FEDERAL EMERGENCY MANAGEMENT AGENCY FEMA 152 / NOVEMBER 1988

SEISMIC CONSIDERATIONS APARTMENT BUILDINGS

EARTHQUAKE HAZARDS REDUCTION SERIES 37

BSSC PROGRAM ON IMPROVED SEISMIC SAFETY PROVISIONS

SEISMIC CONSIDERATIONS: APARTMENT BUILDINGS

BUILDING
SEISMIC
SAFETY
COUNCIL

BUILDING SEISMIC SAFETY COUNCIL

The Building Seismic Safety Council (BSSC) is an independent, voluntary body that was established under the auspices of the National Institute of Building Sciences (NIBS) in 1979 as a direct result of nationwide interest in the seismic safety of buildings. Its membership (see inside back cover) represents a wide variety of building community interests. Its fundamental purpose is to enhance public safety by providing a national forum that fosters improved seismic safety provisions for use by the building community in the planning, design, construction, regulation, and utilization of buildings. To fulfill its purpose, the BSSC:

- Promotes the development of seismic safety provisions suitable for use throughout the United States;
- Recommends, encourages, and promotes the adoption of appropriate seismic safety provisions in voluntary standards and model codes;
- Assesses progress in the implementation of such provisions by federal, state, and local regulatory and construction agencies;
- Identifies opportunities for improving seismic safety regulations and practices and encourages public and private organizations to effect such improvements;
- Promotes the development of training and educational courses and materials for use by design professionals, builders, building regulatory officials, industry representatives, other members of the building community, and the public;
- Advises government bodies on their programs of research, development, and implementation; and
- Periodically reviews and evaluates research findings, practices, and experience and makes recommendations for incorporation into seismic design practices.

The BSSC's area of interest encompasses all building-type structures and includes explicit consideration and assessment of the social, technical, administrative, political, legal, and economic implications of its deliberations and recommendations. It believes that the achievement of its purpose is a concern shared by all in the public and private sectors; therefore, its activities are structured to provide all interested entities (for example, government bodies at all levels, voluntary organizations, business, industry, the design profession, the construction industry, the research community, and the general public) with the opportunity to participate. The BSSC also believes that the regional and local differences in the nature and magnitude of potentially hazardous earthquake events require a flexible approach to seismic safety that allows for consideration of the relative risk, resources, and capabilities of each community.

The BSSC is committed to continued technical improvement of seismic design provisions, assessment of advances in engineering knowledge and design experience, and evaluation of earthquake impacts. It recognizes that appropriate earthquake hazard reduction measures and initiatives should be adopted by existing organizations and institutions and incorporated, whenever possible, into their legislation, regulations, practices, rules, codes, relief procedures, and loan requirements so that these measures and initiatives become an integral part of established activities, not additional burdens. The BSSC itself assumes no standards-making and/or -promulgating role; rather, it advocates that standards-formulation organizations consider BSSC recommendations for inclusion into their documents and standards.

BSSC Program on Improved Seismic Safety Provisions

SEISMIC CONSIDERATIONS:

APARTMENT BUILDINGS

Developed by the
Building Seismic Safety Council
for the
Federal Emergency Management Agency

BUILDING SEISMIC SAFETY COUNCIL
Washington, D.C.
1988

FOREWORD

The Federal Emergency Management Agency (FEMA) is pleased to have sponsored this publication, one of a series of five devoted to the seismic safety of special types of buildings with special occupancy and functional characteristics (i.e., schools, lodging facilities, health care facilities, office buildings, and apartment buildings). Its objective is simply to strongly encourage owners, developers, designers, and regulatory officials concerned with such buildings to become aware of their particular seismic vulnerabilities and of cost-effective means to alleviate such vulnerabilities through the selective use of the *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings.*

Special thanks are due to the principal author of this publication, Earle Kennett, Nanita/Kennett Associates, Gaithersburg, Maryland, and to the BSSC staff and Board of Direction for their efforts in producing this series.

Federal Emergency Management Agency

ACKNOWLEDGMENTS

This document was made possible through very generous contributions of time and expertise on the part of many individuals. The Building Seismic Safety Council is particularly grateful to:

- Earle Kennett of Nanita/Kennett Associates, the principal author of this publication.
- Charles Achilles, Dorothy Walton, and David C. Nilges for their review and comments on behalf of the Institute of Real Estate Management.
- Christopher R. Clark and Stanley W. Crawley for their review and comments on behalf of the American Institute of Architects.

CONTENTS

OVERVIEW

A severe earthquake is one of nature's most terrifying and devastating events and collapsing buildings and falling debris do most of the killing. The Building Seismic Safety Council (BSSC) firmly believes that increased building earthquake resistance is in the best interest of all building owners and developers. Further, the Council is convinced that, once these individuals and organizations seriously consider the social, economic, and legal implications of the earthquake risk to their facilities and operations, they will actively support efforts to improve the seismic resistance of their buildings by requiring their designers to follow up-to-date seismic-resistant design guidelines in all earthquake-prone areas of the nation.

Many building owners and developers and property managers, like many Americans in general, tend to associate earthquakes only with California. They are unaware that earthquakes are a national hazard.

Location of damaging U.S. earthquakes.
(Reproduced from Christopher Arnold, 1984, "Quake Codes," Architectural Technology, Spring.)

Background and basic information is contained in Part I of this publication and more technical details are presented in Part II. Several appendixes provide information on related topics. For further information or assistance, call the BSSC's toll-free number:

1-800-66-NEHRP.

PART I

SEISMIC CONSIDERATIONS FOR APARTMENT BUILDING DECISIONMAKERS

1

EARTHQUAKES AND APARTMENT BUILDINGS

THE SEISMIC HAZARD

A severe earthquake is one of nature's most terrifying and devastating events, and collapsing buildings and falling debris do most of the killing. The major earthquake in Alaska in 1964, for example, released an amount of energy equivalent to 100 nuclear explosions of 100 megatons each, and the 1985 earthquake in Mexico City killed thousands of people. (See Appendix B for a description of apartment building damage as a result of the 1985 Mexico City earthquake.)

Many people assume that earthquakes are primarily confined to the West Coast when, in fact, more than 70 million Americans in 44 states are at some risk from earthquakes (see Figure 1 and Appendix A for a review of the seismicity of the United States).

Indeed, three of the more severe earthquakes in the United States occurred, not on the West Coast, but in the East and Midwest--in Charleston, South Carolina, in 1886; at Cape Anne, Massachusetts, in 1755; and in New Madrid, Missouri, in 1811-12. The New Madrid event involved a series of three major shocks that affected a 2 million square mile area which is equal to about two thirds of the total area of the United States, excluding Alaska. The Charleston earthquake also had a "felt" area of 2 million square miles.

Between 1900 and 1986, about 3,500 lives were lost as a result of earthquakes in the United States and property damage has amounted to approximately $5 billion (in 1979 dollars). Consider, however, the tremendous social and economic loss to the nation if just one earthquake comparable, for example, to the New Madrid event occurred today where several high-density urban areas stand in place of log cabins and Indian settlements. In St. Louis, for example, future earthquakes may cause far more damage than the earthquakes that occurred in the early nineteenth century when population density was low and there were no high-rise buildings. One needs to remember that there were only 2,000 people living in the St. Louis metropolitan area in 1811, as opposed to 2,400,000 today.

It must be recognized, however, that all areas of the country do not have the same risk. In many parts of the eastern United States, for example, wind load design requirements will override earthquake lateral force requirements. Nevertheless, there is a growing awareness of the need for earthquake-resistant building design in many areas of the country previously unconcerned about their risk.

Further complicating the national seismic problem is the fact that science and technology have not yet generated a technique for accurately predicting when an earthquake will occur. Earthquakes are therefore a natural hazard even more difficult to deal with from a life safety standpoint than hurricanes or floods since one has no relatively immediate warning and cannot evacuate the area. However, geologic studies on a nationwide basis are rapidly advancing knowledge on the probability and nature of future earthquakes. These studies should eventually provide a more precise basis for establishing the relationship between seismic risk and appropriate seismic design.

The way in which buildings are designed and constructed ultimately determines the probability and extent of earthquake damage, and observation and experimentation have generated a considerable amount of information on seismic-resistant design and construction. As a result of the study of buildings in and after earthquakes and experimental research in laboratories, where structures can be shaken to simulate the effects of earthquakes, a great deal is known about the relative safety of different types of construction. To accurately assess the seismic performance of a building requires considerable engineering expertise, but one need not be an expert to understand that a building constructed of bricks using poor quality mortar is much more likely to collapse than one that employs a well-engineered steel or reinforced concrete frame to provide integrity.

Nevertheless, since seismic safety is a complex issue that involves a relatively uncommon hazard and community values as well as life safety, this knowledge is not always applied even in areas of high risk. In California, for example, earthquakes have been a constant concern for many years and seismic building codes, although initially inadequate by today's standards, have been in effect for over 50 years. In other parts of the country, however, where the last major earthquake was well before anyone's memory, this is not so and even a moderate earthquake may cause devastating damage.

Apartment building earthquake problems originate in the safety of the building structure and its components (although damage to utility systems also may occur outside the building). A poorly designed structure may incur structural damage or collapse. If collapse occurs, there is a major disaster. Major structural damage, short of collapse, will result in evacuation as a precaution against later collapse, and the consequences of evacuation are a service and revenue loss--often for many weeks, months, or even years. Even without building collapse and injuries, earthquake damage to apartment building nonstructural systems, equipment and contents can approach 50 percent of the worth of the facility.

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AN APPROACH TO SEISMIC HAZARD MITIGATION AND THE COST/BENEFITS OF SEISMIC DESIGN

MITIGATING THE HAZARD

Because of the life safety and economic risks involved, apartment building owners and managers need to understand their local seismic situation to determine the seismic hazard. Once this is done, they will have a rational basis for deciding how much seismic risk they are willing to accept and the degree to which they wish to lessen the risk.

The use of comprehensive, authoritative seismic design provisions--especially the *NEHRP Recommended Provisions*--in developing requirements for apartment buildings generally is considered to be one significant way of lessening the risk to life by bringing to bear authoritative guidance for designing and constructing new buildings in a manner that will prevent their structural collapse during an earthquake.

Life Safety Considerations

Apartment building design must be concerned not only with life safety in terms of death or injury due to building collapse or property damage but also with the safe emergency egress of the inhabitants.

Although promulgation of a seismic building code based on statistical probabilities can contribute significantly to building and occupant safety in an earthquake, it is not possible to describe on firm scientific ground the strongest earthquake that might possibly occur at any specific location and, therefore, there always remains some degree of risk. This risk may be small, but it is always greater than zero.

For an individual building, designed in accordance with *NEHRP Recommended Provisions*, the goal is to provide a level of safety such that:

1. In the "design earthquake" (i.e., one that has only a 10 percent probability of being exceeded in 50 years), there will be limited structural damage. There may, however, be some nonstructural and contents damage but such damage should not

others, such as the ability to structurally evaluate a facility, also relate to design concepts. Although the basic strategy for reducing damage to an apartment facility involves design in accordance with appropriate seismic requirements like the *NEHRP Recommended Provisions*, it also involves an understanding by the design team of all the issues discussed in this publication.

The following guidelines are suggested as seismic performance goals for apartment buildings:

- The damage to the facility should be only what might be reasonably expected after a destructive earthquake and should be repairable and not life-threatening.

- Inhabitants and staff within and immediately outside the facility should be protected during an earthquake.

- Emergency utility systems in the facility should remain operational after an earthquake.

- Occupants should be able to evacuate the facility safely after an earthquake.

- Rescue and emergency workers should be able to enter the facility after an earthquake and should encounter only minimum interference and danger.

- The facility should be able to continue operations or become operational soon after an earthquake.

THE ECONOMICS OF SEISMIC DESIGN

Although the main purpose of seismic design is to save lives and prevent injuries, the decision to design against earthquakes and the setting of standards often is based on economic considerations: What is the cost and what are the benefits of reducing the risk of damage to our building?

Because apartment buildings provide housing, produce revenue for the owners and are expensive to build and operate, the economics of seismic design are particularly critical. Beyond the consideration of life loss, economic analysis on a conventional real estate basis can provide some useful guidance as to the effects of seismic design on apartment building economics.

The major factors influencing the increased costs of seismic design to comply with the *NEHRP Recommended Provisions* are:

- The complexity of the building form and structural framing system of the building--It is much more economical to provide

For the purposes of this example, consider a 200-unit apartment complex with a construction cost of $10,000,000 with 20 percent of the cost attributable to the structural and foundation system; 35 percent to the mechanical, plumbing, and electrical systems; and 45 percent to the architectural systems and components. The cost of seismic design is estimated to be 5 percent of the cost of the structural system or 1 percent of the total construction cost. (Note that construction cost represents only a portion of total project costs that also include design, land acquisition, and site development costs.)

Thus, the assumptions for this example are as follows:

- The apartment complex costs $10,000,000 to construct without seismic design and $10,100,000 to construct with seismic design.

- At the end of 25 years (with a 4 percent inflation rate), the complex without seismic design would be worth $26,660,000 and the complex with seismic design would be worth $26,926,600.

- In future dollars, the earthquake damage to the apartment complex without seismic design will be $3,999,800 (damage to 15 percent of the structure, 15 percent of the mechanical/electrical systems, and 15 percent of the architectural components) and to the complex with seismic design will be $1,066,400 (damage to 5 percent of the mechanical/electrical systems and architectural components).

- In future dollars, the lost revenue to the owner of the apartment complex without seismic design will be $431,892 (based on a loss of operational capability for 8 weeks assuming 90 percent occupancy at an average monthly rental rate of $450). The apartment complex with seismic design remains functional.

- The extra finance charges for the $100,000 investment for seismic design will be $230,000 in future dollars (25-year loan at 8 percent).

Thus, the total future extra costs of the apartment complex without seismic design would be $3,301,092 (-$266,600 in building worth,-$2,932,600 in damage repairs, -$431,892 in lost revenue, and +$330,000 for the principal and finance charges for the seismic investment), and a 15 percent investment would be needed to receive a similar return on the original seismic design investment (Figure 2). In other words, the apartment complex owner would have to invest $100,000 (the original cost of seismic design) at 15 percent per year for 25 years to be able to pay for apartment losses and repairs. This breaks down to probably no more than $500 per apartment, which, if carried forward 25 years, amounts to $20 per apartment per year.

apartment building owner who makes no reasonable provision for seismic design will be in a very tenuous legal situation when the earthquake occurs.

After the 1985 Mexico City earthquake, a Mexico resident sought justice in the case of the loss of his family in an apartment building that collapsed during the earthquake. His claims were based on an investigation of the design, materials, and construction of the particular building, and, as a result, the Mexican federal courts issued arrest warrants for the designers of the building. The case is reported to be the first to be brought against individuals responsible for deaths and injuries during an earthquake.

THE DESIGN/CONSTRUCTION TEAM

The need for space efficiency in an apartment building places a special burden on the design and construction team. In particular, the coordination of the structure with mechanical, electrical, and plumbing systems and equipment requires careful design and information exchange between the design consultants. The introduction of seismic design requirements further increases the demands on the team.

Effective team work starts with recognition by the owner of the special requirements of the building type. Seismic design starts at the inception of the building program, and appropriate seismic design decisions must be made at each phase of the design process. Because seismic performance is also dependent on construction quality and, in particular, on correct construction of critical details, the contractor also is an essential member of the team. Good seismic performance therefore requires understanding and correct decisionmaking by the owner, affects all participants in the design process, and ultimately depends on correct construction execution by the builder and the work force.

PART II

SEISMIC CONSIDERATIONS FOR APARTMENT BUILDING DESIGNERS

3

EARTHQUAKE DESIGN PROBLEMS FOR APARTMENT BUILDINGS

Although this publication is not intended as an engineering design manual, several problems of building design should be recognized by the apartment building owner, manager, planner, architect, and engineer as factors that may substantially increase the earthquake risk to an apartment building. Even though a few of these problems are addressed in seismic building codes, but their solution resides principally in the design/construction team's understanding of seismic-resistant design rather than in specific code provisions. Others, such as damage to building contents, are outside the scope of any seismic code. These problems are:

- Irregularities of the building form in both the horizontal and vertical planes,
- Discontinuities in strength between the major structural elements of the building,
- Inadequate diaphragms,
- Effects of displacement and drift,
- Effects of nonstructural elements on the structural system,
- Deficiencies in the connections that tie the elements of the building together,
- Lack of system redundancy,
- Damage to the nonstructural components and contents of the building,
- Egress complications, and
- Disruption of post-earthquake operations.

It also should be understood that apartment buildings range in size and type from two-story walk-up garden apartments to high-rise towers. The expected earthquake performance and, therefore, the required seismic

The most common structural system presently employed for medium- to high-rise apartment building construction is flat-plate cast-in-place reinforced concrete with randomly placed columns. This structural approach has certain advantages that make it particularly adaptable to apartment building construction since the possibility of placing columns randomly adapts well to the inherently irregular module generated by a typical apartment floor layout since columns can be buried in convenient locations within an efficient layout. Such structural eccentricities, coupled with the changing (however small) travel path of the earthquake forces, can put major stresses on joints and connections.

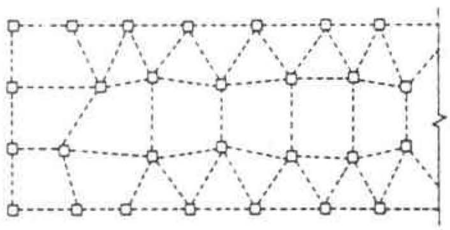


FIGURE 4
Irregular column placement in apartment buildings.

A common apartment building form that presents problems as a seismic design is that of the "re-entrant corner." The re-entrant corner is the common characteristic of overall building configurations that, in plan, assume the shape of an L, T, U, V, H, +, or a combination of these shapes (Figure 5). These building shapes are very useful for apartment complexes since they permit large plan areas to be accommodated in relatively compact form while still providing a high percentage of perimeter rooms with access to air and light. They are commonly used in apartment building design to provide a large number of windowed rooms. The courtyard form is also very common for apartments in tight urban sites. These configurations are so common and familiar that the fact that they represent one of the most difficult problem areas in seismic design may seem surprising. Examples of damage to re-entrant corner type buildings are common. First noted before the turn of the century, this earthquake problem generally was acknowledged by the experts of the day by the 1920s.

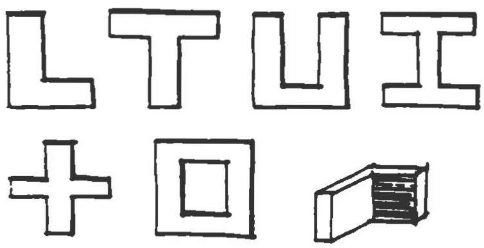


FIGURE 5
Re-entrant corner plan forms.

These shapes tend to produce variations of rigidity and, hence, differential motions between different portions of the building, resulting in a local stress concentration at the "notch" or re-entrant corner (Figure 6). In addition, it is common for the wings of a re-entrant

The setback form--a tower on a parking garage base or a building with "steps" in elevation--also has intrinsic seismic problems that are analogous to those of the re-entrant corner form. The different parts of the building vibrate at different rates, and where the setbacks occur, a "notch" is created that results in stress concentration (Figure 8).

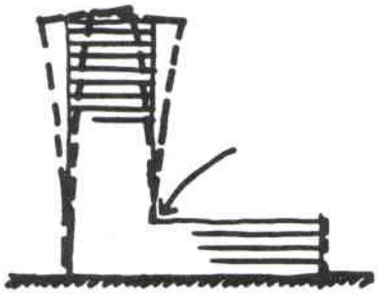


FIGURE 8 Point of stress concentration in setback building.

Program requirements for typical first floor spaces in apartment buildings frequently call for unobstructed areas larger than those that occur at dwelling floors above. A common method employed to achieve the unobstructed space at the first floor is to push out the walls at the ground floor and enclose a larger space with another appropriate structural system. This can cause problems at the joining of the first floor and the upper floors since both systems can respond with different movements during an earthquake.

A similar problem results when the upper dwelling floors are located on top of a multistory parking garage that is designed with a more flexible longer span system than the upper floors.

Typical problems with the building form characteristics of apartment building design are as follows:

- The size and shape of wings used to house and distribute apartment units.

- The placement of off-center circulation cores for more efficient traffic.

STRUCTURAL DISCONTINUITIES

It generally is not recognized that large discontinuities (or abrupt changes) in the strength or stiffness of a building can cause adverse seismic response effects. This is particularly the case where there are abrupt changes in the vertical arrangement of the structure resulting in discontinuities (changes) of strength or stiffness from floor to floor. In apartment buildings, economics may dictate that vertical services such as the elevators, stacks, standpipes, and stairs be floor and the remainder of the structure. This discontinuity may occur because one floor, generally the first, is significantly taller than the remainder, resulting in decreased stiffness (Figure 10a).

- A discontinuity may occur as a result of a common design concept in which some vertical framing elements are not brought down to the foundation but are stopped at the second floor to increase the openness at ground level. This condition creates a discontinuous load path resulting in an abrupt change of strength and stiffness at the point of change (Figure 10b). Discontinuities in the shear walls in the basement caused the failure of the El Faro apartment building during the 1985 earthquake in Chile (Figure 11).

FIGURE 11
The El Faro apartment building after the 1985 Chile earthquake.

- The high overturning moment generated in a discontinuous shear wall, together with the shear distress from orthogonal motion, can cause combined compression and shear failure in the first story columns. For example, the Villa Olympia apartment complex suffered partial collapse as the result of a discontinuous end shear wall supported by poorly reinforced columns (Figure 12).

these points and cause the collapse or partial collapse of the upper floors (Figure 14).

FIGURE 13
Apartment building collapse after the 1986 earthquake in Kalamata, Greece.

Where earthquake forces are not an issue, the "soft" first story presents no problem, but in earthquakes around the world, buildings with this condition have suffered severely.

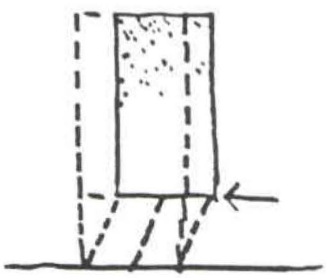
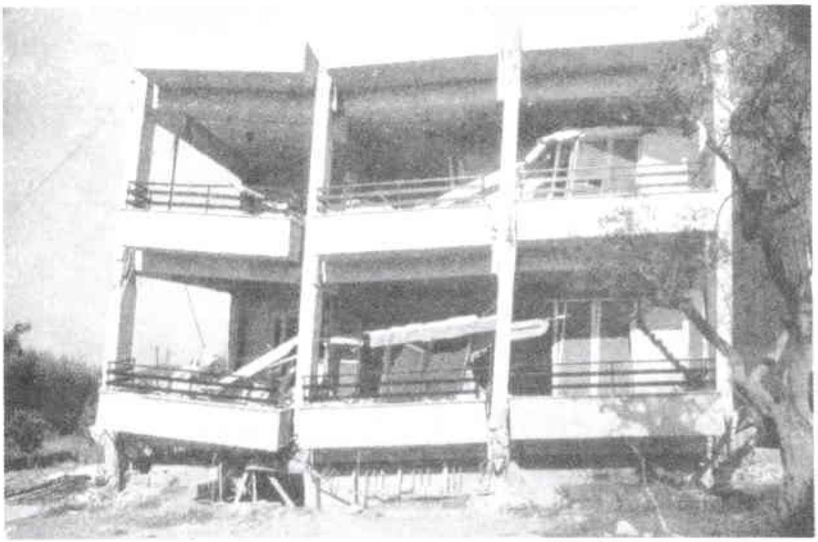


FIGURE 14 Action of "soft" first story in ground motion.

The total collapse of two-thirds of one block of the apartment buildings in the Tlatelolco section of Mexico City during the 1985 earthquake received much publicity because of the disastrous life loss. These high-rise reinforced concrete apartment buildings had flexible first stories and more rigid upper floors that caused an unbalanced stiffness ratio (Figure 15).



(a)

(b)

FIGURE 16
Apartment building with discontinuous shear walls (a) and a neighboring building with continuous shear walls (b). that suffered no damage during the 1986 Greece earthquake.

Particular problems with vertical and horizontal discontinuity inherent in current apartment buildings are as follows:

- The use of rigid shear wall upper floors (apartment units) over more flexible lower floor with longer spans and more open areas of glass and columns (lobbies).

- The collectors (members or reinforcing) are required to transfer the loads from the diaphragm into the shear walls and vice versa.

- Openings or re-entrant corners in the diaphragm must be properly placed and adequately reinforced.

Inappropriate location or excessive size of openings (elevator or stair cores) in the diaphragm create problems similar to those related to cutting a hole in the web or flange of a beam. This reduces the natural ability of the web or flange to transfer the forces and may cause failure in the diaphragm.

Particular issues related to diaphragms in apartment building design are as follows:

- The use of excessively large openings in the floor and roof diaphragms to provide for centralized circulation cores in the lobby.

- The mixing of more flexible diaphragms (steel decking for longer span parking or lobby functions) with more rigid diaphragms (concrete slab for shorter span apartment unit areas) causing discontinuities in the diaphragm stiffness/rigidity.

DISPLACEMENT AND DRIFT

Drift is the lateral displacement of one floor relative to the floor below. Buildings subjected to earthquakes need drift control to restrict damage to interior partitions, elevator and stair enclosures, glass, and envelope cladding systems and, more importantly, to minimize differential movement demands on the seismic resisting structural elements.

Drift control, or the recognition of the amount of potential drift, greatly influences the amount of damage control that is designed into the building. Since damage control generally is not a building code concern for typical buildings and since the state of the art in this area is almost entirely empirical, the drift limits found in codes generally have been established without regard to considerations such as present worth of future repairs versus additional structural costs to limit drift.

Stress or strength limitations imposed by normal design level forces occasionally may provide adequate drift control. However, the design of relatively flexible moment resisting frames and of tall, narrow shear wall buildings for seismic risk areas should be governed, at least in part, by drift considerations. In areas where the potential for high seismic loads is great, drift considerations should be of major concern for buildings of medium height and higher.

FIGURE 18
Tlatelolco apartment building after the 1985 earthquake in Mexico City.

FIGURE 19
Damaged apartment building
after the 1985 earthquake in Chile.

The horizontal services normally required in apartment buildings often are embedded within the concrete slab, thereby eliminating the need for connections between structural elements is more difficult than to provide strength in the members themselves. This has been clearly demonstrated by observation of earthquake damage where damage tends to originate at connections rather than in the structural members.

Furthermore, properly designed structural elements usually are ductile (i.e., their failure is preceded by large permanent deformations that dissipate considerable energy). On the other hand, connections often are relatively brittle. Therefore, a good structural design requires connections to be stronger than the members they connect so as to force failure to take place in the ductile members rather than in the relatively brittle connections.

Any discussion of structural considerations in conjunction with apartment building construction must recognize that the multifamily housing industry appears to be at the beginning of an era of greatly increased prefabrication and systems building. Such systems include precast concrete components, clear span prefabricated truss or beam systems, and a range of preassembled modules and components prepared for insertion in the structural frame. Unfortunately, prefabricated components have not performed well in past earthquakes primarily because of the performance of the connections during an earthquake's horizontal and upward movements.

A connection or joinery problem is illustrated by the performance of the Four Seasons apartment building during the 1964 earthquake in Anchorage, Alaska. The building had been designed to carry the earthquake lateral loading through two reinforced concrete towers. However, because the anchorage of the reinforcement at the bases of the two towers was not adequate, the towers folded over during the earthquake and the entire building collapsed (Figure 21).

SYSTEM REDUNDANCY

The issue of connections is particularly important for structures that rely on a small number of supporting members, such as a roof supported by four columns. If one column or its connection fails, the roof falls. If the same roof is supported by eight columns, the loss of one column may not be serious. Engineers refer to the attribute of having more than the minimum number of structural members as "redundancy." It provides an important additional safety factor. In apartment buildings, nonredundant structures are common because of the need for efficient space design combined with the constraining effects of column location.

In a structural system without redundant components, every component must remain operative to preserve the integrity of the structural system. On the other hand, in a redundant system, one or more of the components may fail without affecting the structural system's ability to resist lateral forces and allow for the escape of occupants.

Redundant characteristics can be obtained by providing several different types of seismic resisting system in a building; however, the designer must be careful to consider the relative stiffness and strengths of the various systems in order to avoid problems.

Redundancy also can be accomplished by increasing the number of elements (columns, shear walls), adding new elements (cross frames, bracing), or modifying some elements (increasing reinforcement and anchoring the framing to change interior nonstructural walls and panels into shear walls).

In a moment resisting frame system, redundancy can be achieved by making all joints of the vertical load-carrying frame moment resisting. Of course, proper ductility must be provided in the members of the structural system. These multiple points of resistance can prevent a catastrophic collapse due to failure of a member or joint. However, if this system is designed with the moment resisting connections limited to the exterior columns (a common practice) clad only in lightweight architectural curtain walls, such a building may experience large deformations during an earthquake and, consequently, a great deal of interior damage.

The "aesthetic" design of a shear wall system can also cause interesting problems. The use of shear walls around a center core can result in excessive bending of the shear walls. Where no redundant or reserve system is provided in addition to such walls, performance has been poor. The design of the exterior that uses long horizontal windows causes the shear wall to become a system of large spandrel beams and small piers. This kind of system also has performed poorly in earthquakes because the short, stubby, stiff columns attract large forces and fail.

Particular issues related to redundancy of structural systems in apartment buildings are as follows:

- The failure to consider the influence of the relative stiffness of such systems.

- The use of limited numbers of columns in large open areas, which causes these elements to become extremely critical.

- The placement of openings (doors and windows) uniformly in the interior and exterior shear walls causing large forces to be concentrated in weak elements.

Regarding redundancy, there is, however, one note of caution. Ca·e must be taken not to add so many redundant elements that they, in fact, become stronger than the primary resisting system.

Apartment building inhabitants are particularly vulnerable to nonstructural damage that affects egress. Electrical fixtures and ceiling or wall finishes that fall on hallways and stairs make movement difficult, particularly if combined with power failure and loss of lights.

Traditionally, building utility systems and equipment have been designed or selected with little, if any, regard to performance when subjected to earthquake forces. Mechanical and electrical equipment supports have been designed for gravity loads only, and attachments of moving equipment to the structure are deliberately designed to be flexible to allow for vibration isolation. In assessing the impact of possible damage, secondary effects from equipment damage must be considered. Fires and explosions resulting from damaged mechanical and electrical equipment represent secondary effects of earthquakes that also are a considerable hazard to life and property.

A strategy commonly used in apartment building design to achieve unobstructed space at the first floor lobby is to hang a ceiling in the first floor and collect and redirect the various vertical services that would otherwise break up the space at the ground floor. These horizontal components, unless seismically restrained, can swing violently during an earthquake and rupture at the joints and connections where they change direction.

Large capacity hot water boilers and other pressure vessels and broken distillation pipes can release fluids at hazardous temperatures. In apartment buildings, the large amount of individual kitchen appliances and their respective fuel supplies can cause personal injury and damage. In addition, the long runs of piping throughout apartment buildings offer ample opportunities for rupture or connection failure. Some of this piping is filled with flammable, toxic, or noxious sub-refrigerants used in air conditioning systems that can be converted to a poisonous gas (phosgene) upon contact with open flame.

Electrical equipment including transformers, free-standing switchboards, emergency generators, and lighting systems can fall over, causing not only damage and injury but also fire (Figures 23-24).

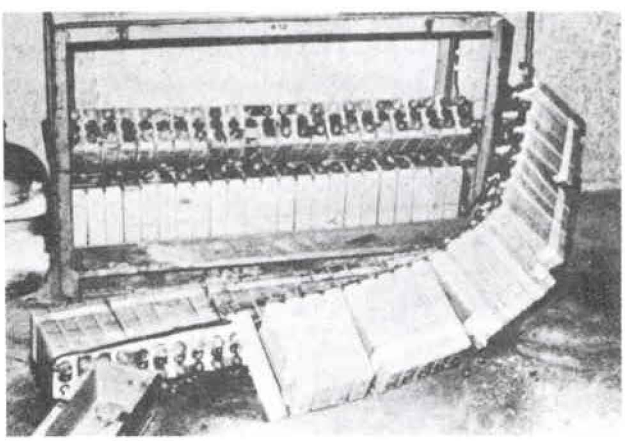


FIGURE 23
Electrical equipment collapse.

Elevator damage is a recurring problem during earthquakes (Figure 26). In fact, during the 1971 San Fernando earthquake, over 600 elevators were damaged. The large number of elevators in apartment buildings make this an especially costly and potentially destructive element of the building. Counterweights can tear loose from their guide brackets or rails, bending the guide rails so that they swing free causing cable and brake shoes to fall, shearing electric cables and, in some cases, smashing through elevator cabs. Additional damage can occur in the elevator machine room penthouse. The controls and motors can be thrown off their bases cutting supports and the electrical cables.

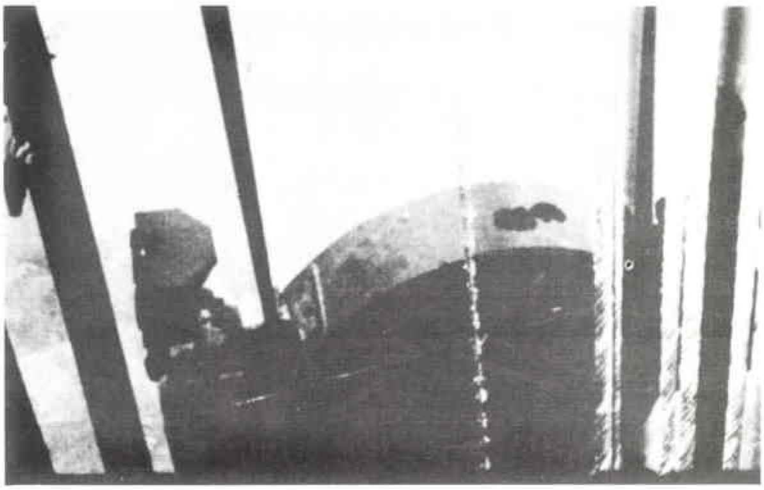


FIGURE 26
Elevator counterweight disengaged from vertical rail (photo courtesy of H. J. Degenkolb).

Even such nonstructural components as glazing systems can create additional problems. This is particularly the case for apartment buildings because of the large amount of glass they usually feature. Although damage patterns for glazing systems have not been well researched, glass breakage is related to support conditions, the temper of the glass and its thickness and size, and the type and direction of loading. Large windows usually break at somewhat lower loads than smaller windows since large windows behave like a membrane or diaphragm. With sufficient space for movement within the frame and if the frame does not rack or glass loading is not high, good performance can be expected if reasonable care is taken in design and placement. Glass joint treatment is a factor in the overall performance of the window unit system; of the edges are restrained, failure is likely. Also, sealants and gasket materials that give flexibility can lose their resiliency with age and exposure.

FIGURE 28
Debris blocking exit.

Past experience has indicated that doors and frames often jam in earthquakes and cannot be opened. Heavy fire doors from rooms leading to egress routes are especially vulnerable because fire safety regulations require a heavy and tight assembly that can become immovable when the door frame is distorted by earthquake motion. The Hanga Roa condominium building suffered failures of the lintels over the door openings during the 1985 earthquake in Chile. These cracks started at the first floor and extended to the fourteenth floor (Figure 29).

Safe, direct egress routes should be planned so that occupants can proceed from the building. Partitions, ceiling systems, lighting systems, and glazing systems that enclose egress routes should be designed as critical components (Figure 30). This is especially true in lobbies where large amounts of ornamentation, hanging lighting, and glass are located (Figure 31). Debris from these elements can easily cause injury and block egress.

Canopies and porches at the entrances to apartment buildings are a particular problem for egress if they are not properly designed for lateral loads. Their collapse may cause casualties amid quickly egressing occupants or they may block the designed exit route for a considerable time after the earthquake.

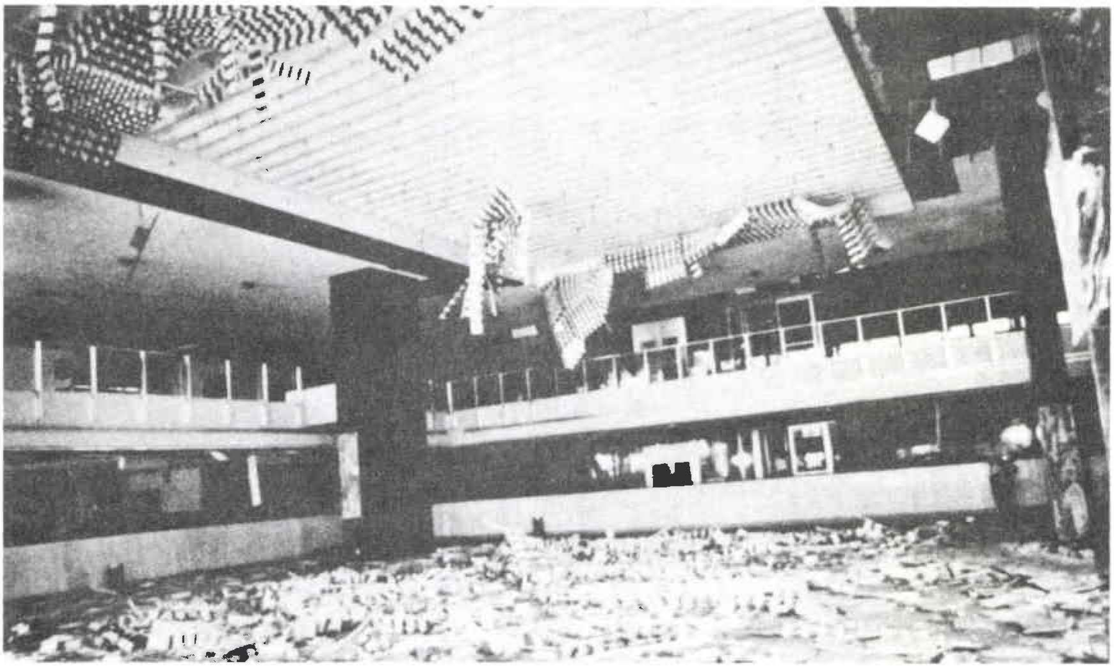


FIGURE 31
Failure of lobby lighting system.

DISRUPTION OF POST-EARTHQUAKE OPERATIONS

Disruption of operations due to property damage often occurs after an earthquake. These disruptions may involve partial closing of certain areas of the building, limited closing for debris removal or minor repairs to nonstructural components and building equipment, prolonged closing for major repairs, or permanent closing for demolition and replacement. It is obvious that such disruptions can be very costly and even damage that is not critical in terms of life safety can cause an inordinate delay in reopening the apartment building and can adversely affect the public's perception of the building's problems. For example, lobby repairs and debris removal can generate a public perception that the building is unsafe and major glass damage can stimulate the perception that the building is both unsafe and uncomfortable).

CONCLUSION

The kinds of problems outlined above all stem from lack of attention to the seismic problem during design. While, as noted, design to a seismic code cannot guarantee freedom from seismic problems, adherence to this code will provide a basic level of safety that is difficult to obtain in any other way. Beyond the mandated requirements of a code,

4

APARTMENT BUILDING SEISMIC DESIGN AND THE *NEHRP RECOMMENDED PROVISIONS*

Two conditions are needed to achieve good seismic design:

- The design team needs to be both experienced in and supportive of earthquake design, and

- Building owners must require such design as an integral part of the design of their buildings.

Although building owners obviously cannot and do not need to know all the technical aspects of earthquake design, they should have some understanding of the range of strategies and solutions that are available to protect their buildings.

The *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings*, developed by recognized researchers and practitioners of seismic design and having the consensus approval of the BSSC membership, provides an authoritative set of seismic design concepts and details. The *Provisions* covers the following major topics:

- Earthquake design characteristics,

- Structural design requirements,

- Procedures for the analysis of earthquake forces,

- Soil-structure interaction,

- Foundation design requirements,

- Nonstructural component design, and

- Basic materials of construction--wood, steel, reinforced concrete, and masonry.

The discussion that follows is a broad look at the strategies expressed in the *NEHRP Recommended Provisions* that are aimed at providing an acceptable and affordable level of safety for apartment facilities.

quantitative measures from which building seismic forces can be determined?

The inertial forces on the building resulting from earthquake shaking are roughly equivalent to the building mass multiplied by the acceleration (based on Newton's law where F = MA). Acceleration is measured as a decimal fraction or percentage of the acceleration of gravity, which is 1.0g.

The *Provisions* supplies two maps that give slightly varying quantities for horizontal accelerations to be used for design purposes at any location in the United States. The differences in the two maps relate to whether they show effective peak accelerations (which generally are less than the peak or maximum accelerations that may occur) or effective peak velocities (which represent another aspect of ground motions that is mathematically derived from acceleration). In any specific location, the map showing A_v (effective peak velocity) or A_a (effective peak acceleration) may govern, the choice being primarily related to the size of the building involved.

The accelerations shown on both maps range from 5 to 40 percent and are illustrated in the form of contour lines indicating areas of equal acceleration (similar to elevation contours on a topographical map). Figure 32 is a small-scale reproduction of one of these maps. The large-scale maps supplied with the *Provisions* superimpose contours on a background of county lines to clarify jurisdictional issues.

Although based on extensive studies, these maps reflect a number of assumptions. The general criterion is that the risk at any location has only a 10 percent probability of being exceeded in 50 years, which translates into a mean recurrence interval of 475 years. This is a statistical number, however, and unfortunately there is no assurance that at a given location the given ground motion will not occur at any time. Studies are constantly being conducted in an effort to provide more accurate information on this crucial point.

The identification of effective peak velocity allows for the development of a Seismic Performance Category or the level of seismic performance to which the building must be designed.

To determine the degree of protection to be provided the building and its occupants, another measure is assigned to the building based on its occupancy or use. The intent is for important buildings--such as hospitals or police stations--and for buildings with a large number of occupants or with occupants whose mobility is restricted--such as apartments, auditoriums, and schools--to receive a higher standard of seismic protection than other buildings where the seismic hazard is less critical. Thus, every building is assigned to one of three Seismic Hazard Exposure Groups (identified as I, II, and II).

The Seismic Performance Category for any building is determined from Table 1, which relates the effective peak velocity, A_v, to the Seismic Hazard Exposure Group (I-III). It can be seen that east of the Rockies where A_v is nearly always less than 0.20 (Figure 32), most apartment buildings will belong to Seismic Performance Category A, B, or C (1988 Edition of the *NEHRP Recommended Provisions*). This procedure provides reasonable seismic protection for all buildings and reflects the varying hazards for alternative locations around the country.

TABLE 1
Seismic Performance Categories

Value of A_v	Seismic Hazard Exposure Group I	II	III
$0.20 \leq A_v$	D	D	E
$0.15 \leq A_v < 0.20$	C	D	D
$0.10 \leq A_v < 0.15$	C	C	C
$0.05 \leq A_v < 0.10$	B	B	C
$A_v < 0.05$	A	A	A

SITE GEOLOGY

The use of the design ground motion shown on the *NEHRP Recommended Provisions* maps is sufficient for most design purposes. For large or important buildings or where significant earthquake activity is suspected, the building owner should require that geological surveys be performed on the building site to evaluate more accurately the level of seismic hazard to be expected.

It is convenient to classify earthquake effects into four distinct categories. When faults shift, causing an earthquake, the split in the fault often appears as a crack or vertical step on the earth's surface. Major displacements (movements of up to 21 feet have been recorded) can occur along the fault line. No economical building design can withstand displacements of this magnitude. Nevertheless, many buildings are located and continue to be located astride faults because of lack of fault identification. Where fault locations are accurately mapped, as is the case in California, the building owner should make certain that the building is not located over a fault and geological studies should be undertaken before making the final site decision.

The second category of earthquake effects involves ground motion. Ground motion does not damage a building by externally applied loads or pressure as in gravity or wind loads, but rather by internally genermined, and appropriate measures can be taken (site location, fill, flood walls, elevated structures, flood shields, etc.).

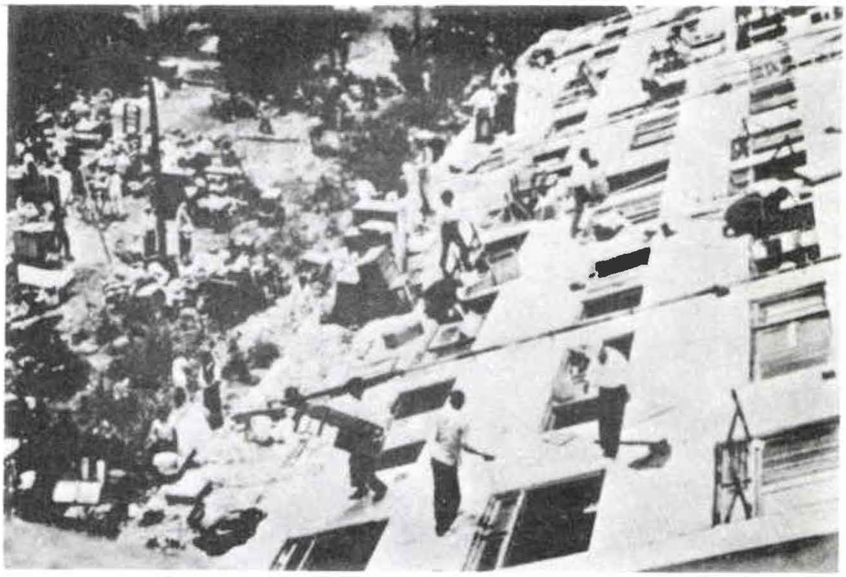


FIGURE 33
Apartment buildings after the 1964 earthquake in Niigata, Japan.

Of the four categories of earthquake effects, seismic design is concerned almost exclusively with that of ground motion. The other effects are best dealt with by land-use planning at the large scale or by site selection at the scale of the individual buildings.

BUILDING OCCUPANCY

Historically, the typical occupancy classifications in building codes are based on the potential hazards associated with fire. Because of the characteristics of the earthquake problem, a specific occupancy classification is necessary. The approach in the *NEHRP Recommended Provisions* defines occupancy exposure to seismic hazards based on, but not limited to, the following:

- The typical number, age, and condition of the occupants within the building type and its immediate environs;
- The typical size, height, and area of the building type;
- The spacing of the building type in relation to public rights-of-way; and

- Unbalanced or random rigid resisting elements--Any configuration that concentrates forces on a small number of rigid element(s) of the building risks failure of those elements (Figure 35).

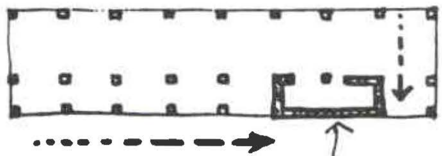


FIGURE 35
Rigid elements in plan will attract earthquake forces.

When the first condition is caused by plan irregularities such as re-entrant corner forms, symmetrical units or wings can be created from the irregular building by the use of seismic joints. Use of this approach, however, can cause some problems. The joints must proceed through the entire building so any nonstructural systems such as interior walls or utility lines also must be designed using separations or flexible joints so that they will not be damaged. Separations of the seismic joints must be wide enough so that the adjacent units do not pound against one another during their respective displacements. Fulfilling these two requirements can be costly and can cause considerable difficulty in architectural detailing. Alternatively, certain structural or massive nonstructural systems (interior nonbearing walls, stairways, etc.) can be located in the building to assist in bringing the center of mass and rigidity closer together so that under ground motion the resistance systems are designed to compensate for geometrical irregularities.

The ***NEHRP Recommended Provisions*** requires more stringent analysis procedures for those building designs with inherent irregular configurations based on their occupancy and seismicity. This ensures that problems of torsion and load transfer caused by any irregularities of the horizontal or vertical systems will be identified initially and taken into account during design.

As discussed above, apartment buildings tend to be replete with areas of discontinuous stiffness resulting from the second condition (unbalanced or random resisting elements). The basic strategy for resolving this problem involves careful choice of the seismic design system in relation to the architectural requirements and consistency in the application of the system. Thus, if open flexible spaces are designed at the base of the building with small repetitive walled spaces above, it is good seismic practice to design the entire building as a frame with appropriate interior partition walls rather than to mix heavy shear wall and frame systems.

- Moment frames.

A fourth system for lateral load resistance is the dual system which is a combination of moment frames with shear walls or braced frames.

Horizontal diaphragms (floors and roofs) connect these elements and assist in transferring the loads to the foundation.

Each of the four vertical structural systems has certain characteristics:

- Shear wall systems are economical (assuming that a regular pattern of solid walls is necessary for functional purposes as they are in apartment buildings) and result in a very stiff structure that reduces nonstructural damage.

- Moment frames resist earthquake forces by providing strong joints. This system, with its absence of structural walls, provides great interior planning advantages but also can result in a more flexible structure that may contribute to nonstructural and contents damage. Because of the importance of the joints, their construction tends to be expensive.

- Braced frame systems combine some of the features of the two other systems. They provide a more open structure than one based on shear walls, but the braces may be some impediment to interior planning. The system may not be as stiff as a shear wall system, but it can be more economical than a moment resistant frame system.

- In the dual system, the principal purpose of the moment frame is to provide a secondary defense during an earthquake with a higher degree of redundancy and ductility. The prescribed forces are assigned either to the overall system or to the shear walls/braced frames alone. The dual system offers certain advantages in that it provides high stiffness for moderate earthquakes and an excellent second line of defense for major earthquakes.

Correctly choosing an appropriate and safe system for an apartment building requires considerable care and experience because of the complexity of the facility and the variety of spaces that must be accommodated. Nevertheless, selection of the correct structural system is extremely important because this decision occurs early in the design process and is difficult to modify or change as the process proceeds.

Because of the many uncertainties in the characteristics of earthquake loads, in the performance of materials and systems of construction for resisting earthquake loads and in the methods of analysis, it is good design practice to provide as much redundancy as possible in the seismic-resisting system of buildings. Redundancy in the structural system of a building provides a second line of defense that may make the

the concrete through the use of spiral or closely spaced stirrup ties (reinforcement) which increases the ductility of the system (the ability of the system or material to distort without collapsing). The major problems with reinforced concrete buildings have occurred in frame structures with inadequate ductility where system collapse occurred after some seconds of earthquake motion.

The expected good performance of modern reinforced masonry buildings contrasts with the highly publicized and dramatic failures of older unreinforced masonry buildings, especially apartment buildings. The proper design and construction of walls and the proper connection of walls to floor and roof diaphragms are critical to the success of the use of these materials during an earthquake. Precast concrete elements, whether they are conventionally reinforced or prestressed, have exhibited significant structural failures in earthquakes, primarily because they were not fastened together with sufficient strength to provide the equivalent of monolithic construction. Since these systems are often used in long-span conditions, issues of redundancy and concentration of stresses must be given serious consideration.

The *NEHRP Recommended Provisions* contains detailed seismic design and detailing requirements for wood, steel, reinforced concrete, and reinforced masonry.

CONNECTIONS

Recognizing the fact that few buildings are designed to resist severe earthquake loads elastically (the ability of the structure to deform, absorb the earthquake energy, and return to its original condition), ductility must be provided whenever the elastic resistance is expected to be exceeded. The need for ductility applies not only to the structural elements but also to the connections between the elements.

Where ductility has not been provided, failures have occurred in connections where the capacity of ductile structural elements was reached or in connections that were too weak to transfer the forces developed in the structural elements.

Specifically, connection failures have occurred in inadequately anchored exterior precast panels, between walls and diaphragms, between beams and walls, between columns and beams, and between columns and foundations--indeed, at any location where two or more different structural elements interact in transferring the loads.

It should be possible to follow direct paths for the vertical and horizontal forces all the way through the building to the foundation and for this path to be thoroughly tied together at each intersection. What the apartment building owner must recognize is that this type of design and detailing process is not normally a consideration when architects and structural engineers design a nonseismic building.

potential injury and costly damage (including loss of operation) can be avoided.

The more common nonstructural elements in an apartment building that should be given special design attention are:

Appendages:	Entrance canopies, overhangs, porches, balconies, parapets, patios, setbacks Roof-mounted mechanical units
Enclosures:	Exterior nonbearing walls Exterior infill walls Veneer attachments
Partitions:	Stairs and shafts Horizontal exits Corridors Fire separation partitions
Ceilings:	Fire-rated and non-fire-rated
Doors/Windows:	Room-to-hallway doors Fire doors Lobby doors and glazing Windows and curtain walls
Lighting:	Light fixtures Emergency lighting
Emergency:	Structural fireproofing Emergency generators/fuel Fire and smoke detection system Fire suppression systems (sprinkler) Smoke removal systems Signage
Mechanical:	Large equipment including chillers, heat pumps, boilers, furnaces, fans Smaller equipment including apartment through-the-wall air conditioning or heating units Tanks, heat exchangers, and pressure vessels Utility and service interfaces Ducts and diffusers Piping
Electrical:	Electrical bus ducts and primary cable systems Electric motor control centers, transformers, and switchgear

ature is replete with reports pointing out that collapse could have been prevented had proper inspection been exercised to ensure that construction was in accord with building plans and specifications.

NONSTRUCTURAL SYSTEMS	FLEXIBILITY/DEFORMATION	ANCHORAGE	BRACING	STABILITY	STRENGTHENING	SEPARATION/ISOLATION	SLIP/CONTROL JOINTS	REDUCED MASS	CONTAINMENT	INCORPORATION	LOCATION
EXTERIOR ELEMENTS		●	●		●			●	○	○	●
ENCLOSURE SYSTEMS	●						●	●		●	
FINISHES/VENEERS	●	●					○	●			
PARTITIONS	○	●				●	●				
CEILING SYSTEMS		●	●		○	●		○		●	
LIGHTING SYSTEMS		●	●		○	○				○	
GLAZING	●				●	●					●
TRANSPORTATION SYSTEM					●	●	●				●
MECHANICAL SYSTEMS	●	●	●					●			●
FURNISHINGS/EQUIPMENT		●		●	●			●			

FIGURE 36 Earthquake strategies for nonstructural components: o identifies possible strategies and ●, high potential strategies.

Severe building damage and collapse have been caused by poorly executed construction joints in reinforced concrete, undersize welds in steel construction, and absence of nuts on anchor bolts in timber construction, to name just a few deficiencies. Recognizing that there must be coordinated responsibility during construction, the *NEHRP Recommended Provisions* delineates the role each party is expected to play in construction quality control:

- The building designer is expected to specify the quality assurance requirements,

- The contractor is expected to exercise the control to achieve the desired quality, and

- The owner/developer is expected to monitor the construction through independent special inspection to protect his own as well as the public interest.

5

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> The information needed to define a specific location's seismic situation can be obtained from the geologists, geophysicists, and seismologists affiliated with local academic institutions; state geologists; regional offices of the USGS and FEMA; national earthquake information centers; and state and regional seismic safety organizations.

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GLOSSARY

GENERAL TERMS

ACCELERATION The rate of increase in ground velocity as seismic waves travel through the earth. The ground moves backward and forward; acceleration is related to velocity and displacement.

ACCEPTABLE RISK The probability of social or economic consequences due to earthquakes that is low enough (for example, in comparison with other natural or man-made risks) to be judged by appropriate authorities to represent a realistic basis for determining design requirements for engineered structures or for taking certain social or economic actions.

AMPLITUDE The extent of a vibratory movement.

ARCHITECTURAL SYSTEMS Systems such as lighting, cladding, ceilings, partitions, envelope systems, and finishes.

COMPONENT Part of an architectural, electrical, mechanical, or structural system.

CONNECTION A point at which different structural members are joined to each other or to the ground.

DAMAGE Any economic loss or destruction caused by earthquakes.

DEFLECTION The state of being turned aside from a straight line. See **drift**.

DESIGN EARTHQUAKE In the *NEHRP Recommended Provisions*, the earthquake that produces ground motions at the site under consideration that have a 90 percent probability of not being exceeded in 50 years.

DESIGN EVENT, DESIGN SEISMIC EVENT A specification of one or more earthquake source parameters and of the location of energy release with respect to the site of interest; used for earthquake-resistant design of a structure.

FRAME, SPECIAL MOMENT A space frame in which members and joints are capable of resisting forces by flexure as well as along the axis of the members.

FRAME SYSTEM, BUILDING A structural system with an essentially completed space frame providing support for vertical loads. Seismic force resistance is provided by shear walls or braced frames.

FRAME SYSTEM, DUAL A structural system with an essentially complete space frame providing support for vertical loads. A moment resisting frame that is capable of resisting at least 25 percent of the prescribed seismic forces should be provided. The total seismic force resistance is provided by the combination of the moment resisting frame and the shear walls or braced frames in proportion to their relative rigidities.

FRAME SYSTEM, MOMENT RESISTING A structural system with an essentially complete space frame providing support for vertical loads. Seismic force resistance is provided by special, intermediate, or ordinary moment frames capable of resisting the total prescribed seismic forces.

INTENSITY The apparent effect that an earthquake produces at a given location. In the United States, intensity is frequently measured by the Modified Mercalli Index (MMI). The intensity scale most frequently used in Europe is the Rossi-Forel scale. A modification of the Mercalli is used in the Soviet Union. See the following section of this Glossary, "Measures of Earthquake Magnitude and Intensity."

JOINT A point at which plural parts of one structural member are joined to each other into one member.

LIQUEFACTION The conversion of a solid into a liquid by heat, pressure, or violent motion.

LOAD, DEAD The gravity load created by the weight of all permanent structural and nonstructural building components such as walls, floors, roofs, and the operating weight of fixed service equipment.

LOAD, LIVE Moving or movable external loading on a structure. It includes the weight of people, furnishings, equipment, and other things not related to the structure. It does not include wind load, earthquake load, or dead load.

LOSS Any adverse economic or social consequences caused by earthquakes.

MASS A quantity or aggregate of matter. It is the property of a body that is a measure of its inertia taken as a measure of the amount of material it contains that causes a body to have weight.

MERCALLI SCALE Named after Giuseppi Mercalli, an Italian priest and geologist, it is an arbitrary scale of earthquake intensity related to

SHEAR A deformation in which parallel planes slide relative to each other and remain parallel.

SHEAR PANEL A floor, roof, or wall component sheathed to act as a shear wall or diaphragm.

STIFFNESS Resistance to deformation of a structural element or system.

STRENGTH The capability of a material or structural member to resist or withstand applied forces.

TORQUE The action or force that tends to produce rotation. In a sense, it is the product of a force and a lever arm as in the action of a wrench twisting a bolt.

TORSION The twisting of a structural member about its longitudinal axis. It is frequently generated by two equal and opposite torques, one at each end.

VALUE AT RISK The potential economic loss (whether insured or not) to all or certain subsets of structures as a result of one or more earthquakes in an area.

VELOCITY The rate of motion. In earthquakes, it is usually calculated in inches per second or centimeters per second.

VULNERABILITY The degree of loss to a given element at risk, or set of such elements, resulting from an earthquake of a given magnitude or intensity, which is usually expressed on a scale of from 0 (no damage) to 10 (total loss).

WALL, BEARING A wall providing support for vertical loads; it may be exterior or interior.

WALL, NONBEARING A wall that does not provide support for vertical loads other than its own weight as permitted by the building code. It may be exterior or interior.

WALL, SHEAR A wall, bearing or nonbearing, designed to resist seismic forces acting in the plane of the wall.

WALL SYSTEM, BEARING A structural system with bearing walls providing support for all or major portions of the vertical loads. Seismic force resistance is provided by shear walls or braced frames.

WAVES A ground motion best described as vibration that is created or generated by a fault rupture. Earthquakes consist of a rapid succession of three wave types: the "P" or primary wave followed by both the "S" or secondary wave and a surface wave.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks or sensation of a jolt like a heavy ball striking the walls. Standing cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frames creak.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture overturned. Weak plaster, Masonry D[1] cracked. Small bells ring (church and school). Trees, bushes shaken visibly or heard to rustle.

VII. Difficult to stand. Noticed by drivers. Hanging objects quiver. Furniture broken. Damage to Masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices also unbraced parapets and architectural ornaments. Some cracks in Masonry C. Waves on ponds, water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of cars affected. Damage to Masonry C; partial collapse. Some damage to Masonry B; none to

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[1]Masonry definitions from C. F. Richter's 1958 book, *Elementary Seismology* (W. H. Freeman and Company, San Francisco, California), are as follows: Masonry A--good workmanship, mortar, and design; reinforced, especially laterally; bound together by using steel, concrete, etc.; designed to resist lateral forces. Masonry B--Good workmanship and mortar; reinforced but not designed in detail to resist lateral forces. Masonry C--Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners but not reinforced or designed against horizontal forces. Masonry D--Weak materials such as adobe, poor mortar, low standards of workmanship; weak horizontally.

Appendix A

SEISMICITY OF THE UNITED STATES

The U.S. Geological Survey (USGS) conducts the major national effort in earthquake-related studies in seismology, geology, and geophysics. At present, the USGS has identified nine areas in the United States as priority study areas:

- The Wasatch Front of Utah
- Puget Sound, Washington
- Anchorage, Alaska
- Southern California
- Northern California
- The central Mississippi Valley
- Charleston, South Carolina
- The northeastern United States including Massachusetts and New York
- Puerto Rico

A considerable amount of data on the earthquake hazard in these areas is available from the USGS and ongoing studies are continually adding to the store of information. Local USGS offices can provide detailed information on specific locations.

The remainder of this appendix presents a review of U.S. seismicity exerpted from a 1987 paper by Walter W. Hays of the U.S. Geological Survey, Reston, Virginia. The paper appears in its entirety in Volume 6 of *Abatement of Seismic Hazards to Lifelines: Proceedings of the BSSC Workshop* (FEMA Earthquake Hazard Reduction Series No. 31).

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Studies of seismicity provide answers to the questions where, how big, how often, and why earthquakes occur. In 1983, Algermissen produced a comprehensive treatment of U.S. seismicity. This information is summarized below for each region of the coterminous United States, Alaska, Hawaii, Puerto Rico, and the Virgin Islands. The Modified Mercalli

SOUTHEAST REGION

The southeastern United States is an area of diffuse, low-level seismicity. It has not experienced an earthquake having an MMI of VIII or greater in nearly 80 years. The largest and most destructive earthquake in the region was the 1886 Charleston earthquake which caused 60 deaths and widespread damage to buildings. It had an epicentral intensity of X and a magnitude (M_S) of approximately 7.7 (Bollinger, 1977). Important earthquakes of the southeast region are listed in Table A-2. The distribution of earthquakes through 1976 in the southeast region is as follows:

MMI	Number
V	133
VI	70
VII	10
VIII	2
IX	0
X	1

Table A-2 Important Earthquakes of the Southeast Region

Date	Location	Maximum MMI (I_o)	Magnitude (Approx. M_S)
Feb. 21, 1774	Eastern VA	VII	
Feb. 10, 1874	McDowell County, NC	V-VII	
Dec. 22, 1875	Arvonia, VA area	VII	
Aug. 31, 1886	Near Charleston, SC	X	7.7
Oct. 22, 1886	Near Charleston, SC	VII	
May 31, 1897	Giles County, VA	VIII	6.3
Jan. 27, 1905	Gadsden, AL	VII-VIII	
June 12, 1912	Summerville, SC	VI-VII	
Jan. 1, 1913	Union County, SC	VII-VIII	5.7-6.3
Mar. 28, 1913	Near Knoxville, TN	VII	
Feb. 21, 1916	Near Asheville, NC	VI-VII	
Oct. 18, 1916	Northeastern AL	VII	
July 8, 1926	Mitchell County, NC	VI-VII	
Nov. 2, 1928	Western NC		

SOURCE: Algermissen (1983).

CENTRAL REGION

The seismicity of the central region is dominated by the three great earthquakes that occurred in 1811-1812 near New Madrid, Missouri. These earthquakes had magnitudes (M_S) ranging from 8.4 to 8.7 and magnitude of 7.3. The distribution of historic earthquakes in the western mountain region is as follows:

MMI	Number
V	474
VI	149
VII	26
VIII	22
IX	0
X	1

Table A-4 Important Earthquakes of the Western Mountain Region

Date	Location	Maximum MMI (I_o)	Magnitude (Approx. M_S)
Nov. 9, 1852	Near Ft. Yuma, AZ	VIII?	
Nov. 10, 1884	Utah-Idaho border	VIII	
Nov. 14, 1901	About 50 km east of Milford, UT	VIII	
Nov. 17, 1902	Pine Valley, UT	VIII	
July 16, 1906	Socorro, NM	VIII	
Sept. 24, 1910	Northeast AZ	VIII	
Aug. 18, 1912	Near Williams, AZ	VIII	
Sept. 29, 1921	Elsinore, UT	VIII	
Sept. 30, 1921	Elsinore, UT	VIII	
June 28, 1925	Near Helena, MT	VIII	6.7
March 12, 1934	Hansel Valley, UT	VIII	6.6
March 12, 1934	Hansel Valley, UT	VIII	6.0
Oct. 19, 1935	Near Helena, MT	VIII	6.2
Oct. 31, 1935 (Aftershock)	Near Helena, MT	VIII	6.0
Nov. 23, 1947	Southwest MT	VIII	
Aug. 18, 1959	West Yellowstone-Hegben Lake	X	7.1
Aug. 18, 1959 (Aftershock)	West Yellowstone-Hegben Lake	VI	6.5
Aug. 18, 1959 (Aftershock)	West Yellowstone-Hegben Lake	VI	6.0
Aug. 18, 1959	West Yellowstone-Hegben Lake	VI	6.5
Mar. 28, 1975	Pocatello Valley, ID	VIII	6.1
June 30, 1975	Yellowstone National Park	VIII	6.4
Oct. 28 1983	Lost River Mountains, ID	VII est.	7.3

SOURCE: Algermissen (1983).

The following generalizations can be made: (1) the earthquakes are nearly all shallow, usually less than 15 km (9 miles) in depth, (2) the recurrence rate for a large (M_S greater than 7.8) earthquake on the San Andreas fault system is of the order of 100 years, (3) the recurrence rates for large earthquakes on single fault segments in the Nevada seismic zone are believed to be in the order of thousands of years, and (4) almost all of the major earthquakes have produced surface faulting. Excluding offshore earthquakes, the distribution in California and western Nevada is given below:

MMI	Number
V	1,263
VI	487
VII	170
VIII	41
VIII-IX	2
IX	8
IX-X	3
X	5
X-XI	2

WASHINGTON AND OREGON REGION

The Washington and Oregon region is characterized by a low to moderate level of seismicity in spite of the active volcanism of the Cascade range. With the exception of plate interaction between the North American and Pacific tectonic plates, there is no clear relationship between seismicity and geologic structure. From the list of important earthquakes that occurred in the region (Table A-6), the two most recent damaging earthquakes in the Puget Sound area (M_S = 6.5 in 1965, M_S = 7.1 in 1949) occurred at a depth of 60 to 70 km. Currently, speculation is occurring over whether a great earthquake can occur as a consequence of the interaction of the Juan de Fuca and the North American tectonic plates. The distribution of earthquakes in the Washington and Oregon region is given below:

MMI	Number
V	1,263
VI	487
VII	170
VIII	40
VIII-IX	2
IX	8
IX-X	3
X	5
X-XI	2

area of more than 77,000 square miles. The distribution of earthquakes in Alaska in terms of Magnitude (M_S) is as follows:

MS	Number
5.0-5.9	757
6.0-6.9	344
7.0-7.9	63
≥ 8.0	11

Table A-7 Important Earthquakes of Alaska

Date	Location	Magnitude (Approx. M_S)
Sept. 4, 1899	Near Cape Yakatage	8.3
Sept. 10, 1899	Yakutat Bay	8.6
Oct. 9, 1900	Near Cape Yakatage	8.3
June 2, 1903	Shelikof Straight	8.3
Aug. 27, 1904	Near Rampart	8.3
Aug. 17, 1906	Near Amchitka Island	8.3
Mar. 7, 1929	Near Dutch Harbor	8.6
Nov. 10, 1938	East of Shumagin Islands	8.7
Aug. 22, 1949	Queen Charlotte Islands (Can.)	8.1
Mar. 9, 1957	Andreanof Islands	8.2
Mar. 28, 1964	Prince William Sound	8.4
Feb. 4, 1965	Rat Islands	7.8

SOURCE: Algermissen (1983).

HAWAIIAN ISLANDS REGION

The seismicity in the Hawaiian Islands is related to the well known volcanic activity and is primarily associated with the island of Hawaii. Although the seismicity has been recorded for only about 100 years, a number of important earthquakes have occurred since 1868 (Table A-8). Tsunamis from local as well as distant earthquakes have impacted the islands, some having wave heights of as much as 15 meters (55 feet). The distribution of earthquakes in terms of maximum MMI is given below:

MMI	Number
V	56
VI	9
VII	9
VIII	3
IX	1
X	1

Table A-9 Important Earthquakes on or Near Puerto Rico

Date	Location	Maximum MMI (I_o)	Magnitude (Approx. M_S)
Apr. 20, 1824	St. Thomas, VI	(VII)	
Apr. 16, 1844	Probably north of PR	VII	
Nov. 28, 1846	Probably Mona Passage	VII	
Nov. 18, 1867	Virgin Islands (also tsunami)	VIII	
Mar. 17, 1868	Location uncertain	(VIII)	
Dec. 8, 1875	Near Arecibo, PR	VII	
Sept. 27, 1906	North of PR	VI-VII	
Apr. 24, 1916	Possibly Mona Passage	(VII)	
Oct. 11, 1918	Mona Passage (also tsunami)	VIII-IX	7.5

SOURCE: Algermissen (1983).

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This information has been presented to alert the reader to the national nature of the seismic hazard. Detailed information about specific areas can be obtained from geologists, geophysicists, and seismologists affiliated with area academic institutions; the regional offices of the USGS and FEMA; the national earthquake information centers; and state and regional seismic safety organizations.

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Appendix B

EARTHQUAKE EXPERIENCE OF APARTMENT BUILDINGS

Apartment building owners in many parts of the United States face earthquake risks involving possible life loss and injury, property damage, and disruption of facility operations. The experience of apartment buildings in the 1985 Mexico City earthquake is described briefly below to illustrate the potential problems.

An earthquake of magnitude 8.1 occurred in the state of Michoacan, Mexico, in September 1985. Extensive damage occurred in concentrated areas of Mexico City where hundreds of multistory buildings collapsed, thousands were damaged, and several thousand lives were lost (estimates range between 5,000 and 20,000). Sixty-five percent of all buildings damaged or destroyed were residential housing units with most being multifamily apartment buildings (single family dwellings suffered very little damage). Of these, over 15 percent collapsed. Total losses to the multifamily housing sector have been estimated at several thousand dead and over $560 million (U.S. dollars).

The most tragic cases included the collapse of the Nueva Leon apartment building in the Tlatelolco housing complex, the collapse of the Benito Juarez high-rise apartments, and the collapse of two apartment buildings in Colonia Postal. In the Tlatelolco complex, 60 buildings required minor repair (including wall and finishing work), 32 required major repair (including structural and foundation work), and 8 had to be demolished because they were near a state of collapse. In order to make the needed repairs, 10,000 people were temporarily displaced.

The Tlatelolco complex, known as the largest apartment housing complex in Latin America, was composed of three superblocks with 102 apartment buildings housing over 100,000 people in approximately 2,000 units at the time of the 1985 earthquake (Figure B-1). The complex was built using the criteria that prevailed in the 1960s and 1970s and was conceived of as a city within a city featuring very large high-rise apartment buildings, integrated urban services, green areas, and spaces for social events. Generally the inhabitants are relatively well educated (15 percent college educated and over half with high school educations) and have relatively high incomes (most with incomes five times the minimum wage).

The Nueva Leon apartment building was a 14-story reinforced concrete building constructed as part of the Tlatelolco complex. The structure was about 45 feet wide and 550 feet long with a braced frame of concrete "X" bracing in both directions (Figure B-2). The collapse of this apartment building caused the worst single building death toll in the Mexico City earthquake--over 500 dead.

FIGURE B-2
The Nueva Leon apartment building prior to the 1985 Mexico City earthquake.

The causes of collapse have not been determined precisely due to the almost total destruction of the building. Stub columns, which were located throughout the building, often are excessively loaded in shear during earthquakes due to their shortening and probably were a major factor in the collapse. In addition, the lack of a suitable number of column reinforcing ties may have contributed to the column failures. These failures may have led to a failure of the longitudinal "X" bracing, resulting in large story drifts and, thus, eccentric loading on the lateral "X" bracing which resulted in collapse. Since this was an apartment building, it was heavily occupied by families at the early hour when the earthquake occurred.

Appendix C

THE BSSC PROGRAM ON IMPROVED SEISMIC SAFETY PROVISIONS

BACKGROUND

Regulation of the design and construction of buildings in the United States has historically had as its principal aim the protection of public health and safety and, specifically, protection of the public from the actions of the individual property owner. In recent years, however, regulatory attention has been given to a growing array of public welfare issues such as the economic and social community impacts of large-scale property losses due to natural or man-made disasters.

In the case of earthquake hazard mitigation, the federal government is responsible for the performance of federal buildings and for limiting the financial loss exposure that stems from the President's authority to declare disaster areas and to provide a wide range of post-disaster services and assistance. Except for certain types of facilities, however, the federal government does not have the authority to prescribe standards affecting nonfederal buildings.

The Building Seismic Safety Council (BSSC) was conceived as an entirely new type of instrument for dealing with this complex regulatory environment and the related technical, social, and economic issues involved in developing and promulgating building earthquake hazard mitigation regulatory provisions that are national in scope. By bringing together in the BSSC all of the needed expertise and all relevant public and private interests, it was believed that the issues related to the seismic safety of buildings could be resolved and the jurisdictional problems overcome through authoritative guidance and assistance backed by a broad consensus.

The BSSC was established in 1979 under the auspices of the National Institute of Building Sciences (NIBS). It is an independent, voluntary membership body representing a wide variety of building community interests. Its fundamental purpose is to enhance public safety by providing a national forum that fosters improved seismic safety provisions for use by the building community in the planning, design, construction, regulation, and utilization of buildings.

that these measures and initiatives become an integral part of established activities, not additional burdens. The BSSC itself assumes no standards-making and -promulgating role; rather, it advocates that code- and standards-formulation organizations consider BSSC recommendations for inclusion into their documents and standards.

PROGRAM FOR IMPROVED SEISMIC SAFETY PROVISIONS

It is in this context and with funding from the Federal Emergency Management Agency (FEMA) that the BSSC initiated its multiphased Program on Improved Seismic Safety Provisions directed toward the creation of authoritative, technically sound resource documents that can be used by the voluntary standards and model code organizations, the building community, the research community, and the public as the foundation for improved seismic safety design provisions.

The genesis of the effort of which the BSSC program is a major element began with initiatives taken by the National Science Foundation (NSF) as a part of its earthquake research support program. Under agreement with the National Bureau of Standards (NBS), the *Tentative Provisions for the Development of Seismic Regulations for Buildings* (referred to in this report as the *Tentative Provisions*) was prepared by the Applied Technology Council (ATC). As the ATC noted, the document was the product of a "cooperative effort with the design professions, building code interests, and the research community." Its purpose was to "...present, in one comprehensive document, the current state of knowledge in the fields of engineering seismology and engineering practice as it pertains to seismic design and construction of buildings." The document included many innovations, however, and ATC acknowledged that a careful assessment was needed.

Following the issuance of the *Tentative Provisions* in 1978, NBS released Technical Note 1100, "Analysis of Tentative Seismic Design Provisions for Buildings." In this note, NBS reported its "...systematic analysis of the logic and internal consistency of [the *Tentative Provisions*]." Based on its determination of the need to deal with unresolved public comments on the *Tentative Provisions* and issues raised in its own analysis, NBS issued a *Plan for the Assessment and Implementation of Seismic Design Provisions for Buildings* in November 1978 as its final submission to NSF. This plan included the following tasks:

1. A thorough review of the *Tentative Provisions* by all interested organizations;

2. The conduct of trial designs to establish the technical validity of the new provisions and to predict their economic impact;

designs called for in Task 2 of the 1978 NBS plan could be evaluated and to recommend a specific trial design program plan. Subsequently, the BSSC created a special BSSC-NBS Trial Design Overview Committee (Committee 12) and charged it to, among other activities, revise the Committee 10A plan to accommodate a multiphased effort and to refine the *Tentative Provisions*, to the extent practicable, to reflect the recommendations generated during the earlier review. The Overview Committee completed the revised plan in August 1982. It was released in November 1982 as *Plan for a Trial Design Program To Assess Amended ATC 3-06 Tentative Provisions for the Development of Seismic Regulations for Buildings* (NBSIR 82-2589/BSSC 82-1).

THE TRIAL DESIGN EFFORT

The BSSC then initiated the effort to develop the actual trial designs, which were to include the following building types and structural systems:

<u>Building Types</u>

Low-, mid-, and high-rise residential (R) buildings,
Mid- and high-rise office (O) buildings,
One-story industrial (I) buildings, and
Two-story commercial (C) buildings.

<u>Structural Systems</u>

1. Lateral load systems

    a. Shear walls
        (1) Cast-in-place concrete
        (2) Precast and prestressed-precast concrete
        (3) Masonry
        (4) Plywood on wood studs

    b. Braced frames--conventional steel

    c. Unbraced frames
        (1) Cast-in-place concrete both special and ordinary (as defined in the amended *Tentative Provisions*)
        (2) Steel, both special and ordinary, conventional and pre-engineered

2. Vertical load systems

    a. Bearing wall buildings
        (1) Walls
            (a) Cast-in-place concrete
            (b) Precast and prestressed-precast concrete
            (c) Masonry
            (d) Plywood on wood studs

Such changes were not permitted even if an alternative structural type would have cost less than the specified type under the early version of the *Provisions*, and this constraint may have prevented the designer from selecting the most economical system.

Phase II concluded with publication of:

- A draft version of the recommended provisions, *The NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings*, that included three parts--the draft provisions, the draft commentary to the provisions, and an appendix that presented Chapters 13-15 of the original ATC document concerning existing buildings;

- An overview of Phases I and II of the BSSC program that included the BSSC-NBS Overview Committee's analysis of the results and the executive summaries from the reports of the design firms participating in the program as well as a series of appendixes that presented the initial amendments to the original ATC document, the original trial design program plan, the plan for studies to be conducted in Phase III of the program, the detailed contract work plans for Phases I and II, and a list of the members of the BSSC technical committees.

- The design firms' reports.

DEVELOPMENT OF THE 1985 EDITION OF THE *NEHRP RECOMMENDED PROVISIONS*

The draft provisions issued at the conclusion of Phase II reflected the initial amendments to the original ATC document as well as further refinements made by the Overview Committee during Phases I and II of the program. They represented an interim set of provisions pending their balloting by the BSSC member organizations during Phase III of the BSSC program, which began in July 1984.

The first ballot, which was conducted in accordance with the BSSC Charter, was organized on a chapter-by-chapter basis using a form that provided for four responses: yes, yes with reservations, no, and abstain. All "yes with reservations" and "no" votes were to be accompanied by an explanation of the reasons for the vote and the "no" votes were to be accompanied by specific suggestions for change if those changes would change the negative vote to an affirmative.

All comments and "yes with reservation" and "no" votes received as a result of the first ballot were compiled. Proposals for dealing with these responses then were developed for consideration by the Technical Overview Committee and, subsequently, the BSSC Board of Direction. The draft provisions were then revised to reflect the changes deemed appropriate by the BSSC Board and were submitted to the BSSC membership for balloting again in August-September 1985.

a result of the balloting for the 1988 Edition; and to prepare recommendations for resolving issues raised as a result of the balloting.

The TCs were composed of individuals nominated by organizations deemed by the BSSC Board to have both an interest and expertise in the various subjects to be addressed. When additional technical expertise was deemed necessary, the Board made additional appointments. Basically, the TCs were charged to consider new developments (e.g., newly issued standards) and experience data that had become available (e.g., as a result of the 1985 Mexico City earthquake) since issuance of the 1985 Edition of the *Provisions* as well as those issues left unresolved at the conclusion of the Phase III effort.

The unresolved issues, which numbered 58, focused on the risk maps; the Seismicity Index and Seismic Performance Categories; R factors (inelastic reduction factors); strength versus working stress design; drift limits; C_T factors (approximate periods of vibration); P-delta limits (gross stability); modal analysis procedures, soil-structure interaction; foundation design requirements; and various issues in the chapters on architectural, mechanical and electrical components and systems, wood, steel, concrete, and masonry. Each unresolved issue was addressed by at least one TC; some were submitted as proposals for change for the 1988 Edition, some were incorporated as minor editorial revisions, some were considered and rejected at the TC level, and some were deferred for study in future update efforts due to the lack of available data or time.

A number of new issues also were raised for consideration during the update effort and some were more philosophical than technical. It was deemed appropriate, for example, to have all the TCs and the TMC reassess the intent of the *Provisions* as stated in the opening paragraphs of the 1985 Edition, and some committees also discussed whether damage control in areas of low seismicity should be considered in the *Provisions* in addition to life safety. As a result of these deliberations, several revisions were proposed to clarify the overall objectives of the document. Another cluster of new issues concerned the relationship of the *NEHRP Recommended Provisions* to other structural and seismic provisions. The idea of working towards a common format to ease incorporation of one body's standards into another's was endorsed. Several proposals also were made to bring the *Provisions* into conformance with the new editions of the *Uniform Building Code* and Structural Engineers Association of California's *Blue Book*. These proposals did not simply involve direct adoptions; rather, they recognized the importance and validity of the research behind the changes in the other documents. Other new standards such as the ACI-ASCE 530-88 masonry code and the LRFD specification for steel design being developed by the American Institute of Steel Construction also stimulated proposals for change.

The TCs and TMC worked throughout 1987 to develop specific proposals for changes needed in the 1985 Edition of the *Provisions*. In December 1987, the Board reviewed specific proposals for change that had been

BUILDING SEISMIC SAFETY COUNCIL
MEMBER ORGANIZATIONS

AFL-CIO Building and Construction Trades Department
AISC Marketing, Inc.
American Concrete Institute
American Consulting Engineers Council
American Council of Independent Laboratories, Inc.
American Institute of Architects
American Institute of Steel Construction
American Insurance Services Group, Inc.
American Iron and Steel Institute
American Plywood Association
American Society of Civil Engineers
Applied Technology Council
Associated General Contractors of America
Association of Engineering Geologists
Association of Major City Building Officials
Association of Wall and Ceiling Industries International
Brick Institute of America
Building Officials and Code Administrators International
Building Owners and Managers Association International
California Geotechnical Engineers Association
Canadian National Committee on Earthquake Engineering
Concrete Masonry Association of California and Nevada
Concrete Reinforcing Steel Institute
Earthquake Engineering Research Institute
General Reinsurance Corporation[1]
Interagency Committee on Seismic Safety in Construction
International Conference of Building Officials
Masonry Institute of America
Masonry Institute of Washington
Metal Building Manufacturers Association
National Association of Home Builders
National Association of Housing and Redevelopment Officials
National Center for Earthquake Engineering Research[1]
National Concrete Masonry Association
National Conference of States on Building Codes and Standards
National Elevator Industry, Inc.
National Fire Sprinkler Association
National Forest Products Association
National Institute of Building Sciences
National Ready Mixed Concrete Association
Oklahoma Masonry Institute
Permanent Commission for Structural Safety of Buildings[1]
Portland Cement Association
Prestressed Concrete Institute
Rack Manufacturers Institute

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[1]Non-voting member.

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