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Aseismic Design of Building Service Systems: The State-of-the-Art

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A search for information was conducted to define the state-of-the-art of aseismic design of building service systems and to identify areas of needed research. The study focused primarily on service systems essential to the continuous operation of hospital facilities in post-earthquake periods. A review of the literature pertaining to seismic performance of nonstructural systems is presented. An evaluation of code and standard regulations applicable to the aseismic design of service system components is also presented. Information obtained from direct contact with several federal agencies, the State of California, and practicing architects and engineers is summarized. The findings from a field visit of two hospitals currently under construction in earthquake-prone areas are reported. Deficiencies in current design/evaluation practice are identified and recommendations for research are presented.

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ASEISMIC DESIGN OF BUILDING SERVICE SYSTEMS: THE-STATE-OF-THE-ART

C.W.C. Yancey and A.A. Camacho

A search for information was conducted to define the state-of-the-art of aseismic design of building service systems and to identify areas of needed research. The study focused primarily on service systems essential to the continuous operation of hospital facilities in post-earthquake periods. A review of the literature pertaining to seismic performance of nonstructural systems is presented. An evaluation of code and standard regulations applicable to the aseismic design of service system components is also presented. Information obtained from direct contact with several federal agencies, the State of California, and practicing architects and engineers is summarized. The findings from a field visit of two hospitals currently under construction in earthquake-prone areas are reported. Deficiencies in current design/evaluation practice are identified and recommendations for research are presented.

Key Words: Aseismic design; building service systems; codes; earthquake; hospitals; standards.

1. INTRODUCTION

1.1 BACKGROUND

Prior to the occurrence of the San Fernando, California earthquake of February, 1971, there was a prevailing attitude that the economic and life-safety consequences of nonstructural damage to buildings were secondary considerations in earthquake-resistant design. Consequently, the design of a building, regardless of use, was almost exclusively concerned with mitigating damage to the structural system. The general practice was to delegate much of the responsibility for detailing the installation of architectural elements and electrical, plumbing and mechanical equipment to manufacturers and contractors. The lack of code and standard regulations indicated that building regulatory organizations were also not concerned with the seismic performance requirements of nonstructural systems. As a result of underestimating the importance of using rational design principles in detailing nonstructural systems, a pattern of recurring nonstructural damage, accompanied in some cases by loss of lives, has emerged. This pattern was documented in several accounts of building damage caused by the Great Alaska Earthquake of 1964. The impetus for change in attitude, however, was created by the comprehensive study of the consequences of the San Fernando Earthquake of 1971. One revelation was that, while the structural systems of most major buildings were not irreparably damaged, the extent and cost of the nonstructural damage was great. It then became evident to both the public and private sectors that considerable effort was needed to mitigate nonstructural damage in future earthquakes. Thereafter was initiated the transition toward parity in the design process for nonstructural and structural building systems. To date, the major portion of the corrective actions has been in the areas of revision of building codes and adoption of regulatory statutes.

While current codes and standards are generally applicable to all classes of building occupancy, certain classes of occupancy have higher priorities within the context of continuous post-earthquake operation. Although the classification of building occupancy and use is a subjective process, hospitals are always included in the most critical class regardless of the criteria used in identifying the class of "critical-use facilities." Furthermore, hospitals are among the most complex building facilities from the standpoint of building service system requirements. Hospitals encompass most of the problems and requirements encountered in other critical-use facilities. Hence, the aseismic design of service systems in hospitals has been given high priority by organizations such as the Veterans Administration, the State of California, and the Army, Navy and Air Force. These organizations, as well as others, are devoting considerable effort toward advancing the state-of-the-art while addressing some specific problems relating to recurring earthquake damage of nonstructural components. It is through their efforts to develop design criteria that the need for additional field data and information has been identified.

The National Bureau of Standards engaged in a pilot study to define the state-of-the-art in the area of aseismic design of nonstructural building systems. The study concentrated on the service systems contained in the buildings of a hospital facility that are critical for continuous operation (hereafter called essential buildings). However, much of the information reported herein is applicable to building service systems in general.

This pilot study was conducted jointly by the Building Services Section and the Structures Sections in the Center for Building Technology (CBT).

The activity was coordinated with the overall Disaster Mitigation Program being conducted by CBT.

1.2 OBJECTIVES

This study was conducted to: (1) identify the essential building service systems required by hospitals and other life-saving facilities in the process of administering uninterrupted medical services in the immediate post-earthquake period; (2) identify and evaluate the prevailing aseismic design philosophies for components of building service systems; (3) determine which code and standard requirements for building service system components are either non-existent or deficient in their coverage; and (4) identify analytical and experimental research programs which are requisite to the development of aseismic design criteria for building service systems.

1.3 SCOPE

While recognizing that the continuous, post-earthquake, functioning of hospitals requires the aseismic performance of all nonstructural systems, this study concentrated on the components comprising the building service systems. Thus, the authors attempted to define the state-of-the-art in the aseismic design of five essential building service systems: (1) fire protection, (2) environmental control, (3) sanitation and water supply, (4) emergency power and (5) general services. The literature and code requirements were reviewed and evaluated with particular attention given to those service system components usually installed in the essential buildings of a hospital facility. Hence, the performance requirements for equipment located outside the building such as buried fuel storage tanks, utility mains, ground-supported stacks and tanks, etc., were not considered in this study. Also, the design requirements for the structural system and architectural elements such as suspended ceilings, building facades and partitions were not studied in depth. Other nonstructural elements such as furniture and medical equipment and supplies were not considered.

2. APPROACH AND ORGANIZATION OF REPORT

2.1 APPROACH

The study included the following activities: (1) identification of services essential to the continuous operation of hospital facilities, (2) identification of the components that comprise the selected service systems, (3) definition of the damage incurred by various components in past earthquakes, (4) evaluation of current code and standard requirements for earthquake resistance, (5) identification of problem areas and deficiencies in the state-of-the-art and (6) preparation of a list of needed research activities. A discussion of these activities is presented in the following paragraphs.

Identification of Services Essential to the Continuous Operation of Hospital Facilities

Currently there are no widely accepted guidelines for defining the essential services for the operation of hospitals in the post-disaster period. In the State of California, a Hospital Operations Subcommittee (of the state-appointed Building Safety Board) is charged with defining essential services within the context of post-earthquake emergency service. In this pilot study, information made available by the subcommittee and other pertinent literature were used to identify some general aseismic performance requirements for hospitals. Then a list of essential services neccessary to satisfy these requirements was established with the aid of the limited literature on the subject. From the overall list of essential services, five building services were selected for further study.

Identification of the Components that Comprise the Selected Service Systems

NBS identified the constituent components of the five selected building service systems named in the introduction. This part of the study focused primarily on electrical and mechanical equipment and the devices commonly used to attach the equipment to the building frame. A preliminary list of components was prepared and submitted to several practicing engineers for review and comments. Based on their comments, a final list of components was established.

Defining the Damage Incurred by Various Components In Past Earthquakes

Reports of three recent earthquakes [8, 9, and 42][1] were reviewed to identify recurring patterns of damage inflicted on building service systems. Thus, the documents were used to determine both the relative frequency of occurrence and the relative degree of certain types of damage experienced by the electrical and mechanical components.

Evaluation of Current Code and Standard Requirements for Earthquake Resistance

Because current design philosophies on aseismic performance of non-structural building systems are largely implied in existing code and standard provisions, aseismic design requirements in fifteen code and standard type documents were reviewed and evaluated. The evaluations consisted of:

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[1] The numbers in brackets indicate references which are listed in section 7.

(1) determining the type of requirements,
(2) identifying the range of service system components covered by the code,
(3) explaining the basis for some provisions,
(4) determining the similarities and differences in the design/analysis methods recommended and
(5) identifying deficiencies in the code provisions.

Identification of Problem Areas and Deficiencies in the State-Of-The-Art

Presently, the state of California and several federal agencies are sponsoring research and planning activities which are intended to mitigate the nonstructural damage of critical facilities during and after earthquakes. Many of the studies that are needed to support the decision-and policy-making processes are being conducted by California-based Architectural and Engineering firms. To gain insight into problems pertaining to the design and installation of building service system components, NBS established liaison with representatives of sponsoring government agencies and with principals in several of the firms performing the studies.

Initially, NBS contacted the Veterans Administration, the U.S. Department of Health, Education, and Welfare, the U.S. Army's Construction Engineering Research Laboratory, the General Services Administration and the California Department of General Services to learn of their current research and disaster planning activities. Several A & E firms were visited; these firms, as well as the above-mentioned agencies, were requested to identify aseismic design/analysis problems facing practicing engineers and architects and to suggest areas of research needed to improve design capability. To observe current construction practice as it applies to earthquake resistance of nonstructural systems in hospitals, two hospitals under construction in California were visited. Based on the information obtained from the abovementioned liaison activities, NBS identified some problems which impede the development of aseismic design criteria.

Preparation of a List of Needed Research Activities

Finally, specific research needs in the area of aseismic design/evaluation of nonstructural systems were identified and discussed. The recommendations are intended to provide the basis for detailed analytical and laboratory studies aimed at developing comprehensive aseismic design criteria.

2.2 ORGANIZATION OF THE REPORT

The information obtained in the literature survey is discussed in section 3.1. A discussion of the results of the code and standard evaluation activity is presented in section 3.2. The findings of the inquiries made to the various government agencies and the A & E firms and the information obtained from the field visit are summarized in section 3.3. The general seismic performance requirements and the essential services needed to satisfy these requirements are tabulated in section 4.1. Section 4.2 contains tables which summarize much of the damage information obtained on the five selected building service systems. A discussion of the tables is included. The main elements needed for a design/evaluation methodology are discussed in section 4.3. The problem areas that were identified and the research recommendations are described in chapter five.

3. STATE-OF-THE-ART

3.1 LITERATURE SURVEY

This section presents the findings from a survey of the literature on the seismic performance of nonstructural components in buildings. This survey was a major activity in attempting to assess the state-of-the-art on aseismic design of nonstructural systems. The reference sources included: papers presented at earthquake conferences, articles in professional publications, reports of government agency-sponsored studies, and state government legislation. The documents were reviewed with the following objectives: (1) identifying the components of the five nonstructural systems selected for study, (2) defining past and present aseismic design philosophies, (3) determining the nature of the damage incurred by nonstructural components, (4) identifying deficiencies in the state-of-the-art and (5) identifying needs for improved design and installation practices.

Literature on the seismic performance of nonstructural building components dates from the Great Alaska Earthquake of 1964 [8]. The aftermath of this natural disaster was thoroughly studied and comprehensively documented under the sponsorship of the National Academy of Sciences [25]. Most of the engineering reports in reference [25] deal with geological and seismological aspects and with the response of structural systems to the earthquake. Nonstructural system response was covered only in a peripheral sense. There was one report by Ayres, Sun and Brown [8] whose primary purpose was to document the nonstructural damage in buildings and to make recommendations for improved design practice. The investigation which served as the basis for this report was performed about two years after the March, 1964 earthquake. The investigation team conducted field studies of several damaged buildings which had not been repaired. They also examined available damage reports, engineering drawings and project files to compile the necessary data. The report summarizes damage incurred by the following nonstructural systems and components:

- Traction-type and hydraulic elevators
- Escalators
- Mechanical systems including boilers; furnaces; flues; plumbing; piping; fans; ducts; compressors; HVAC systems; tanks; fire sprinklers; pumps; and gas systems
- Lighting fixtures
- Electrical systems including conduits; switchboards; panelboards; bus ducts; and motor starters
- Communication and signal systems
- Emergency power and lighting systems
- Facades and glazing
- Ceilings
- Partitions
- Furniture and storage racks

Discussions are presented, in the Ayres et al report, on the damage inflicted on each of the listed items. The discussions are supplemented by photographs of the damaged areas. Damage summaries are presented for each system of component and a set of design and installation recommendations for preventing particular types of damage are also presented. The recommendations generally are in the form of guidelines for improved practice; however, the guidelines are not supported by analysis. That is, no calculations are presented to substantiate that the recommended support details can accommodate seismic forces for differential and gross deflections caused by the supporting elements of the structure. Nevertheless, the damage report was a significant contribution to the then sparse data base on nonstructural damage. Some of their recommendations were followed in repairing damaged nonstructural components in buildings.

The interest in aseismic design of buildings was increased by the occurrence of an earthquake in California's San Fernando Valley in February, 1971. Immediately following the earthquake, disaster investigation teams were assembled to evaluate the results. Using the experience gained in Alaska in 1964, many survey teams collected data, prepared reports and made recommendations. Among other factors, the economic and life safety consequences of nonstructural damage to buildings made a significant impact on legislators, planners, building owners, engineers, architects and code officials. Although several reports contained discussions on nonstructural damage, only one was found that was entirely devoted to examining and analyzing this kind of damage. The report [9] was included in one of three volumes by the National Oceanic and Atmospheric Administration. The authors of the report, Ayres and Sun, used a similar format to the one they used in reporting nonstructural damage in the Great Alaska Earthquake of 1964. Photographs and drawings were used to illustrate typical damage. The text provided discussions of the damage and a list of recommendations for improved practice was included for each system or component.

The Alaska and the San Fernando earthquakes were natural experiments in which design and construction practices and code effectiveness were tested by extreme loadings. Therefore, references [8] and [9] serve as bases for assessing the state-of-the-art in aseismic design of nonstructural systems in buildings. They highlight many of the recurring problems in design and installation by pointing out damage patterns common to both earthquakes. It bears mentioning that reports [8] and [9] were prepared by mechanical and electrical engineers with nominal structural engineering input. The authors of the documents cited the need for some multi-discipline studies of the existing data.

The issue of earthquake-resistant design criteria for building service systems was discussed in a paper [10] presented at a disaster mitigation workshop in August, 1972, in Boulder, Colorado. The paper's authors addressed the repeated damage inflicted on such nonstructural components as elevators, suspended ceilings, lighting fixtures, storage racks and some components of mechanical systems. In general, the paper did not present design criteria. But it did discuss some corrective measures which were intended to mitigate or prevent certain types of damage. One shortcoming of the recommendations appears to be the absence of any quantitative requirements for allowable lateral and vertical force and allowable deflection. The contribution made by this paper to the state-of-the-art is that it has defined some characteristic damage patterns and that some areas needing additional research were identified.

The publications discussed in previous paragraphs pertain to nonstructural building systems irrespective of building occupancy and use. The unique requirements of hospital facilities were not of particular concern. Hospitals incorporate relatively complicated building service systems (i.e. plumbing, electrical, medical, etc.) and they require backup systems (e.g. emergency power) that are not needed by many other types of buildings. Recognizing this fact, Merz [24] has attempted to identify and rank order the importance of the nonstructural systems used in hospitals.

He has discussed the behavior of these systems and offered some guidelines for improving their seismic resistance. Ideally, the guidelines can apply to components in existing buildings (i.e. retrofitting) as well as to those in new buildings. The hospital nonstructural systems identified by Merz and listed in the designated order of priority were: (1) fire protection, (2) hazardous materials, (3) emergency power, (4) communications, (5) transport, (6) mechanical, (7) medical, (8) architectural and (9) other equipment. The list is generally applicable to many other classes of building use, although the order of priority may be significantly different. The priority listing is subjective and its rationale may be subject to debate. Such a discussion is beyond the purview of this survey. There does seem to be an implicit agreement within the literature that the fire protection system should have number one priority.

Merz's discussion of the response of nonstructural systems to ground motion provides a foundation for developing analytical procedures. He indicates that the type of response analysis applicable to a particular component depends on its physical characteristics. Based on the physical characteristics, the equipment can be classified as either rigid, flexible or having drift limitations. As an example of this approach, Merz states that "the analysis of rigid equipment response requires consideration of rigid body dynamics." This classification type of approach could lead to the development of a design methodology in which a design procedure is selected according to the designated class of the component/attachment system.

Most of the literature surveyed has been generated from studies conducted by or for Federal agencies and from actions taken by state governments.

For example, the California Legislature enacted Senate Bill (SB) 519 [32] to meet the need for maintaining continuous functioning of hospitals in the post-earthquake period. The bill, effective as of March 7, 1973, duly recognized the high probability of "strong seismic disturbances" throughout the State of California. The intent of the Legislature as declared in Section 2 is stated as follows:

> "It is the intent of the Legislature that hospitals, which house patients having less than the capacity of normally healthy persons to protect themselves, and which must be completely functional to perform all necessary services to the public after a disaster, shall be designed and constructed to resist, insofar as practicable, the forces generated by earthquakes, gravity and winds. In order to accomplish this purpose the Legislature intends to establish proper building standards for earthquake resistance based upon current knowledge,..."

The State Department of Public Health was authorized to make regulations to carry out the act. In an article on the background of this bill, Meehan [23] indicates that Title 17 (see paragraph 3.2.6 for a discussion of this regulation) of the California Administrative Code gives the building regulations for California hospitals. Title 17 also contains the special provisions for the seismic load levels and performance. SB 519 established a Building Safety Board which was authorized to act as a board of appeals with regard to seismic structural safety of hospitals. The board has established five standing subcommittees. One of these subcommittees, Hospital Operations, is charged with defining necessary or essential services which must remain functional following a disaster.

The issue of functionality is a very complicated one. Many questions arise such as what constitutes the essential services and how long should they be required to remain functional.

The Veterans Administration (VA) is another agency whose interest in earthquake-resistant design of hospitals has increased since the San Fernando earthquake of 1971. Prior to that event, VA buildings were designed for seismic loads in accordance with the local or national building codes used by the locality. A study of this VA policy was prompted by building collapse and consequent loss of life at the VA San Fernando Hospital. The principal objective of the study was to prepare a critique of current local and national building codes and to recommend revisions for VA design. Based on recommendations made in the report of the study [40], the VA adopted, in 1972, the the concept that a hospital facility should remain in continuous operation after an earthquake. As noted above, this intention was also declared in California's Senate Bill 519. The committee appointed by the VA to conduct the study was charged with the task of recommending code requirements to ensure continuous service. It was the adoption of this concept of continuity of essential services which heightened the VA's concern for the performance of nonstructural building systems. In fact, it was on the basis of some of the recommendations made by the VA-appointed committee that two new VA Construction Standards were adopted: (1) CD-54 [38] and (2) CD-55 [39]. The requirements of CD-55 are discussed below in paragraph 3.2.5. It is interesting to note that CD-54 contains the requirement that emergency facilities shall be designed on the basis of "the hospital continuing in operation at normal bed capacity for a 4-day period immediately following an earthquake." This is is the only instance noted in the literature in which the required time period of continuous post-earthquake operation is stated. The rationale for the 4-day requirement is that disruptions in normal outside utility services and site access facilities (i.e. roadways, bridges and helicopter landing areas) will either be repaired or circumvented by alternates within this period of time.

Another study was conducted for the Veterans Administration to establish protection provisions for hospital equipment, furniture, and supplies [3]. The study was primarily directed toward new construction and was concerned with such items as x-ray units, desks, chairs and pharmaceutical supplies. The researchers started with the basic assumption that the new hospital facilities will be built according to VA Standards CD-54, CD-55 and H08-8.

Further, it was assumed that the buildings will remain structurally intact and that their major electrical and mechanical systems will remain functional in the post-earthquake period. The essential post-earthquake activities have been placed into three categories: (1) patient care (e.g., operating rooms), (2) medical support (e.g., x-ray), and (3) non-medical support (e.g., building maintenance). Using the lists of essential activities, the investigators determined the equipment, furniture and supplies required to perform the essential activities. Then, they provided a range of techniques for restraining the nonstructural items against the effects of seismic forces. This report [3] provided information useful in establishing the essential service systems required by hospital facilities.

Some of the government-sponsored studies have not focused on hospitals per se, but on buildings in general. Nevertheless, the information provided by these more generic studies was useful to this literature survey.

The Public Buildings Service of the General Services Administration (GSA) authorized two studies aimed at improving aseismic design criteria for buildings under its charge. One study addressed the need to improve the design criteria for structural components in buildings. The second study [2] authorized by GSA and, reviewed for this report, was intended to develop improved criteria for nonstructural components. In addition to a survey of the literature and a critical analysis of selected building codes, the GSA report on nonstructural components presents comprehensive seismic criteria for the review and evaluation of nonstructural components. The criteria are divided into two parts: an evaluation system for existing buildings and design criteria for components in new construction. The system for evaluating existing buildings consists of a research phase, in which nonstructural component information is assembled, and an evaluation phase, in which the assembled information is systematically reviewed to predict the seismic performance of the in-place nonstructural components. Based on this two-phase approach, decisions can be made for future action. Because this systems approach was developed for all classes of public buildings, it has potential application in the field of retrofitting existing buildings for improved seismic resistance. The design criteria in [2] for components in new construction include: seismic design standards; illustrations showing the probable response motions of nonstructural components to earthquake accelerations; recommended configurations and guidelines for advantageously selecting, arranging and constructing nonstructural components for mitigating damage; and checklists which would aid GSA personnel in reviewing new designs.

In summary, the number of publications on the seismic performance of nonstructural building systems is sparse. The majority of the literature dates to the early seventies when reports of the effects of the Great Alaska Earthquake were published. The reports reviewed in this survey have largely resulted from studies performed for federal agencies and from activities conducted by the State of California. Several reports, [8, 9 and 25], were useful in providing descriptions of typical damage incurred by various nonstructural components during three recent earthquakes. Recommended actions for improved design and installation practices have been offered by the authors of the reports based on their assessments of the damage. Most of the recommendations are concerned with restraining the components against seismic force effects. Interaction between structural and nonstructural systems in buildings is discussed by Merz [24] and McCue et al.[22], but no interdisciplinary studies involving architects and mechanical, electrical and structural engineers were reported. One of the studies [40], which was sponsored by a federal agency (VA), had as one of its primary objectives the development of new codes or standards for aseismic design of nonstructural systems in hospitals. As a result of this study, the VA adopted Construction Standards CD-54 [38] and CD-55 [39]. CD-54 contains the requirement that emergency facilities shall be designed on the basis of the hospital continuing in operation at normal bed capacity for a 4-day period immediately following an earthquake. The State of California enacted legislation [32] specifically intended to ensure the continuous operation of hosiptal facilities in the post-earthquake period. GSA is another agency concerned with aseismic design of buildings. One of the studies conducted for GSA [2] was intended to develop improved criteria for nonstructural components in buildings.

3.2 REVIEW OF CODES, STANDARDS AND REGULATIONS

This section presents a discussion of the aseismic design requirements of selected codes, standards and statutory regulations for building service systems. These documents were reviewed with emphasis on the following key factors:

- historical development
- comparative numbers of service system components covered by the seismic performance sections
- implications of design philosophy
- indication of the incorporation of current knowledge in the performance requirements

The traditional philosophy with respect to the design and evaluation of buildings for seismic events is that the structural and nonstructural systems can be uncoupled and considered independently. Thus, architectural elements and plumbing, mechanical and electrical systems, as well as other nonstructural components are treated as being subjected to forces applied by the structural components to which they are attached. This seismic force input is usually accounted for in codes by assigning certain design force factors to the various nonstructural components. An equivalent static force is computed and is considered to be applied to the approximate center of gravity of the component being analyzed. The equivalent static force is also a function of the weight of the equipment and a "seismic risk factor." All of the codes and standards discussed in this section use the same basic formulation for computing the equivalent static force:

$$F_p = ZC_p W_p \tag{1}$$

where,

F_p = Lateral force applied to the nonstructural component,

Z = Numerical coefficient which depends on the seismic risk of the zone in which the building is located,

C_p = Horizontal force factor which varies with the type of nonstructural component, and

W_p = The weight of a part or portion of a structure or of a nonstructural component.

The major difference between code provisions for a particular component lies in the magnitude of the C_p value. Also, some codes are more comprehensive than others in their treatment of the nonstructural components for which C_p values are presented.

3.2.1 Uniform Building Code (UBC) [37]

The UBC, having been first published in 1927, has traditionally been the national model from which local jurisdictions and some federal building regulatory agencies have developed aseismic design requirements. Section 2314 of UBC, Earthquake Regulations is germane to earthquake-resistant design. Reflecting the national applicability of the UBC regulations, equation (1) above can be adjusted to account for the seismic risk of areas throughout the continental United States, Hawaii and Alaska. Values of Z (see equation 1) are assigned according to the UBC Seismic Risk Map of the United States. The map is divided into four zones; the significance of the zones and the associated Z values are as follows:

Table 1 - Seismic Risk Zones in the UBC

Zone	Comments[a]	Value of Z
0	No damage.	0.0
1	Minor damage; distant earthquakes may cause damage to structures with fundamental periods greater than 1.0 seconds; corresponds to intensities V and VI on the M.M.[b] Scale.	0.25
2	Moderate damage; corresponds to intensity VII on the M.M. Scale.	0.50
3	Major damage; corresponds to intensity VIII and higher on the M.M. Scale.	1.0

Footnotes:

[a] These comments are direct quotes from the UBC's Seismic Risk Map of the United States.

[b] Modified Mercalli Intensity Scale of 1931.

The bases for the seismic risk map are stated on the map. Table 1 indicates that the value of Z doubles as the number of the risk zone increases and it has a maximum of 1.0.

There is no explanation given as to how the C_p values in the UBC are derived. The UBC table of C_p values does not include factors for such mechanical and electrical equipment as elevators, panelboards, pumps, switchgear and lighting fixtures. By comparison with some of the other codes in the survey, the list of nonstructural components is generally not as comprehensive. When using the UBC design approach, there is no variation of C_p according to the height above ground of the floor on which the component is located, except for the following components: tanks, towers, storage racks, chimney, smokestacks and penthouses.

When using the UBC method, the designer selects the values of Z and C_p from the respective tables, establishes the weight of the component and computes the equivalent static force from equation 1. The device for supporting or bracing the component is then sized on the basis of its resisting force F_p. Interaction between the supporting structural elements and the component is not explicitly accounted for in this approach. It is important to note also that the UBC regulations apply equally to all classes of building use. Therfore, nonstructural components in critical-use facilities such as hospitals are not subject to more stringent performance requirements than those in other classes of buildings.

3.2.2 City of Los Angeles Building Code [21]

The provisions reviewed for this study are those in Section 91.2305, Horizontal Forces, Division 23, Loads and General Design of the Los Angeles

Building Code. Prior to a city ordinance in May 1973, Section 91.2305 was identical to Section 2314 of the UBC with one exception. The exception was that in addition to the equivalent static load analysis discussed previously, the city adopted a set of Rules of General Application (RGA's). Two of the RGA's are applicable to this study and they are RGA 4-74 [19], "Recommended Standards for Suspended Ceiling Assemblies" and RGA 12-69 [20], "Standard for Lighting Fixture Supports." These are both performance standards; compliance with these standards can be substantiated either by calculation or test procedures. RGA 4-74 applies to the structural members used primarily to support acoustical panels or acoustical lay-in tiles, with or without light fixtures. RGA 12-69 requires a shake-table compliance test for the support system of lighting fixtures that have more than one point of support. RGA 12-69 and the Tri-Services Manual [36] are the only two code documents found in this study which explicitly require tests for acceptance of nonstructural components.

Several noteworthy changes were incorporated in the May 1973 ordinance concerning the design of nonstructural components. First, the Los Angeles Building Code acknowledged a class of "Essential Facilities" whose continuous post-earthquake operation is necessary to "preserve the peace, health and safety of the general public." Included in these facilities are hospitals and other life-support facilities. A general requirement for the building elements and critical equipment in the essential facilities is that they be designed, detailed and constructed to withstand the maximum acceleration and deflections of the structure without disrupting the post-earthquake operations or service. Also, the revised regulations require dynamic analysis of all buildings except those which are 160 feet or less in height, and are essentially regular in shape and in stiffness, over the entire height. The results of the dynamic analysis of the structure can then be used to aid in designing and detailing the nonstructural elements. Any building - irrespective of the class of the facility - 160 feet or less in height may still be designed using static analysis.

3.2.3 City and County of San Francisco Building Code [30]

The 1975 edition of the San Francisco Building Code was reviewed and found to be similar to the UBC in the requirement of a static analysis for nonstructural components. The table of C_p values in the San Francisco Code included several components not covered by UBC. For example, C_p values are included for elevator equipment and anchorage of major mechanical and electrical equipment. In the basic formula for lateral force on nonstructural components (equation 1 above), the value of Z is given as 1.0, indicative of zone 3 on the UBC Seismic Risk Map. Thus, the formula is reduced to:

$$F_p = C_p W_p \tag{2}$$

3.2.4 Tri-Services Manual, April 1973 [36]

This manual governs the design of facilities for the U.S. Army, Navy and Air Force in earthquake-prone areas. Section 8 of the manual prescribes the criteria for structural design of anchorages and supports for mechanical and electrical equipment. Although the design methodology for most mechanical and electrical components reduces to a static analysis, there are some notable departures from the UBC basic formulation.

First, the manual presents a seismic risk map for the continental United States which is divided into five risk zones. It is recalled that the UBC Seismic Risk Map is divided into four risk zones. The damage associated with each zone of the Tri-Services Manual is indicated in table 2.

Table 2 - Seismic Risk Zones in Tri-Service Manual

Zone	Damage
0	None
1	Minor
2	Moderate
3	Major
4	Great

In the Tri-Services method, zone values used in the analysis will depend on two factors: (1) the specific seismic risk zone in which the building site is located and (2) the relative importance of the occupancy of the facility. Facilities are classified as having either a "High-Loss-Potential" or a "Low-Loss-Potential." Included in the class of High-Loss-Potential facilities are hospitals and physically annexed outpatient buildings. The values of Z for all facilities range from 0 to 1.5 depending on the combination of seismic risk zone and class of loss potential. The 1.5 value applies to High-Loss-Potential facilities located in zone 4. By comparison with the Z values given in the UBC (see table 1), it is seen that the 1.5 value is 50% greater than the highest value in the UBC.

The second departure is that equipment mounted in buildings is classified according to its weight and to the rigidity of the support system, in accordance with the following classification: (1) rigidly mounted equipment is that for which the fundamental period of vibration is less than or equal to 0.05 seconds and whose weight is less the 15 kips. An example of rigidly mounted equipment is an electric motor bolted to a concrete floor; (2) equipment whose weight does not exceed one-tenth of the dead load of the floor at the equipment level and (3) equipment whose weight and support conditions fall between (1) and (2). Supports for equipment in the first group may be designed by simplified static analysis that uses equivalent static force. Supports for equipment in the second group are excluded from the scope of the manual as they are seen as requiring a rigorous dynamic analysis. The analysis would have to consider the interaction between the equipment and the structural element to which it is attached. The design of supports for the third group of equipment assumes that the equipment and its support system can be approximated by a single-degree-of-freedom system. The method involves the calculation of an equivalent static force:

$$F = ZKCW \qquad (3)$$

where,

F = Equivalent static lateral force,

Z = Seismic probability coefficient (same symbolism as in equation 1)

K = Numerical coefficient set forth in the SEAOC code [31] and dependent on the type of structural system,

C = Seismic force coefficient, and

W = Weight of equipment.

The most significant difference between equation 3 and that given in the UBC lies in coefficient C. The formula for the seismic force coefficient is:

$$C = (C_s)\ (A_h)\ (M.F.) \qquad (4)$$

where,

C_s = A soil constant dependent on the allowable soil bearing pressure for the site,

A_h = Estimated design acceleration for the height of the floor level on which the equipment is located, and

M.F. = Appendage magnification factor dependent on the approximate periods of the appendage and the building.

Thus, C appears to be a refinement of the C_p factor discussed in paragraph 3.2.1, in that influence of site conditions (C_s) and the effect of height equipment above the ground (A_h) are introduced. The appendage magnification factor accounts for the concept of transmissibility in vibration theory.

The most critical condition occurs when resonance exists between the equipment and the structural element. Therefore, when the period of the equipment/support system approaches the period of the structure, the magnification factor will become infinitely large. Referring to equation 3 this condition results in a very large equivalent static lateral force. The equipment support design would have to be changed to attenuate this undesirable effect. The important point is that the principles of structural dynamics are explicitly incorporated in this design method to account for the condition of resonance.

In addition to the requirements discussed above, the Tri-Services Manual has established specific requirements for the performance of lighting fixture supports. First, there are some prescriptive details pertaining to the installation of pendant-supported, recessed and surface-mounted flourescent fixtures. Then, there is a provision for the use of a shaker-table test to show compliance with performance requirements. All of the above-mentioned fixture types may be tested dynamically in lieu of performing a static analysis. The apparatus and test procedure in the Tri-Services test method are similar to those described in the Los Angeles RGA 12-69 [20]. An important difference between the two methods is in the specification of the input frequency and acceleration magnitude. RGA 12-69 specifies a single input frequency (1 Hertz) and an acceleration level of 0.2g. On the other hand, the Tri-Services method specifies acceleration-magnitudes of 0.375g, 0.25g, 0.13g and 0.06g, depending on the seismic risk zone. In the Tri-Services method, the input frequency must be adjusted to produce the specified acceleration magnitude.

The Tri-Services Manual also contains requirements for the various piping systems (i.e. sprinkler risers, air, vacuum and plumbing in buildings). According to current practice, design requirement for all piping included in the fire protection system are governed by the provisions of the National Fire Protection Association (NFPA) sprinkler standard [26]. This standard prescribes some acceptable sway bracing details and typical arrangements of flexible joints for sprinkers. The NFPA standard also gives installation recommendations intended to prevent piping damage during earthquakes. The Tri-Services manual contains requirements for all non-fire protection piping. These requirements are in the form of allowable span tables for different pipe sizes, pipe materials and end conditions (e.g. pinned-pinned). The allowable spans were calculated using equations for the fundamental period of vibration. The maximum allowable period of vibration of the pipes was set at 0.05 seconds and the equations were solved for span lengths. The pipe supports must be designed to resist the zone-dependent, equivalent static forces, calculated for the weight of the pipe full of water.

3.2.5 VA Construction Standard CD-55 [39] and VA Handbook H08-8 [16]

Construction Standard CD-55 establishes the Veterans Administration's policy for the design of nonstructural components of buildings to resist seismic damage. Implementation of the objectives of this standard relies heavily on the conclusions of site evaluation studies. A study is required for each VA Hospital site; the study is intended to establish "the charateristics of strong ground motion," including a peak horizontal ground acceleration. Also, the studies must project building damage according to the Modified Mercalli (MM) scale of intensities. When the studies project damage of MM Intensity VI (on a scale of I - XII) or greater, earthquake-resistant design is required. The design requirements contained in CD-55 are prescriptive in nature; general design and construction measures are presented in the following areas:

(1) Consideration of the seismic accelerations and deflections at various elevations and locations when placing heavy mechanical and electrical equipment.

(2) Use of restraining devices to limit differential movements between nonstructural elements and the building elements.

(3) The provision of flexibility in electrical and mechanical systems which must cross seismic joints in buildings.

(4) The reinforcement of field-fabricated nonstructural components to resist damage from seismic motions.

(5) The earthquake-resistant design - internally and externally - of

> electrical and mechanical equipment used in locations where the site evaluation studies estimate damage of Modified Mercalli Intensity VIII or greater.

In addition to complying with the above-mentioned requirements, the design must also be in accordance with VA Handbook H08-8. The requirements in H08-8 for nonstructural elements are based on the Uniform Building Code's equivalent static force method. In addition, H08-8 includes several provisions recommended by a VA-appointed advisory committee on earthquakes. While the VA method of computing forces for nonstructural elements is similar to that given in the UBC, the VA seismic force factors (C_p's) are more site-specific. This refinement is attributed to the VA site evaluation studies mentioned above. The horizontal ground acceleration obtained from a study is expressed as "A_{max}." The importance of A_{max} is reflected in the table of force factors (C_p's) for nonstructural components. Two C_p values are tabulated for each component. The higher of the two C_p values is used when $A_{max} \geq 0.15g$ and the lower C_p value is used when $A_{max} < 0.15g$. The C_p values are based on the hospital design requirements of the California State Department of Public Health. In regions where no earthquake activity has previously occurred, new structures and major additions must be designed for a minimum A_{max} of 0.05g.

3.2.6 State of California Administrative Code, Title 17, Public Health, Chapter 8, Safety Construction of Hospitals [12]

The seismic design of nonstructural systems as governed by Title 17 uses the same basic formulation as that presented in the UBC (see paragraph 3.2.1 above). Since all of California is considered to be in seismic risk zone 3 of the Uniform Building Code, the value of Z is implicitly taken as 1.0.

The table of C_p values is the most comprehensive of those encountered in this survey. Moreover, two sets of C_p values are presented to account for the relative importance of the buildings during the post-disaster period. The distinction is made between "essential buildings or structures" and "non-essential buildings or structures". Namely, "non-essential buildings or structures are those which are not required for the complete functioning of a hospital to perform all necessary services to the public after a disaster."

Those buildings or structures required for the continuing operation of the hospital are classified as essential buildings. This approach is similar to that established in the Tri-Services Manual (see paragraph 3.2.4). The higher C_p values are assigned to the nonstructural systems which are housed in essential buildings. For either class of building use, the C_p values are recommended minimums which may be increased to account for unusually important or expensive equipment or for equipment located in the upper levels of multi-story buildings. Title 17 also requires that the mechanical and electrical drawings show the complete systems and the details for fastening the equipment to the structure to resist seismic forces.

3.2.7 Working Draft of Recommended Comprehensive Seismic Design Provisions for Buildings ATC-3-04 [6]

A working draft of a report being prepared by the Applied Technology Council (ATC) was reviewed. The draft, dated January 31, 1976, reports on the current status of a project whose objective is to develop comprehensive aseismic design provisions that can be adopted by jurisdictions throughout the United States. Chapter four of the report contains recommended design requirements for structural and architectural elements and for mechanical and electrical equipment in buildings. The design method described therein specifies a static analysis similar to that in the UBC [37]. The various components and their supports are designed to resist an equivalent static force. Three formulas are presented for computing the design force. One formula is applied to structural elements, another to architectural elements and a third to electrical and mechanical equipment. For the design of electrical and mechanical equipment and their attachment devices, the formula is:

$$F_p = A\ C_p\ M\ W_p\ P\ m \tag{5}$$

where,

A = The coefficient representing the effective peak ground acceleration,

C_p = The force factor for various components,

M = The amplification coefficient for a component in the building,

W_p = The weight of the component,

P = The performance level coefficient which ranges from 0.0 to 1.5, and

m = The component attachment amplification factor which depends on the ratio of the fundamental period of the component/attachment system to that of the building.

The most notable difference between the Tri-Services formula (see equations 3 and 4) and equation 5 is that the latter uses a performance level factor P. Nonstructural systems are required to meet one of four levels of performance: (1) none, (2) low, (3) good and (4) superior. A value of P is assigned to each of these performance levels. The performance level applicable to a particular nonstructural component is dependent on the use of the building.

There are three groups of building use, with classification assigned according to their importance to post-disaster recovery and continuous operation during and after an earthquake. Hospital buildings are included in the most critical group. All of the electrical and mechanical equipment in the most critical group must be designed for the maximum performance level factor, which is 1.5.

The codes and standards previously discussed reflect the state-of-the-art of aseismic design of nonstructural building systems. The prevailing design method involves the calculation of an equivalent static design force. The component/attachment systems are to be designed to resist the effect of this force, whose point of application is at the center of gravity of the component. The basic formula for the design force is presented in the UBC [37]. Variations and refinements of the basic formula are given in other codes depending on whether the document considers the physical properties of the building (e.g. the height of the floor on which the component is located), the earthquake response characteristics of the ground (e.g. peak ground acceleration) and the dynamic characteristics of the component/attachment system (e.g. the fundamental period of vibration). The class of building use is also accounted for in several codes. In general, the provisions of the codes surveyed do not explicitly account for the effect of interaction between the structural system and the nonstructural components. The nonstructural component is to be analyzed as a dynamically uncoupled system, with no consideration being given to the interdependence of the two systems.

3.3 CURRENT SEISMIC RESEARCH ON NONSTRUCTURAL ELEMENTS

Contacts were made with Federal agencies and the California Building Safety Board in order to review their current efforts in seismic research on nonstructural elements.

The organizations contacted were :

- Construction Engineering Research Laboratory (CERL)
- Veterans Administration (VA)
- Building Safety Board (BSB)
- National Science Foundation (NSF)

The results of the interviews of each of the above organizations are presented in this section.

3.3.1 Construction Engineering Research Laboratory (CERL) Activities

There is a current CERL project entitled "Nonstructural Hardness Against Earthquakes and Other National Disasters." The objectives of the program are to update the aseismic design criteria in the Tri-Services Manual [36] and to establish a classification system for all essential equipment in hospitals. All nine of the essential systems identified by Merz [24] and the three essential functions described by Stone, Marraccini & Patterson [3] are included in the scope of the study.

There are five categories into which the nonstructural components can be placed: (1) structural support requirements; (2) code and standard requirements; (3) specification writing for equipment procurement; (4) physical compliance testing and (5) statistical (i.e. reliability) analysis based on past performance. Moreover, CERL is analyzing the failures of a wide range of nonstructural building components based on shock test data obtained from an extensive test program conducted by the Army Defense System on the fragility of internal and life support systems in critical facilities. However, the applicability of such data to seismic provisions remains to be established. The project also includes a contract with A & E firms to develop specifications for nonstructural elements in the following four major areas: (1) design and monitoring procedures for equipment; (2) testing procedures; (3) analytical procedures, and (4) treatment of failure data. These specifications will serve as a basis for changes to existing design codes.

3.3.2 Veterans Administration Activities

The Veterans Administration is conducting a program in which the seismic resistance of VA hospitals located in risk zones 2 and 3 (according to the UBC Seismic Risk Map) is being assessed. The studies are being conducted by local A & E firms and involve the evaluation of the hospitals compliance with the latest VA design criteria [16], [38] and [39]. The A & E firms are charged with determining the non-compliant elements in the existing facilities and advising the VA of the economic feasibility of upgrading the deficient buildings and components to meet the current standards.

3.3.3 National Science Foundation Activities

One of the impediments to advancing the state-of-the-art in designing and detailing of nonstructural systems is the lack of understanding of the interaction occurring between structural and nonstructural systems during a seismic event. The traditional design/analysis approach is to uncouple the systems and treat them separately. Thus, the behavior of the nonstructural system is considered to be activated by the motion of the structural system and then the structural system is implicitly assumed to become stationary. In a current NSF funded study [22] the relationship and interaction between the primary (i.e., structural) system and nonstructural system is being determined. The assumption is that the building consists of a number of interdependent systems. Thus the seismic response of the building's primary system influences and is influenced by the architectural and other nonstructural systems. Recognizing that there are several levels of interaction, the investigators have been classifying the nonstructural systems according to their means of attachment to the structural elements. The first class consists of architectural elements which because of their means of connection, must respond in the same manner as the structure. The second class consists of elements supported by one structural element such as a beam. The third class is comprised of those architectural elements which are supported by more than one structural element. Efforts are currently aimed at developing simplified analytical models for these different classes of architectural systems in order to predict their dynamic responses. Although the scope of this research program is limited only to architectural systems, it could be applied to other nonstructural components as well.

3.3.4 Current California Building Safety Board Activities

Senate Bill 519 [32] authorized the California Department of Health to adopt regulations to carry out the intent of SB 519. It also established a Building Safety Board to advise the Department of Health with regard to seismic safety and to act as an appeals board in the enforcement of the Act. The Building Safety Board has established subcommittees on architectural, mechanical, electrical, structural, geotechnical and hospital operations. These subcommittees act as liaison between the board and the respective technical associations.

In particular, the Hospital Operations subcommittee is currently trying to define those activities and supporting services considered essential to the continued functioning of the hospital following the occurrence of an earthquake. The implications of such a definition of functionality are great. Does SB 519 intend that a duplication of essential hospital services be necessary so as to assure functionality? Moreover, SB 519 not only covers construction of new hospital, but also existing ones. Thus, questions like: "Does the Bill intend that all existing hospitals shall be upgraded to the new standards?" are being considered by the subcommittee.

4. POST EARTHQUAKE PERFORMANCE OF BUILDING SERVICE SYSTEMS IN HOSPITALS

4.1 POST EARTHQUAKE PERFORMANCE REQUIREMENTS OF HOSPITALS

It is an identified requisite that hospitals shall remain functional subsequent to the occurrence of an earthquake [32]. By definition, a hospital is functional when (1) it provides protection to the resident patients during the earthquake; (2) sustains the resident patients and (3) provides treatment to new arriving casualties resulting from the earthquake. In order to accomplish these objectives, the following general requirements were established:

(1) The hospital building must be able to survive the earthquake. That is, the structural integrity of the building must be maintained, and,

(2) The life support and treatment facilities must be operational after the earthquake.

These general requirements are further developed into subsets called Operational Requirements. Table 3 describes this concept.

TABLE 3 - POST-EARTHQUAKE PERFORMANCE REQUIREMENTS FOR HOSPITALS

BASIC PRECEPT	OBJECTIVES	GENERAL REQUIREMENTS	OPERATIONAL REQUIREMENTS
Hospitals Must Remain Functional	Protect Resident Patients	Building Integrity	- Structural Integrity - Fire Protection - Hazardous Materials Protection
	Sustain Resident Patients	Life Support and Operational Treatment Facilities	- Emergency Power - Environmental Control - Sanitation and Water Supply - Patient Care System - General Services
	Treatment of New Casualties		

As mentioned in Chapter 2, this study did not address all the operational requirements listed in column 4 of Table 3. Rather, five essential building service system have been selected:

(1) Fire Protection
(2) Emergency Power
(3) Sanitation and Water Supply
(4) Environmental Controls
(5) General Services

4.2 RECORDED EARTHQUAKE DAMAGE TO ESSENTIAL SERVICE SYSTEMS

4.2.1 Explanation of Tables Describing Earthquake Damage

The primary objective of this section is to summarize the damage which has occurred to essential building service system components during past earthquakes. The overall purpose of acquiring the information was to identify recurring problem areas and to establish a basis for research recommendations. Tables 4 through 8 summarize the information obtained in the survey. For each of the five essential service systems, Column 1 of the tables identifies their major components. The majority of the information for the second column in the tables, "Relative Degree of Damage," was obtained from the nonstructural damage reports prepared by Ayres, et al., [8], [9], and [10]. However, the degree of damage entries reflect the subjective judgement of the authors of this report. It should be noted that the entries were derived from a weighting process which accounted for such factors as differences in the types of construction in which the components were installed and variations in the location of similar equipment from building to building. The term "relative degree of damage" refers to the relative technical difficulty involved in repairing the system or component and assumes an adequate supply of replacement parts and sufficient manpower to perform the work. No connotation of relative expense involved in the repair work is implied in this damage classification.

Column 3 of the tables, "Consequences of Damage," refers to the implied consequence of the reported damage to the components. The entries "inoperative," "partially inoperative," and "operative," indicate whether the systems and components generally remained functional as a consequence of the damage. The fourth column of the tables describes the most frequently recurring types and/or causes of damage.

4.2.2 Summary of Recorded Earthquake Damage

The following observations are made in summarizing the damage to essential service systems:

(1) Fire Protection Systems

Very little earthquake damage has been inflicted on the various components of fire protection systems in buildings (see table 4). This result is particularly significant in view of the fact that some studies (e.g. reference 24) have concluded that the fire protection system should be given top design priority among the essential service systems. It is interesting to note that there are standard seismic-resistance requirements governing the design of bracing and support assemblies used in fire protecting piping trees (see table 9).

(2) Emergency Power Systems

(a) The available documentation regarding emergency power systems more uniquely reflects the damage picture for hospitals and other life support facilities than the information gathered for the other four service systems mentioned herein, because emergency power systems are much more common to life support facilities than they are to other classes of building occupancy.

(b) While there has not been much major damage inflicted on emergency power systems, some electrical equipment has been rendered inoperative by secondary effects (see table 5). The most frequent causes of damage to the larger pieces of equipment have been the excessive movement of unanchored supports and the lack of top bracing on taller units. In most cases the excessive movement occured because of the presence of vibration isolation devices.

(c) Rigid electrical distribution conducts were damaged as a result of local failures in the structural supports.

(d) The damage to light fixtures has been adequately summarized by Ayres and Sun [10] as follows: "The various types of light fixtures behave differently under seismic conditions depending upon their inherent design and their connections to ceilings. Suspended fixtures that are free to twist and rack are severely damaged when failures occur in supporting stems or chains and at their ceiling support points. Surface mounted fixtures sustain very little damage if properly installed, and recessed fixtures are damaged when they are not securely fastened to the suspended ceilings."

(3) Sanitation and Water Supply Systems

The damage sustained by components of Sanitation and Water Supply systems in multi-story buildings has largely depended on the location of the equipment within the building. Heavy equipment, such as pumps and large storage tanks, which were located on roofs, in penthouses or on upper floors, have sustained moderate damage when the support systems failed (see table 6). As a result of inadequate support and bracing, some tanks have tipped or overturned, causing ruptures in pipe connections and loss in service. Pumps mounted on machine-vibration isolators have been damaged as a result of excessive lateral translation. In general, sanitation and water supply piping has performed satisfactorily. The most frequent type of damage, which is due to differential movement between main and branch piping or between the piping and the connected equipment, has been the rupture of screwed fittings.

(4) Environmental Control Systems

(a) When considering the damage sustained by the mechanical equipment comprising the Environmental Control System, it is important to recognize the following:

(i) mechanical components such as pumps, fans and compressors may be rigidly mounted to the structure or they may be mounted on vibration isolators; and

(ii) depending on the architectural design, mechanical equipment may be located in the upper part of the building (e.g., roof or penthouse) or the lower part (e.g., basement).

(b) Machines mounted on vibration isolators or not rigidly attached to a floor slab, beam, column, etc., have fared much worse in recent earthquakes. The resulting excessive lateral movement, tipping or overturning, frequently has caused pipe connection ruptures as well as some internal damage to machinery.

(c) Because of the tendency of earthquake-induced ground motions to be amplified in the upper floors of many buildings, massive mechanical equipment located in these regions frequently is more severely damaged than had the same equipment been located in the basement or on the first floor. While table 7 does not indicate the location of the damaged equipment, the written and pictorial accounts presented in the reference reports tend to confirm the correlation between degree of damage and location of the damaged equipment within the buildings.

(5) General Services

(a) It is extremely important to the functioning of hospitals, especially multi-story ones, that people movers remain operative in the aftermath of an earthquake. It is probably because of their relative importance and common use in multi-story buildings that elevators have been comprehensively surveyed in recent earthquake damage studies.

(b) Damage incurred by traction-type elevators during the San Fernando Earthquake in 1971 and the Great Alaska Earthquake of 1964 was extensive. As shown in table 8, the type of damage ranged from broken guiderails to misalignment of the cars. Much of the damage resulted in loss of elevator service; this severe consequence attests to the characterization of the elevator by Ayres and Sun [10] as "a vital - but extremely weak - link in life safety systems...."

(c) Hydraulic-type elevators and escalators have survived earthquakes with relatively minor damage (see table 8) and almost no loss of service. It should be noted, however, that these two classes of people movers are not common to high-rise buildings. Where they are used in hospital facilities, they would appear to offer a much more reliable means of egress and ingress than the traction-type elevators.

4.3 PRESENT STATUS OF ASEISMIC DESIGN/EVALUATION METHODOLOGY

4.3.1 Review of the Main Elements

A comprehensive design/evaluation methodology for any type of system should consist of several primary elements. The main elements are: (1) code provisions which establish performance requirements for the system, (2) analytical methods which help in predicting the response of a component to design loads and (3) laboratory test procedures which can be used as evaluation tools. Thus, the present status of aseismic design of building service systems can partially be determined by reviewing the code requirements governing the performance of the systems' components. In addition, the state-of-the-art is indicated by the availability of applicable design guides, analytical procedures and physical test procedures. As mentioned in section 3.2, one of the key factors, for which the codes and standards were reviewed, was the number of service system components covered by the seismic provisions. Further, all sources of information mentioned in chapter 3 were drawn from to determine the availability of analytical procedures and laboratory test methods for evaluating service system components.

Table 4

Recorded Earthquake Damage to Essential Service Systems - Fire Protection

Essential Service System (1)	Relative Degree of Damage (2)	Consequence of Damage (3)	Most Frequently Reported Type/Cause of Damage (4)
FIRE PROTECTION			
Sprinkler System			
risers	Minor	Operative	No specific damage reported
distribution mains	Minor	Operative	"
valves	Minor	Operative	"
branch pipes	Minor	Operative	"
sprinkler heads & controls	Minor	Operative	"
support hangers, bracing & clamps	Minor	Operative	"
Standpipes			
mains	Minor	Operative	No specific damage reported
risers	Minor	Operative	"
clamps & hangers	Minor	Operative	"
Pumps			
main unit	Minor	Operative	No specific damage reported
pipe connections	Minor	Operative	Secondary damage due to support movement
supports	Moderate	Partially Inoperative	Excessive movement of unanchored supports
Pressure Tanks			
tank	Minor	Operative	No specific damage reported
supports	Moderate	Inoperative	Damage due to support failure
Suction Tanks			
tank	Minor	Unknown	No specific damage reported
supports	Minor	Unknown	"

Table 5

Recorded Earthquake Damage to Essential Service Systems - Emergency Power

Essential Service System (1)	Relative Degree of Damage (2)	Consequence of Damage (3)	Most Frequently Reported Type/Cause of Damage (4)
EMERGENCY POWER			
Motor-Generator Set			
motor & generator	Moderate	Inoperative	Sheared off isolation mountings
cooling components			
- radiator	Minor	Operative	No specific damage reported
- piping	Minor	Operative	"
controls	Minor	Operative	"
fuel piping	Minor	Operative	"
starting batteries	Minor	Operative	"
mufflers	Minor	Operative	"
supports	Moderate	Inoperative	Excessive movement of isolation mountings
Transformers			
main unit	Minor	Operative	No specific damage reported
wiring connections	Minor	Unknown	No specific damage reported
supports	Moderate	Inoperative	
Switchgear			
main unit	Moderate	Partially Inoperative	Relays and switches malfunctioned
conduits	Minor	Operative	No specific damage reported
supports	Moderate	Partially Inoperative	"
Panelboards			
housing	Minor	Operative	Overturning of tall units
conduits	Moderate	Partially Inoperative	Rigid conduit failure due to structural support failure
supports	Moderate	Inoperative	Lack of anchorage to structure
Elec. Distribution Network			
busducts	Minor	Operative	Some secondary damage due to structural failure
feeders	Minor	Operative	Some secondary damage due to structural failure
connectors	Minor	Operative	Some secondary damage due to structural failure
supports	Minor	Operative	Some secondary damage due to structural failure

Table 5 (cont'd)

Essential Service System (1)	Relative Degree of Damage (2)	Consequence of Damage (3)	Most Frequently Reported Type/Cause of Damage (4)
EMERGENCY POWER (Contd.)			
Lighting			
lighting fixtures			
- recessed	Moderate	Inoperative	Separation due to ceiling racking
- surface mounted	Minor	Inoperative	"
- stem & chain suspended	Major	Inoperative	Separation of stem at structural connection; twisting of fixture

Table 6

Recorded Earthquake Damage to Essential Service Systems - Sanitation and Water Supply

(1) Essential Service System	(2) Relative Degree of Damage	(3) Consequence of Damage	(4) Most Frequently Reported Type/Cause of Damage
<u>SANITATION & WATER SUPPLY</u>			
Pumps and Motors			
pump-motor unit	Minor	Operative	No specific damage reported
pipe connections	Minor	Operative	Rupture due to excessive movement
supports	Moderate	Inoperative	Mountings sheared off
Hot & Cold Water Storage Tanks			
tank body	Minor	Operative	No specific damage reported
pipe connections	Minor	Operative	"
supports	Moderate	Inoperative	Mountings sheared off
Piping (Air, Steam, Vacuum, Gas)			
pipes	Minor	Operative	No specific damage reported
fittings	Moderate	Inoperative	Rupture due to excessive movement
supports	Minor	Operative	Hanger assembly failure
Water Heaters			
heater body	Minor	Operative	Dents due to overturning
pipe connections	Minor	Operative	Secondary damage due to legs
supports	Moderate	Inoperative	Collapse of legs
Plumbing Fixtures	Minor	Operative	Fixture loosened from mounts

Table 7

Recorded Earthquake Damage to Essential
Service Systems - Environmental Control

(1) Essential Service System	Relative (2) Degree of Damage	(3) Consequence of Damage	Most Frequently (4) Reported Type/Cause of Damage
ENVIRONMENTAL CONTROL			
Compressors (Air, Medical, Refrigeration)			
main unit	Minor	Operative	Generally secondary damage
pipe connections	Minor	Operative	Rupture due to relative movement
supports	Moderate	Operative	Vibration isolator failure
Fans (Air Supply, Exhaust)			
main unit	Minor	Operative	Damage due to unrestrained movement
supports	Moderate	Inoperative	Suspended and isolated supports failed
Chillers			
main unit	Minor	Operative	Some damage due to shearing of support
pipe connections	Minor	Operative	Some damage due to shearing of support
supports	Moderate	Inoperative	Excessive movement when unanchored
Boilers			
main unit	Minor	Operative	Damage due to unrestrained movement
pipe connections	Minor	Operative	Severed due to differential movement
supports	Moderate	Inoperative	Excessive movement when unanchored
Duct Network			
main distribution ducts	Minor	Operative	Swaying of long duct runs;
branch distr. ducts	Minor	Operative	Breakage at bends
Heat Exchangers			
main unit	Minor	Operative	No specific damage reported
pipe connection	Minor	Operative	"
supports	Minor	Operative	"
Chimneys, Flues & Vents	Moderate	Inoperative	Damage to boiler vent connections due to movement

Table 7 (cont'd)

(1) Essential Service System	(2) Relative Degree of Damage	(3) Consequence of Damage	(4) Most Frequently Reported Type/Cause of Damage
<u>ENVIRONMENTAL CONTROL (*Contd.*)</u>			
HVC and Fuel Piping			
pipes	Minor	Operative	Reported failures mostly at elbows & bends due to excessive differential movement.
fittings	Moderate	Inoperative	Reported failures mostly at elbows & bends due to excessive differential movement.
supports	Minor	Operative	Hanger assembly failures
Pumps			
main unit	Minor	Operative	No specific damage reported
pipe connections	Minor	Operative	Rupture due to relative movement
supports	Moderate	Inoperative	Excessive movement of unanchored supports
Condensers			
main unit	Unknown	Unknown	No specific damage reported
pipe connections	Unknown	Unknown	"
supports	Unknown	Unknown	"

Table 8

Recorded Earthquake Damage to Essential Service Systems - General Services

Essential Service System (1)	Relative Degree of Damage (2)	Consequence of Damage (3)	Most Frequently Reported Type/Cause of Damage (4)
GENERAL SERVICES			
People Movers			
Elevators - Traction Type	Major	Inoperative	
guide rails	Major	Inoperative	Broken
motor-generators	Major	Inoperative	M-g units moved off their mounts
counterweights	Major	Partially Inoperative	Jumped out of guide rails
control panels	Moderate	Partially Inoperative	Fell when not anchored to the floor or wall
car	Minor	Partially Inoperative	Out of alignment/falling weights
support system		Operative	
Elevators - Hydraulic Type	Minor	Operative	No specific damage reported
Escalators	Minor	Operative	"
machine and drive	Minor	Operative	"
controllers	Minor	Operative	"
trusses & tracks	Minor	Operative	"
Communication System			
intercom/pa system	Moderate	Partially Inoperative	Broken wires
telephone equipment	Moderate	Partially Inoperative	Broken wires
switchboards	Minor	Operative	No specific damage reported

The information on design/evaluation that was obtained from the investigation is summarized in tables 9 through 18. Tables 9 through 13 are intended to show the extent of code and standard coverage for the components of building service systems and to indicate the availability of design guides, analytical procedures and physical test methods. Each one of the five tables contains information pertinent to one of the five service systems included in this study. The first column lists the major components of the essential service systems (i.e. fire protection, emergency power, sanitation and water supply, environmental control and general services). The second and third columns present the damage history of these components as interpreted from the information documented in references 2, 8, 9, and 10 and that were obtained through direct contact with design engineers and architects. The frequency of occurrence of earthquake damage entries (second column) was established subjectively as the source documents generally did not contain numerical summaries of the damage incurred by each component in each building surveyed. Only for components in traction-type elevators is a numerical damage summary presented [9]. Thus, the frequencies of occurrence were established by comparing the qualitative summaries presented in the above-mentioned reports for the various components. A three-level (i.e. low, medium, high) scale was used. The relative degree of damage data presented in the third column of tables 9 through 13 is a repeat of the second column of tables 4 through 8. The rationale for the establishment of these qualitative summaries was presented in section 4.2.

The fourth column of tables 9 through 13 indicates whether specific aseismic design requirements are cited in a code, standard, or other regulatory document for the listed components. The fifth column indicates whether there

TABLE 9 - AVAILABLE TOOLS FOR THE DESIGN OF FIRE PROTECTION SYSTEMS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Essential Service System	Frequency of Occurrence of Earthquake Damage to the Essential Systems	Relative Degree of Damage Sustained by the Systems in Documented Earthquakes	1/ Covered by Code or Standard Requirements	1/ Applicable Design Guides and Recommended Practice	Existing Analytical Procedure		Applicable Physical Test Procedures	Usual Method of Assembly of Components	
					Cited in a Code	Cited in a Reference Source		Field Assembly of Components	Pre-Assembled or Packaged Component
FIRE PROTECTION									
Sprinkler System	Low	Minor	Yes	Yes	No	No	None	X	
risers	Low	Minor	Yes	Yes	No	No	None		
distribution mains	Low	Minor	Yes	Yes	No	No	None		
valves	Low	Minor	Yes	No	No	No	None		X
branch pipes	Low	Minor	Yes	Yes	No	No	None		X
sprinkler heads & controls	Low	Minor	No	No	No	No	None		
support hangers, bracing & clamps	Low	Minor	Yes	Yes	No	No	None		
Standpipes	Low	Minor	Yes	Yes	No	No	None		
mains	Low	Minor	Yes	Yes	No	No	None		
risers	Low	Minor	Yes	Yes	No	No	None		
clamps & hangers	Low	Minor	Yes	Yes	No	No	None		
Pumps	Low	Minor	--- 1a/	---	No	No	None		
main unit	Low	Minor	No	No	No	No	None		
pipe connections	Low	Minor	No	No	No	No	None		X
supports	Low	Moderate	Yes	Yes	No	No	None	X	
Pressure Tanks	Low	Minor	---	---	No	No	None	X	
tank	Low	Minor	No	No	No	No	None		
supports	Low	Moderate	Yes	Yes	No	No	None	X	
Suction Tanks	Low	Minor	---	---	No	No	None		
tank	Low	Minor	No	No	No	No	None		X
supports	Low	Minor	Yes	Yes	No	No	None	X	

1/ See table 14

1a/ --- Denotes that no entry is appropriate

TABLE 10 - AVAILABLE TOOLS FOR THE DESIGN OF EMERGENCY POWER SYSTEMS

(1) Essential Service System	(2) Frequency of Occurrence of Earthquake Damage to the Essential Systems	(3) Relative Degree of Damage Sustained by the Systems in Documented Earthquakes	(4) 2/Covered by Code or Standard Requirements	(5) 2/Applicable Design Guides and Recommended Practice	(6) Existing Analytical Procedure	(7)	(8) Applicable Physical Test Procedures	(9) Usual Method of Assembly of Components	(10)
					Cited in a Code	Cited in a Reference Source		Field Assembly of Components	Pre-Assembled or Packaged Component
EMERGENCY POWER									
Motor-Generator Set									
motor & generator	Low	Moderate	No	No	No	No	None		X
cooling components									
-radiator	Low	Minor	No	No	No		None		X
-piping	Low	Minor	No	No	Yes [36]	No	None	X	
controls	Low	Minor	No	No	No	No	None		X
fuel piping	Low	Minor	No	No	Yes [36]	No	None	X	
starting batteries	Low	Minor	No	Yes	No	No	None		X
mufflers	Low	Minor	No	Yes	No	No	None		X
supports	Low	Moderate	Yes	Yes	No	No	None	X	
Transformers									
main unit	Low	Minor	No	No	No	No	None		X
wiring connections	Low	Minor							
supports	Medium	Moderate	Yes	Yes	No	No	None		
Switchgear									
main unit	Low	Moderate	No	No	No	No	None		X
conduits	Low	Minor		Yes	No	No	None		
supports	Medium	Moderate	Yes	Yes	No	No	None		
Panelboards									
housing	Low	Minor		Yes					X
conduits	Low	Moderate		Yes	No	No	None		
supports	Medium	Moderate	Yes	Yes	No	No	None	X	
Elec. Distribution Network									
busducts	Low	Minor	Yes	Yes	No	No	None	X	
feeders	Low	Minor	Yes	Yes	No	No	None	X	
connectors	Low	Minor	Yes	Yes	No	No	None		
supports	Low	Minor	Yes	Yes	No	No	None	X	
Lighting									
lighting fixtures -recessed units	Medium	Moderate	Yes	Yes	No		Yes [18]&[31]	X	
-surface-mounted units	Low	Minor	Yes	Yes	No		Yes [18]&[31]	X	
-stem and chain suspended units	High	Major	Yes	Yes	No		Yes [18]&[31]	X	

2/ See Table 15

TABLE 11 - AVAILABLE TOOLS FOR THE DESIGN OF SANITATION & WATER SUPPLY SYSTEMS

(1) Essential Service System	(2) Frequency of Occurrence of Earthquake Damage to the Essential Systems	(3) Relative Degree of Damage Sustained by the Systems in Documented Earthquakes	(4) 3/Covered by Code or Standard Requirements	(5) 3/Applicable Design Guides and Recommended Practice	(6) Existing Analytical Procedure: Cited in a Code	(7) Existing Analytical Procedure: Cited in a Reference Source	(8) Applicable Physical Test Procedures	(9) Usual Method of Assembly of Components: Field Assembly of Components	(10) Usual Method of Assembly of Components: Pre-Assembled or Packaged Component
SANITATION & WATER SUPPLY									
Pumps and Motors	---	---	---	---	No	No	None		
pump-motor unit	Low	Minor	No	No	No	No	None		X
pipe connections	Medium	Minor	No	No	No	No	None	X	
supports	Medium	Moderate	Yes	Yes	No	No	None	X	
Hot & Cold Water Storage Tanks	---	---	---	---	No	No	None		
tank body	Low	Minor	No	No	No	No	None		X
pipe connections	Medium	Minor	No	No	No	No	None	X	
supports	Medium	Moderate	Yes	Yes	No	No	None	X	
Piping (Air, Steam, Vacuum, Gas)								X	
pipes	Low	Minor	Yes		Yes [36]	Yes [33,41]	None	X	
fittings	Medium	Moderate	Yes		Yes [36]	Yes [33,41]	None		X
supports	Low	Minor			Yes [36]	No	None	X	
Water Heaters									
heater body	Low	Minor	No	No	No	No	None		X
pipe connections	Low	Minor	No	No	No	No	None	X	
supports	Medium	Moderate	Yes	Yes	No	No	None	X	
Plumbing Fixtures	Low	Minor	No	No	No	No	None		

3/See Table 16

TABLE 12 - AVAILABLE TOOLS FOR THE DESIGN OF ENVIRONMENTAL CONTROL SYSTEMS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Essential Service System	Frequency of Occurrence of Earthquake Damage to the Essential Systems	Relative Degree of Damage Sustained by the Systems in Documented Earthquakes	4/ Covered by Code or Standard Requirements	4/ Applicable Design Guides and Recommended Practice	Existing Analytical Procedure		Applicable Physical Test Procedures	Usual Method of Assembly of Components	
					Cited in a Code	Reference Source		Field Assembly of Components	Pre-Assembled or Packaged Component
<u>ENVIRONMENTAL CONTROL</u>									
Compressors (Air, Medical Refrigeration)	---	---	---	---	No	No	None		
main unit	Low	Minor	No	No	No	No	None		X
pipe connections									
supports	Medium	Moderate	Yes	Yes	No	No	None		
Fans (Air Supply, Exhaust)									
main unit	Low	Minor	No	No	No	No	None		X
supports	Medium	Moderate	Yes	Yes	No	No	None		
Chillers	---	---							
main unit	Low	Minor	No	No	No	No	None		X
pipe connections	Low	Minor							
supports	Low	Moderate	Yes	Yes	No	No	None	X	
Boilers									
main unit	Low	Minor	No	No					
pipe connections	Medium	Minor							
supports	Medium	Moderate	Yes	Yes	No	No	None	X	
Duct Network									
main distribution ducts	Low	Minor	Yes	Yes			None		
branch dis. ducts	Low	Minor	Yes	Yes			None		
Heat Exchangers	---								
main unit	Low	Minor							X
pipe connection	Low	Minor							
supports	Medium	Minor		Yes					
Chimneys, Flues & Vents	Medium	Moderate	Yes	Yes	No	No	None	X	
HVC & Fuel Piping	---	---	Yes	Yes					
pipes	Low	Minor	Yes	Yes	Yes	Yes [33,41]			
fittings	Low	Moderate	Yes	Yes	Yes	Yes [33,41]			
supports	Low	Moderate	Yes	Yes	Yes				
Pumps									
main unit	Low	Minor	No	No	No	No	None		X
pipe connections	Low	Minor	No	No					
supports	Medium	Moderate	Yes	Yes	No	No	None		
Condensers									
main unit									
pipe connections									
supports									

4/ See Table 17

TABLE 13 - AVAILABLE TOOLS FOR THE DESIGN OF GENERAL SERVICES SYSTEMS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Essential Service System	Frequency of Occurrence of Earthquake Damage to the Essential Systems	Relative Degree of Damage Sustained by the Systems in Documented Earthquakes	5/Covered by Code or Standard Requirements	5/ Applicable Design Guides and Recommended Practice	Existing Analytical Procedure		Applicable Physical Test Procedures	Usual Method of Assembly of Components	
					Cited in a Code	Cited in a Reference Source		Field Assembly of Components	Pre-Assembled or Packaged Component
GENERAL SERVICES									
People Movers									
elevators - traction type	High	Major	Yes	No	No	No	None	X	
-guide rails	Medium	Major	Yes	No	No	No	None		X
-motor-generators	Medium	Major	No	No	No	No	None		X
-counterweights	High	Minor	Yes	No	No	No	None		X
-control panels	Low	Moderate	No	No	No	No	None		X
-cars	Medium	Minor	Yes	No	No	No	None		X
-support system	Low	Minor	Yes	No	No	No	None	X	
elevators - hydraulic type	Low	Minor	Yes	No	No	No	None	X	
escalators	Low	Minor	No	No	No	No	None	X	
-machine & drive	Low	Minor	No	No	No	No	None		X
-controllers	Low	Minor	No	No	No	No	None		X
-trusses & tracks	Low	Minor	No	No	No	No	None		X
Communication System	Low	Moderate	Yes	No	No				
intercom/pa system	Low	Moderate	Yes	No	No	No	Yes [15]	X	
telephone equipment	Low	Moderate	Yes	No	No	No	Yes [15]	X	
switchboards	Low	Moderate	Yes	No	No	No	Yes [15]		X

5/See Table 18

are guides or manuals of recommended practice pertaining to the design of service system components and their attachment systems. In the process of classifying documents, Chapter 4 in reference 6 is classified in this study as a design guide in that the recommended provisions are a model by which local jurisdictions can adopt aseismic requirements for nonstructural building systems.

The names of the codes and standards containing aseismic design provisions are listed in tables 14 through 18 adjacent to the components of each system. The numbers in parentheses in these tables correspond to the list of references at the end of this report. As was discussed in section 3.2 of this report, the aseismic design methods adopted by the codes and standards (references 12, 16, 21, 30 and 37) involve the calculation of an equivalent static force. The force is to be applied to the center of gravity of the equipment and the supports must be sized to resist the seismic force. Thus, in many cases the fourth column of tables 9-13 will show a yes entry for code requirements covering design of the support while showing a no entry for the main unit. A case in point is the fourth column of tables 9-13 entries for pumps in table 9.

Tables 14 through 18 also give the names and reference numbers of the applicable guides and manuals of recommended practice. Most of the code and standard requirements mentioned in tables 14 through 18 have been newly adopted or revised since 1971. Therefore, some of the components for which medium or high frequency of occurrence of damage and moderate or major degree of damage are given in tables 9 through 13 were not covered by earthquake resistant design requirements at the times of the Great Alaska (1964) and San Fernando (1971) earthquakes. For example, prior to 1971, there was not

TABLE 14 - IDENTIFICATION OF AVAILABLE CODES & DESIGN GUIDES - FIRE PROTECTION SYSTEM

Essential Service System	Name of Code or Standard [Reference No.]	Design Guides [Reference No]
FIRE PROTECTION		
Sprinkler System	Nat'l. Fire Code-Vol. 13, Chap.3 [26]; State of Calif.-Title 17 [12]; San Francisco Bldg Code [30]	Nat'l. Fire Code-Vol. 13, Appen.13 [26]; ATC-3, Chap. 4 [6]
risers	Same As Above	Same As Above
distribution mains	Same As Above	Same As Above
valves	Same As Above	Same As Above
branch pipes	Same As Above	Same As Above
sprinkler heads & controls	-	-
support hangers, bracing & controls	Same As Above	Same As Above
support hangers, bracing & clamps	Same As Above	Same As Above
Standpipes	Nat'l. Fire Code-Vol. 13, Chap.3 [26]; State of Calif.-Title 17	Nat'l. Fire Code-Vol. 13, App. 13 [26]; ATC-3, Chap. 4 [6]
mains	Same As Above	Same As Above
risers	Same As Above	Same As Above
clamps & hangers	Same As Above	Same As Above
Pumps		
main unit	Not Applicable	Not Applicable
pipe connections		
supports	San Francisco Bldg. Code [30]; State of Calif. Admin. Code Title 17 [12]; Tri-Services Manual [36]; UBC [37] L.A. Bldg. Code [21]	ATC-3, Chapter 4 [6]
Pressure Tanks		
tank		
supports	San Francisco Bldg. Code [30]; State of Calif. Admin. Code Title 17 [12]; Tri-Services Manual [36]; UBC [37]; L.A. Bldg. Code [21]	ATC-3, Chapter 4 [6]
Suction Tanks		
tank		
supports	San Francisco Bldg. Code [30]; State of Calif. Admin. Code Title 17 [12]; Tri-Services Manual [36]; UBC) [37]; L.A. Bldg. Code [21]	ATC-3, Chapter 4 [6]

TABLE 15 - IDENTIFICATION OF AVAILABLE CODES & DESIGN GUIDES - EMERGENCY POWER SYSTEM

Essential Service System	Name of Code or Standard [Reference No.]	Design Guides [Reference No.]
EMERGENCY POWER		
Motor-Generator Set		
motor & generator	Not Applicable	Not Applicable
- radiator	" "	" "
- piping	" "	" "
controls	" "	" "
fuel piping	" "	ATX-3, Chapter 4 [6]
starting batteries	" "	
mufflers		
supports	VA Hankbook H08-8 [16] ; Calif. Admin. Code-Title 17[12] ; Tri-Services Manual [36] ; San Francisco Bldg. Code [30]	ATC-3, Chapter 4 [6]
Transformers		ATC-3, Chapter 4 [6]
main unit		Same As Above
wiring connections		Same As Above
supports	VA Handbook H08-8 [16] ; Calif. Admin. Code-Title 17 [12] ; Tri-Services Manual [36] ; San Francisco Bldg. Code [30]	
Switchgear		ATC-3, Chapter 4 [6]
main unit		
conduits		Same As Above
supports	San Francisco Bldg. Code [30] ; Handbook H08-8 [16] ; Calif. Admin Code-Title 17 [12] ; Tri-Services Manual [36]	Same As Above
Panelboards		ATC-3, Chapter 4 [6]
housing		Same As Above
conduits		Same As Above
supports	San Francisco Bldg. Code [30] ; Handbook H08-8 [16] ; Calif. Admin Code-Title 17 [12] ; Tri-Services Manual [36]	
Elec. Distribution Network	San Francisco Bldg. Code [30] ; VA Handbook H08-8 [16] ; Calif. Admin. Code-Title 17 [12]	ATC-3, Chapter 4 [6]
busducts	Same As Above	Same As Above
feeders	Same As Above	Same As Above
connectors	Same As Above	Same As Above
supports	Same As Above	Same As Above
Lighting		
lighting fixtures	Tri-Services Manual [36] ; Calif. Admin. Code-Title 17 [12]; RGA 12-69 [20] ; VA Handbook H08-8 [16]	ATC-3, Chapter 4 [6]
- recessed	Tri-Services Manual [36] ; Calif. Admin. Code-Title 17 [12]; VA Handbook H08-8 [16]	Same As Above
- surface-mounted	Tri-Services Manual [36], VA Handbook H08-8 [16]; Calif. Admin. Code-Title 17 [12]	Same As Above
- stem and chain suspended	Tri-Services Manual [36], RGA 12-69 [20]; VA Handbook H08-8 [16] Calif. Admin. Code-Title 17 [12]	Same As Above

TABLE 16 - IDENTIFICATION OF AVAILABLE CODES & DESIGN GUIDES - SANITATION & WATER SUPPLY SYSTEM

Essential Service System	Name of Code or Standard [Reference No.]	Design Guides [Reference No.]
SANITATION & WATER SUPPLY		
Pumps and Motors		
main unit	Not Applicable	Not Applicable
pipe connections	" "	" "
supports	VA Hankbook H08-8 [16]; Calif. Admin. Code-Title 17[12]; San Francisco Bldg. Code [30]; Tri-Services Manual [36]	ATC-3, Chapter 4 [6]
Hot & Cold Water Storage Tanks		
tank body	Not Applicable	Not Applicable
pipe connections	" "	" "
supports	VA Handbook H08-8 [16]; UBC [37]; Calif. Admin Code-Title 17 [30]; San Francisco Bldg. Code [30]; Tri-Services Manual [36]	ATC-3, Chapter 4 [6]
Piping (air, steam, vacuum, gas)	VA Handbook H08-8 [16]; Calif. Tri-Services Manual [36]	ATC-3, Chapter 4 [6]; Tri-Services Manual, Appen. H [36]
pipes	Same As Above	
fittings	Same As Above	
supports	Same As Above	
Water Heaters		
heater body	Not Applicable	Not Applicable
pipe connections	" "	" "
supports	VA Handbook H08-8 [16]; Calif. Admin. Code-Title 17 [12]	ATC-3, Chapter 4 [6]
Plumbing Fixtures		

TABLE 17 - IDENTIFICATION OF AVAILABLE CODES & DESIGN GUIDES - ENVIRONMENTAL CONTROL SYSTEM

Essential Service System	Name of Code or Standard [Reference No.]	Design Guides [Reference No.]
ENVIRONMENTAL CONTROL		
Compressors (Air, Medical, Refrigeration)		
main unit	Not Applicable	Not Applicable
pipe connections		
supports	VA Handbook H08-8 [16]; Calif. Ad Code, Title 17 [12]; Tri-Serv. Manual [36] ; San Francisco Bldg. Code [30]	ATC-3, Chapter 4 [6]
Fans (Air Supply, Exhaust)		
main unit		
supports	VA Handbook H08-8 [16] ; Calif. Ad Code, Title 17 [12]; Tri-Serv. Manual [36]; San Francisco Bldg. Code [30]	ATC-3 Chapter 4 [6]
Chillers		
main unit		
pipe connections		
supports	VA Handbook H08-8 [16]; Calif. Ad Code, Title 17 [12]; Tri-Serv. Manual [36]; San Francisco Bldg. Code (26)	
Boilers		
main unit		
pipe connections		
supports	VA Handbook H08-8 [16]; Calif. Ad Code, Title 17 [12]; Tri-Serv. Manual [36]; San Francisco Bldg. Code [30]	ATC-3, Chapter 4 [6]
Duct Network		
main distribution ducts	Tri-Services Manual [36]	ATC-3 Chapter 4 [6]
branch distribution ducts	Tri-Services Manual [36]	ATC-3 Chapter 4 [6]
Heat Exchangers		
main unit		
pipe connection		
supports	VA Handbook H08-8 [16]; Calif. Ad Code, Title 17 [12]; Tri-Serv. Manual [36]; San Francisco Bldg. Code [30]	ATC-3 Chapter 4 [6]
Chimneys, Flues & Vents	UBC [37]; Calif. Ad Code Title 17 [12] L.A. Bldg. Code [20] San Francisco Bldg Code [30]	ATC-3 Chapter 4 [6]
HVC and Fuel Piping	Tri-Services Manual [36]; VA Handbook H08-8 [16]; Calif. Admin. Code-Title 17 [12]	ATC-3 Chapter 4 [6]
pipes	Same As Above	Same As Above
fittings	Same As Above	Same As Above
supports	Same As Above	Same As Above
Pumps		
main unit		
pipe connections		
supports	Tri-Services Manual [36]; VA Handbook H08-8 [16]; Calif. Ad. Code, Title 17 [12]	ATC-3, Chapter 4 [6]
Condensers		
main unit		
pipe connections		
supports	Tri-Services Manual [36]; VA Handbook H08-8 [16]; Calif. Admin. Code-Title 17 [12]	ATC-3 Chapter 4 [6]

TABLE 18 - IDENTIFICATION OF AVAILABLE CODES & DESIGN GUIDES - GENERAL SERVICES SYSTEM

Essential Service System	Name of Code or Standard [Reference No.]	Design Guides [Reference No.]
GENERAL SERVICES		
People Movers		
elevators - traction type	San Francisco Bldg. Code [30] ; State of Calif. Title 17 [12] ; VA Handbook H08-8 [16]	
guide rails	Same As Above	
motor-generators		
counterweights	Same As Above	
control panels		
cars	Same As Above	
support system	Same As Above	
elevators - hydraulic type	Same As Above	
escalators		
machine and drive		
controllers		
trusses and tracks		
Communication System	State of Calif. Title 17 [12]; VA Handbook H08-8 [16]	ATC-3, Chapter 4 [6]
intercom/pa system	Same As Above	Same As Above
telephone equipment	Same As Above	Same As Above
switchboards	Same As Above	Same As Above

in existence any code or standard governing the seismic design of elevator components. It should also be noted that tables 14 through 18 do not reference the "IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations" [17]. The omission is because the design philosophies applicable to nuclear power generating stations may differ considerably from the philosophies regarding hospital service system equipment. It is necessary to evaluate both sets of design philosophies before attempting to transfer nuclear power design technology to hospital service system equipment design.

The sixth and seventh columns of tables 9 through 13 indicate whether there were any analytical procedures found in the literature--either in codes or other reference sources--which are applicable to the listed components. As shown in the tables, analytical procedures are cited for piping systems in the Tri-Services Manual [36], in an article by Watwood et al. [41] and in a report by Shipley et al. [33]. The Tri-Services method uses the equivalent static force formulation and seems to be more generally applicable to building service systems than the method discussed by Watwood et al. The latter method involves a dynamic analysis of nuclear power piping, with particular emphasis on nuclear class I and II piping. The prediction of seismic response of light secondary systems--including light mechanical or electrical equipment and piping--is the subject of a paper by Singh and Ang [34]. In this paper a decoupled stationary random vibration model is developed for predicting the systems' response to strong motion earthquakes. The method is primarily intended for analyzing secondary systems in nuclear power plants, where the requirements in RDT F9-2T [28] call for dynamic analyses. Nevertheless, the analytical procedures described by Singh and Ang are based on random vibration theory and seem applicable to some building service systems as well. Of particular interest in the analysis of building service systems is a discussion by Singh and Ang of the effect on the predicted response of decoupling the structural and nonstructural systems (i.e., ignoring the dynamic interaction between these two systems).

The eighth column of tables 9 through 13 is intended to show whether methods of testing the service system components have been documented in the literature. Compliance testing is recognized as an alternative to analytical procedures for gaining approval from building regulatory organizations for the use of systems and components. The only components for which test methods are standardized and documented are light fixtures. As discussed in section 3.2, both Los Angeles RGA 12-69 [20] and the Tri-Services Manual [36] describe a shaker-table test for evaluating light fixture assemblies.

In addition, DeCapua and Hetman [15] have derived a procedure for establishing hydraulic shaker-table tests for communications equipment. The procedure is primarily intended for establishing a region-dependent, simulated earthquake test environment for equipment housed in multi-story telephone buildings. Nevertheless, much of the methodology seems applicable to telephone equipment located in hospital facilities. DeCapua and Hetman first established upper-bound response spectra by examining the in-building response of a number of telephone building types. Then they digitally generated an artificial earthquake accelerogram to match the characteristics of the upper-bound response spectra. To account for variations in earthquake hazards across the country, a scaling technique was applied to the synthesized acceleration time history. The simulated time history was then converted to a displacement history for use on a hydraulic shaker-table.

The ninth and tenth columns of tables 9 through 13 use check marks to indicate which components are assembled at the building site and which ones are pre-assembled or packaged before being delivered to the site. These classifications are important when identifying who has the responsibility for the aseismic design of the components and for establishing the type of code or standard requirements governing the seismic performance of the components. For example, the earthquake-resistant design of a packaged unit such as a compressor may be explicitly covered by manufacturer, industry, federal, etc., specifications and standards while the equipment's supports may be designed according to building code regulations such as UBC [37].

4.3.2 Conclusions

The following observations are made in summarizing this review.

(1) Codes and standards are largely deficient in aseismic provisions for pre-assembled equipment such as compressors, pumps and storage tanks. The equivalent static force analysis adopted in the present edition of the codes applies primarily to the design of equipment supports and attachment devices.

(2) There is a scarcity of documented analytical methods with which to predict the seismic response of building service system components. Analytical procedures for the evaluation of piping systems are the major exception to this deficiency. However, most of the present analytical development in the piping area is aimed at critical equipment in nuclear power plants. A dynamic analysis method for light secondary systems in nuclear power plants was found to have potential application to some building service system components.

(3) The largest deficiency is in the area of physical test procedures. Currently, there are dynamic test methods available for evaluating lighting fixture assemblies. The adequacy of these methods may be questionable; the damage summary tables of section 4.2 indicate that one category of lighting fixture has been highly susceptible to major damage in recent documented earthquakes, despite the fact that the fixtures were approved through the use of a dynamic test.

(4) Although Ayres et al. [10] and Merz [24] have offered some recommendations for improved design and installation practice, there are very few design guides and manuals of recommended practice currently available for the use of architects and design engineers. The NFPA Standard [26] contains some widely accepted installation practices and bracing details for sprinkler system design for earthquake resistance. The GSA report [2] presents some recommendations and some typical installation details which are intended to mitigate seismic damage.

5. RESEARCH RECOMMENDATIONS

A list of research needs was arrived at as the result of review of current literature and discussion with designers and government agencies. The following seven research areas are recommended for further study:

RECOMMENDATION 1 - Research should be undertaken to develop standardized compliance tests for mechanical and electrical equipment.

It is of little use for the structural engineer to design the anchorage for the mechanical and electrical equipment to survive the seismic lateral and vertical forces if the eqipment's housing and/or internal components cannot adequately resist these forces. The need for physical test methods is made explicit by the tables in section 4.3. It is therefore, recommended that research be initiated toward the development of new or the modification of existing standard test methods for many of the critical electrical and mechanical equipment elements identified in this report.

RECOMMENDATION 2 - More input to the process of determining capacity and operating time requirements of emergency systems necessary.

As indicated in paragraph 3.3.4, the hospital operations subcommittee, in particular, is currently trying to define those activities and supporting services considered essential to the continued functioning of the hospital following the occurrence of an earthquake.

There are two basic parts that require further clarification. First, a determination must be made as to what extent the essential systems in a hospital must be post-earthquake operational. For example, what percentage of the normal hospital electrical load must the emergency power system be able to supply? Secondly, the length of time required for the essential systems to be functional in an emergency mode following the occurrence of an earthquake must be established.

Compounding this problem area is the uncertainty of assessing how badly the community itself would be damaged by the earthquake. Such things as the probable damage incurred by the community's utility systems, transportation network, and other hospitals have to be considered in establishing a solution to this problem. In addition, cost effectiveness of the solutions must be considered.

RECOMMENDATION 3 - A study is needed to determine the applicability of current aseismic design criteria to the retrofit of existing hospitals.

As a result of the above-mentioned field visits, personal contacts and literature survey, it was found that there is an apparent excess number of hospital beds currently available in areas highly susceptible to earthquake activity. Therefore, there is not likely to be many new hospitals built in these areas in the foreseeable future. Thus, retrofitting older hospitals for seismic resistance is a major concern among hospital administrators, community planners, architects and engineers.

Part of the problem is that it is not feasible, from a technical point of view, to extend the useful life of hospitals constructed prior to the adoption of new aseismic provisions beyond the period which was originally designated. In addition, not every modification necessary for upgrading an old hospital to the new aseismic design standards can be made because of the interconnection between the building elements.

RECOMMENDATION 4 - A study is needed to resolve the conflicting requirements of isolating vibrating and noisy mechanical equipment from the structure and of anchoring the equipment against excessive movement.

Large pieces of mechanical equipment such as pumps, boilers, chillers and cooling towers are often installed on the roofs and upper floors of hospital buildings. To attenuate the vibration and noise transmission to patient areas, various types of vibration isolation devices are placed between the equipment and the supporting structural element. Generally, these isolation devices are not bolted to the floor slab, wall, column, etc. As a result, large horizontal and vertical displacements may occur when the structure is subjected to seismic forces. As indicated in the tables of section 4.2, the predominant cause of damage to mechanical equipment in recent earthquake reports was the unrestrained movement of the support assemblies. The conflicting requirements of vibration isolation and equipment anchorage need to be thoroughly investigated with the objective of developing a set of installation and remedial guidelines.

RECOMMENDATION 5 - Research aimed at the development of design guides for the sizing and spacing of pipe bracing should be undertaken.

It is recognized that all pipes within a building may not need to be braced against seismic forces to ensure the post-earthquake functioning of piping systems. A dynamic analysis of the various piping systems would determine which piping runs require bracing. Such analyses - as are conducted for nuclear power plants - are generally not economically feasible in building design. The research program would involve the mathematical modeling of typical piping systems and the analysis of the effect of the various bracing strengths and spacings on the response of the systems. Based on the research effort, a design guide could be developed for locating and sizing bracing members.

RECOMMENDATION 6 - Research is needed to develop an improved acceptance test for suspended lighting fixtures and their supports.

As indicated in table 5, stem-and chain-suspended lighting fixtures have incurred major damage in recent earthquakes. Ironically, lighting fixtures are one of the few pieces of equipment for which there is an existing test method (see tables 9-13). However, some procedural deficiencies in the test method have been noted in the literature [8,9, and 10]. A laboratory investigation could examine these deficiencies, while utilizing the test apparatus and test setups described in the City of Los Angeles RGA 12-69 [20] and the and the Tri-Services Manual, TM 5-809 -10 [36].

RECOMMENDATION 7 - An analytical evaluation of the force factors (C_p values) used in design of supports for nonstructural elements is needed.

As indicated in section 3.2, the basis for the C_p values listed in most seismic codes has not been adequately explained. The lack of understanding of the factors which influence the C_p values is a shortcoming in the state-of-the-art in that the C_p value is central to the Equivalent Static Force method of design/analysis. The recommended research would seek to evaluate the basis and adequacy of the current values. The range of dynamic forces applicable to various nonstructural elements would be established. C_p values could be analyzed to determine their sensitivity to various parameters. Then equivalent static forces which account for the dynamic effects could be derived.

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