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3

Essential Facilities, Qualification Programs, Systems, and Equipment

Essential facilities are the backbone of emergency efforts immediately after an earthquake. Their continued and successful operation is of the utmost importance for the community's well-being.

Early use of the essential facility concept came with the Civil-Defense Emergency Operating Centers. Then in 1975, the Structural Engineers Association of California (SEAOC) published recommendations for lateral force design and defined "essential facilities." The 1976 *Uniform Building Code* adopted SEAOC's definition in Paragraph 2312, Section (k), which reads.

> **2312(k) ESSENTIAL FACILITIES.** Essential facilities are those structures or buildings which must be safe or usable for emergency purposes after an earthquake in order to preserve the health and safety of the general public. Such facilities shall include, but not be limited to
>
> 1. Hospitals and other medical facilities having surgery or medical treatment areas.
> 2. Fire and Police Stations.
> 3. Municipal Government Disaster Operation and Communication Centers deemed to be vital in emergencies.

Some governing bodies have decided that facilities such as computing centers and general services buildings also fall into the essential facility category even though they are not specified in the building codes. In the case of computing centers, substantial savings may be realized by providing seismic protection programs for the survivability of the equipment. Expensive and sensitive computer equipment if correctly protected will not be as likely to be damaged. Equipment that is damaged must be repaired or replaced, often at very high cost. Relatively inexpensive protection measures taken in the design phase may reap substantial savings when a damaging earthquake strikes. Prior determination of potential damage to equipment

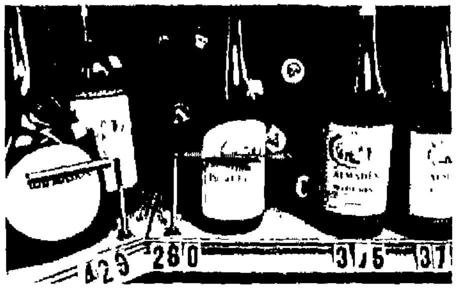


FIGURE 3.1. Wire retainer allows for easy removal of shelved items. Photograph courtesy of Robert Reitherman.

and seismic risk dictates to the design team just when and at what levels seismic protection is needed.

Equipment seismic qualification is not limited to essential facilities by this book. Retailers, for instance, have used and can continue to use recommendations for shelved items. A simple shelf addition such as a parapet or wire retainer as shown in Figure 3.1 allows the easy removal of shelf contents and yet restrains the items during an earthquake.

DESIGN EARTHQUAKES

Chapter 2 is titled "Earthquake Resistant Design," not "Earthquake Proof Design," for very specific reasons. It is beyond current comprehension and economic feasibility to earthquake proof much of anything. Responsible designers have long realized this and have approached the problem accordingly.

Prior to addressing the seismic qualification program for the facility in question, the design team needs to assess the regional seismicity. Figure 3.2*a* is a seismic map showing expected qualitative seismic risk values for the United States, Canada, and Mexico. This map has been adapted and compiled from the sources indicated in the figure. Figure 3.2*b* is a seismic risk map showing expected bedrock-acceleration values for the contiguous United States. This map was developed by Algermissen and Perkins in 1976.

Reference to these maps during design projects provides designers with a general base of information sufficient to begin assessing the seismic risk problem. As extreme examples, designers in Milam County, Texas (the central part of the state), would not need to overly concern themselves with earthquake design for building equipment. Designers of essential facilities in San Benito, California (south of the Bay Area), on the other hand, can expect maximum potential damage and therefore earthquake resistance of building equipment should be a major concern.

For essential facility projects located in California, the designers can begin by referring to the local city or county Seismic Safety and Public Safety

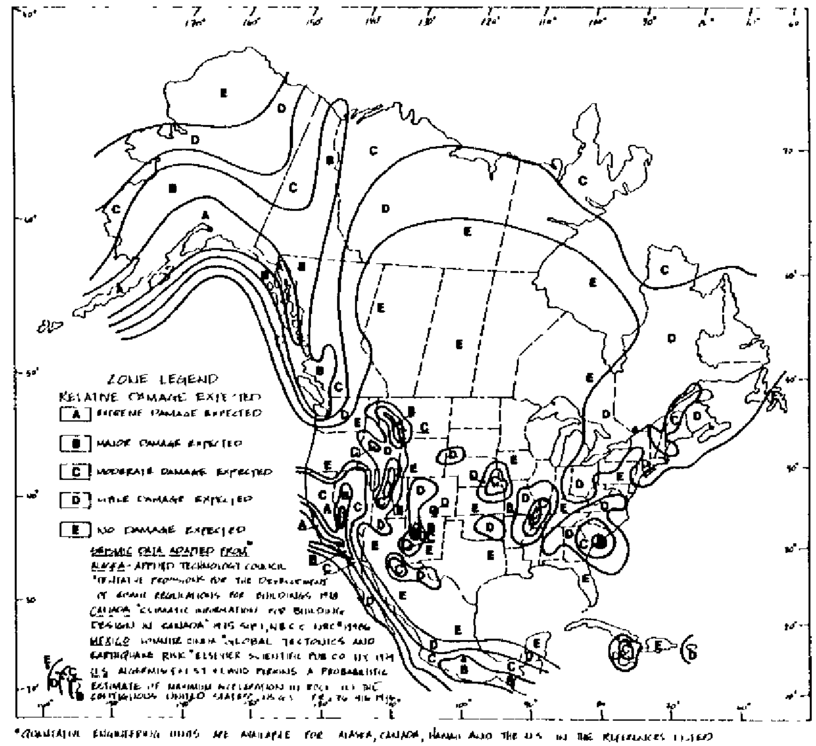
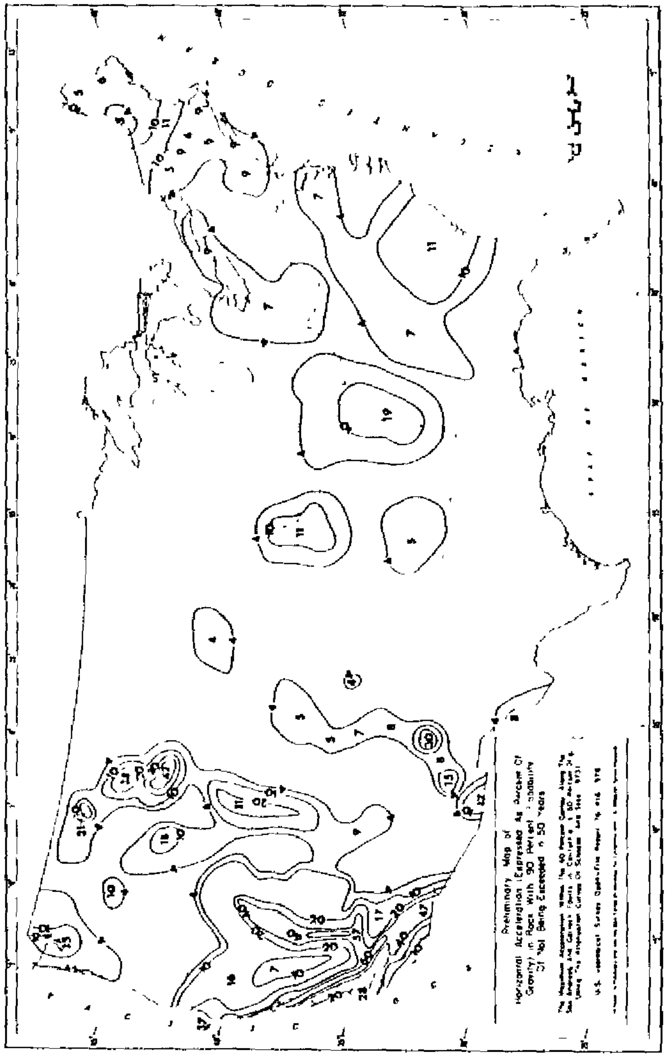


FIGURE 3.2*a*. Relative seismic risk zone map—expected damage.

Elements. These documents are available through the local planning departments and describe in general terms the maximum credible and maximum expected earthquakes for the region. They are the rough beginnings of what can be termed the design earthquake. This information is generally more detailed than that found in Figure 3.2 and provides the grounds for preliminary conceptual designs prior to the actual determination of the design earthquake for the specific site.

It should be noted that Figure 3.2b designates the expected bedrock accelerations. Building and equipment response probably will be significantly different from the expected bedrock responses shown. The variables leading to these different responses include:

- Depth of soil.
- Depth and condition of sediments (consolidated versus unconsolidated).
- Groundwater content.



SEISMIC RISK DEVELOPED BY ALGERMISSEN AND PERKINS

FIGURE 3.2*b* Seismic risk developed by Algermissen and Perkins, 1976. U.S.G.S. Open File Report 76-416, 1976. Reproduced from NBS Special Publication 510, ATC 3-06 NSF Publication 78-8

- Building shape.
- Building structural type.
- Shear building.
- Moment resisting.
- Space frame.
- Number of floors.
- Equipment rigidity.
- Equipment location.
- Equipment connections.

To adequately define how a building, and subsequently the equipment, will respond, these variables must be considered when selecting or deriving the design earthquake.

To accurately predict equipment response, with any degree of certainty, the free-field design earthquake should be applied to the building so that floor responses at the equipment locations can be determined. Derivation of the floor response can be arrived at by using a step-by-step time-history analysis of the building structure. This is a complex solution and referral to structural engineers versed in its usage is suggested.

Design earthquakes are generally presented in the response spectrum or time-history format. Figures 3.3*a* and 3.3*b* are examples of such design earthquakes in the response spectrum format. Figure 3.3*a* is the "classical" 1940 El Centro earthquake. The other is a smoothed synthesized design earthquake. The reader will note that the El Centro plot contains five curves. These various curves represent selected percentage levels of critical damping. The synthesized design earthquake contains two smoothed curves. The term "maximum credible earthquake" is the largest earthquake expected at the site. The lower curve is the "maximum probable earthquake" and represents the earthquake that is likely to occur during the useful lifetime of the facility. The foregoing terminology generally refers to the free-field earthquakes.

Various industry standards have defined their own design earthquakes for equipment:

- Safe Shut-Down Earthquake (SSE).
- Design Basis Earthquake (DBE).
- Operating Basis Earthquake (OBE).
- Design Contingency Earthquake (DCE)
- Design Operating Earthquake (DOE).

The different titles are somewhat indicative of the industry from which they arise. The first three have their genesis in the nuclear power industry, while

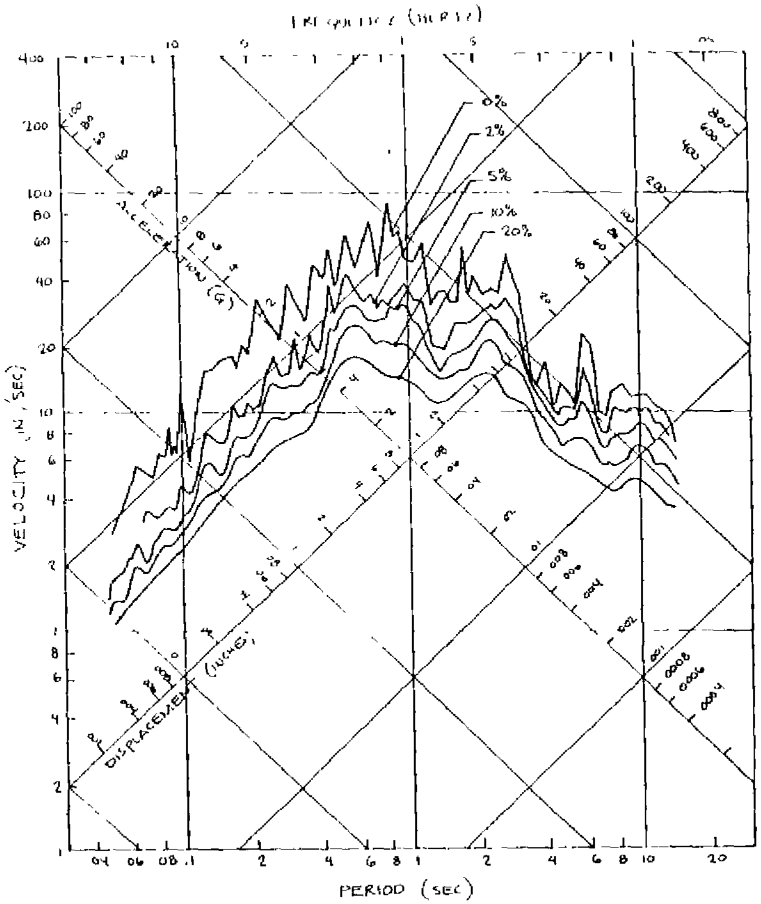


FIGURE 3.3a Hypothetical response spectrum.

the last two were developed for the Trans-Alaska pipeline (Anderson and Nyman, 1977). Their philosophy, however, remains the same. These design earthquakes all allow the design team to compare the structure or component with that of an earthquake that is likely to occur for the particular site.

In the case of essential facilities, some equipment is more critical to the functional aspects of the facility than others. Thus it is logical to define two design levels: one aimed at critical equipment and the other aimed at support equipment. This book utilizes two such design earthquakes:

- Critical Equipment Earthquake (CEE).
- Support Equipment Earthquake (SEE).

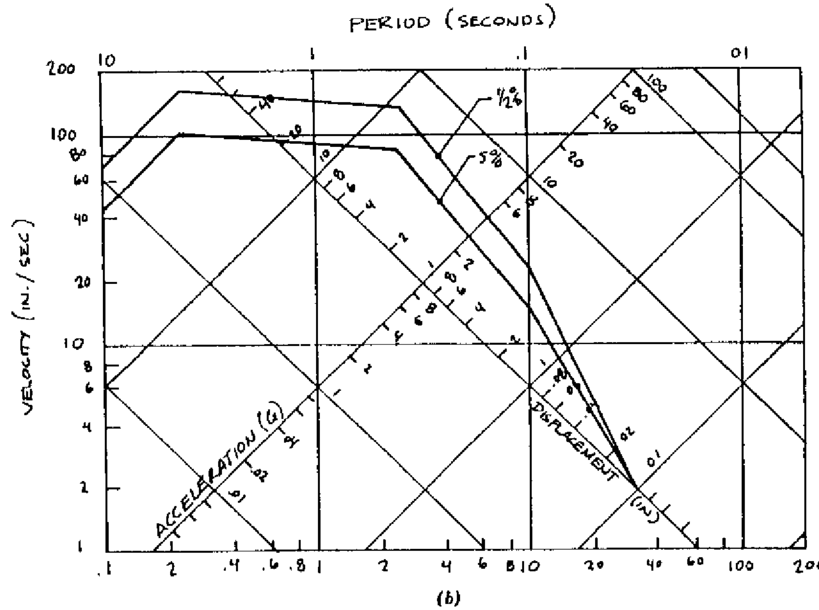


FIGURE 3.3b. Hypothetical smoothed response spectrum.

Both of these design earthquakes are expressed originally as functions of ground motion at the particular site. The characteristics of this dual-level approach are presented below.

- The Critical Equipment Earthquake is the maximum earthquake that can reasonably be expected to occur based on a consideration of regional tectonics within the known existing geologic framework. This earthquake has a very low probability of being exceeded during the life of the essential facility.
- The Support Equipment Earthquake is the largest earthquake that the facility is likely to experience while it is in service. This earthquake has a recurrence interval from 25 to 75 years. It is possible that the facility may experience more than one SEE during its lifetime.

Formulation of the design earthquake requires interaction of several professions such as:

- Architects.
- Civil engineers.
- Engineering geologists.
- Geologists

- Mechanical engineers.
- Seismologists.
- Structural engineers.

The geologist, engineering geologist, and seismologist interact and prepare the initial geotechnical report. They examine the regional and local geology, the tectonic framework, and the local subsurface geology. From their field observations and computer modeling they estimate the recurrence intervals and magnitudes for the various faults that could affect the facility to be designed. This information is used to postulate the expected ground motion at the site through computer models of ground interactions as the earthquake waves travel from the hypocenter to the site. The geotechnical report usually presents this information in the response spectrum or time history format.

The architect, civil engineer, structural engineer, and mechanical engineer have the task of transforming the ground response motion into the floor response motion. The earthquake waves undergo transform functions as they pass from soil to structure and on through the structure from level to level. These transform functions are based on the foundation characteristics, building structure characteristics, building geometry, damping, and so on. The derived floor response or equipment location response is also most often presented in the response spectrum format. The anticipated floor response for both the CEE and SEE is the environment for which the facility equipment must be designed.

Whether the design team applies the CEE or SEE depends on whether the equipment involved is considered to be critical or not. The CEE (higher level) is intended for use on equipment that must operate during and after an earthquake or where it is required for life support. The lower level SEE is intended for use on ancillary support equipment that is required only for day-to-day operation of the facility.

SEISMIC QUALIFICATION METHODS

The five basic methods by which a piece of equipment may be seismically qualified are

- Seismic test.
- Mathematical analysis.
- Past experience.
- Design team judgment.
- Combined qualification approaches.

The following discussion describes in detail each of these methods.

Seismic Testing

Dynamic seismic testing should be considered as the primary avenue to qualification when the equipment will be required to remain operational before, during, and after the earthquake (seismic category "A" as discussed in the next section) or if it is too complicated for an adequate mathematical analysis. Figure 3.4 is a photograph of a value subjected to a biaxial earthquake test on one of Wyle Laboratories' seismic test machines at its Norco, California facility.

The objective of seismic testing is to provide the dynamic earthquake motions in the laboratory situation that simulate the predicted building floor motion as defined by the response spectrum supplied in the design requirements. This spectrum is called the required response spectrum (RRS). The seismic test table response spectrum is termed the test response spectrum (TRS) and must envelop the RRS to be considered a valid test. The two principal types of seismic testing are proof testing and fragility testing. Proof testing is designed for equipment that meets one of the following conditions:

- The equipment is to be tested to a specific requirement for a specific application.
- The equipment is likely to require retesting for each application.

Fragility testing determines the maximum capability of the equipment for both single and multiple frequency waveforms in a manner that can be used to show compliance with future requirements. Fragility tests are conducted until the equipment fails through one mechanism or another. Malfunction (operational failure) criteria are easy to confirm by fragility test methods. Structural failures may be slightly more difficult to monitor and require a test procedure specifically designed for each individual piece of equipment. Fragility testing is an approach that equipment manufacturers may wish to

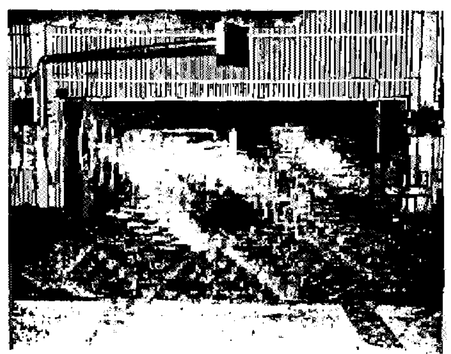


FIGURE 3.4. Staged time lapse of a valve undergoing a biaxial seismic test. Photo courtesy of Wyle Laboratories Scientific Services and Systems Group, Robert "Gene" Marshall, photographer.

take in order to supply equipment to more than one facility in an earthquake prone area.

When the design team specifies dynamic testing, they are required to provide the testing laboratory with a test specification, which should include the following information and requirements.[3]

- Description of in-service mounting conditions. The seismic test shall simulate these conditions.
- Description of equipment orientation.
- Axial test requirements (single axis or biaxial). Incoherent phasing between axes shall be ensured by employing separate driving signals for each axis.
- Required response spectrum (RRS).
- The test response spectrum (TRS) will envelop the RRS.
- The test laboratory shall be consulted for applicable waveforms.
- Data obtained from all the specimen response accelerometers as well as from the table response accelerometers shall first be recorded on analog tape, thus allowing the subsequent analysis and plotting of any required accelerometer record. In this case, all the table response data shall be analyzed and plotted.
- Required duration of strong motion for the earthquake simulation.
- A resonance search shall be conducted by a low level uniaxial sine sweep frequency test in each major equipment axis from 0.5 to 30 hertz. A sweep rate of 1 octave/minute shall be employed. All data shall be recorded on an oscillograph recorder.
- Accelerometers shall be mounted on both the test table and the test specimen.
- Description of the parameters that are to be examined (i.e., failure criteria, etc.).
- Specimen operational characteristics shall be monitored and recorded before, during, and after the dynamic testing program.
- Results of the dynamic testing program shall be prepared in a written report format. The report shall be certified by a registered professional engineer and include, but not be limited to, the following information.
  - Test levels.
  - Details of deviations.
  - Anomalies.
  - Repairs.

[3] The author wishes to express his gratitude for the assistance provided by Wyle Laboratories in the development of the following.

  - Photographs of test setups and failures.
  - Test log.
  - Equipment listing.

Many problems with equipment have been encountered in past earthquakes. The last section of this chapter, beginning with Figure 3.146, contains photographs of examples of past failures. Dynamic seismic testing can reduce the failure potential by alerting the product designers of equipment weaknesses prior to installation. Several points have been excerpted below from an unpublished work by C. W. Roberts of Wyle Laboratories entitled "*Environmental Simulation—A Powerful Tool for the Product Designer*." The paper further emphasizes the case for dynamic testing to demonstrate operability of equipment and its value as a viable method for product design.

- Designers often soft mount equipment on vibration isolators to protect it against plant induced vibrations (or vice versa) without consideration for (motion restraint). Unfortunately, those isolators capable of performing the best job against the relative high frequency plant induced vibration will often amplify the effect of low frequency earthquakes. Dynamic seismic testing can check these mounting systems as well as the equipment response to assess survivability.
- Plug-in devices (such as connectors and printed circuit boards) vibrate loose. These items should be designed with some type of positive latch. Dynamic seismic testing can alert the product designer to potential problems before they occur.
- Easy-access type design features, such as roll out racks, magnetic door latches, etc., will open or unlatch during an earthquake and should be replaced with positive latching features.
- Devices which are obviously sensitive to the dynamic environment such as mercury wetted switches, lightly sprung relays, etc., should not be used in earthquake applications. If they are used, they should be mounted in a manner so as to minimize the amplification of earthquake effects (i.e., at the bottom of the cabinet). Dynamic seismic testing can alert the product designer to potential problems.
- Many users will have seismic design specifications that require cabinets to be designed with no resonant frequencies below 33 hertz. Determining resonant frequencies analytically, even for relatively simple cabinets is a costly task. It is costly both economically and in time and effort expended. In the laboratory, a prototype cabinet with masses installed to simulate equipment, can be instrumented and subjected to a low-amplitude sine-sweep excitation. Resonant frequencies are very easily and accurately detected. Design changes to eliminate undesirable resonances or damping characteristics such as stiffeners, additions of foam rubber strips to door

frames, etc., can be more readily conceived in the "three dimensional" environment of prototype hardware and the "real world" atmosphere of simulated dynamic conditions.

- The typical cabinet structure is not designed with earthquake loads in mind. Panel faces are commonly attached with either self-tapping screws (which back out) or tack welds (which break). Cabinet anchoring provisions are commonly inadequate. Cabinets should be constructed using through bolts and locknuts or at least 25 percent welds.
- Many equipment cabinet designers will locate heavy equipment at the top of the cabinet for functional purposes. An example is shown in Figure 2.10. This "top heavy" arrangement has been observed to produce large dynamic moments, excessive deflections and high stresses during earthquake simulations.

As useful as seismic testing is, it should not be employed for all qualification projects. Seismic testing will prove to be a valuable research tool for examinations of equipment. In practice, however, it should be used where the results of the test provide the best information for the money expended on qualification.

Recent draft legislation in a state with a recognized seismic probability would have had manufacturers testing virtually all the equipment that they would be selling to certain essential facilities for base anchorage. This is an inappropriate use of testing and would have been analogous to using a bulldozer for planting a rose bush. Where base anchorage is the only concern, the qualification program can be best completed by mathematical analysis, which is discussed below.

Mathematical Analysis

A mathematical analysis may be applicable to all the seismic categories from "A" to "E," which are discussed in the next section, depending on the nature of the equipment and its intended use. Analysis is the preferred method of seismic qualification when the following criteria can be met:

- The equipment is required only to operate after an earthquake (i.e., the only concern during the earthquake is its structural integrity).
- The equipment can be mathematically modeled.

Examples of required mathematical analyses are shown in Table 3.1 for representative equipment conditions. Mathematical analyses are often not recommended for complex equipment. Several decisions must be made when equipment is considered for analysis. Is a simple static analysis to be used or a dynamic analysis? The simple static analysis is appropriate where equipment only need be adequately anchored. More complex installations of equipment require the construction of a dynamic math model for further

TABLE 3.1. Mathematical Analysis Required

If the Equipment is:	Analyze for:	By Using:
Rigid with high center of gravity	Overturning	Simple overturning and pull-out conditions of anchorage system
Rigid with low center of gravity	Shear failure of anchors	Static coefficient method for shear of anchorage system
Flexible equipment (simple)	Natural frequency, velocity, displacement and acceleration, and base anchorage	Simple dynamic math model response spectrum and base shear method or static coefficient method
Flexible equipment (complex)	Natural frequency, velocity, acceleration, and base shear	Complex dynamic math model, response spectrum, computer solution, base shear

consideration. Using the dynamic model, one can calculate the resonant frequencies. If the equipment in question is rigid, the response equals the zero period acceleration of the response spectrum. If the equipment is flexible, it is necessary to compute the dynamic response of the equipment. Rigid equipment can generally be defined as equipment with a natural frequency in the high frequency range (say more than 20 hertz). This is termed the "zero period acceleration" and is the maximum acceleration contained in a response spectrum. Flexible equipment is equipment with a fundamental frequency in the low frequency range (say less than 20 hertz). Computing the dynamic response for both rigid and flexible equipment can be conducted by means of a modal analysis. An example of such an analysis was made in conjunction with Figure 2.11.

An equipment stress analysis is the final step required for the mathematical analysis track. At this point, the designer is in the position of declaring the equipment to be qualified or not qualified. If the equipment meets all the design requirements, the designer should provide adequate documentation. If the equipment does not meet the design requirements, it should be reconsidered.

Past Experience

In many cases equipment can be qualified by past experience. The value of this qualification approach is realized as an economic saving to the facility owner and a time saving to the design team. To be valid, the past experience qualification procedure must be adequately documented and fully approved by the governing agency, the design team, and the facility owner.

Dispersal of the seismic qualification information for future projects could be best performed by a computer network. Computer companies currently have existing systems on line that could be adapted to meet agency requirements for documentation. The computer companies could sell time-sharing to the design teams, who would then be able to assess which equipment had been previously qualified for particular environments. Equipment manufacturers would be prompted to provide the computer data base with their most up-to-date qualified equipment in order to remain competitive. The computer system would be capable of providing the design team with fast, inexpensive information.

This approach is not without precedent. A similar auditing system provided the seismic qualification records for the Alaska Pipeline (Anderson and Nyman, 1977). Although these records were not intended for public dispersal, the computer programs easily could have been adapted for this function. Similar proposals have been suggested for the nuclear power industry.

In setting up such a network, the computer company would work directly with the governing agencies, selected architects and engineers, and representative equipment manufacturers. They would all need to collaborate to establish a usable data base. Some of the information that may be useful to such a program is:

- Manufacturer name.
- Equipment name, model number, and so forth.
- System of which the equipment is a part.
- Seismic qualification status
  - Methods of qualification.
  - Qualified by whom.
  - Design earthquake utilized, and so forth

Further examination of this proposal will indicate the need for more detailed information and how the logistics of such a network might work.

This author believes that with proper exploration and implementation, the past experience alternative can become a viable seismic qualification procedure.

Design Team Judgment

An economic saving can also be realized as a result of the design team's judgment. The design team has the option of qualifying equipment through

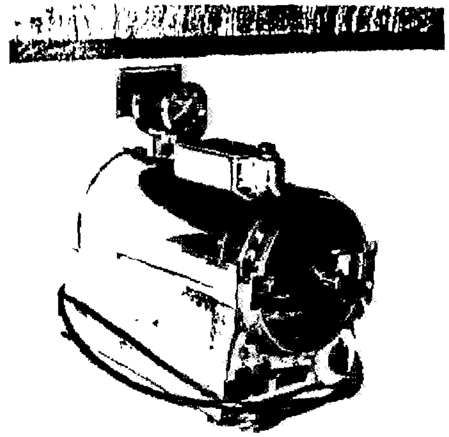


FIGURE 3.5. Tabletop sterilizer requiring design team judgment for seismic qualification.

inspection, adequate architectural detailing, or suggested installation techniques for which the facility owner will be responsible. Figure 3.5 shows an example sterilizer. The design team can make suggestions to the facility owner with respect to installation details for this type of equipment. Modular installation details for this type of equipment are discussed in Chapter 4. Design team judgment is also needed when off-the-shelf commodity items or daily use items, such as electric light switches, telephones, filing cabinets, and vending machines are used. These items can often be qualified by design team judgment and simple installation recommendations to the facility owners. Design team judgment is an excellent method that can be used to review existing facilities that have not received adequate seismic detailing.

Combined Qualification Approach

In some cases it may be advantageous to combine certain portions of the qualification methods discussed earlier. For example, a combined qualification program might be for an emergency power supply system. The normal operating loads on the diesel engine itself are generally greater than the seismic environment. Therefore, the engine might be qualified by static analysis for base anchorage, assuming that vibration isolation is not used. The radiator portion of the driving engine is generally a cantilevered structure on the front of the skid and may be dynamically sensitive. This characteristic would justify a dynamic analysis of the radiator to determine its natural frequency, and possible excursions and to determine methods of bracing it.

The power transfer panel often contains dynamically sensitive switching that does not lend itself easily to mathematical modeling, which may justify some kind of seismic testing. After these items have all been qualified, the design team may apply their judgment in installing flexible fuel lines.

The abbreviated example presented here shows how the design team might arrive at the justification for combining the approaches for a completely qualified system or individual piece of equipment. This approach can often save both time and money for the overall qualification requirements established for a building program.

Backfitting Essential Facilities

A quick tour through most existing facilities sadly illustrates a lack of seismic awareness for the building equipment. One is especially disturbed on examining essential facilities.

The A.I.A. Research Corporation postulated in a 1977 study that essential facilities such as metropolitan hospitals, police stations, and fire stations can expect an increase in the request for services on the order of between 300 and 700 percent as a result of a significant earthquake. Most existing essential facilities are not ready for such an event. The newer facilities are getting better as building codes begin to address equipment requirements. Most essential facilities were, however, built prior to the initiation of equipment requirements.

It is not at all uncommon to see emergency lighting loosely sitting atop filing cabinets, vibration isolated emergency power supplies without motion restraints, and piping without lateral bracing. The list of black marks goes on and on. Unfortunately, the chance for the survival of many existing essential facilities does not appear to be very good.

There is only one major code that has pointedly addressed the problem of backfitting. As discussed in Appendix 1, existing elevators in California all require modifications to their seismic resistance. The reader is referred to Appendix 1 for further discussion on the particular pros and cons of the elevator code.

If we truly expect our existing essential facilities to remain operational, campaigns for altering the code requirements must be sought. This backfitting approach is fairly common practice in the nuclear power industry and should be employed at least for critical equipment within essential facilities. As a beginning, the programs could be fairly simple. Architects and engineers versed in seismic qualification can make tours of facilities documenting the deficiencies that are most likely to place a facility out of commission in the event of an earthquake. The price to pay for an operating hospital is rather small when compared with the potential harm that may result from one that is incapable of operating.

Facility administrators may apply many of the diagrammatic installation details of Chapter 4 for effective backfit programs. Facility personnel can, themselves in many cases, spot deficiencies and correct the situation relatively easily and inexpensively. Such a program might include installation of shelf parapets on casework to restrain shelved items and to anchor filing cabinets to prevent their toppling. While an architect or engineer may be useful in pointing out and prescribing intricate details, the normal operating staff can provide quite a number of minor changes that will significantly increase the facility's potential for operability.

SEISMIC DESIGN CATEGORIES

Seismic design categories allow the design team to rationally specify seismic design procedures for various types of equipment. We learn in subsequent sections how to apply the seismic category concept so that essential facilities will remain operational during and after a major earthquake. Simply writing a general code provision such as the UBC 1979 does not give us the necessary assurance that the facilities *will* remain operational. To attain the needed assurance, a seismic plan must be developed. The plan should be consistent so that all members of the design team will be conversing with the same vocabulary. This section outlines a basic method by which the design team in conjunction with the owner can identify and seismically categorize the nonstructural elements in an essential facility.

First, the architect, together with the other members of the design team, and the facility owners review all the facility functions from a systems point of view. This involves defining which functions are critical to the facility operation, which are only required for smoothness of operation, and which fall into the miscellaneous category. The functional review leads to the identification of the various operational systems, which are comprised of the individual equipment items. The following is an example list of the types of systems under consideration.

- Air handling.
- Ceiling (lighting, acoustics, etc.).
- Communication.
- Data processing.
- Emergency power supply.
- Fire protection.
- Heating supply.
- Kitchen.
- Medical.
- Office.

- Piping
- Records retrieval.
- Security monitoring.
- Sewage disposal
- Various life support.
- Vertical circulation (elevators)
- Water supply.

This list of systems is incomplete and continues on for many different types of facilities. Each of the systems listed above is composed of individual elements. Emergency power supply systems (unless D.C powered), for instance, generally have a driving engine, a generator, vibration isolation (always in conjunction with motion restraints), a starter mechanism, battery charging unit exhaust provisions, distribution network, marked convenience outlets, fuel supply, and fuel storage capabilities. Some organized method is required to assess the relative importance of the various systems and items necessary for the overall operation of the essential facility. To meet this requirement, the seismic categories given in Table 3 2 are proposed. To identify the system and equipment, a dual letter designation is suggested. Therefore, from Table 3 2 we know that the previous example of the emergency power supply system can be placed in seismic category "A." The battery charger that is a component of that system, however, would be best classed in seismic category "C." Putting the two designations together in the dual letter format yields a seismic category for both the system and the equipment of "A-C," as shown in Figure 3.6 The letter on the left designates the seismic category of the overall system, while the letter on the right designates the seismic category of the individual piece of equipment. Figure 3.7 diagrammatically shows the decision process required for the use of the seismic category method

TABLE 3.2. Seismic Category Definitions

Seismic Category	Definition
Critical equipment "A"	Systems or equipment that are required for the operation of the essential facility, life support, or where failure will directly and adversely affect the function of other critical systems or equipment
Support equipment "B	Systems or equipment required for support functions, the facility can operate on a limited basis if a failure occurs
Support equipment "C"	Systems or equipment required for prolonged operation of the facility on a day-to-day basis
Support equipment "D"	All portable systems or equipment not in seismic category "A"
Miscellaneous equipment "E"	Convenience or miscellaneous systems or equipment

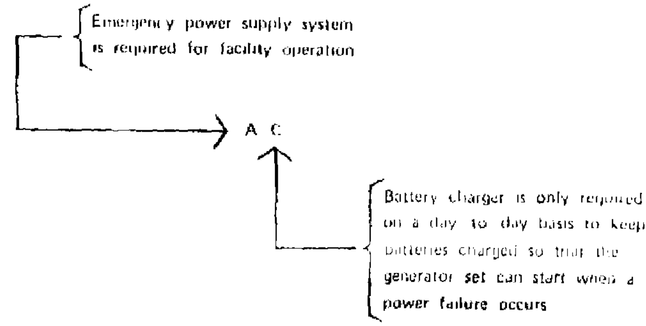


FIGURE 3.6. System and equipment seismic category identification

Once the equipment and its operational system have been seismically categorized, the design team is ready to apply their resources to qualify the equipment The seismic qualification approach depends on several factors

- System category
- Equipment category.
- Essential functions that equipment must perform.
- Expected earthquake intensity.
- Expected level of shaking at equipment or subcomponent location.
- Inherent design of equipment.
- Life expectancy of the facility.
- Mounting characteristics of equipment.
- Past experience of equipment.
- Proximity of equipment to other equipment items.

When these items are taken into account, the design team can rationally define the seismic category for both the system and the individual piece of equipment.

The systems and equipment section of this chapter suggests seismic categories for approximately 150 systems and equipment items. The list may seem long, but in reality is rather short The seismic category provides for a common ground for the qualification of many different types of equipment.

The seismic categories are then used for establishing a basis for a logical seismic qualification approach and are applied to the seismic design specifications discussed in the next section.

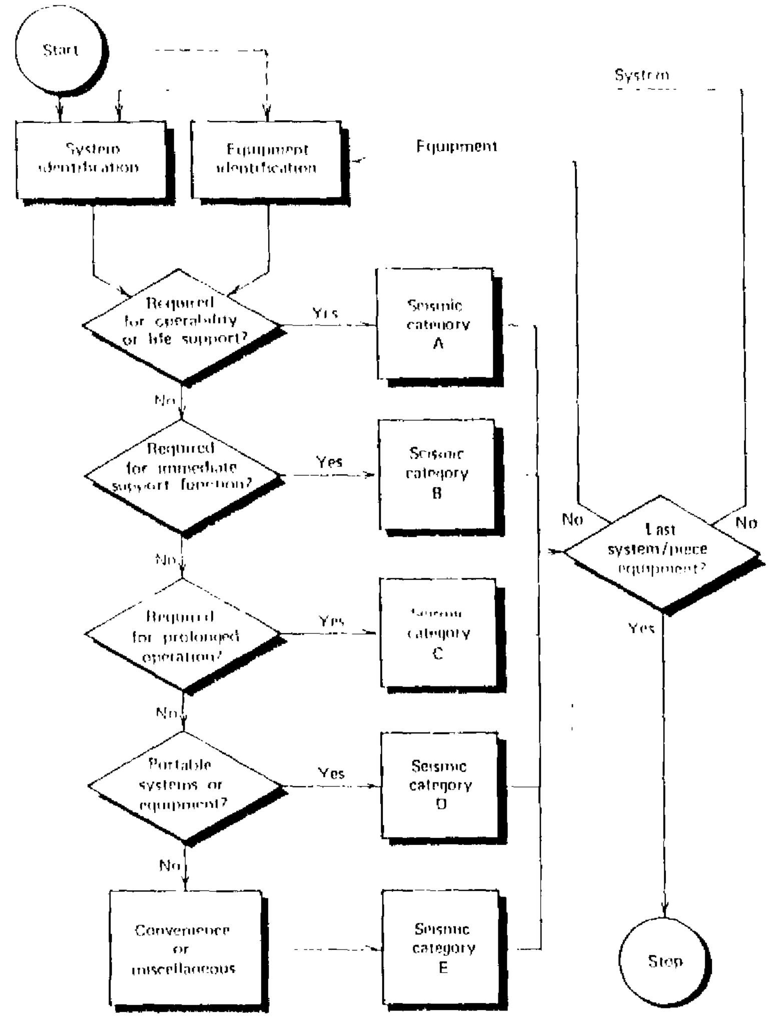


FIGURE 3.7. Seismic category decision process

SEISMIC DESIGN SPECIFICATION MODELS

Once the design team has successfully determined the seismic categories for the facility operational systems and the individual equipment items that comprise its systems, they need a specific design approach to qualify or plan the facility. In this section, two seismic design specifications are proposed

for use by design teams Seismic Design Specification-1 (SDS-1) and Seismic Design Specification-2 (SDS-2). SDS-1 applies to systems and equipment that can be included in seismic category "A" or "B," while SDS-2 applies to systems and equipment that can be included in seismic category "C," "D," or "E."

Floor response spectra, equipment location response spectra and static design coefficients must be supplied to the individual or organization performing the seismic qualification by the design team. This applies to both SDS-1 and SDS-2. The type of information required depends mostly on whether the qualification required will be performed at the system level, equipment level, or subcomponent level. The author wishes to express his gratitude to Wyle Laboratories for their assistance in the development of these model specifications.

Seismic Design Specification-1 (SDS-1)

SDS-1 provides the seismic design criteria for equipment included in seismic categories "A" and "B." For consistency within this specification, the following terms are defined:

- **Design Acceleration (*A*)** The equipment acceleration value expressed in units of gravity
- **Design Spectrum** The curves of maximum responses of equipment subjected to a specific earthquake (critical equipment and support equipment). The response spectrum format is generally expressed as acceleration, velocity, or displacement versus frequency (1/period) for a designated equipment damping.
- **Design Team** Architects/engineers responsible for the essential facility design.
- **Equipment Weight (*W*)** The total equipment weight including contents such as oil and water.
- **Critical Equipment Earthquake** The maximum ground motion possible at the site from any earthquake. Consideration must be given for expected effects felt at the site due to the distance from the hypocenter, local geology, soil conditions, and so forth.
- **Support Equipment Earthquake** The maximum ground motion likely to occur within the life expectancy of the facility.
- **Owner** Individual, organization, company, or government agency responsible for managing the facility.
- **Seismic Category**

  A Systems or equipment required for the operation of the facility and life support, or whose failure could directly and adversely affect the function of other required systems or equipment.

B Systems or equipment that are required for support functions. The facility can operate on a limited basis if a failure occurs.

- **Seismic Force (*F*)** Static force coefficient that represents the equivalent seismic inertial force.
- **Seismic Load** The inertial force applied to equipment at its location as a result of an earthquake and the building/component interface.
- **Seismic Qualification** Demonstrated means by which the equipment can be shown to resist the expected seismic loads in a manner that satisfies the design objectives.

Depending on the seismic category and the nature of the equipment, seismic qualification can be demonstrated by the following means.

- Shake table tests.
- Mathematical analysis
  - Dynamic
  - Equivalent static coefficient
- Past experience.
- Design team judgment
- Any combination of the above.

The critical equipment earthquake design response spectrum will be used where seismic qualification is required of equipment that must remain operational because of its importance to the functioning of the facility after an earthquake or where it involves life support functions. Seismic qualification of other equipment in seismic category "A" and "B" will use the support equipment earthquake design response spectrum. The design team supplies those performing the seismic qualification (the manufacturer, owner, private consultant, or the design team itself) with the following requirements and information.

- Applicable critical equipment earthquake, required response spectra (with damping).
- Applicable support equipment earthquake, required response spectra (with damping).
- Applicable floor design accelerations.
- Applicable equivalent static coefficients
- Identification of which critical damping factors are to be used with respect to the design spectra.

The organization or individual bidding on the seismic qualification shall supply the design team with the following information prior to commencing the seismic qualification program:

- Price quotation for the proposed method of qualification.
- Detailed qualification plan.
  - If by analysis: method of analysis, design criteria for analysis, and professional credentials of those conducting the analysis.
  - If by test: detailed test plan, mounting of specimen, operational loads of specimen, proposed instrumentation of specimen, test machine capabilities, choice of waveform(s).
  - If by past experience: detailed characteristics of the experience (test or analysis report).
  - If by design team judgment: detailed explanation of rationale behind the decision.

The design team and owners shall review and approve all proposals submitted prior to the actual seismic qualification program. The owner shall notify the successful bidder when the seismic qualification program is to begin for each equipment item. The individual or organization performing the seismic qualification shall notify the owner prior to any seismic test programs so that the design team or owner may witness the test at their option.

The seismic qualification program is to be carried out as mutually agreed upon by the bidder (his proposal plus required revisions where applicable), the design team, and the owner. A seismic qualification procedure flow loop is shown in Figure 3.8. The qualification report shall include proof of the following:

- Seismic test (where applicable)
  - Mounting to simulate actual in-service installation.
  - Test in two perpendicular horizontal axes and vertical axis. The test may be conducted in each direction independently. The design spectra must be multiplied by 1.5 to compensate for the single axis test. If the test is conducted in two axes simultaneously, the design spectra must be multiplied by 1.2 for life support equipment or any equipment required for the continued operation of life support equipment, and two support equipment earthquake (SEE) complete tests must be conducted prior to conducting the critical equipment earthquake (CEE). The lower level SEE is more likely to occur over the lifetime of the facility and their cumulative effects should be examined to ensure operability after the higher level CEE.

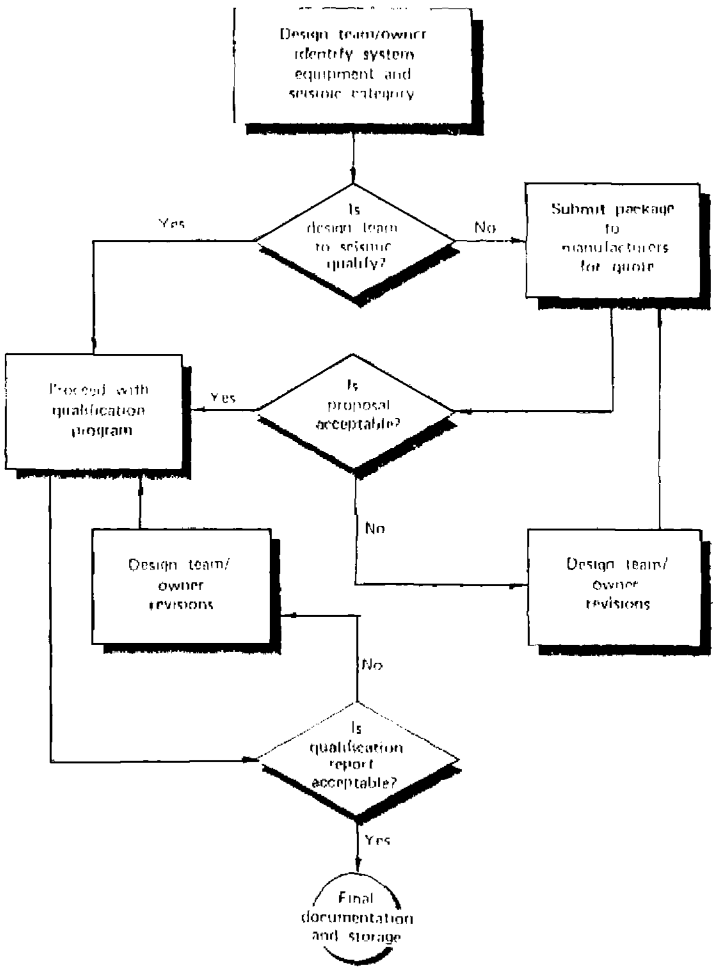


FIGURE 3.8. Seismic qualification procedure flow loop

Waveforms

1. Resonant frequency search (sine sweep test) at not greater than 2 octaves/minute from 0.1 to 33 hertz in all three major axes. This test is to be a low-amplitude test and should be conducted in all test programs.
2. Earthquake tests shall employ waveforms that are appropriate to the specific test. Seismic tests may employ any of the following: time histories, random motions, random motion with superimposed sine beats, or complex waveform tests. In any case, the required response spectrum must be enveloped by the test response spectrum for the test to be considered valid.

- Criteria for testing.
- Test machine calibration
- Installation details.
- Continuous monitoring of equipment before, during, and after seismic test to assure operation of equipment.
- Performance anomalies observed.
- Equipment that has been earthquake tested is acceptable for installation provided that the test does not result in nonrepairable failure.

● Mathematical analysis (where applicable).
  - Seismic forces are imposed in two horizontal axes and the vertical axis.
  - Installation details must be provided.
  - Static ($F = AW$) or dynamic analyses may be performed.
  - Operational loads must be combined with seismic loads.
  - Total seismic response from three axis analysis may be taken as square root sum of the squares of each individual response to each direction.
  - Maximum deflection of the equipment must be reported.

All equipment is to be designed and installed to resist overturning, sliding, and content spillage Friction due to elastomeric feet and so forth will be ignored in all seismic calculations and tests. The results of the seismic qualification required by SDS-1 must be documented in a step-by-step form suitable for audit.

Seismic Design Specification-2 (SDS-2)

SDS-2 provides the seismic design criteria for equipment included in seismic categories "C," "D," and "E." The seismic categories are defined below:

C. Systems or equipment required for prolonged operation of the facility on a day-to-day basis

D. All portable systems or equipment not in seismic category "A"

E. Convenience or miscellaneous systems or equipment.

The principal requirement of SDS-2 is that the equipment remain anchored during and after an earthquake. Anchorage of the equipment and subcomponents, which include items such as base plates, equipment enclosures, cabinets, legs, supporting structures, connections, rolling stock, and cantilevered supports, will be designed to resist sliding, rolling, and content spillage and/or overturning. There will not be an allowance made for friction at the base of equipment supports because of the use of elastomeric feet to resist sliding.

The equipment shall be analyzed in two mutually perpendicular horizontal directions and the vertical direction. A static coefficient analysis ($F = AW$) is the recommended approach. The design acceleration coefficient "A" is to be provided by the design team. The total seismic response from the three axis analysis may be taken as the square root sum of the squares of the individual responses to each direction.

A proposal is not required of the bidder for SDS-2. The bidder, however, must submit a seismic qualification price quotation to the design team prior to execution of the analysis. The design team and owner will review, approve, and notify the successful bidder when to perform the analysis.

Several other methods are available by which the equipment can be qualified when the SDS-2 recommended approach is not applicable:

- Seismic testing.
- Dynamic mathematical analysis.
- Past experience.
- Design team judgment.
- Any combination of the above.

Those performing the qualification must coordinate any approach other than that recommended with the design team.

SYSTEMS AND EQUIPMENT QUALIFICATION

This section discusses the systems and equipment with which this book is concerned. The major systems are divided alphabetically and are listed below.

- Access floor systems.
- Air handling systems.
- Communication systems.
- Data processing systems.
- Elevator systems.
- Emergency power supply systems.
- Fire protection systems.

- Kitchen systems.
- Lighting systems.
- Medical systems.
- Piping systems.
- Suspended ceiling systems.
- Water systems.
- Miscellaneous equipment.

The discussion of each system contains a short general statement and a suggestion for the overall system seismic category. Examples of the types of facilities most likely to contain major components of the system in question are also listed.

Individual examples of equipment within each system are included in alphabetical order. A general statement describes important aspects of the equipment item, and photographic examples are given for most pieces of equipment. Suggestions for the equipment seismic category, the appropriate seismic specification and seismic qualification approaches are given for each equipment item. It should be noted that these suggestions should be examined in detail by the design team for each application to ensure adequate seismic qualification. Reference is also made in most cases to Chapter 4 for diagrammatic examples of installation details. In some cases, reference is made to "similar generic" details where specific details are not supplied.

Subjective scenarios are given for the degree of damage possible and the type or consequence of damage for inadequately protected equipment. The relationships given here are in part based on observations of past performance of specific pieces of equipment in earthquakes and in part on extrapolations from the performance of similar pieces of equipment. None of the scenarios is directed toward individual manufacturers nor their equipment.

For some equipment items reference is made to photographic examples of damaged equipment that can be found in the final pages of Chapter 3. The author wishes to apologize for the quality of some of the photographs, as the originals were either unavailable or untraceable, which necessitated copies being made directly from previous publications.

This section of Chapter 3 and all of Chapter 4 are designed to be used in handbook fashion by design professionals, governing agencies, facility owners, manufacturers, and students. First the applicable system is identified and then the individual equipment within that system is located. The design team then notes the suggestions for the qualification approach listed for the equipment. Reference is easily made by figure number to Chapter 4 for the suggested diagrammatic installation details. This handbook approach should lead to new and existing (backfitted) facilities that are much more likely to remain operational after earthquakes.

Access Floor Systems

Access or raised floor systems generally imply lift-out floor modules. Freestanding, as well as earthquake resistant, interlocking systems are available and are commonly used where data processing or communications equipment is required. If the access floor system should fail during an earthquake, the equipment that it supports is also more than likely to fail.

SYSTEM SEISMIC CATEGORY

- "A" critical system.

SYSTEM FOUND IN

- Business establishments.
- Communication centers.
- Computing/data processing centers.
- Emergency operating centers.
- Fire stations.
- Government administration buildings.
- Hospitals
- Police stations

Access Floor Systems

Floor Panels

Access floor panels support heavy, expensive pieces of equipment and must remain in place so that the supported equipment will not be damaged.

EQUIPMENT SEISMIC CATEGORY

- "A" critical equipment

SEISMIC SPECIFICATION

- SDS-1.

SEISMIC QUALIFICATION APPROACH

- Equivalent static coefficient analysis.
- Design team judgment.
  - Select a floor manufacturer that has built-in earthquake protection measures.

REFERENCE FIGURES FOR INSTALLATION DETAILS

- 4.1, 4.2.

RELATIVE DEGREE OF DAMAGE OF INADEQUATELY PROTECTED EQUIPMENT

- Moderate to major.

MOST LIKELY TYPE OR CONSEQUENCE OF DAMAGE FOR INADEQUATELY PROTECTED EQUIPMENT

- Dislodged panels.
- Dislodged equipment due to shifting floor
- Floor collapse.
- Inoperable equipment supported by floor
- General cleanup required.

Access Floor Systems

Stanchions

Floor stanchions (Figure 3.9) are the support columns for the access floor system. For the best performance, the stanchions should be anchored to the subfloor, braced between each other, and anchored to the floor panels.

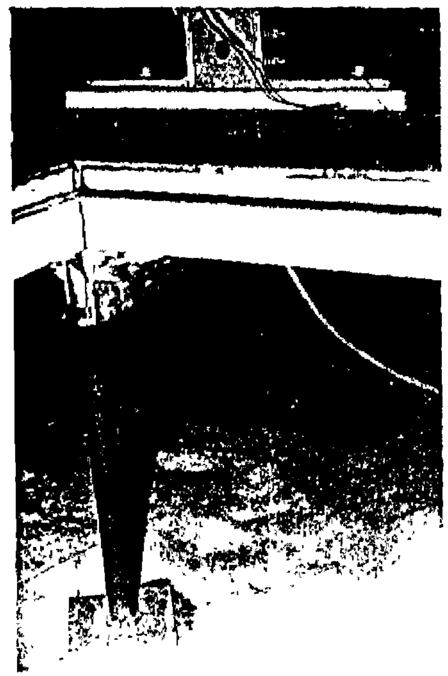


FIGURE 3.9. Access floor stanchion that is anchored neither to the subfloor nor to the access floor frame.

EQUIPMENT SEISMIC CATEGORY

- "A" critical equipment

SEISMIC SPECIFICATION

- SDS-1

SEISMIC QUALIFICATION APPROACH

- Equivalent static coefficient analysis
- Design team judgment
  - Select a floor manufacturer that has built-in earthquake protection measures

REFERENCE FIGURES FOR INSTALLATION DETAILS

- 4.1, 4.2

RELATIVE DEGREE OF DAMAGE OF INADEQUATELY PROTECTED EQUIPMENT

- Minor to moderate

MOST LIKELY TYPE OR CONSEQUENCE OF DAMAGE FOR INADEQUATELY PROTECTED EQUIPMENT

- Shifting of floor.
- Collapse of floor.
- *Inoperable equipment supported by floor.*
- General cleanup required.

Air Handling Systems

Air handling equipment is found in most building types. Most facilities can operate on a limited basis if failures should occur.

SYSTEM SEISMIC CATEGORY

- "B" support system

SYSTEM FOUND IN

- All facilities

Air Handling Systems

Air Grilles, Registers, and Diffusers

These items (Figure 3.10) are not required for the successful operation of the system, but do present a danger to personnel if they fall.

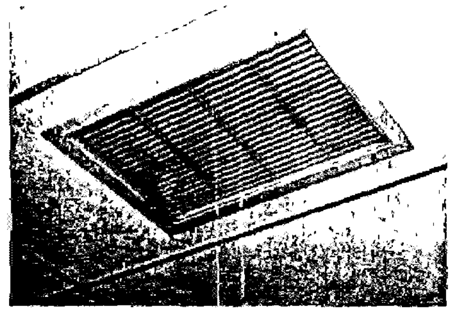


FIGURE 3.10. Air grille that does not have a safety wire suspending it from the structure above. Photo courtesy Ruhnau Evans Ruhnau Associates.

EQUIPMENT SEISMIC CATEGORY

- "E" miscellaneous equipment.

SEISMIC SPECIFICATION

- SDS-2.

SEISMIC QUALIFICATION APPROACH

- Design team judgment
  - Screw and nut installation recommended; sheet metal screws and friction fits common fail.
  - Retaining safety wire.

RELATIVE DEGREE OF DAMAGE OF INADEQUATELY PROTECTED EQUIPMENT

- Minor

MOST LIKELY TYPE OR CONSEQUENCE OF DAMAGE FOR INADEQUATELY PROTECTED EQUIPMENT

- Fallen registers.
- Potential for personnel injury.
- General cleanup.

REFERENCE FIGURES FOR EXAMPLE OF DAMAGED EQUIPMENT

- 3.148, 3.152, 3.153.

Air Handling Systems

Chillers and Heaters

Chillers (Figure 3.11) and heaters are generally complicated equipment items that must be at least anchored to prevent fluid leaks. Flexible inlet and outlet connections improve their survivability.

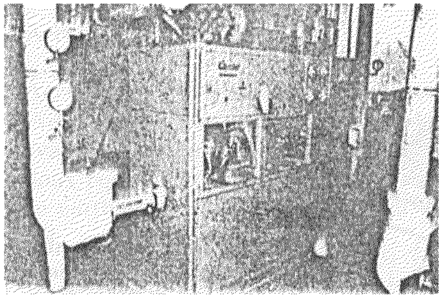


FIGURE 3.11. Physical plant air conditioning unit with flexible connections. The air conditioning unit as well as its subcomponents should be considered.

EQUIPMENT SEISMIC CATEGORY

- "B" support equipment.

SEISMIC SPECIFICATION

- SDS-1.

SEISMIC QUALIFICATION APPROACH

- Equivalent static coefficient analysis.
  - Base anchorage.
- Dynamic analysis.
  - Manufacturer generic qualification.

REFERENCE FIGURES FOR INSTALLATION DETAILS

- 4.5, 4.6.

RELATIVE DEGREE OF DAMAGE OF INADEQUATELY PROTECTED EQUIPMENT

- Moderate to major.

MOST LIKELY TYPE OR CONSEQUENCE OF DAMAGE FOR INADEQUATELY PROTECTED EQUIPMENT

- Shifted equipment.
- Toppled equipment.
- Broken supply lines.
- Inoperative equipment.
- Flooding potential with some equipment.

REFERENCE FIGURE FOR EXAMPLE OF DAMAGED EQUIPMENT

- 3.151.

Air Handling Systems

Duct Work

Duct work (Figure 3.12) needs lateral bracing and flexible joints at junctions. Bracing should not bend or wrap around other equipment.

EQUIPMENT SEISMIC CATEGORY

- "C" support equipment.

SEISMIC SPECIFICATION

- SDS-2.

SEISMIC QUALIFICATION APPROACH

- Design team judgment.
  - Flexible connections at rigid building interfaces.
- Equivalent static coefficient analysis.
  - Support and lateral bracing.

REFERENCE FIGURES FOR INSTALLATION DETAILS

- 4.3, 4.4, 4.96 and Appendix 3.

RELATIVE DEGREE OF DAMAGE OF INADEQUATELY PROTECTED EQUIPMENT

- Moderate.

MOST LIKELY TYPE OR CONSEQUENCE OF DAMAGE FOR INADEQUATELY PROTECTED EQUIPMENT

- Duct work collapse.
- Ruptured duct work if flexible connections are not provided at rigid building interfaces.

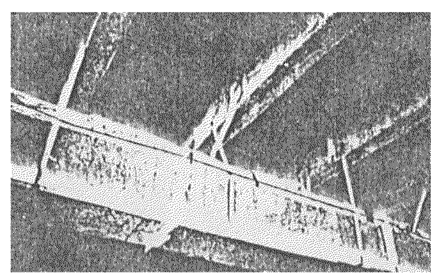


FIGURE 3.12. Ductwork showing transverse bracing.

- Inoperative portions of air system
- General cleanup required

REFERENCE FIGURES FOR EXAMPLE OF DAMAGED EQUIPMENT

- 3.149, 3.150

Air Handling Systems

Fan Units, Floor Mounted

Air handling fan units (Figure 3.13) range from small to very large. If vibration isolators are employed, motion restraints are required. Consideration should also be given to line connections.

EQUIPMENT SEISMIC CATEGORY

- "B" support equipment

SEISMIC SPECIFICATION

- SDS-1.

SEISMIC QUALIFICATION APPROACH

- Equivalent static coefficient analysis
  - Base anchorage
- Dynamic analysis.
  - Employ motion restraints if vibration isolation is used

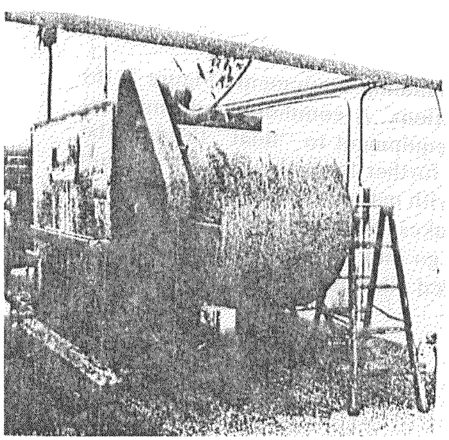


FIGURE 3.13. Roof mounted fan unit showing fixed mounting and flexible service line connections.

REFERENCE FIGURES FOR INSTALLATION DETAILS

- 4.5, 4.78, 4.79, 4.80, 4.81, 4.82, 4.83, 4.84, 4.85, 4.86.

RELATIVE DEGREE OF DAMAGE OF INADEQUATELY PROTECTED EQUIPMENT

- Minor to moderate.

MOST LIKELY TYPE OR CONSEQUENCE OF DAMAGE FOR INADEQUATELY PROTECTED EQUIPMENT

- Shifting or overturning of the fan unit.
- Resonance of equipment if vibration isolators are used without motion restraints (may result in major damage).
- Possibly inoperative fan units.
- Cleanup required.

REFERENCE FIGURES FOR EXAMPLE OF DAMAGED EQUIPMENT

- 3.151, 3.174, 3.177.

Air Handling Systems

Fan Units, Suspended

Suspended fans (Figure 3.14) obviously present special problems should they fall. The fan unit should be anchored to a structural wall wherever possible.

EQUIPMENT SEISMIC CATEGORY

- "B" support equipment.

SEISMIC SPECIFICATION

- SDS-1

SEISMIC QUALIFICATION APPROACH

- Equivalent static coefficient analysis
  - If rigidly mounted (natural frequency generally above 30 hertz).
  - Lateral bracing
- Dynamic analysis
  - If flexibly mounted.
  - Motion restraints are required if vibration isolation is employed

REFERENCE FIGURES FOR INSTALLATION DETAILS

- 4.6, 4.78, 4.79, 4.80, 4.81, 4.82, 4.83, 4.84, 4.85.