropriate vibration input (RRS) to the panel with the actual devices installed but inoperative or with the device's dynamic properties simulated. The dynamic response at the devices' locations is measured and is used as input criteria to qualify the devices separately in an operating condition (see 8.4 and 8.5, NOTE). The purpose of installing the nonoperating devices is to ensure that the panel exhibits the dynamic characteristics it will have when in use.

It is noted that an equipment that has been shake-table tested should, in general, not be installed in a plant, unless it can be demonstrated that the accumulated stress cycles already experienced by the equipment will not degrade its ability to perform its safety function.

Regardless of whether devices or assemblies are to be proof tested, fragility tested, or generically tested, there are certain common considerations. These are listed in 8.1.1 through 8.1.6.

8.1.1 Mounting

The equipment to be tested shall be mounted on the vibration table in a manner that simulates the intended service mounting. The mounting method should be the same as that recommended for actual service and should use the recommended bolt size, type torque, configuration, weld pattern and type, etc. The effect of electrical connections, conduit, sensing lines, and any other interfaces shall be considered and included in the setup unless otherwise justified. The orientation of the equipment during the test shall be documented and shall be the only one for which the equipment is considered qualified unless adequate justification can be made to extend the qualification to an untested orientation. The method of mounting the equipment to the shake table shall be documented, and a description of any interposing fixtures and connections shall be provided. Interposing fixtures, when used, shall be such that their use will not filter out or change any frequencies from the input motion. The effect of such fixtures and connections must be evaluated and addressed in the report when they are only used during qualification and not for in-service mounting.

8.1.2 Monitoring

Functional and vibrational response parameters must be considered for monitoring Class 1E equipment during vibration testing.

Sufficient monitoring instrumentation shall be used to evaluate the functionality of the equipment before, during, and following its vibration test exposure. Details of executing this requirement must be obtained from documents that pertain to the specific equipment. It should be noted that compliance with this requirement often takes a significant effort in test planning and implementation.

Sufficient vibration response monitoring instrumentation shall be used to allow determination of the applied vibration levels. It is recommended that vibration response monitoring instrumentation also be used to determine the response of the equipment along all three orthogonal input axes simultaneously, at those points within the structure that reflect the equipment response associated with its structural integrity and its functionality. This data may be useful for structural design analysis, functionality failure analysis, future design changes or device change-out, determining in-structure response spectra, and other applications. The location of the vibration sensors and the functional monitoring system(s) shall be documented.

8.1.3 Refurbishment

Any refurbishment performed on equipment during a test program may be classified into maintenance or repair according to its degree. Examples of maintenance activities include calibration of relays and

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retorquing of hardware. Examples of repairs include welding or rewelding of portions of an equipment, replacing damaged components, such as sheared bolts, and retightening loose electrical terminals.

8.1.3.1 Maintenance

When maintenance is required, the severity of the problem shall be determined and documented in detail in the test report. Maintenance may be performed and testing continued. When maintenance is performed during OBE testing, it becomes part of the post-earthquake field maintenance checks and procedures for the equipment.

8.1.3.2 Repairs

When repairs are necessary during the OBE test, retest is required unless justified otherwise. When repairs are necessary during or after the SSE test, the general requirement is to retest unless justified otherwise. When the condition requiring repair during the SSE tests does not interfere with the performance of the safety function, during or after the test, then the SSE can be shown to be not cumulative due to testing in other axes and does not unacceptably affect equipment performance in subsequent qualification tests, such as the loss-of-coolant accident (LOCA), then continuation without retest may be justifiable. When repairs constitute a design change, the equipment must be retested, unless justified otherwise. When repairs are made, the details shall be included in the test report.

8.1.4 Exploratory tests

Exploratory vibration tests are generally not part of the seismic qualification requirements, but may be run on equipment to aid in the determination of the best test method for qualification or to determine the dynamic characteristics of the equipment. These low input level vibration tests are normally described as resonance searches. They are generally performed at input levels well below the required seismic qualification vibration level. These tests can be performed in several ways. The most common method is the resonance search that is performed as a slowly swept sinusoidal vibration test with the input uniaxial. The equipment responses may be measured biaxially or triaxially to determine resonances and cross coupling. A second method involves impacting the equipment in a controlled manner at critical points on the structure, capturing the impact and response data, and computing the transfer function between impact and response locations. The output is the transfer function and associated phase information. A third method involves the use of a broadband random input signal and simultaneous measurement of response at locations of interest.

The transfer function and associated phase relationship between excitation and response locations are computed.

8.1.4.1 Resonance search by base excitation

This method offers the advantage that it can be performed on the same type of vibration equipment used for the qualification vibration test. The resonance search is generally performed just prior to the qualification seismic vibration test as the information gathered may be useful in performing it. Resonances are determined by instrumenting the structure with accelerometers at the input location and at those locations where the structural response is desired. Generally, a slowly swept low-level sinusoidal vibration should be employed. The sweep rate should be two octaves per minute, or less, to ensure resonance buildup. A 1.96 m/s^2 (0.2 *g*) peak input is the conventional input level, but it may be adjusted lower to avoid equipment damage or higher to take nonlinearities into consideration. It is recommended that the resonance search be carried beyond 33 Hz, for example, to 50 Hz or to the RRS cutoff frequency, whichever is higher, to obtain data on equipment dynamic characteristics that may be valuable to justify qualification for other dynamic loads.

The user is cautioned that if the equipment is not mounted on its service foundation for the resonance search, the mass and stiffness of the mounting used may have a significant effect on the accuracy of the results.

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When large equipment is tested on a table, coupled table/equipment modes may exist, which should not be interpreted as equipment modes.

Structural resonances are normally detected by observing amplifications of the input motion in the test item. Phase relationships between the sinusoidal input signal and the structural response at the point of measurement may also be helpful in defining resonances. A higher degree of confidence in establishing resonance is obtained by combining amplification and phase data. Similar results may be obtained by base excitation with low-level broadband random motion. In this case, transfer functions and phase data are obtained by *fast Fourier transform* (FFT) analysis of excitation and response time histories. Caution must be exercised to ensure that the number of data samples acquired and the resolution bandwidth correspond to the transfer function accuracy desired. An FFT analyzer is usually required for this technique.

8.1.4.2 Resonance search by impedance methods

Resonance search by impedance methods may be accomplished by exciting the structure with a small portable shaker or by impact testing. The induced vibration under such conditions is usually of small amplitude in nature. Caution should be exercised in applying the test results for large amplitude earthquake response conditions. See 9.2 for further discussion.

8.1.4.3 Application of resonance search data

All resonances should be recorded for possible use as the following:

a) Design information
b) Necessary data for certain test methods
c) Data for use in potential qualification efforts

When it can be shown that the equipment is not resonant at any frequency within the amplified frequency range of the RRS, it may be considered rigid and analyzed or tested accordingly. On the other hand, when resonances exist, or when the configuration of the equipment is such that critical resonant frequencies cannot be ascertained due to either the complexity of the equipment or the inaccessibility of critical parts, the equipment should be tested according to one of the various methods of 8.6 or another justifiable method.

It must be noted that, because of nonlinearities, resonance responses at high levels may differ in frequency and damping from those at low levels, and further, that resonance response may not be excited at all at low levels. Therefore, a low-level exploratory test may not be conclusive as an indication of either equipment dynamic response or lack of resonances. When nonlinearities are suspected, it may be necessary to perform the exploratory test at more than one input level.

8.1.5 Vibrational aging

Seismic qualification tests on equipment designed to show adequacy of performance during and/or following an SSE must be preceded by tests that produce the equivalent fatigue effect of the number of OBEs specified for each site and the equivalent fatigue effects of specified in-plant vibration resulting from normal and transient plant operating conditions. It is suggested that the equivalent conditions consistent with the service life of the facility be simulated if possible; however, as a minimum, the equivalent fatigue effects consistent with the qualified life of the equipment must be achieved.

The purpose of the vibrational aging is to show that the lower levels of normal and transient vibration, associated with plant operation and the lower intensity earthquake that has a higher probability of occurrence, will neither adversely affect an equipment's performance of its safety function nor cause any condition to exist that, if undetected, would cause failure of such performance during a subsequent SSE. These tests may also provide part of the aging requirement of IEEE Std 323-2003. Vibration-aging tests shall be performed preceding the OBE and SSE tests.

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8.1.5.1 Aging from nonseismic vibration conditions

Portions of the seismic tests may be used to provide part of the aging requirement of IEEE Std 323-2003 for the specified nonseismic related vibration due to normal and transient plant operating conditions and in-plant vibration. It shall be demonstrated that the equivalent amplitude response cycles achieved in the seismic tests, excluding those required for the seismic low-cycle fatigue requirement, exceed the amplitude response cycles required for the nonseismic vibration loads (see 8.6.5 and Annex D for discussion on equivalent cycles). Credit may be taken for any test preceding the SSE. However, special care must be taken in establishing equivalency when the nonseismic vibration loads, such as a safety relief valve (SRV) discharge load, contain significant frequency content greater than 33 Hz, or when the applied nonseismic forcing function is substantially different from that achieved during the base excited motions simulated in the tests discussed in 8.2 through 8.5. In the latter case, the nonseismic loading could result in excitation of equipment vibration modes not excited by base motions.

The amplitude response cycles may be determined by analysis as discussed in Clause 7 or by short tests conducted with the equipment in a simulated nonseismic vibration condition.

8.1.5.2 Seismic aging (OBE)

Seismic qualification tests on equipment must include OBE tests, preceding the SSE, that produce a number of equivalent maximum peak cycles (at least as given in 8.6.5) for each specified seismic event. The number of OBEs shall be justified for each site or shall produce the equivalent effect of five OBEs.

8.1.6 Loading

Seismic qualification tests on Class 1E equipment shall be performed with the equipment subjected to normal operating conditions (electric loads, mechanical loads, thermal loads, pressure, etc.), and other plant conditions that may adversely affect the safety function. Simulation of these loads is acceptable if it is justified. If not included as part of the test, the absence of the loading effect shall be justified.

8.1.6.1 Hydrodynamic loads

Some of the equipment in nuclear power plants is subjected to vibratory loads that are categorized as hydrodynamic loads. These include the loads associated with SRV discharge and the LOCA. Hydrodynamic loads affect the aging requirement (see 8.1.5) and the seismic testing requirement.

Since the structural integrity and operability of the components must be evaluated under the simultaneous effects of the seismic and other vibratory loads, a combined spectrum is required for the RRS, that is, OBE or SSE combined with vibratory loads. The RRS for testing may be obtained by an appropriate combination of the individual spectra, such as SRSS or absolute sum.

8.2 Proof and generic testing

Proof testing is used to qualify equipment for a particular requirement. A proof test requires equipment to be subjected to one of the tests described in 8.6. The equipment must be subjected to the particular response spectrum, time history, or other parameters defined for the mounting location of the equipment. No attempt need be made to explore the failure thresholds of the equipment. Therefore, the proof test requires the preparation of a detailed specification. The specification is usually written by the ultimate user as an application requirement. The equipment is tested to the specified performance requirement and not to its ultimate capability. Generic testing may be considered a special case of proof testing. The specification is usually written to encompass most, or all, of the known requirements. The objective is to show qualification for a wide variety of applications during one test. The resultant generic RRS typically encompasses a wide

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frequency bandwidth with relatively high acceleration levels. The user is cautioned that the enveloping of a variety of requirements can produce a very severe test motion.

8.3 Fragility testing

Fragility testing is used to determine the ultimate capability of equipment. Such information may later be used to prove adequacy for a given requirement or application.

Fragility testing should be performed in a manner that yields equipment capability data that can be related to and compared with any of the various requirements from various installations and agencies.

For some requirements, an equipment's capability can be best defined by a demonstration of its response to sine-beat (or transient) type excitation. For other requirements, it may be defined by a demonstration of its response to continuous sine excitation. Still other equipment capability may be defined by a demonstration of its response to multifrequency waveforms. A measurement of the equipment's fragility level for a particular motion excitation constitutes a demonstration of its ultimate capability to perform its required safety function when subjected to that motion.

Variations in the seismic environment have been shown to influence the fragility level of an equipment or system. One such variation is the directional nature of the excitation. In addition, the environment may possess the characteristics of a shock, a transient, or a steady-state vibration. The tests outlined in 8.6 may be performed to establish fragility data using the guidelines of that subclause to ensure proper application (see Annex C for additional guidance on fragility testing).

8.4 Device testing

Devices shall be tested simulating operating conditions to either the levels dictated by expected service requirements or their ultimate capability. The devices shall be mounted on the shake table in a manner that dynamically simulates the recommended mounting. When a device is intended to be mounted on a panel, the panel should be included in the test mounting or the response at the device mounting location should have been monitored during the assembly testing (see 8.5), in which case the device may then be mounted directly to the shake table for the simulation of in-service excitation.

Some types of equipment, such as cabinets with bolted doors or panels, produce impacts, rattling, chatter, or banging. These impacts are transmitted throughout the equipment and result in increased acceleration levels at frequencies much higher than the original frequencies input to the shake table. A low-frequency input thereby produces high-frequency response that may adversely affect devices mounted in the equipment and must be considered in their qualification. When this is the case, assembly testing is preferred, or the device mounting location RRS obtained in the assembly test must include the effect of impacts in the time history by analyzing the motion to sufficiently high frequencies. Devices may then be tested using the methods described in 8.6 or any other justifiable method. When such impacts are present, additional provisions should be included to demonstrate that the time history for device testing is conservative in terms of duration, amplitude, and frequency content. Methods of demonstrating adequate frequency content include plotting a TRS or a PSD to higher frequencies.

8.5 Assembly testing

It is preferred that large complex assemblies be tested simulating operating conditions and be monitored for proper functional performance; however, in cases such as control panels containing parts of many systems, it is not always practical to simulate all conditions simultaneously. It is acceptable, therefore, to test such equipment in an inoperative mode with the actual or simulated devices, including nonsafety related devices, installed. The test should determine the vibration response at the device location by either direct

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measurement at full excitation or by determination of the transfer function from the assembly mounting points to the device mounting points. The resulting vibration response of the device at its location in the assembly shall be less than the vibration to which the device is qualified. In either case, the test methods described in 8.6 or other justifiable methods may be used. The assembly shall be examined following the test and the integrity of any untested Class 1E parts (for example, wiring) verified.

NOTE—It should be recognized that when testing assemblies with dummy devices installed, the TRS from the device location may be excessive due to overtest of the assembly since it is not practical to closely envelop all RRS with the table motion.

8.6 Test methods

8.6.1 Introduction

Present test methods generally fall into three major categories. They are proof or generic testing (see 8.2) and fragility testing (see 8.3). The types of motion available to best simulate the postulated seismic environment fall into two categories: single frequency and multiple frequency. The method chosen will depend upon the nature of the expected vibration environment and also somewhat on the nature of the equipment. The various technical requirements appropriate to each test method may provide extra benefits for specific applications.

In general, the proof or generic test seismic simulation waveforms, or both, should

a) Produce a TRS that closely envelops the RRS using single- or multiple-frequency input as required to provide a conservative (but not overly so) test-table motion.

b) Have a peak acceleration equal to or greater than the RRS ZPA.

c) Not include frequency content above the RRS ZPA asymptote.

d) Have a duration in accordance with the requirements of 8.6.5.

Consideration must also be given to the choice of single-axis or multiple-axis testing as described in 8.6.6 and margins as noted in Clause 5.

8.6.1.1 Artificially broadened response spectra

For a floor-level motion, the RRS may be dominated by a single structural resonance. For this case, the RRS is usually broadened to cover the uncertainty in the building structural frequency. This has the effect of making the RRS artificially conservative since the response peak can occur only at a specific frequency and not throughout the entire broadened band. An acceptable testing procedure in this case is as follows:

When the center frequency in the broadened area is f_c, testing may be conducted at this frequency and in addition at the frequencies $f_c \pm \Delta f_c, f_c \pm 2\Delta f_c$, …, $f_c \pm n\Delta f_c$, where Δf_c corresponds to a 1/6 to 1/3 octave interval to envelop the entire broadened area. The TRS generated during each individual test must have the same shape and width as the original narrowband response spectrum (similar to Figure 4). The specification should state clearly the existence of this case to avoid confusion with an RRS that results from genuine broader frequency motion requirements.

8.6.1.2 TRS analysis

TRS must be computed using either justifiable analytical techniques or response spectrum analysis equipment and should be developed over the frequency range of interest. It is recommended that the TRS be computed with 1/6 octave or narrower bandwidth resolution. Any filtering of the acceleration signal performed within the frequency range of analysis must be defined.

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8.6.1.3 Damping selection

The RRS are usually specified at several levels of damping. When available, the RRS with a damping of 5% is the recommended choice for use in testing. The application of damping for testing is described in 6.3.2.

8.6.2 Single-frequency test

When the seismic ground motion has been filtered due to one predominant structural mode, the resulting floor motion may consist of one predominant frequency. In this case, a short duration steady-state vibration can be a conservative input excitation to the equipment. Further, single-frequency testing may be used to determine (or verify) the resonant frequencies and damping of equipment. If it can be shown that the equipment has no resonances, only one resonance, widely spaced resonances that do not interact, or if otherwise justified, single-frequency testing may be used to fully test the equipment.

The TRS from single-frequency testing results from each individual frequency and may not be generated as the composite of several nonsimultaneous single-frequency tests unless otherwise justified.

8.6.2.1 Derivation of test input motion

For any waveform employed, the shake-table motion should produce a TRS acceleration at the test frequency at least equal to that given by the RRS. The peak input acceleration must be at least equal to the ZPA of the RRS except at low frequencies where the RRS goes below and stays below the ZPA for which the value of the RRS must be met. See 8.6.6 for guidance on the number of axes required for testing. For flexible equipment with more than one predominant frequency, and when the RRS has the characteristics of a multiple-frequency broadband response spectrum, the conditions in 8.6.2 may be difficult to fulfill. Specifically, it may not be practical to attempt a demonstration where modes do not interact to reduce the seismic fragility of equipment. When this is the case, single-frequency tests may be applied according to 8.6.2.1.2 based on the expected behavior or fragility of equipment under vibratory conditions used to determine its seismic qualification.

8.6.2.1.1 Equipment performance assessed by structural integrity alone

When the performance of equipment can be assessed by structural integrity alone, in terms of stress and strain such as in structures and static electrical or passive devices, then the maximum response in equipment governs without regard to the precise vibratory nature or frequency content of the excitation. The motion of the shake table should produce a TRS at the test frequency of 1.5 times that given by the specified RRS peak unless justified to be less. This conservatively allows for combined multimode response. The choice of the preceding factor depends on the shape of the RRS with the largest value (1.5) applicable to a broadband RRS. As a consequence, the TRS need not completely envelop the RRS. Alternatively, when all the resonances of the equipment can be definitely established by an actual test, it will be sufficient for the single-frequency TRS to envelop the RRS only at the equipment resonances with one single-frequency input.

8.6.2.1.2 Equipment performance assessed by structural integrity and operability

When the performance of equipment must be assessed by the combination of structural integrity and operability, as for example in electromechanical devices such as relays or instruments, then the precise vibratory nature and frequency content of the excitation will produce equipment responses that determine its fragility. Justification must be provided so that the 1.5 factor (see 8.6.2.1.1) is sufficient to allow for combined multimodal response and to produce a vibratory motion to adequately simulate the effects that the intended multifrequency motion would have on equipment performance. The choice of the factor depends on the nature of the equipment and the shape of the RRS with the largest value, which may require a factor greater than 1.5, applicable to broadband RRS. Consequently, the TRS need not completely envelop the RRS provided proper justification is given. In addition, testing must be performed at all equipment

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resonances and at frequencies spaced no farther apart than 1/2 octave intervals up to the cutoff frequency unless otherwise justified. Alternatively, when all the resonances of the equipment can be definitely established by an actual test, it will be sufficient for the single-frequency TRS to envelop the RRS only at the equipment resonances with one single-frequency input.

8.6.2.2 Continuous-sine test

A test at any frequency should consist of the application of a continuous sinusoidal motion at the frequency and amplitude of interest and with a total duration and low-cycle fatigue potential at any frequency, at least as given in 8.6.5. The test frequencies of interest are those at the resonances of the equipment being tested and others as given in 8.6.2.1. The maximum acceleration corresponds to that for which the equipment is to be qualified and should at least produce the maximum response acceleration given in 8.6.2.1.

8.6.2.3 Sine-beat test

A test at any frequency should consist of the application of a series of at least five sine beats with a sufficient pause between each so that no significant superposition of equipment response motion results. The sine beats consist of sinusoids at the frequency and amplitude of interest, as shown in Figure 2. Each sine beat should consist of a number of cycles of motion (usually 5 or 10) to produce a TRS acceleration in accordance with the criteria given in 8.6.2.1. The test frequencies of interest are those at the resonances of the equipment being tested and others as given in 8.6.2.1. The total test duration and the low-cycle fatigue potential at any frequency should be at least as given in 8.6.5.

For a given beat-peak amplitude, the degree of test conservatism will increase as the number of cycles per beat increases until the conservatism approaches that of the sinusoidal waveform in 8.6.2.2.

NOTE 1—As used in this recommended practice, the amplitudes of the sinusoids represent acceleration, and the modulated frequency represents the frequency of the applied seismic stimulus.

NOTE 2—Beats are usually considered to be the result of the summation of two sinusoids of slightly different frequencies, with the frequencies within the beats as the average of the two, and the beat frequency as half the difference between the two. However, as used herein, the sine beats may be amplitude-modulated sinusoids with pauses between the beats.

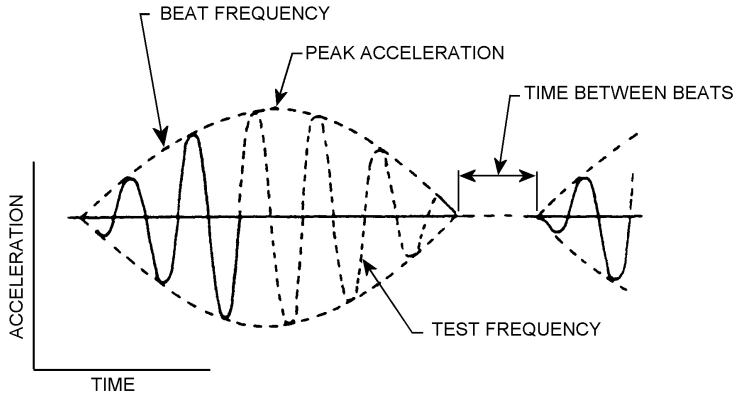

Figure 2—Sine beat

8.6.2.4 Decaying-sine test

A test at any frequency should consist of the application of at least five decaying sinusoids at the frequency and amplitude of interest with a sufficient pause between the sinusoids so that no significant superposition of equipment response motion results. The total test duration and low-cycle fatigue potential at any frequency should be at least as given in 8.6.5. The decaying sinusoids consist of a single frequency of exponentially decaying amplitude, as shown in Figure 3. The test frequencies of interest are those at the resonances of the equipment being tested and others, as given in 8.6.2.1. The peak acceleration of the

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sinusoid corresponds to that for which the equipment is to be qualified and should at least produce the maximum response acceleration given in 8.6.2.1. For a given peak amplitude, the degree of conservatism will increase as the decay rate decreases until the conservatism approaches that of the sinusoidal waveform in 8.6.2.2.

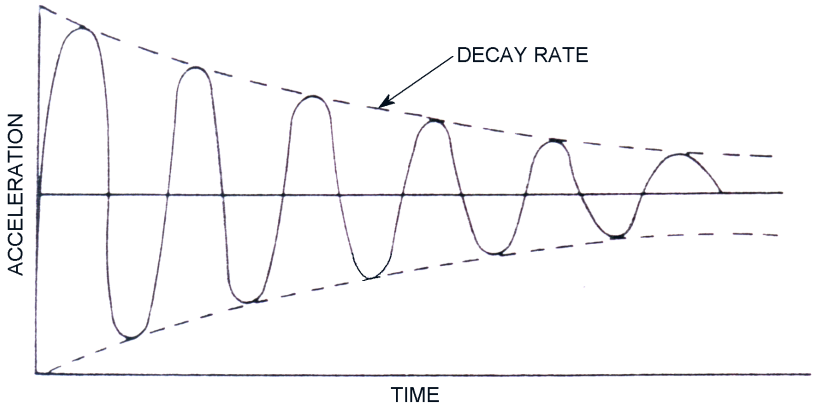

Figure 3—Decaying sine

8.6.2.5 Sine-sweep test

In this test, a sinusoidal input with continuously varying frequency is applied to the equipment. The frequency band should cover the range for which the equipment is to be qualified, including the equipment resonances and other frequencies, as given in 8.6.2.1. This closely approaches the conservatism of the continuous-sine test in terms of producing maximum response. The percentage of steady-state resonance response obtained depends on the sweep rate and the equipment damping. For sweep rates of two octaves per minute or less, and for typical equipment damping, this percentage exceeds 90. Maximum response is obtained separately at every frequency in the test range. Consequently, this test produces the most thorough search for all resonant frequencies, and it is customarily used for this purpose as an exploratory test, with a low input level such as 1.96 m/s^2 (0.2 *g*).

To qualify the equipment, the total sine-sweep test duration and equivalent maximum peak cycles at any frequency should be at least as given in 8.6.5. The maximum acceleration corresponds to that for which the equipment is to be qualified and should at least produce the maximum response acceleration given in 8.6.2.1. The TRS may not be a composite of the entire frequency sweep. It must be the response spectrum centered around any single frequency.

8.6.3 Multiple-frequency tests

Seismic ground motion is recognized to contain multiple-frequency energy content up to approximately 33 Hz. When this relatively broadband ground motion has not been strongly filtered by the building or the soil or both, the resulting floor motion that affects the equipment tends to retain the original broadband characteristics. Furthermore, even if strong filtering is present but is caused by two or more distinct building modes, the floor motion will still comprise a complex wave with dominant frequencies at each of the building or soil natural frequencies, or both. In these cases, multiple-frequency testing is applicable for qualification. Specific shake-table excitation includes random or complex time histories, depending on the frequency distribution necessary to simulate the required floor motion. The intent is to produce a table motion that reasonably approximates that which is postulated to occur at the mounting of the equipment for the particular earthquake.

Multiple-frequency testing is intended to provide a broadband test motion that is particularly appropriate for producing a simultaneous response from all modes of a multidegree-of-freedom system whose malfunction may be caused by modal interaction. Multiple-frequency testing provides a closer simulation of a typical seismic motion without introducing a higher degree of conservatism.

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There are a number of available waveforms that may be used as test motions to simulate the particular seismic excitation at the mounting of the equipment. Several types of multiple-frequency tests employing these different waveforms are given in 8.6.3.2 through 8.6.3.4. Some test types will be better than others for simulating a specific type of equipment excitation condition, and the degree of conservatism will vary from one type of test to another. The choice of test type will depend on the extent to which the ground motion is filtered by the dynamic characteristics of the building, or soil, or both, to produce the excitation to the equipment at the particular floor level of the building. Other waveforms, or types of multiple-frequency tests, not specifically discussed herein may also be employed provided they can be shown to possess similar characteristics for exciting the equipment being tested. Generally, the criteria described in 8.6.3.1 for the derivation of the test input motion are used to justify the adequacy of the test.

8.6.3.1 Derivation of test input motion

For any waveform employed, the motion of the shake table must be adjusted so that

a) The TRS envelops the RRS over the frequency range for which the particular test is designed.

b) For comparison of the TRS and the RRS, the TRS is computed with a damping value equal to or greater than that of the RRS, using the appropriate damping values in 6.3.2 and 8.6.1.3.

c) The shake-table maximum peak acceleration is at least equal to the ZPA of the RRS (see Annex A for suggestions on the measurement of ZPA).

d) The total test duration and low-cycle fatigue potential are as those in 8.6.5.

e) The time history indicates frequency content at least as broad as that defined by the amplified region of the RRS.

f) The time history indicates waveform stationarity, that is, the statistical parameters (for example, frequency content and amplitude probability distribution) do not vary significantly throughout the test.

To account for the factors in items a) through f), it is necessary to show that the frequency content of the test waveform is at least as broad as the frequency content of the amplified region of the RRS (except perhaps at the low-frequency end, see the following items j) and m). There are several techniques for showing this; for example, show that

g) The enveloping of the RRS by the TRS is obtained with similar spectrum shapes so that similar amplifications at significant spectrum peaks in the amplified regions of the spectra result.

h) The frequency content of the Fourier transform of the test waveform is compatible with the amplified portion of the RRS

i) The frequency content of the test waveform PSD is compatible with the amplified portion of the RRS.

It is also intended that stationarity exists over the strong motion portion of the test waveform. This can be demonstrated by showing that the frequency/amplitude content of the waveform is statistically constant with time (see Annex B for further explanation of frequency content and stationarity). The RRS occasionally requires high acceleration levels at the lowest frequencies that require very high test-table displacement capability. The general requirement for enveloping the RRS by the TRS can be modified under the following criteria:

j) In those cases where it can be shown by a resonance search that no resonance response phenomena exist below 5 Hz, it is required to envelop the RRS only down to 3.5 Hz. Excitation must continue to be maintained in the 1 Hz to 3.5 Hz range to the capability of the test facility.

k) When resonance phenomena exist below 5 Hz, it is required to envelop the RRS only down to 70% of the lowest frequency of resonance.

l) When the absence of resonance response phenomena or malfunction below 5 Hz cannot be justified, the general requirement applies and the low-frequency enveloping should be satisfied down to 1 Hz.

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m) Under any circumstances, failure to envelop the RRS at, or above, 3.5 Hz must be justified.

In the performance of a test program, the TRS may, on occasion, not fully envelop the RRS. The general requirement for a retest may be exempted if the following criteria are met:

n) A point of the TRS may fall below the RRS by 10%, or less, provided the adjacent 1/6 octave points are at least equal to the RRS and the adjacent 1/3 octave points are at least 10% above.

o) A maximum of five of the 1/6 octave analysis points may be below the RRS, as in item n), provided they are at least one octave apart.

8.6.3.2 Time history test

A test may be performed by applying to the equipment a specified time history that has been synthesized to simulate the seismic input. It must be demonstrated that the actual motion of the shake table is as severe as, or more severe than, the required motion. This can be accomplished by a direct comparison of the table-motion time history with the specified motion by means of an oscilloscope or oscillograph trace. A comparison can further be made through the use of response spectra of the required motion and the table motion. In the latter method, a response spectrum of the specified motion (RRS) is developed for the appropriate damping given in Clause 6. Subsequently, a table motion is developed so that its TRS envelops the RRS according to the general criteria of 8.6.3.1.

It should be recognized that these two comparison methods can have significantly different degrees of sensitivity and, hence, differing adequacy for testing different physical effects. For example, when very low frequencies are important, direct comparisons of displacement time histories are useful. On the other hand, if intermediate to high frequencies (up to 33 Hz) are important, then comparison of accelerations or a computation of response spectra is more useful.

8.6.3.3 Random-motion test

A test may be performed by applying to the equipment a random excitation, the amplitude of which is adjusted either manually or automatically in multiple-frequency bands. The exact bandwidth of individual bands employed is left to the discretion of the test engineer. Typically, 1/3 octave bands are considered for analog synthesis equipment. Digital synthesis equipment may require narrower bands or intervals. However, the use of wider bands may be adequate in some cases where unfiltered ground-level motion is intended. On the other hand, use of very narrow (that is, 1/6 octave) bands may be necessary when filtering by building resonances is intended in the input motion. In any event, the process involves use of an aggregate of multiple narrowband signals that is input to the shake table, with each band adjusted until the TRS envelops the RRS according to the criteria given in 8.6.3.1. For an analog signal synthesis system, the multiple-band frequency source may be either a random noise generator and multiple-channel filter combination or multiple signals taped on individual channels of an analog tape recorder. A third practical signal synthesis system is a digital computer program that has the capability of computing the inverse of the shaker system transfer function and applying it to the desired table-motion time history. For all types of signal sources, a gradual buildup, hold, and decay of the signals provide a realistic simulation of an actual seismic event.

8.6.3.4 Complex-motion tests

In many cases, the required motion may represent significant filtering of ground motion by one or more sharp building or soil resonances, or both. The corresponding RRS may include medium-to-low level amplification over a broad frequency range, with highly amplified narrowbands associated with each building resonance. For these cases, the use of a random motion test (even with narrow individual bandwidth resolution) may require an unreasonably high maximum peak value of the input so as to meet the higher amplification associated with the building resonances. It is permissible to synthesize a complex signal that comprises the summation of several different types of individual narrowband components superimposed on lower level broadband random motion. This approach affords a better chance of producing

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a table motion whose TRS will envelop the RRS, according to the criteria of 8.6.3.1, without introducing excessive ZPA levels. Several typical methods of synthesizing complex signals are described in 8.6.3.4.1 through 8.6.3.4.5. For each of these test methods, the criteria of 8.6.3.1 must be met. Success in the use of any one of these methods will depend on the type of synthesis equipment available, the exact shape of the RRS, and the experience of the test engineer. The following methods have been utilized sufficiently to warrant special mention. However, further combinations of these and other signal components may be used as necessary to produce the required table motion.

8.6.3.4.1 Random motion with sine dwells

To meet an RRS that includes a moderately high peak random excitation may require an unreasonably high peak value of the input. In this case, a broadband random motion is first synthesized similar to the description given in 8.6.3.3. The levels of individual frequency bands are adjusted until as much of the RRS, or the lower level broadband portion of the RRS, is enveloped by the TRS using a peak input acceleration that is at least equal to, but not substantially greater than, the required ZPA. Then a sine dwell is added at each frequency corresponding to a sharp peak of the RRS until this TRS envelops the RRS according to the criteria given in 8.6.3.1. The duration of the sine dwell is made equal to the total test duration. When more than one sine-dwell frequency is required, all must be initiated simultaneously and continue for the duration of the test run. (For the case of artificially broadened spectra, 8.6.1.1 may apply. In this case, a series of tests, each with a different sine-dwell frequency, may be performed to cover the broadened area.) This technique generally affords the maximum amount of amplification possible for a given narrowband RRS.

8.6.3.4.2 Random motion with sine beats

This motion is similar to that of 8.6.3.4.1 except that sine beats are used in place of sine dwells. The same criteria of motion synthesis, test duration, and simultaneous initiation of sine beats are applicable in this type of test. (For the case of artificially broadened spectra, 8.6.1.1 may apply, in which case a series of tests, each with a different sine-beat frequency, may be performed to cover the broadened area. See Figure 4.) Multiple applications of sine beats, spaced throughout the duration of the test, are applied for each required frequency. The number of cycles per beat becomes an additional parameter that can be adjusted for best results to meet the enveloping criteria of 8.6.3.1. The optimum number of cycles per beat may be determined from Figure 5, which gives resonance amplifications of sine beats for different cycles per beat and damping values.

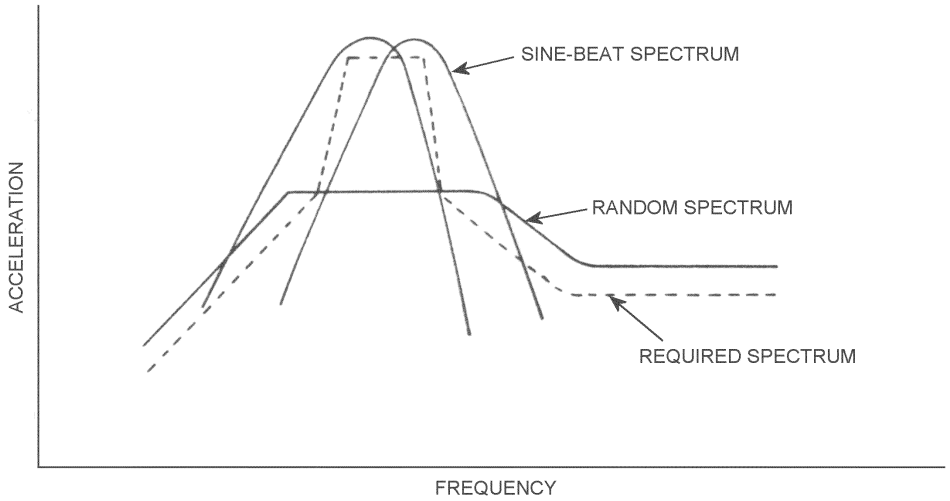

Figure 4—Random spectrum with superimposed sine beats

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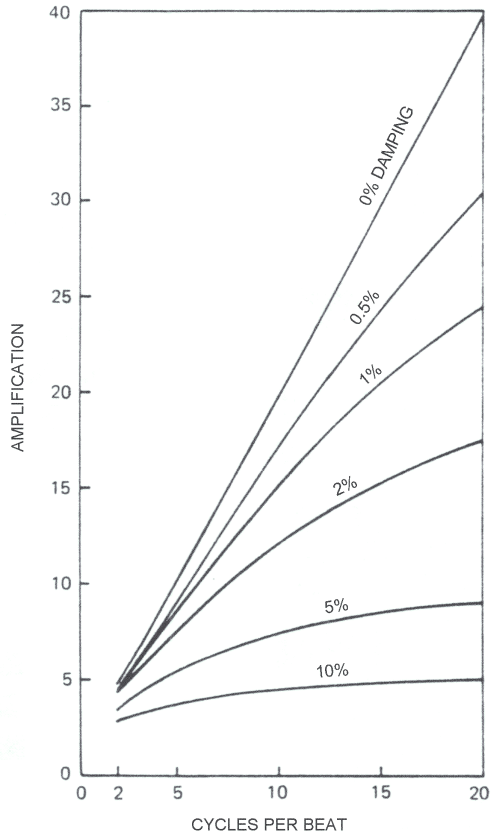

Figure 5—Resonant amplification versus cycles per beat

8.6.3.4.3 Combination of multiple sinusoids

This motion consists of the summation of multiple sine waves (sinusoids) with distinct frequencies that include the resonant frequencies of the equipment up to the cutoff frequency. The frequencies of the sinusoids are typically spaced at 1/3 octave intervals, or narrower, to meet the enveloping criteria of 8.6.3.1. All sinusoids must be initiated simultaneously and continue for the duration of the test run. Each frequency must have individual amplitude and phase controls. When many distinct frequency sinusoids are combined, the result approaches broadband random motion. This method can be readily used in digital synthesis of required table motion.

8.6.3.4.4 Combination of multiple sine beats

This motion is similar to that of 8.6.3.4.3 except that a series of sine beats at each distinct frequency is used in place of the sinusoids. The same criteria of 8.6.3.4.3 for the test frequencies, octave spacing, simultaneous initiation of the sine beats, and continuously repeated and test duration are applicable in this type of test. As in 8.6.3.4.2, the number of cycles per beat can be adjusted for best results to meet the enveloping criteria of 8.6.3.1. As with the combination of multiple sinusoids, if many distinct frequency sine beats are combined, the result approaches broadband random motion.

8.6.3.4.5 Combination of decaying sinusoids

A complex wave comprising the aggregate of multiple decaying sinusoids can sometimes be used to produce a medium bandwidth TRS with a reasonably low ZPA. The frequencies of the component signals should be spaced typically at 1/3 octave or narrower intervals to meet the enveloping criteria of 8.6.3.1. The decaying

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sinusoids should have individual decay rate controls over the damping range from 0.5% to 10%. Each frequency must have individual amplitude and phase controls. All frequencies must be initiated simultaneously and continuously reinitiated for the duration of the test run. It is desirable to vary the decay rate and the amplitude of each frequency to optimize the fit of the TRS to the RRS. The resulting motion must be justifiable as representative of the strong motion portion of the SSE.

8.6.4 Other tests

When there are vibration tests other than those described in 8.6.2 and 8.6.3 that are equally justifiable and that conservatively simulate the expected seismic environment, they may be used instead.

The following factors must be considered to justify the test method employed to qualify equipment:

a) Bandwidth of the RRS compared to that of the TRS and equipment characteristics and responses
b) Duration of the test compared to the defined seismic event
c) Peak acceleration of the test input and the magnification observed (that is, the indicated frequency distribution of the input)
d) Natural modes and vibration frequencies of the equipment
e) Typical equipment damping
f) Fragility levels
g) Low-cycle fatigue potential
h) In any case, the TRS must envelop the RRS according to the criteria of 8.6.3.1.

8.6.5 Test duration and low-cycle fatigue potential

To properly account for vibration buildup and low-cycle fatigue effects, it is necessary to specify the duration and the fatigue-inducing properties of the input test waveform.

The duration of the strong motion portion of each test should at least be equal to the strong motion portion of the original time history used to obtain the RRS, with a minimum of 15 s. For multiple-frequency tests, the stationary part of the test defines the strong motion portion of one multiple-frequency waveform employed. For single-frequency tests, the duration is the sum of the individual durations of all tests at all different single frequencies (exclusive of the pause between beats). Note that the individual test duration at any single frequency should be sufficient to produce a TRS acceleration in accordance with the criteria of 8.6.2.1.

The fatigue-inducing potential of the test waveform should be at least equivalent to the strong motion portion of the earthquake response motion at the mounting of the equipment. This equivalence may be ensured for multiple-frequency testing by showing that the test waveform has a stationarity similar to that of the earthquake response motion or that the test waveform generates a similar number of equivalent maximum peak-stress cycles when exciting a given structural resonant frequency.

See Annex D for further discussion of test duration and equivalent number of maximum peak-stress cycles.

8.6.6 Multiaxis tests

Seismic ground motion occurs simultaneously in all directions in a random fashion. However, for test purposes, single-axis, biaxial, and triaxial tests are allowed. If single-axis or biaxial tests are used to simulate the 3D environment, they should be applied in a conservative manner to account for the absence of input motion in the other orthogonal direction(s). One factor to be considered is the 3D characteristics of the input motion. Other factors are the dynamic characteristics of the equipment, flexible or rigid, and the degree of spatial cross-coupling response. Single and biaxial tests should be applied to produce adequate levels of excitation to equipment where cross coupling is significant and yet minimize the level of over-testing where the cross coupling is not significant. To expose potential failure modes, single-axis and biaxial tests must be

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performed in a number of directions as described in 8.6.6.1 and 8.6.6.2. In terms of total duration and fatigue induced, these tests are intended to be conservative.

8.6.6.1 Single-axis tests

Single-axis tests should conservatively reflect the seismic event at the equipment mounting locations and thereby account for the absence of motion in the other orthogonal directions. Single-axis tests are justified when the input motion can be shown to be essentially unidirectional or when the equipment being tested can be shown to respond independently in each of the three orthogonal axes. The former is the case when a device is normally mounted on a panel that amplifies motion in one direction, when it is restrained to motion in one direction, or its response in one direction does not produce stresses at the same location as a response in any other orthogonal direction. The latter is the case when an equipment has very low cross coupling among all axes or when other justification can be given.

For single-axis tests, it is permissible to perform the required OBEs followed by the SSE in each axis in sequence or any other justifiable method whereby adequate OBE aging can be demonstrated.

8.6.6.2 Biaxial tests

Biaxial tests should conservatively simulate the seismic event at the equipment mounting location. They should account for the absence of motion in one orthogonal direction for independent input motions in the other two orthogonal axes or for the absence of motion in two orthogonal directions if dependent inputs are used. The factors to be considered include the directional nature of the input motion and the cross coupling of the equipment. Biaxial testing should be performed with simultaneous inputs in a horizontal and vertical axis. The selection of the horizontal axis may include the principal axes or some other direction selected to expose potential failure modes by testing the equipment in its most vulnerable direction.

Independent random inputs are preferred, and when used, the test shall be performed in two steps with the equipment rotated 90° about the vertical axis for the second step. To provide statistically independent simulated motions, the table time histories should have coherence values of less than 0.5 when computed with at least 12 data samples. Alternatively, an absolute value of less than 0.3 correlation coefficient for all time delays may be used (see Annex E for further explanation). It is permissible to perform the required OBEs followed by the SSE in the first step, followed by the same sequence in the second step, or any other justifiable method whereby adequate OBE aging can be demonstrated.

When independent random inputs are not used, four tests should be run with

a) The inputs in phase.
b) One input 180° out of phase.
c) The equipment rotated 90° about the vertical axis and the inputs in phase.
d) The same equipment orientation as item c) but with one input 180° out of phase.

It is permissible to perform the required OBEs followed by the SSE in item a) followed by the same sequence in items b), c), and d), or any other justifiable method whereby adequate OBE aging can be demonstrated.

8.6.6.3 Triaxial tests

Triaxial tests, when performed, must be done with a simulator capable of independent motions in all three orthogonal directions. To provide statistically independent simulated motions, the table time histories should have coherence values of less than 0.5 when computed with at least 12 data samples. Alternatively, an absolute value of less than 0.3 correlation coefficient for all time delays may be used (see Annex E for further explanation).

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8.6.7 Line-mounted equipment

The seismic qualification of line-mounted items of equipment, such as instrumentation and control components, devices, HVAC damper actuators, and valve actuators and their attached functional accessories for which operability must be demonstrated, requires special consideration. In establishing a seismic qualification program for such equipment, it must be recognized that the most critical seismic loading condition for line-mounted components will occur as a result of the response of the line (e.g., piping or duct system) in which the component is located. This most critical condition provides an input motion to the component that is predominantly single frequency, that is, the natural frequency of the line in the vicinity of the component.

The following test method has been used to envelop the SSE seismic qualification requirements for power-plant line-mounted equipment.

The line-mounted equipment should be exposed to a series of single-frequency tests at equipment resonant frequencies and 1/3 octave frequency increments throughout the range of 2 Hz through 32 Hz, or higher, if hydrodynamic loads must be considered. At each test frequency, the input amplitude should correspond to the levels specified by the system designers. This amplitude may be independent of direction. Therefore, the motion should be applied at the same frequencies and accelerations in each of the three orthogonal axes separately. It must be shown that the test amplitude is due only to the frequency of interest. Typical methods that can be employed include the use of bandpass or tracking filters. The test duration at each frequency should be the period of time required to establish full operability of the equipment or 10 s, whichever is longer.

The test procedure must be supplemented by an evaluation of any applicable pipe reaction nozzle loads imposed on the equipment. The definition of procedures for nozzle loads evaluation is considered to be beyond the scope of this recommended practice and is, therefore, not discussed further.

Further clarification and guidance may be obtained from IEEE Std 382-1996.

8.7 Test documentation

See Clause 11 for test documentation requirements.

9. Combined analysis and testing

9.1 Introduction

Some types of equipment cannot be practically qualified by analysis or testing alone. This may be because of the size of the equipment, its complexity, or the large number of similar configurations. Large equipment, such as motors, generators, and multibay equipment racks and consoles, may be impractical to test at full levels due to limitations in vibration test equipment. This clause specifically treats these types of equipment.

9.2 Modal testing

Modal testing and analysis can serve as an aid to qualification of large and complex systems that have not been qualified by the methods given in Clause 8. Modal testing is a useful method for determination of resonant frequencies, mode shapes, and often as a lower bound for modal damping. As a part of a model verification for a complex structure, a modal test may be performed to correlate the frequencies and mode shapes, determined during the analysis, with the measured response of the complex system. Two fundamentally different methods of modal testing are currently in use. These are commonly referred to as

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the *normal-mode* and the *transfer-function* methods. The normal-mode method involves mounting shakers to the structure and exciting the structure one mode at a time. The transfer-function method involves exciting all structural modes within a particular bandwidth simultaneously, computing the transfer function between points of excitation and response, and employing computer aided techniques to determine the resonant frequencies, damping, and mode shapes within that bandwidth.

9.2.1 Normal-mode method

With the equipment to be tested and mounted to simulate in-service mounting conditions, portable exciters should be attached to the structure at points previously determined to best excite the vibration modes to be analyzed. The structure should be instrumented with accelerometers, displacement transducers, or other motion-sensing devices with sufficient bandwidth to determine structural response. The structure should then be excited with a slowly swept sinusoidal vibration covering the frequency range of interest.

9.2.2 Transfer-function method

The transfer-function method is based upon the use of digital signal processing techniques and the FFT algorithm to measure the transfer function between input and response locations on the structure. Transfer functions are obtained by exciting the structure with an impulse, sine-sweep, or random vibration employing the type of exciters used for the normal-mode method. Caution must be exercised when selecting the location for exciting the equipment. A transfer function is obtained by measuring the input and the corresponding response and then dividing the Fourier transform of the response by the Fourier transform of the input. Modal parameters are identified by performing computations on the transfer function, at each node, until sufficient data is acquired to accurately describe the mode shapes and other modal parameters. Caution must be exercised so that the number of averages acquired correspond to the desired accuracy of the transfer function.

9.2.3 Analytical methods utilizing test data

Various analytical options exist for using the test data obtained. The resulting measurement of dynamic response parameters, such as resonant frequencies, mode shapes, and amplitude, can be used to verify the calculated values of previously formulated analytical models of the equipment. Alternatively, the measured mode shapes can be used directly in a response spectrum or time history analysis. Specifically, the measured deflection between points for a participating mode shape can be scaled up according to the mode's deflection in the specified response spectrum. Finally, mathematical techniques are available to extract models directly from the parametric measurements. A mass and stiffness matrix can be extracted from the data by a series of formulae involving the matrix of mode shapes and the vectors of the modal mass, stiffness, and characteristic frequencies. These mass and stiffness matrices define a mathematical model of the structure that reproduces the measured characteristic response data.

If the structure exhibits significant nonlinearity in its response as a function of excitation level, the parametric measurements made in low-level excitation tests should be used with caution.

9.2.4 Qualification

Combined analysis and testing methods can adequately evaluate Class 1E equipment. These methods may be used to establish input response requirements at subcomponent locations. The qualification of the subcomponent is demonstrated by full-level testing of that component to a level equal to or greater than the established response at that location.

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9.3 Extrapolation for similar equipment

The qualification of complex equipment by analysis only, without justification, is not recommended because of the great difficulty in developing an accurate equipment model and in obtaining numbers to describe the model physical parameters (see Clause 7). There are, however, many instances of equipment, similar to a type that was qualified, which differs only in size or in the specific qualified devices located in the assembly or structure. In such cases, it is neither practical nor necessary to test every variation of the basic qualified version. Qualification by similarity using test and/or analysis applies in these situations. Extrapolation for similar equipment using experience is covered in Clause 10.

9.3.1 Test method

A full test program, as described in 8.6, and preliminary exploratory (resonance search) tests, as described in 8.1.4, are conducted on a typical piece of equipment. Data on modal frequencies, damping, and responses throughout the equipment must be taken and recorded.

9.3.2 Analysis

When it can be shown that no resonances exist in the frequency range of interest, the equipment may be analyzed as a rigid equipment (see 7.2). When a resonance search is utilized, assurance should be obtained that adequate test methodologies are followed to verify the absence of resonant frequencies. In addition, assurance should be obtained that changes from the originally tested equipment did not result in the formation of previously nonexistent resonances. This can be done by simple testing or analysis.

When the equipment is not rigid, the effects of the changes shall be analyzed using the techniques of 7.2 or other justifiable means. For very complex equipment, this requires sufficient knowledge of the equipment to include the significant structural parameters to enable the responses at all points of interest to be calculated.

The test results combined with the preceding analysis allow the model of similar equipment to be adjusted to take into consideration the parametric quantities affected and allow revision of the analysis for the modal frequencies of the similar equipment. The result is a verified analytical model that can be used to qualify the similar equipment.

9.3.3 Equipment similarity

Where qualification of an equipment item is achieved by extrapolation of qualification results based on test, analysis, or combination thereof (Clauses 7, 8, and 9), the extrapolation must be based on similarity and should consider excitation, physical system, and safety function.

9.3.3.1 Excitation

Similarity of excitation constitutes likeness of the following parameters: spectral characteristics, duration, directions of excitation axes, and location of measured response, for the motions relative to the equipment mounting. Ideally, these parameters should be as alike as is practical or conservative by comparison for excitations whose similarity is to be established.

9.3.3.2 Physical systems

Equipment similarity must be established for an equipment assembly, or a device, or both, or subassembly (including mounting), depending on the configuration of the new equipment to be qualified. For a complete assembly, similarity may be demonstrated through comparison of make, model and serial numbers, and consideration of dynamic properties and construction.

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Since the end objective of qualification by the similarity method includes a consideration of the expected dynamic response, a rational approach can be used to establish similarity of dynamic structural properties by an investigation of physical parameters of equipment systems. This can be done by comparing the predominant resonant frequencies and mode shapes. These dynamic characteristics are dependent on parameters such as the following:

a) Equipment physical dimensions

b) Equipment weight, its distribution, and center of gravity

c) Equipment structural load transferring characteristics and stiffness to resist seismic excitation

d) Equipment base anchorage strength and stiffness to ensure structural integrity and adequate boundary conditions

e) Equipment interfaces with adjacent items or connecting accessories such as cables and conduits

The relative dissimilarity of all the physical parameters of the preceding list items a) through e) needs to be bounded to ensure that adequate similarity exists between equipment assemblies. Assurance should be obtained that equipment differences from previously qualified equipment do not result in a change in the dynamic response characteristics of the item being qualified compared to the item used for similarity and do not introduce new mechanisms for malfunction. Constraints and limitations associated with the previously qualified equipment used to demonstrate similarity would apply to the equipment being qualified, unless otherwise justified.

For the equipment where seismic qualification can be demonstrated by showing that individual safety devices are performing properly during the earthquake, a device or subassembly similarity evaluation approach may be considered. The similarity of physical systems should be addressed for the individual device. In this case, the justification for similarity lies in the careful examination of the dynamic properties, anchorage, and the mechanical or electrical operating principle(s) or both. The demonstration that similar equipment behavior will result between the previously qualified equipment and the equipment under investigation must be based on similarity of physical parameters. When significant differences exist for complex devices, it may not be possible to demonstrate similarity by analysis. For such cases, testing is the preferred approach.

9.3.3.3 Safety function

Equipment being qualified must be capable of performing its safety function(s) during and/or after an earthquake. The safety function during the earthquake may or may not be the same as after the earthquake. Therefore, for each qualification, the safety function must be defined during and after the earthquake. The qualification data must provide documented evidence to support the demonstration of safety function as defined for each application. Where an active function or absence of a spurious function is required during the earthquake, the qualification data must provide sound evidence that the equipment being qualified will perform as required.

9.4 Shock testing

Laboratory shock testing performed in conformance with various military standards (for example, MIL-S-901C-1963), consists of subjecting the component to high-impulse shock-type loads (accelerations). Unless these accelerations are of sufficiently high magnitude (far higher than the earthquake levels) and sufficient duration, shock testing without additional vibration testing is not considered adequate seismic simulation. Since the primary objective of testing is to verify the seismic adequacy of components, the use of shock data can provide only an approximation of the adequacy of the equipment tested. This is the result of the difficulty encountered in matching the frequency content and duration with that of the shock experienced in seismic service.

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9.5 Extrapolation for multicabinet assemblies

In many cases, it is impractical to test a multicabinet assembly of similar cabinets due to limitations in the size of testing facilities. The qualification of a single cabinet, or a few connected cabinets, may not be extrapolated to qualify a larger number of cabinets connected together in a lineup without adequate justification. This is because

a) Individual cabinets in the array may have different mass loading or mass distribution, or different structural stiffness, or both.
b) The connected cabinets may exhibit different dynamic response, such as different torsional modes compared to the smaller number originally qualified.
c) The response of subcomponents mounted in different locations may be affected.

The approaches given in 9.3 may be used to justify the extrapolation of tests on a single cabinet, or a small number of connected cabinets, to qualify an assembly.

9.6 Other test/analysis

In addition to 9.2 through 9.5, analysis may be used to

a) Explain unexpected behavior during a test.
b) Obtain a better understanding of the dynamic behavior of the equipment so that the proper test can be defined.
c) Obtain a measure of expected response before a test.

10. Experience

10.1 Introduction

Guidelines are presented in this clause to seismically qualify equipment by comparison to experience data for a reference equipment class that has been exposed to earthquakes or testing, supplemented with analysis as required. Use of experience may not be appropriate for all applications; limitations are given in 10.4.2.

10.2 Earthquake experience data

Earthquake experience data may be obtained from equipment in facilities that have experienced natural earthquakes.

Qualification based on earthquake experience data involves five steps that will be covered, as follows:

a) Characterization of earthquake motions experienced by the reference equipment (see 10.2.1)
b) Establishment of the earthquake experience-based seismic capacity for a reference equipment class (see 10.2.2)
c) Characterization of the earthquake experience reference equipment class (see 10.2.3)
d) Comparison of the candidate equipment to the earthquake experience reference equipment class (see 10.2.4)
e) Documentation of the qualification process (see Clause 11)

10.2.1 Characterization of the earthquake experience motions

Earthquakes selected as the basis for a reference equipment class shall be characterized as follows:

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a) Ground motion recordings or conservative estimates from a minimum of four earthquake reference sites containing reference equipment are required to establish a reference equipment class. The four reference sites should be selected from at least four earthquakes.

b) The free-field ground motion of each reference site should be established by recorded data within two structure diameters of the site structure. The recording location should have the same geological/geotechnical conditions as those for the reference site-structure location. The measurement of two structure diameters starts at the perimeter of the facility's foundation. Estimates may be made of free-field ground motion for a reference site that either has no nearby recordings or lies more than two structure diameters from the recording location, provided the estimates are conservatively derived and justified. To make the ground motion estimates for these two cases, multiple attenuation relationships developed using strong-motion recordings from earthquakes with similar tectonic environments, crustal properties, and seismological parameters are to be used. The range of parameters used to develop the attenuation relationship must encompass those of the reference site and the earthquake. The appropriate level of conservatism is the average of the 5% critically damped response spectrum estimates obtained from the attenuation relationships.

c) The ground response spectrum assigned to a reference site shall be the average of two orthogonal horizontal components of the 5% critically damped response spectra at the reference site. The effects of vertical seismic motion are implicitly included in the use of earthquake experience data, since the reference sites subjected to the real earthquakes included seismic motion in all three directions of motion. The vertical component of seismic motion during a postulated earthquake at a nuclear power plant is judged not to be any more significant, relative to the horizontal components of seismic motion, than in the reference sites. Therefore, only the horizontal components of motion are used in the earthquake experience-based method. See item g) in 10.4.2 for limitations regarding vertical seismic motion.

d) The free-field motion shall be considered an estimate of the excitation experienced by all the reference equipment at the reference site.

10.2.2 Earthquake experience spectrum (EES)

The EES is a response spectrum that defines the seismic capacity of a reference equipment class. The EES shall be the weighted average of the ground response spectra for the reference sites. The weight factor, as provided in Equation (1), shall be the ratio of the number of independent items at each reference site to the total number of independent items at all reference sites.

$$A_{EES,i} = \frac{\sum_{n=1}^{m} N_n A_{n,i}}{\sum_{n=1}^{m} N_n} \quad (1)$$

where

$A_{EES,i}$ = spectral acceleration of the EES, at 5% critical damping and frequency i

$A_{n,i}$ = spectral acceleration, at 5% critical damping, at reference site n and frequency i

m = number of reference sites [see item a) in 10.2.1 for minimum number]

N_n = number of independent equipment items at reference site n

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10.2.3 Characterization of reference equipment class

A reference equipment class is a group of similar equipment that shares a range of physical, functional, and dynamic characteristics and whose performance in earthquakes has been demonstrated. The similarity of the reference equipment that defines an equipment class should be based upon an extension of the principle of similarity of 9.3.3.2 and 9.3.3.3. The attributes of the equipment class, the number of independent items in the equipment class, and functionality of the equipment during the earthquake are defined in 10.2.3.1 through 10.2.3.3.

10.2.3.1 Attributes of equipment class

The attributes of the equipment that constitute the earthquake experience reference equipment class shall be defined such that those features important to seismic ruggedness can be assured and any seismic vulnerability can be identified and precluded in the candidate equipment. These equipment ruggedness and vulnerability attributes of the earthquake experience reference equipment class shall be defined in terms of the following inclusion rules and prohibited features.

a) Inclusion rules define the bounds of equipment included in the reference equipment class. These rules define an acceptable range of equipment physical characteristics, design details, dynamic characteristics, and functions for which seismic ruggedness has been demonstrated by earthquake experienced data. The following factors must be considered and evaluated when developing inclusion rules: equipment type, manufacturer, weight, mechanical and structural design details including internal components and structures, features, size and shape, vintage, function, capacity rating, load path including mounting, governing industry standards, materials, natural frequencies, moveable subassemblies, attached items or components, and modifications necessary to achieve the defined seismic capacity. Not all of these factors may be applicable or important to a particular class of equipment. It is the intent of this subclause to ensure that the critical seismic characteristics are defined and demonstrated by the experience data.

   The diversity of features represented in the reference equipment shall be described in the inclusion rules. In those cases where diversity is limited, the reference equipment class shall be narrowed to the specific features represented in the reference equipment. In developing a reference equipment class for in-line components in distribution systems (e.g., a solenoid valve on a piping system), if more than half of the items are judged not to have experienced distribution system amplification (i.e., the in-line component is located immediately adjacent to a distribution system support providing seismic restraint), a limitation shall be applied in terms of an inclusion rule for the reference equipment class.

b) Prohibited features are design details, materials, construction features, or installation characteristics that have resulted in seismic induced failure of the equipment to maintain its structural integrity and perform its specified function at earthquake excitations up to and including the defined seismic capacity level. Failure data from other sources (e.g., nonreference earthquake sites and test results) should also be reviewed and considered in defining prohibited features.

   Prohibited features should include any attributes that would contribute to fatigue failure from low-cycle loads from a combination of a number of OBE and SSE events. See Annex D for a discussion of low-cycle fatigue.

10.2.3.2 Number of independent items

The reference equipment class should include a minimum number of independent items that performed satisfactorily. Independent items are components and equipment that: (a) have different physical characteristics or (b) experienced different seismic motion characteristics, e.g., different earthquakes, different sites, different buildings, or different orientations/locations in the same building. For example, two or more identical items of equipment located side by side are considered a single independent item for each earthquake experienced.

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For earthquake experience reference equipment classes, the minimum number of independent items should be 30. Where less than 30 independent items constitute the reference equipment class, the EES should be reduced by the applicable reduction factor given in Table 1 to produce the same statistical confidence level as a reference equipment class comprising 30 independent items. Unless otherwise justified, the number of independent items shall not be less than 15.

Table 1—EES reduction factor base on number of independent items

Number of independent items	EES reduction factor
30	1.0
25	0.9
20	0.8
15	0.7

10.2.3.3 Reference equipment class functionality

The functions that the reference equipment performed during and/or after the earthquake must be defined. An appropriate justification that these functions were performed must exist in the definition of the reference equipment class (see Clause 5). This justification shall demonstrate one of the following:

a) All of the equipment defining the reference equipment class performed the required functions during and/or after the earthquake.

b) All of the equipment defining the reference equipment class was functional after the earthquake, and where necessary, a quantitative assessment of functionality during the earthquake shall be established based on knowledge of the required operation of the equipment and consideration of credible seismic failure modes that may prevent equipment operation. Data from analysis and/or testing of similar equipment (e.g., from Clauses 7, 8, or 9) may be used in the quantitative assessment of functionality.

10.2.4 Qualification of candidate equipment

The requirements for qualifying a candidate equipment item using earthquake experience data are as follows:

a) The RRS should be enveloped by the EES for the reference equipment class over the frequency range of interest (typically, 1 Hz to 33 Hz). Failure of the EES to envelop the RRS must be justified. For line-mounted equipment, the RRS for comparison to the EES should be the in-structure response spectra where the distribution system is supported. Note that this approach accounts for in-line amplification only if the reference equipment are mounted in-line and not at a distribution system support [see item a) in 10.2.3.1].

b) The minimum RRS used for comparison with the EES shall be the 5% critically damped, median-centered horizontal in-structure response spectrum. This RRS, as defined in the qualification specification, shall be derived from the SSE. Equipment qualification for multiple seismic events of lower levels than the RRS, such as five OBEs, is achieved when applying the methods of 10.2 to the evaluation of the single enveloping RRS, because the equipment is shown to have no credible low-cycle fatigue failure modes considering the number of specified earthquake cycles [see item b) in 10.2.3.1].

c) The candidate equipment shall be verified to be within the inclusion rules of the reference equipment class [see item a) in 10.2.3.1].

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d) The candidate equipment shall be verified to exclude the prohibited features of the reference equipment class [see item b) in 10.2.3.1].

e) The safety function of the candidate equipment including the enclosed or attached devices or subassemblies, if applicable, during and/or after the earthquake shall be demonstrated by the reference equipment class (see 10.2.3.3).

f) The mounting of the candidate equipment, including the enclosed or attached devices or subassemblies, shall be evaluated in accordance with the qualification specification requirements.

g) Since equipment capacities may change with vintage, candidate equipment of a newer or an older vintage than the reference equipment shall be evaluated for any significant changes in design, material, or fabrication that could reduce its seismic capacity compared to the reference equipment class.

h) The qualification of the candidate equipment shall be documented in accordance with the requirements in Clause 11.

10.3 Test experience data

Test experience data may be obtained from test results from previous qualifications. Test experience data is most often applicable to establishing seismic qualification for a reference equipment class based on using the test results for five or more individual items. The test experience data should meet the requirements of Clause 8, including the seismic aging (OBE) requirements in 8.1.5.2. The minimum OBE requirement shall be five OBEs. Use of a single test of an item to qualify a different candidate item is covered in Clause 9.

Qualification based on test experience data involves five steps that will be covered, as follows:

a) Characterization of test motions experienced by the reference equipment (see 10.3.1)

b) Establishment of the test experience-based seismic capacity for a reference equipment class (see 10.3.2)

c) Characterization of the test experience reference equipment class (see 10.3.3)

d) Comparison of the candidate equipment to the test experience reference equipment class (see 10.3.4)

e) Documentation of the qualification process (see Clause 11)

10.3.1 Characterization of test experience input motions

Test input motions used as the basis for a reference equipment class shall be characterized as follows:

a) The test input motions shall be multifrequency and meet the relevant requirements of 8.6.

b) The test input motions shall be characterized by the test response spectra in the front-to-back, side-to-side, and vertical directions.

c) The test input motions shall be recorded at the mounting point of the equipment.

d) The test input motions should have broadband response spectra shape with an amplified region of one octave or more. If the TRS is narrowband, the peak spectral acceleration in the narrowband region shall be reduced by a factor of 0.7.

e) The test input motion shall be biaxial or triaxial. If the equipment is susceptible to cross-coupling effects, a reduction factor of 0.7 should be considered for the biaxial TRS.

10.3.2 Test experience spectra (TES)

The TES define the SSE seismic capacity of a reference equipment class in the front-to-back, side-to-side, and vertical directions. The TES shall be the frequency-by-frequency mean of the response spectra from successful tests without malfunction. The TES should be below the lower envelope of test spectra that produce failures. In some cases, however, the failure test spectra may have regions of lower spectral amplitude that are not likely to have affected the failure mode. Thus, on a case-by-case basis, the TES may

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be greater than certain portions of the lower envelope of failure data. Note that the resulting TES does not necessarily represent a broadband response spectrum to which the reference equipment was qualified. The TES should only be interpreted as a bound to which peak-broadened narrowband RRS are to be compared as required in item b) in 10.3.4.

Development of an OBE TES is not necessary if the OBE is not more than 1/2 the SSE, since the equipment has been subjected to OBE testing as required in 8.1.5.2. If the OBE is greater than 1/2 SSE, an OBE TES is required unless low-cycle fatigue vulnerabilities are identified and eliminated as prohibited features as required in item b) in 10.3.3.1.

10.3.3 Characterization of reference equipment class

A reference equipment class is a group of similar equipment that shares a narrow range of physical, functional, and dynamic characteristics and whose performance in tests has been demonstrated. The similarity of the reference equipment that defines an equipment class should be based upon an extension of the principle of similarity of 9.3.3.2 and 9.3.3.3. The reference equipment class may include more than one manufacturer or product series when all of the items are constructed in the same general manner, contain the same basic subcomponents, and respond dynamically in the same manner. For example, significant natural frequencies of the reference equipment would lie within approximately 1/3 octave. The attributes of the equipment class, the number of independent items in the equipment class, and functionality of the equipment during the test are defined in 10.3.3.1 through 10.3.3.3.

10.3.3.1 Attributes of equipment class

The attributes of the equipment that constitute the test reference equipment class shall be defined such that those features important to seismic ruggedness can be assured and any seismic vulnerability can be identified and precluded in the candidate equipment. These equipment ruggedness and vulnerability attributes of the test reference equipment class shall be defined in terms of the following inclusion rules and prohibited features.

a) Inclusion rules define the bounds of equipment included in the reference equipment class. These rules define an acceptable range of equipment physical characteristics, design details, dynamic characteristics, and functions for which seismic ruggedness has been demonstrated by testing experience data. The following factors must be considered and evaluated when developing inclusion rules: equipment type, manufacturer, weight, mechanical and structural design details including internal components and structures, features, size and shape, vintage, function, capacity rating, load path including mounting, governing industry standards, materials, natural frequencies, moveable subassemblies, attached items or components, and modifications necessary to achieve the defined seismic capacity. Not all of these factors may be applicable or important to a particular class of equipment. It is the intent of this subclause to ensure that the critical seismic characteristics are defined and demonstrated by the experience data. One of the inclusion rules shall be that the equipment class only applies to the manufacturers included in the reference equipment.

b) Prohibited features are design details, materials, construction features, or installation characteristics that have resulted in seismic induced failure of the equipment to maintain its structural integrity and perform its specified function at test excitations up to and including the defined seismic capacity level. The bases for resolution of test anomalies shall be considered in developing the list of prohibited features. Failure data from other sources (e.g., earthquake experience data) should also be reviewed and considered in defining prohibited features.

   Prohibited features should include any attributes that would contribute to fatigue failure from low-cycle loads from a combination of a number of OBE and SSE events. See Annex D for a discussion of low-cycle fatigue. Note that the test experience data used to develop a test reference equipment class includes OBE test data; this data can be used to determine whether the reference equipment includes attributes that are sensitive to low-cycle fatigue. An alternative method for addressing low-cycle fatigue sensitive attributes is to develop a TES for OBE in the same manner as that required in 10.3.2 for defining the TES for SSE.

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10.3.3.2 Number of independent items

The reference equipment class should include a minimum of five independent items that performed satisfactorily. Independent items are components and equipment that (a) have different physical characteristics, or (b) experienced different seismic motion characteristics. For example, two or more identical items of equipment subjected to the same test input motions are considered a single independent item. The number of independent items shall be sufficient to demonstrate that the full range of dynamic response parameters possessed by the defined equipment class have been exhibited in the testing.

10.3.3.3 Reference equipment class functionality

The functions that the reference equipment performed during and/or after the tests must be defined. An appropriate justification that these functions were performed must exist in the definition of the reference equipment class (see Clause 5).

10.3.4 Qualification of candidate equipment

The requirements for qualifying a candidate equipment item using test experience data are as follows:

a) The RRS should be enveloped by the TES for the reference equipment class over the frequency range of interest (typically, 1 Hz to 33 Hz). Failure of the TES to envelop the RRS must be justified.

b) The RRS used for comparison with the TES should be the in-structure response spectrum at the mounting location of the candidate equipment. This RRS, as defined in the qualification specification, shall be derived from the SSE. If the RRS is peak-broadened to account for uncertainty or variation of location, then it should be justified that the actual response spectrum at the mounting location is narrowbanded (see 10.3.2).

c) The RRS used for comparison with the TES should be computed for the same damping value as the TES. When the damping values of the RRS and the TES are different, additional guidance in 6.3.2 may be used for making the comparison.

d) The candidate equipment shall be verified to be within the inclusion rules of the reference equipment class [see item a) in 10.3.3.1].

e) The candidate equipment shall be verified to exclude the prohibited features of the reference equipment class [see item b) in 10.3.3.1].

f) The safety function of the candidate equipment including the enclosed or attached devices or subassemblies, if applicable, during and/or after the earthquake shall be demonstrated by the reference equipment class (see 10.3.3.3).

g) The equipment mounting shall be evaluated in accordance with the qualification specification requirements.

h) Since equipment capacities may change with vintage, candidate equipment of a newer or an older vintage than the reference equipment shall be evaluated for any significant changes in design, material, or fabrication that could reduce its seismic capacity compared to the reference equipment class.

i) The qualification of the candidate equipment shall be documented in accordance with the requirements in Clause 11.

10.4 Special considerations

10.4.1 Inherently rugged equipment

Experience shows that certain types of equipment possess high resistance to seismic inertia loads. This may be the result of inherent characteristics required to accommodate operational or shipping loads and the application of explicit design standards. Such equipment is inherently rugged. Where inherent seismic

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ruggedness can be established through analysis, testing, or earthquake experience, or where the seismic loads are but a small fraction of the operating loads, the rules for characterizing the reference equipment class (i.e., the attributes and number of independent items defined in 10.2.3 and 10.3.3) and the procedure for defining the seismic capacity of the reference equipment class (i.e., the EES and TES defined in 10.2.2 and 10.3.2) may be simplified and reduced. In this case, the characterization of the reference equipment class and the technical justification for the assigned seismic capacity level (EES or TES) shall be developed and documented as the reference data for this special case.

10.4.2 Limitations

Earthquake or test experience-based qualification is limited by the following considerations. If these limitations exist, then seismic qualification methods described in Clause 7, 8, or 9 shall be used or the experience-based qualification shall be supplemented by the following qualification methods.

a) Some types of equipment have complex features or their design varies significantly with time. These applications require more detailed considerations of design variability, which may render the application of experience data impractical (e.g., microprocessor-based system). In these cases, qualification by other methods shall be used.

b) In certain cases where functionality during an earthquake is required, such as (1) operation of switching devices or electromechanical equipment where inertia loads could cause an inadvertent change in state (e.g., relays, contactors, switches, and breakers) or (2) operation of equipment under degraded voltage or current conditions and timing requirements; it is extremely difficult to establish functionality during the event from the earthquake experience data per 10.2.3.3. Therefore, other qualification methods shall be used.

c) If there is an insufficient number or diversity of independent items, or an insufficient number of reference sites in the case of earthquake experience data to adequately define a reference equipment class, then other qualification methods shall be used.

d) Use of earthquake experience data assures equipment seismic qualification in combination with normal operating loads. For equipment subject to other concurrent loads (e.g., hydrodynamic, SRV discharge), the effect of the loads must be addressed by supplemental qualification methods.

e) For pressure boundary components, the capability of the component to perform the specified pressure retaining functions in combination with an earthquake must be addressed separately using appropriate criteria.

f) Applications that require equipment to be exposed to harsh environments or aging (e.g., IEEE Std 323-2003) prior to or during an earthquake require special consideration. In such cases, qualification methods other than experience-based methods shall be used.

g) When using earthquake experience-based qualification, if the vertical RRS exceeds the horizontal RRS and the functionality of a candidate equipment item could be adversely affected by the vertical RRS, use of another seismic qualification method shall be used.

h) If a candidate equipment item contains an item that could experience a fatigue failure from low-cycle loads (see Annex D), the item shall be evaluated using an alternative method, such as those covered in 7.6 or 8.6.5.

11. Documentation

11.1 General

The documentation for seismic qualification of equipment shall consist of a qualification specification and a qualification report as described in 11.2 and 11.3, respectively. The documentation should demonstrate that the equipment to be qualified performs its safety function when subjected to the earthquake motions for which it is to be qualified.

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NOTE—Proprietary data should be available for audit and source documents identified and referenced.

11.2 Qualification specification requirements

The following information should be provided in the equipment qualification specification as appropriate:

a) Physical description of equipment

b) Identification of safety-related devices and circuitry and their safety functions, during and after the SSE

c) Typical operational settings (or ranges) for adjustable devices

d) Equipment mounting details, including all interface connections

e) RRS for the horizontal axis and the vertical axis, with applicable damping values and indication of artificially broadened areas (see Clause 6 and 8.6.1.1). General specifications, which contain RRS for different locations, should indicate which ones apply to a given equipment item.

f) When an RRS is not furnished, maximum accelerations of either floor or structure motion at all significant frequencies, or a time history.

g) The required earthquake strong motion time duration

h) The required number and amplitude of the OBE and SSE

i) Environment in which the equipment is designed to perform its safety function

j) Applicable loading and interface requirements

k) Acceptance criteria for qualification of equipment, its installation, and mounting

l) Deflection requirements, if applicable

m) Special requirements for tests, analyses, or experience-based methods

n) Applicable margin requirements, if any (see IEEE Std 323-2003)

Once these requirements have been defined, it can be determined whether qualification will be obtained by analysis, test, experience, or a combination thereof.

11.3 Seismic qualification report

The following information should be provided in the seismic qualification report:

a) Identification of the equipment being qualified. For complex equipment, identify each Class 1E component and specify the component's functional requirement. The qualification package should include or reference the original testing, analysis, or experience-based report, or combination, if more than one qualification method is used. Documentation should include references to all drawings, bills of material, instruction manuals, etc., necessary to perform an adequate review.

b) RRS levels

c) A detailed summary of the qualification test, analysis procedure, experience data used, and results (including pertinent anomalies and their dispositions). When a component or subassembly of equipment is qualified separately, the procedure used should also be summarized.

d) Comparison of qualification specification requirements to the qualification results and a conclusion.

e) An approved signature and date are required.

The additional information identified in 11.3.1 through 11.3.4 should be provided, depending on the method of qualification.

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11.3.1 Analysis

When analysis is performed, the method and data used and the failure modes considered should be presented in a format that is readily auditable by persons skilled in such analysis. Boundary conditions, including anchoring and other interfaces, must be clearly defined. Input/output data required to support performance claims and any mathematical model verification testing performed should be included or referenced in the report. The reaction force(s) at the interface connection(s) to the support structure should also be included.

A statement should be made verifying that any computer programs used were validated on the computer hardware on which the program was executed. Computer programs, options, version numbers, dates, and systems utilized should be identified.

11.3.2 Testing

If testing is used as a qualification method, the seismic qualification report should contain the following:

a) For the equipment being qualified
   1) Tested equipment identification (including devices)
   2) Tested equipment functional specification
   3) Tested equipment settings and limitations when appropriate
b) Test facility information including
   1) Location
   2) Testing equipment and calibration
c) Test method and procedures including monitoring for operability and acceptance criteria
d) Equipment mounting details, including all interface connections
e) Test data (including proof of performance, TRS plots, time histories, PSD or Fourier analysis, coherence checks as necessary, number of OBEs and SSEs applied, duration, etc.), type of multifrequency testing employed, and the acceleration time history of the input motion should be provided in addition to the TRS. As a minimum, a time history of the SSE table motion should be provided for one test in each of the three directions of excitation.
f) Test results and conclusions, including statement of any anomalies

The evaluation of equipment operability should be based on a prespecified set of acceptance criteria. Any revision or adjustment of the criteria after a test failure or a test with observed anomalies, to make the test satisfactory, should not be considered acceptable instead of a retest without proper justification. When an anomaly is experienced during testing, it should be documented in the report. When the equipment is not modified to eliminate the anomaly, then the use of the equipment must be justified and this justification filed with the equipment qualification report. Any equipment refurbishment performed during testing must be documented in the test report and reconciled. This data should become part of the post-earthquake field maintenance checks and procedures for that equipment to maintain required seismic qualification.

11.3.3 Combined analysis and testing

If proof of performance is by analysis and testing or by extrapolation from similar equipment, the seismic qualification report should contain the following:

a) Reference to the specific method of combined analysis and testing used
b) Description of equipment involved
c) Analysis data
d) Test data
e) Justification of results

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When extrapolation of data is made from similar equipment, a description of the differences between the items of equipment involved is required. Justification that the differences do not degrade the seismic adequacy below acceptable limits (may require some additional analyses or testing) and any additional supporting data should be included.

11.3.4 Experience

If the experience-based method is used to qualify a candidate equipment item, then the seismic qualification should include documentation of (a) the reference data, and (b) the candidate equipment qualification as described in 11.3.4.1 and 11.3.4.2.

11.3.4.1 Reference data

Documentation of the reference data on which experience-based qualification is based should satisfy the requirements in Clause 10 and include the following:

a) Characterization of experience motions (see 10.2.1 and 10.3.1).

b) Development of EES or TES (see 10.2.2 and 10.3.2).

c) Characterization of reference equipment class (see 10.2.3 and 10.3.3).

The reference data may be specific to the subject equipment qualification or may be generic in nature and included by reference.

Documentation records for earthquake experience data should include the results of reviews, inspections, or interviews recorded sufficiently soon after an earthquake to demonstrate that the reference equipment performed its function during and after the earthquake prior to any repairs or adjustments.

Particular attention must be given to documentation of equipment taken from past earthquakes, which may have been recorded a considerable period of time after the earthquake, to establish its authenticity and applicability. The basis for the use and acceptance of such data should be clearly stated in the qualification report.

Documentation for test experience data should include results of reviews of seismic qualification test reports including but not limited to data needed to identify the equipment type, make and model, the test input motion, SSE and OBE response spectra, and the functional performance.

Documentation should include identification of materials, parts, and components and modifications to characterize the attributes of the reference equipment.

The effect of any malfunctions must be recorded and their effects traced so the prohibited features are identified. The documentation should include records of malfunctions, repairs, and condition of the reference equipment.

11.3.4.2 Candidate equipment qualification

Documentation of how the candidate equipment is seismically qualified for its intended application should follow the outline of the seismic qualification report (see 11.3) and should include the following:

a) Documentation of or reference to the reference data from 11.3.4.1 used for the seismic qualification of the candidate equipment

b) Documentation of the qualification of the candidate equipment that demonstrates that the requirements in 10.2.4 or 10.3.4 are met

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Justification must be provided to show that the candidate equipment is acceptable per the reference equipment class by compliance to inclusion rules and prohibited features. The differences between the reference equipment and the candidate equipment must be addressed. Additional analysis or testing may be needed to justify that the differences do not degrade the seismic capacity below acceptable limits. The documentation must demonstrate that the reference equipment is capable of performing the required functions under conditions equal to or more severe than that required for the candidate equipment.

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Annex A

(informative)

Measurement of ZPA

ZPA is one of the parameters that must be measured to show that the TRS properly envelops the RRS. The ZPA of the TRS is required to envelop the ZPA of the RRS considering only frequencies of the test-table motion time history lying within the RRS amplified region. To clarify concepts that follow, this may be called the ideal ZPA of the TRS.

The ZPA is the value of the response spectrum analyzed to a frequency higher than those contained in the motion time history. Typical test-table time histories usually contain frequencies higher than those corresponding to the RRS amplified region. The higher frequencies are usually generated by the following:

a) Waveform distortions from the hydraulic excitors
b) Any looseness and rattling between the test-machine table, fixturing, and the test item
c) Any looseness and rattling within the test item itself

Any of these influences may preclude the accurate measurement of the true or actual ZPA for the test even when the analysis is performed to 100 Hz or 200 Hz. In addition, even when the true ZPA of the TRS has been obtained by an analysis to a sufficiently high frequency, there is no direct way of knowing when the true ZPA magnitude equals the ideal ZPA of the TRS without further analysis. The following methods may be employed to obtain the true and the ideal ZPA.

The principal TRS must be the analysis of the total waveform that exists at the point of measurement at the same value of damping as the RRS. When the shape of the TRS is similar to the shape of the RRS, a reasonably accurate measure of the ZPA can be obtained from the TRS high-frequency asymptote. When the TRS tends to increase in the high-frequency region, a supplemental analysis may be performed at a significantly different damping value. The true ZPA is indicated at the high-frequency end where the two TRS curves coincide. When the two curves do not meet, then the true ZPA can only be found by carrying the analysis out to a higher frequency.

When the true ZPA of the TRS indicates that no high frequencies beyond the amplified region of the RRS are contained in time history, then it is also the ideal ZPA.

When the true ZPA of the TRS indicates that high frequencies are present, a supplemental analysis may be performed on the waveform by low-pass filtering the signal at or above the RRS cutoff frequency. This will show the value of the ideal ZPA that must equal or exceed the ZPA of the RRS.

For digital systems, there may be hardware/software constraints associated with block size, sampling rate, and anti-aliasing filters. It is recommended that analysis be performed only to the maximum RRS frequency of interest. The ZPA should then be determined by

a) The peak acceleration shown on the digitized time history with the anti-aliasing filters set at the cut-off frequency.
b) Examining a strip chart time history that has been filtered at the cutoff frequency.

Care should be taken to ensure that the upper frequency selected does not exceed the response of the chart recorder. An alternative to the strip chart is an oscillograph that inherently has a greater frequency response.

These analysis techniques may also be used where a response point is being measured for use as an RRS for a subsequent component or device test. For this test application, it is suggested that a waveform to the filtered RRS be synthesized first, with the higher frequencies added as required to obtain the overall RRS. Use of PSD to ensure adequate frequency content may be used as an alternate procedure.

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Annex B

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Frequency content and stationarity

This topic is best divided into two parts: (a) frequency content and (b) the stationarity of the frequency content. The objective of both concerns is to produce an input waveform that is a good simulation of the postulated seismic excitation. Even with the TRS enveloping the RRS, as the TRS shape deviates from that of the RRS, the frequency content of the waveform can change radically. Although this will usually mean considerable over-test at some frequencies, it may not always be conservative at others. There are a number of techniques that may be used to show that the frequency content of the synthesized waveform is adequate, for example, as follows:

a) The enveloping of the RRS by the TRS is obtained with similar spectrum shapes so that similar amplifications result at significant spectrum peaks in the amplified regions of the spectra

b) The frequency content of the Fourier transform of the test waveform is compatible with the amplified region of the RRS

c) The frequency content of the PSD of the test waveform is compatible with the amplified portion of the RRS

Having shown a proper frequency content, it is also required to show that it is statistically constant with time within a reasonable tolerance.

To satisfy stationarity, all the required frequencies in multifrequency waveforms must be statistically present during the strong motion portion. One way to show this is with the time interval TRS. A definition of this follows.

The time interval response spectrum is different from the conventional response spectrum analysis in that the peak detection of the SDOF oscillators' responses is performed as a function of time intervals. For example, a 30 s duration could be divided into five 6 s intervals with a response spectrum produced for each time interval. It should be noted that the input time history is continuous for the full duration, that is, it is not divided into time intervals. As a practical matter, the minimum time interval must be some multiple of the period of lowest frequency. A basis for comparison can be formed from a similar analysis of actual representative earthquake time histories.

Another method of showing frequency stationarity includes use of a time interval PSD. The strong motion portion of the table acceleration time history can be separated into several intervals and a PSD computed for each. Comparison of several PSDs must show that all frequencies are statistically present to a similar degree for each time interval. A basis for comparison can be formed from a similar analysis of actual representative earthquake time histories.

Another method of showing adequate frequency stationarity is to show time histories of the test input waveform components. This can be accomplished by dividing the waveform into narrowband (for example, 1/3 octave) components and showing the time history for each. Each frequency component should be statistically continuous during the test duration. Thus, the peak amplitude probability density for each 1/3 octave waveform should be a Rayleigh distribution. Any other method that has been justified can be used to show stationarity.

It is anticipated that each test waveform synthesis methodology should demonstrate stationarity once, that is, the demonstration of stationarity would not be required for each test.

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Annex C

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Fragility testing

C.1 Excitation motion

Fragility testing may be performed by using any of the various excitation waveforms described in 8.6. For example, to determine its fragility level to single-frequency transient excitation, the equipment may be subjected to any single-frequency excitation such as sine-beat motion. The sine beats may be applied over a frequency range from 1 Hz to 33 Hz. The sine-beat motion is in turn applied at each natural frequency of the equipment as determined by a resonance search test. However, where equipment resonances are not well defined, the frequency interval between tests may be narrowed to 1/2 octave or less, for more conservatism. On the other hand, when broadband resonance response occurs because of nonlinear effects in the equipment, the frequency interval can be broadened to avoid unwarranted fatigue. The amplitude at each frequency should be increased until malfunction occurs. The number of oscillations per beat should be in the range of 5 to 10 with the number of beats dependent on the test frequency and the duration of the earthquake being simulated. From this data, curves showing input level versus frequency may be plotted. Additionally, fragility response spectra can be plotted at desired values of damping from the single-frequency input data.

In a manner similar to that used for sine beats, and at the same frequencies, the equipment may be subjected to continuous sinusoidal excitation. Additional frequencies may be used to more completely define the low points on the input excitation fragility plot. Further, a series of fragility response spectra can be plotted at desired damping values from the steady-state continuous sine data. The response spectra thus obtained are classical resonance curves centered at the test frequencies.

To demonstrate the equipment's fragility level capability to multiple-frequency excitation, it should be subjected to random excitation. The overall spectrum level and shape must be adjusted to determine the fragility response spectrum.

When there is an additive effect of multimodal response, the fragility response spectrum is lower than that determined from the single-frequency excitation.

C.2 Application of results

The general guidelines for applying the fragility data are as follows:

a) When the RRS is broadband, then the multifrequency fragility curve of the appropriate damping should be overlaid on the RRS and demonstrated to be higher than the required spectrum.

b) When the requirement permits single-frequency testing, it may be permissible to use the fragility spectrum obtained from the single-frequency test data to overlay the RRS.

c) When the RRS consists of a high narrow peak (for example, a peak due to a predominant horizontal building resonance), then the single-frequency fragility response spectrum of the appropriate damping should be overlaid on the required spectrum and demonstrated to be higher than the required spectrum.

d) When the RRS is a combination of items a), b), and c), then a combination of the fragility data may best demonstrate the equipment's capability and may be used with appropriate justification.

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The fragility response spectrum may be further used as input to a probabilistic risk assessment study of the system in which the tested component is to be included. In this case the fragility response spectrum is first transformed to a probabilistic fragility function, which gives the frequency of failure for the tested component as a function of excitation amplitude. More details of this use can be obtained from appropriate texts on probabilistic risk assessment.

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Annex D

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Test duration and number of cycles

Test duration alone may not be sufficient to ensure adequate equipment response relative to low-cycle fatigue capability. When the strain range in structural elements is doubled, the fatigue effect is increased exponentially, such as by a factor of six. The strain range of significance for low-cycle fatigue consists of a malfunction occurring in approximately 100 cycles or less. Therefore, a conservative seismic test requires, in addition to adequate duration, that the input causes a sufficient number of strong motion-response cycles in the equipment. In accordance with 8.6.5, the input waveform should generate a response at any point in an equipment sufficient to cause a total amount of fatigue at least equivalent to that produced by the earthquake input motion at the mounting of the equipment. The number of strong motion cycles in a filtered (for example, building floor, cabinet, pipe) response time history depends on several factors, such as the amplification by resonances (soil, building, equipment), the damping, and the location of the equipment in the building.

Typically, the filtered response will contain one or more maximum peak cycles plus an assortment of cycles with peaks of varying fractional amplitude. The fractional peak cycles can be converted to equivalent maximum peak cycles by the use of Figure D.1, which is based on a fatigue curve (stress versus number of cycles, S/N) with an exponent of 2.5. This figure plots the number of fractional cycles, as a function of the percentage of maximum peak amplitude, which is needed to obtain one equivalent maximum peak cycle. Any combination of number and amplitude of fractional cycles could be used. For example, to obtain five equivalent maximum peak cycles, any of the following combinations is adequate:

a) Fifteen fractional cycles at 65% of maximum peak

b) Ten fractional cycles at 75% of maximum peak

c) Four fractional cycles at 70% plus ten fractional cycles at 65% of maximum peak

Thus, by determining the distribution of peak amplitudes in a given filtered response waveform and using Figure D.1, the total number of equivalent maximum peak cycles can be determined.

A typical filtered response to earthquake strong motion can be approximated by a narrowband random waveform whose peak amplitude probability distribution is given by a Rayleigh distribution. This property, together with the center frequency and time duration of the filtered motion, permits determination of the number of equivalent peak-stress cycles by use of Figure D.1. A subsequent relationship that results between equivalent maximum peak cycles and filter center frequency for stationary random motion is given in Figure D.2 for three different strong motion durations. Therefore, any equipment response that results from stationary random motion should approximate these results.

For ground-level excitation, simulation should include multifrequency content up to the cutoff frequency, and the equivalent number of fatigue cycles for any equipment resonance up to the cutoff frequency can be determined directly from Figure D.2.

For equipment excited by structural floor motion, only resonances up through the predominant building frequency range need be considered, since building response is negligible beyond that range. For the case with a 5 Hz predominant building frequency, an average number of at least ten equivalent stress cycles should be used for 15 s duration.

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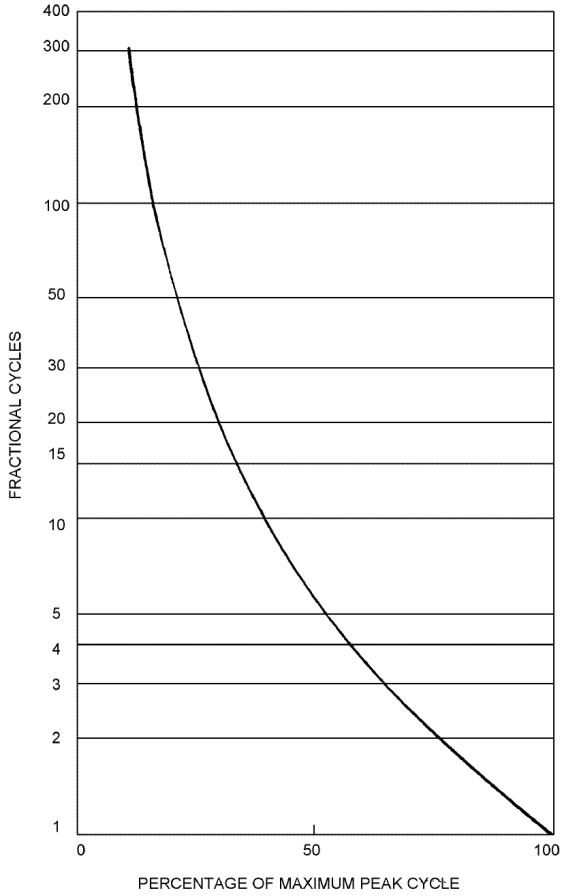

Figure D.1—Fractional cycles to obtain one equipment maximum peak cycle

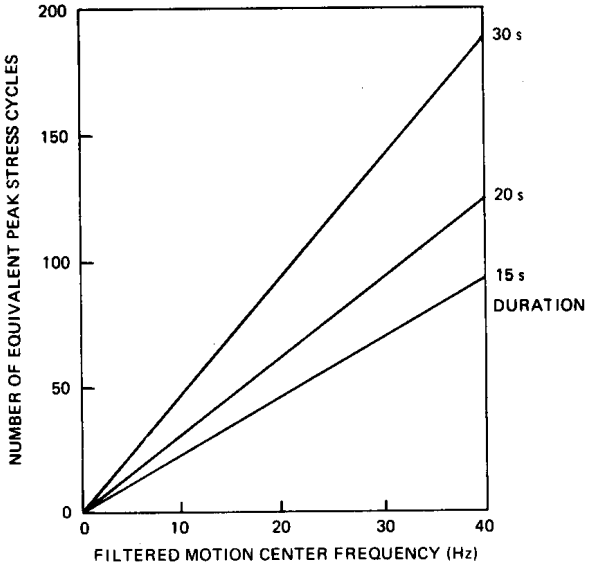

Figure D.2—Equivalent peak-stress cycles induced by stationary random motion

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For some test input waveforms, that is, sine dwell or sine beat, the peak distribution of the filtered structural response waveform produced is similar to that for the input itself. Therefore, the peak-stress cycle potential can be determined directly from the input waveform, which in accordance with 7.6, should contain at least ten equivalent maximum peak cycles. For single-frequency sine-beat testing, the total number of cycles for a test at any frequency is defined in 8.6.2.3 by the number of beats and cycles of motion within the beat. This will ensure at least five maximum peak (ZPA) cycles and several other fractional peak (less than ZPA) cycles, for a test at any frequency. The fractional peak cycles can be resolved into a smaller number of equivalent maximum peak cycles with the use of Figure D.1. For example, the total fractional peak cycles in five sine beats with ten cycles and five cycles of motion per beat are equivalent to approximately 17 and 6 maximum peak cycles, respectively.

Therefore, for these motions, a total of 22 and 11 equivalent maximum peak cycles are obtained, respectively. For other types of test motions whose response waveforms are also similar to that of the excitation, a similar computation of equivalent peak cycles using Figure D.1 should be performed.

For narrowband response waveforms that result from approximately stationary random synthesized excitations, the peak amplitude distribution is known to be Rayleigh. Therefore, Figure D.2 can be used directly to determine the equivalent number of peak-stress cycles for a given filtered frequency and duration. However, the existence of adequate fatigue potential in an excitation waveform of this type is assured providing that adequate stationarity has been included. Thus for this case, establishing the number of equivalent peak-stress cycles is not necessary when adequate stationarity is shown to be present in the waveform. Nevertheless, the equivalent peak-stress cycle count procedure can be used as a check on the adequacy of stationarity in the waveform.

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Annex E

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Statistically independent motions

The three orthogonal earthquake motion components (two horizontal and one vertical) are known to be approximately statistically independent when measured at a distance from the epicenter. Thus, artificially generated time histories, to be used for either analysis or test simulations of multiaxis motions, should possess a similar amount of statistical independence. This can be verified either by the use of the coherence function or by the correlation coefficient function.

Coherence is defined specifically as the ratio of the squared magnitude of the cross-spectral density and the product of the two power spectral densities for the two time histories whose independence is compared. Thus, it is also a function of frequency, with a value of zero for perfectly independent signals and a value of +1.0 for perfectly dependent signals. The coherence between two record motions given simultaneously can be computed by separating them into multiple segments (data samples), computing the coherence for each corresponding pair, and averaging the results. The estimated values of the resulting coherence function are very much dependent on the number and duration of the individual time segments utilized. The required minimum 15 s of strong motion for one simulated seismic event can conveniently be separated into at least 12 such segments. This should lead to a plot whose maximum value is less than 0.5 for sufficient statistical independence.

For time histories whose mean value is zero, the correlation coefficient is defined specifically as the ratio of the cross correlation function and the product of the RMS values of the two signals whose independence is compared. Thus, it is a function of time delay (or time shift) between the two signals and has a value of zero for independent signals, tending toward +1.0 for dependent signals. Computation of correlation coefficient is typically performed for time delays up to completion of the strong motion. This should lead to a function whose absolute value is less than 0.3 for sufficient statistical independence.

Orthogonal components of in-structure floor motions may or may not be statistically independent, depending on whether building cross coupling occurs. The degree of motion independence may vary with frequency in such cases.

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Annex F

(informative)

Bibliography

[B1] IEEE 100, *The Authoritative Dictionary of IEEE Standards Terms,* Seventh Edition.

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