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ABSTRACT

Elementary and secondary schools deserve special attention with respect to seismic safety because of their special occupancy characteristics and their importance to immediate and long-term earthquake disaster relief and recovery efforts. Seismic safety provisions, when incorporated in a sound design from the very beginning, usually amount to only about 1.5 percent of the cost of construction. General information concerning the seismic hazard and seismic design for elementary and secondary schools is contained in part 1 of this publication. Part 2 contains more technical considerations for school designers including basic design problems that affect the seismic performance of schools, and the ways in which the National Earthquake Hazards Reduction Program (NEHRP) "Recommended Provisions for the Development of Seismic Regulations for New Buildings" in particular and understanding of seismic design issues in general can work to protect elementary and secondary schools. Figures and photographs are included with the text; appended are a glossary, measures of earthquake magnitude and intensity, earthquake experiences of California schools, and seismicity information by region. The last 14 pages of the document contain information about the Building Seismic Safety Council (BSSC). (30 references) (MLF)

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Seismic Considerations— Elementary and Secondary Schools

EARTHQUAKE HAZARDS REDUCTION SERIES 34

Issued by FEMA in furtherance of the
Decade for Natural Disaster Reduction.

BUILDING
SEISMIC
SAFETY
COUNCIL

**Program
on
Improved
Seismic
Safety
Provisions**

SEISMIC CONSIDERATIONS:

ELEMENTARY AND SECONDARY SCHOOLS

Revised Edition

BSSC Program on Improved Seismic Safety Provisions

SEISMIC CONSIDERATIONS:

ELEMENTARY AND SECONDARY SCHOOLS

Revised Edition

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

BUILDING SEISMIC SAFETY COUNCIL
Washington, D.C.
1990

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Building Seismic Safety Council reports include the documents listed below; unless otherwise noted, single copies are available at no charge from the Council:

Abatement of Seismic Hazards to Lifelines: Proceedings of the Building Seismic Safety Council Workshop on Development of an Action Plan, 6 volumes, 1987

Action Plan for the Abatement of Seismic Hazards to New and Existing Lifelines, 1987

Guide to Use of the NEHRP Recommended Provisions in Earthquake-Resistant Design of Buildings, 1990

Improving the Seismic Safety of New Buildings: Societal Implications: Selected Readings, 1986

NEHRP (National Earthquake Hazards Reduction Program) Recommended Provisions for the Development of Seismic Regulations for New Buildings, 1988 Edition, 2 volumes, 1988

Seismic Considerations for Communities at Risk, 1990*

Seismic Considerations: Elementary and Secondary Schools, Revised Edition 1990

Seismic Considerations: Health Care Facilities, Revised Edition, 1990

Seismic Considerations: Hotels and Motels, Revised Edition, 1990

Seismic Considerations: Apartment Buildings, 1988

Seismic Considerations: Office Buildings, 1988

Strategies and Approaches for Implementing a Comprehensive Program to Mitigate the Risk to Lifelines from Earthquakes and Other Natural Hazards, 1989 (available from the National Institute of Building Sciences for $11)

For further information concerning any of these documents or the activities of the BSSC, contact the Executive Director, Building Seismic Safety Council, 1201 L St., N.W., Suite 400, Washington, D.C. 20005.

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*This publication replaces *Improving the Seismic Safety of New Buildings: A Community Handbook of Societal Implications*, Revised Edition, 1986, and *Improving the Seismic Safety of New Buildings: A Non-Technical Explanation of the NEHRP Recommended Provisions*, 1986.

FOREWORD

The Federal Emergency Management Agency (FEMA) is pleased to have sponsored the development and the updating of this publication, one of a series of five devoted to the seismic safety of specific building types with special occupancy and functional characteristics (i.e., schools, lodging facilities, health care facilities, office buildings, and apartment buildings). Owners, developers, designers, and regulatory officials concerned with such buildings are encouraged 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*. This revised edition of *Seismic Considerations: Elementary and Secondary Schools* reflects the content of the 1988 Edition of the *Provisions*.

Special thanks are due to Christopher Arnold, Building Systems Development, Inc., San Mateo, California, and Earle Kennett, Kennett/Nanita Associates, Gaithersburg, Maryland, who authored the initial edition of this publication, and to the BSSC staff and Board of Direction for their efforts in producing this revision.

Federal Emergency Management Agency

ACKNOWLEDGMENTS

This publication 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 Christopher Arnold of Building Systems Development, Inc., and Earle Kennett of Kennett/Nanita Associates for their contributions in developing and promoting the first edition of this publication; to John F. Meehan, past Chief Structural Engineer for California's Office of the State Architect, for his technical review of the original publication and for his contribution of photographs; and to Ivan Viest, Consulting Engineer, Bethlehem, Pennsylvania, who developed material for later reports in the *Seismic Considerations* series that has been used in this revision.

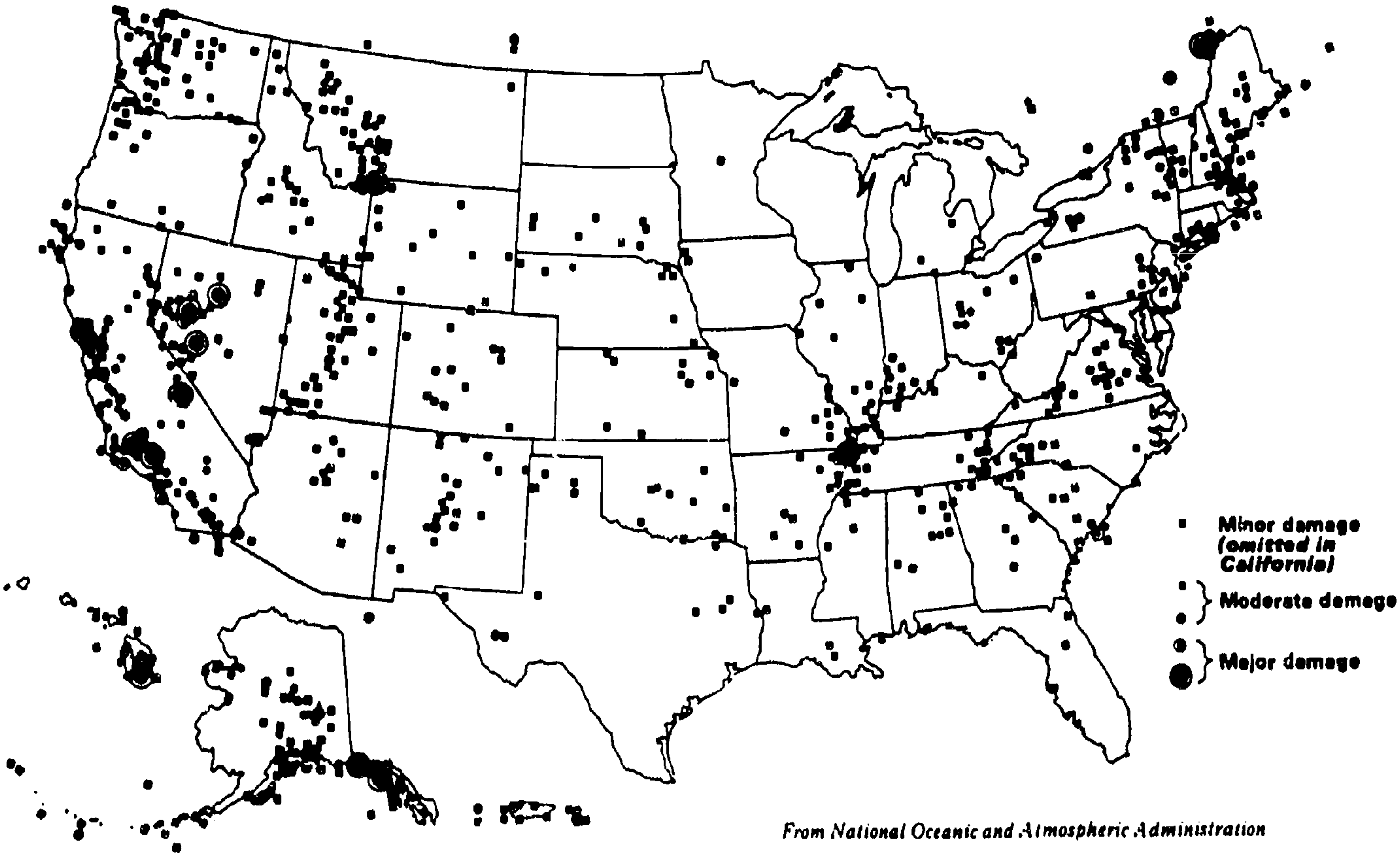
CONTENTS

OVERVIEW

Need for Seismic Hazard Awareness

A severe earthquake is one of nature's most terrifying and devastating events and collapsing structures 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. The Council also 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 that their designers follow up-to-date seismic-resistant design guidelines in all earthquake-prone areas of the nation.

Many building owners and developers, like many Americans in general, tend to associate earthquakes only with California. They are unaware that earthquakes are a national hazard. In fact, earthquakes have occurred and continue to occur in the majority of states and some of the most severe earthquakes recorded in this nation have occurred, not on the West Coast, but in the Midwest and East.



Damaging U.S. earthquakes.

From National Oceanic and Atmospheric Administration

Importance of Seismic Safety for Schools

Elementary and secondary schools deserve special attention with respect to seismic safety because of:

- Their special occupancy characteristics and
- Their importance to immediate and long-term earthquake disaster relief and recovery efforts.

Also of concern is the fact that demographic changes are expected to stimulate a significant amount of school construction during the 1990s in some areas of the country. The need to replace aging school facilities is another factor to be considered since, during the next 10 years, an astonishing 50 percent of existing school buildings will be between 40 and 80 years old.

Elementary and secondary school design presents special problems:

- The occupancy of these schools by society's most precious resource, its children, is required by law and, therefore, the moral and legal responsibility for properly protecting occupants is very great. The occupancy density also is one of the highest of any building type (1 person per 20 square feet) and, after an earthquake, the children are very likely to be frightened, which can make emergency egress difficult at best and virtually impossible if the structure is badly damaged.
- Schools often are very complex facilities featuring both relatively small classrooms, laboratories, and offices and large, open assembly areas.
- After an earthquake, community damage will result in an influx of people in need of shelter and, if the school building is not functional, it becomes another disaster-related liability rather than an asset.
- Closure of schools for any length of time represents a very serious community problem, and major school damage can have a disastrous and long-term economic effect on a community.

The NEHRP Recommended Provisions

Specific guidance for overcoming the structural and, to some extent, the nonstructural seismic problems specific to elementary and secondary schools is available in the *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings*. This set of guidelines was first issued with the consensus approval of the BSSC membership (see the back of this publication for a list of current members) in 1985; a planned three-year update effort produced the 1988 Edition; and work on the 1991 Edition is under way. The *Provisions* contains information on such technical topics as ground motion and site geology, building occupancy and configuration considerations, structural systems and the connection of system elements, building materials, and nonstructural components and contents.

Economics of Seismic Design

Earthquake resistance need not be expensive. In fact, seismic safety provisions, when incorporated in a sound design from the very beginning of the planning effort by a competent team, usually amount to only about 1.5 percent of the cost of construction. In the case of a $3,000,000 school, for example, seismic design would add only about $37,500 to the construction cost--an amount that would have to be invested at 13 percent per year for 25 years to provide sufficient funds to pay for typical earthquake damage.

California's Experience

Experience has shown that seismic design for school buildings pays off. A large number of California school buildings have been constructed to comply with the *Field Act* of 1933--an act that has set stringent seismic requirements for school facility design and construction. Since the *Field Act* was implemented, school buildings in California have been tested in a number of earthquakes, and, to date, no students or teachers have been killed or injured in a post-*Field Act* school building during an earthquake.

The damaging Kern County earthquakes of 1952 involved one earthquake of Richter magnitude 7.6 followed a month later by one of magnitude 5.8. Of the 40 area schools constructed prior to the *Field Act*, 40 percent suffered severe damage, 33 percent suffered moderate damage, 25 percent suffered slight damage, and 2 percent had no damage. Of the 18 schools constructed in accord with the *Field Act*, 61 percent had no damage, 33 percent suffered slight damage, and only 6 percent had moderate damage. The 6.7 magnitude earthquake in Coalinga in 1983 and the 5.9 magnitude earthquake in Whittier Narrows in 1987 tended to confirm the adequacy of *Field Act* structural requirements in that damage to *Field Act* schools, while not insignificant, was almost completely nonstructural. In the 1989 Loma Prieta earthquake, of the 1,544 public schools surveyed in the impacted area, only three suffered serious damage and there were no casualties. The fact that some non-life-threatening damage is suffered by *Field Act* schools tends to indicate that the requirements are not too restrictive, but emphasizes the need for attention to nonstructural elements and building contents.

Decision-maker Concerns

The BSSC, on behalf of the Federal Emergency Management Agency and concerned organizations in both the public and private sectors of the building community, urges each elementary and secondary school decision-maker to give full consideration to the implications of seismic risk in the design of their facilities. This enlightened self-interest will bear many tangible and intangible returns.

Contents of This Publication

General information concerning the seismic hazard and seismic design for elementary and secondary schools is contained in Part I of this publication and more technical details are presented in Part II. Appendixes provide information on related topics.

PART I

SEISMIC CONSIDERATIONS FOR ELEMENTARY AND SECONDARY SCHOOL DECISION-MAKERS

1

EARTHQUAKES AND SCHOOLS

Earthquakes--A National Hazard

A severe earthquake is one of nature's most terrifying and devastating events, and collapsing structures and falling debris do most of the killing. Media coverage of the 7.1 magnitude Loma Prieta earthquake in 1989 showed the nation just how horrifying an earthquake can be while also illustrating that modern buildings, designed and constructed under up-to-date seismic regulations, will perform well. Such regulations, however, have not been imposed in many areas of high to moderate seismic risk.

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 B for an overview of U.S. seismicity). Indeed, three of the most severe U.S. earthquakes 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 continental 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). Since 1987, however, earthquake-related property damage has more than exceeded that amount:

- The 1987 Whittier Narrows earthquake in Los Angeles caused three deaths and over $350 million in property damage.

- The 1989 Loma Prieta earthquake in the San Francisco Bay area caused 62 deaths and over $5 billion in property damage.

Further, consider the tremendous social and economic loss to the nation if just one earthquake comparable, for example, to the New Madrid event occurred today where a number of high-density urban areas such as Memphis and St. Louis 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.

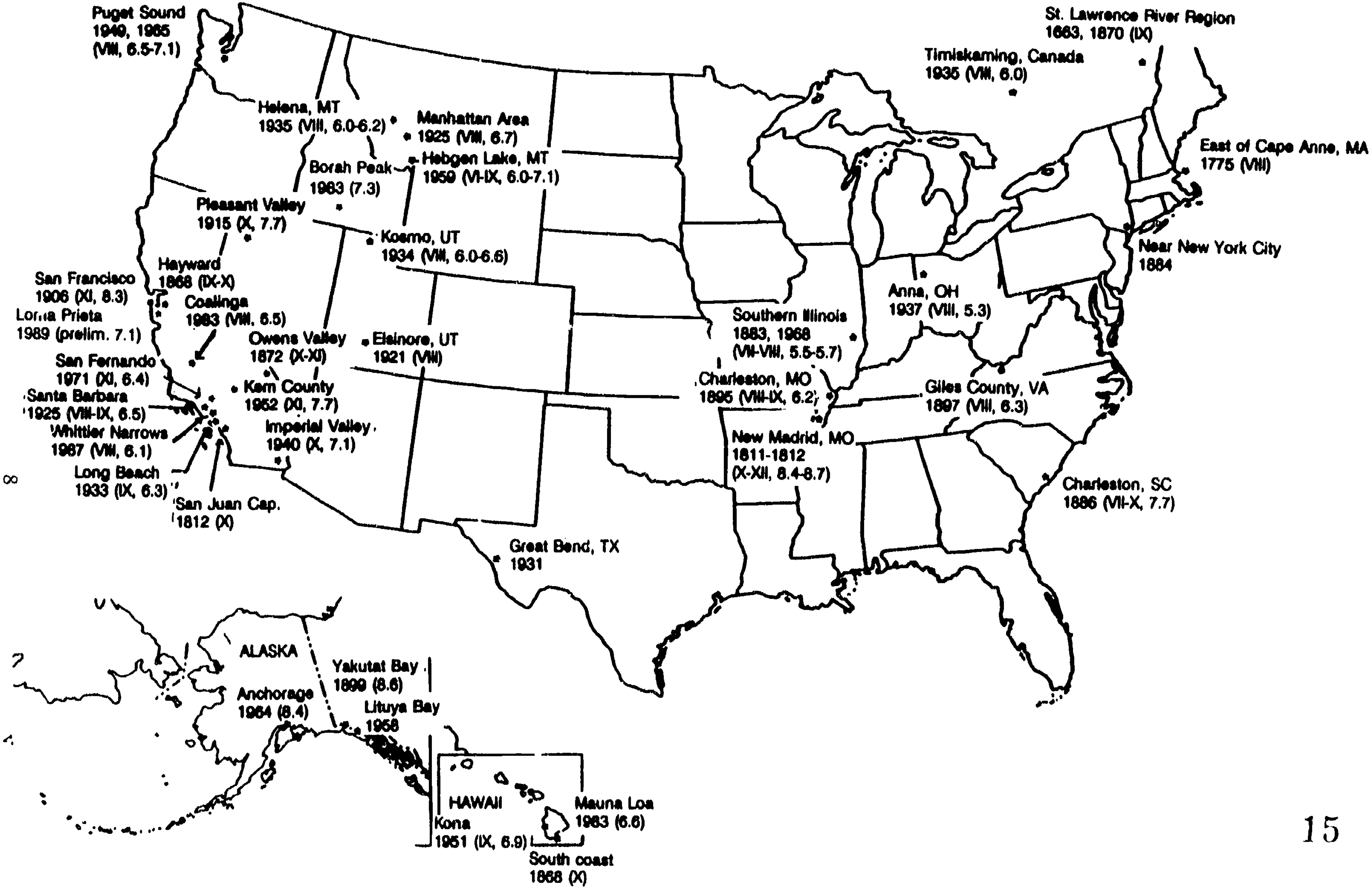


FIGURE 1
Damaging U.S. earthquakes.
When available, Modified Mercalli Intensity and/or Richter/surface wave magnitude data are given in parenthesis.

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 eventually should 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 effective 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 do devastating damage.

Schools Pose Special Earthquake Problems

This situation is especially critical with respect to elementary and secondary schools. Although school construction is similar to that of other buildings, the size, occupancy and purpose of these buildings dictate that seismic safety (like fire safety) be given special attention:

- The occupancy of elementary and secondary schools by society's most precious resource, its children, is required by law and, therefore, the moral and legal responsibility for properly protecting occupants is very great. The occupancy density also is one of the highest of any building type (1 person per 20 square feet) and, after an earthquake, the children are very likely to be frightened, which can make emergency egress difficult at best and virtually impossible if the structure is badly damaged.

- Schools often are very complex facilities featuring both relatively small classrooms, laboratories, and offices and large assembly areas.

- After an earthquake, community damage will result in an influx of people in need of shelter and, if the school building is not functional, it becomes another disaster-related liability rather than an asset.
- Closure of schools for any length of time represents a very serious community problem, and major school damage can have a disastrous long-term economic effect on a community.

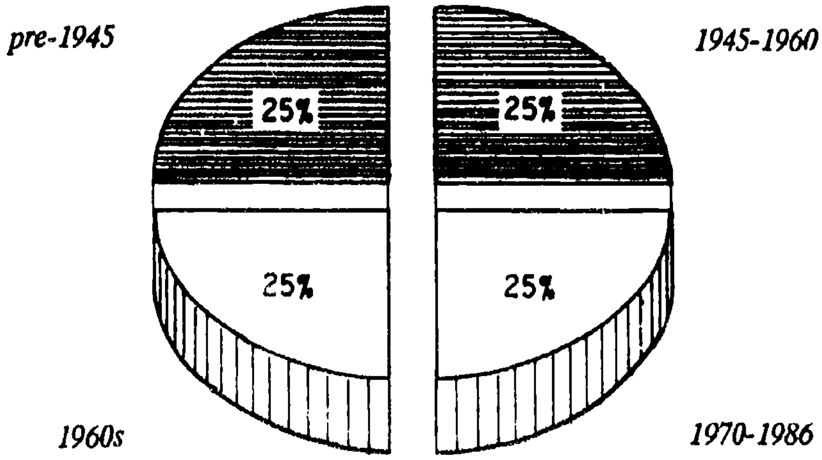
Decision-Maker Concerns

Given these factors, it is apparent that earthquake resistance should be given serious attention during the design and construction of school buildings in areas at risk from earthquakes. An unsafe school building structure may incur structural damage during an earthquake and may 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 loss--probably for months or even years. Even without building collapse and no injuries, earthquake damage to school equipment and contents can approach 50 percent of the worth of the facility.

Also of concern is the fact that a significant amount of school construction is expected to occur during the remainder of this century. Unlike the uniform growth of the U.S. school population during the 1950s and 1960s, the enrollment declines that characterized the 1970s and early 1980s were not evenly distributed nationally and, in the future, most school districts are expected to experience enrollment fluctuations (increases followed by declines). For example, although enrollment in the West is predicted to increase 40 to 48 percent by 2000, the Northeast is expected to experience a decrease in elementary school enrollment of from 13 to 21 percent and, in high school enrollment, of over 30 percent. In the South, enrollment is expected to increase from 17 to 19 percent while the Midwest will see a 3 to 7 percent decrease.

These enrollment estimates, however, reflect only one aspect of the future school construction picture. Replacement of aging facilities is another. Almost half of the nation's schools were built prior to 1960 with almost one quarter having been constructed between 1920 and 1945 (Figure 2, data from the U.S. Energy Information Administration, *Characteristics of Commercial Buildings*, 1983).

FIGURE 2
Construction date of existing schools.



Thus, during the next 10 years, an astonishing 50 percent of existing school buildings will be between 40 and 80 years old. This aging school facility inventory presents a unique seismic problem since, even in California, seismic design of schools started only in 1934. In other areas of the country at risk from earthquakes, seismic design remains a rare occurrence even today.

The need to replace aging school facilities and the major regional migrations that are causing increased school enrollment in some areas suggest that there will be a resurgence of school building construction and, in fact, there is already strong evidence of such an increase on a national scale. This opportunity to protect the nation's children from seismic hazards by applying seismic design in the construction of new school facilities in much the same way that they are protected from fire and other hazards by higher standards of safety should not be missed.

2

SEISMIC HAZARD MITIGATION AND THE COST/BENEFITS OF SEISMIC DESIGN

Need for Local Seismic Hazard Assessment

Those responsible for elementary and secondary schools need to research their local seismic situation to determine the precise 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 up-to-date seismic design provisions--especially the *NEHRP Recommended Provisions*--in developing requirements for elementary and secondary schools generally is considered to be one significant way of lessening the risk to life by bringing to bear the best available guidance for designing and constructing new buildings in a manner that will prevent their structural collapse during an earthquake. (Appendix A presents a review of the California experience with seismic-resistant school design that illustrates just how great a difference it can make.)

Life Safety Considerations

School 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 students, faculty, staff, and visitors. 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 occur at any specific location and, therefore, there always remains some degree of risk. This risk may be small, but it is greater than zero.

For an individual building designed in accordance with *NEHRP Recommended Provisions*, the intent is to ensure a level of safety such that in the "design earthquake" (i.e., one that has only a 10 percent probability of being exceeded in 50 years), structural damage will be limited. There may, however, be some nonstructural and contents damage but such damage will not be life-threatening. Any damage, structural or nonstructural, generally will be repairable. For a large earthquake of low probability of occurrence (e.g., one with a predicted occurrence interval of thousands of years), there may be structural damage and considerable nonstructural damage, but life-threatening collapse, while possible, is improbable. It must be emphasized, however, that it is not practical to obtain absolute safety from any natural or man-made hazard. A major earthquake may produce some damage (both structural and nonstructural) in even the most earthquake-resistant structures, but use of the *NEHRP Recommended Provisions* will provide a high level of life safety when applied by competent engineers knowledgeable about earthquake matters.

Property Damage Considerations

Although the *NEHRP Recommended Provisions* is written to minimize the risk to life safety, as a by-product, its use will reduce building damage costs, especially during a moderate earthquake. In highly seismic areas where moderate earthquakes occur frequently, any increase in building costs will be more than offset by reduced damage costs--a factor especially important with respect to publicly financed buildings whose repair and replacement costs will be borne by the taxpayer.

Building codes primarily regulate the design and construction of a building's structural system--the members that provide support for the building. Good performance of the structural system during an earthquake does not necessarily mean that there will not be considerable damage to the building or even life loss or injury, but poor performance of the structure will most certainly result in heavy property damage, life loss, and injury.

The analysis of a structural system and its design in relation to some specified ground motion do not alone make a building earthquake resistant; additional design details are necessary to provide adequate resistance in buildings. While experienced earthquake designers normally provide them, some aspects of seismic design have not been required in some areas and, consequently, may be overlooked by design teams inexperienced in earthquake design. Chapters 3 and 4 of this publication discuss some of these issues and offer possible solutions.

Performance Requirements

Those responsible for an elementary or secondary school also should consider additional seismic performance requirements to protect the occupants and contents of their building. Some of these requirements may require managerial solutions through emergency planning procedures whereas others, such as the ability to structurally evaluate a facility, also relate to design concepts. Although the basic strategy for reducing damage to a school facility involves design in accordance with up-to-date and 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 elementary and secondary schools:

- Students and teachers within and outside the school must be protected during an earthquake and must be able to evacuate the school quickly and safely after an earthquake.

- Emergency systems in the school must remain operational after an earthquake.

- Rescue and emergency workers must be able to enter the school immediately after an earthquake, encountering minimum interference and danger.

- The property damage to the school must be only what can be tolerated after a destructive earthquake.

- The school must remain functional for any planned disaster response role.

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 to establish seismic design standards often is based on economic considerations: By how much can we afford to reduce the risk of damage to our building? Because school facilities provide an essential community service 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 concerning the effects of seismic design on school economics.

In general, the added cost of seismic design will be in increased design and analysis fees, additional materials (steel reinforcement, anchorages, seismic joints, etc.), and additional elements (bracing, columns, beams, etc.). 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--It is much more economical to provide seismic resistance in a building with a simple form and framing.
- The overall cost of the structural system in relation to the total cost of the building--For a typical school, the structural system usually represents between 10 and 15 percent of the building cost.
- The stage of design at which increased seismic resistance is considered--The cost of seismic design can be greatly inflated if no attention is given to it until after the configuration of the building, the structural framing plan, and the materials of construction have been selected.

In the best case (a simple building with short spans where earthquake requirements are introduced at a very early stage of project planning), the increased cost for seismic design should be in the range of 1 to 4 percent of the structural system or between 1.5 and considerably less than 1 percent of the building cost. In the worst case (a complex, irregular building with long spans where earthquake requirements are considered only after the major design features are frozen), the increase can be considerably more--perhaps as large as 25 percent of the structural cost or up to almost 5 percent of the building cost. In addition, because of the importance of utilities and other nonstructural elements, an additional cost must be estimated for ensuring their protection, but this should not exceed 0.5 percent of construction cost.

The average increase in cost of school facilities conforming to the *NEHRP Recommended Provisions* should be less than 1.5 percent of the construction cost of the building, which, of course, is only a part of the total project costs. The actual construction cost of an elementary school, for example, is only about 50 percent of the total project cost, which also includes technical expenses, administrative expenses, land cost, and site development. The cost of equipping a modern school further reduces the impact of a small increase in construction cost. And, because of the high level of wages and salaries, the capital cost of construction represents only a small percentage of yearly operating costs.

These costs also can be considered to be a kind of insurance against the failure of individual elements and pieces of equipment in the building. When looked at in this way, such expenditures take on a new perspective. For instance, the difference between disruption of electricity in a school and severe damage to or destruction of a $50,000 emergency power generator or electrical transformer may lie in an additional $250 for seismic snubbers or restraints. The cost implications of damage to expensive equipment are great in terms of both direct repair or replacement costs and indirect costs resulting from the effect of unusable equipment on school operations.

It is illustrative to examine the increased costs and benefits of seismic school design in terms of the rate of return to the school owner and the public on the increased investment in the building over a 25-year period. This assumes that a damaging earthquake will occur before the end of the 25 years, which is a reasonable probability in many areas.

If the two alternatives--with and without seismic design--are compared, the rate of return on the extra investment can be determined. This rate of return is the initial rate that the investment would have to be earning if, after 25 years, the community wanted to use the investment to pay for earthquake damage to the school, repairs that would need to be paid for in future inflated dollars.

For the purposes of this example, consider a 50,000 square foot school building with a construction cost of $60.00 per square foot with 25 percent of the cost attributable to the structural and foundation systems, 21 percent to the mechanical and plumbing systems, 13 percent to the electrical system, 33 percent to the architectural systems, and 8 percent to fixed equipment. The cost of seismic design is estimated to be 5 percent of the cost of the structural system or 1 percent of total building construction. (Remember that construction cost represents only a portion of total project cost which also includes design, land acquisition, and site development costs.)

The assumptions for this example are as follows:

- The school costs $3,000,000 to construct without seismic design and $3,037,500 to construct with seismic design.
- At the end of 25 years (with a 4 percent inflation rate), the school without seismic design will be worth $7,998,000 and the school with seismic design will be worth $8,097,975.
- In future dollars, the earthquake damage to the school without seismic design will be $1,199,700 (damage to 15 percent of the structure, 15 percent of mechanical/electrical systems, and 15 percent to the architectural components) and to the school with seismic design will be $267,933 (damage to 5 percent of the mechanical/electrical systems and architectural components).
- The extra finance charges for the $37,500 investment for seismic design will be $125,344 in future dollars (25 year loan at 8 percent).

Thus, the total future extra costs of the school without seismic design would be $906,398 (a negative $99,975 difference in building worth, a negative $931,767 difference in damage repairs, and a positive $125,344 for the principal and finance charges for the seismic investment) and a 13 percent investment would be needed to receive a similar return on the original seismic design investment. In another words, the school board would have had to invest $37,500 (the original cost of seismic design) at 13 percent per year for 25 years to be able to pay for school repairs. In essence, then, seismic design for schools represents both increased life safety of the nation's children and a sound investment economically.

If earthquake damage is severe, the financial loss affects not only the educational facility and the community as a whole but also the staff and other businesses and professionals who provide goods and services to the school. Earthquake damage therefore will have a very broad effect on community business activities.

In addition, although they cannot yet be quantified, liability risks must be considered by school boards and others responsible for schools. Few data are available that reflect the magnitude of the risks that educational facility decision-makers face in terms of liability for casualties incurred in their buildings during an earthquake, but this will almost certainly be decided by the courts after the next earthquake that causes life loss. As soon as the earthquake threat is identified and means of reducing its effect are documented, the school that makes no reasonable provision for seismic design will be in a very tenuous legal situation when the earthquake occurs.

Further, it has been determined in California that school board members are individually liable for the occupants of a school building if the building has been found to be unsafe and proper steps have not been taken to correct the deficiencies or close the building. Needless to say, when the school boards in California became aware of this liability, they pursued every means necessary to correct unsafe buildings. Many school boards in the West also are exploring more stringent seismic regulations based on the expected liability that they will incur as a result of the earthquake performance of their school buildings.

Liability for earthquake losses also may have a considerable impact on designers. After the 1985 earthquake in Mexico City, for example, a Mexico resident sought justice in the case of the loss of his family in an apartment building that collapsed as a result of the earthquake. His claims were based on an investigation of the design, materials, and construction of the building, and, as a result, the Mexican federal courts issued arrest warrants for the designers of the building. This case is reported to be the first to be brought against individuals as being responsible for deaths and injuries during an earthquake, but it is unrealistic to expect it to be the last.

Design/Construction Team Concerns

The complexity of school design places a special burden on the design and construction team. In particular, the coordination of the structural system 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 decision-making by the owner, affects all participants in the design process, and ultimately depends on correct construction execution by the contractor and the building force.

PART II

SEISMIC CONSIDERATIONS FOR SCHOOL DESIGNERS

3

EARTHQUAKE DESIGN PROBLEMS OF ELEMENTARY AND SECONDARY SCHOOLS

School Building Inventory

There are over 80,000 elementary and approximately 30,000 secondary schools in the United States. The post World War II "baby boom" caused major school construction during the 1950s and 1960s followed, in the 1970s and early 1980s, by major declines in school construction and large numbers of school closings. Since about 1985 there has been an increase in school construction due to the obsolescence of older facilities, internal migration from the Northeast to the West and Sun-belt states, new foreign immigrations, and a slight increase in school age populations.

In 1983, schools accounted for approximately 6,000 million square feet of space or almost 12 percent of the total nonresidential space in the nation. At the same time, schools are estimated to represent only 4.5 percent of the actual number of nonresidential buildings, meaning that they account for a very significant amount of square footage per building. In addition, only assembly buildings, which provide 14 square feet of space per person, have a higher occupancy density than schools, which provide 20 square feet per person. (For comparison, note that the occupant density of office buildings is 100 square feet per person and of lodging, health care, and retail facilities is 50 square feet.)

The age of a facility is of considerable importance with respect to seismic performance and, as indicated earlier, fully half of the nation's existing schools will be between 40 and 80 years old by the end of the century. Even in California, seismic design based on analysis only dates back about 50 years. Even buildings constructed as late as the early 1970s may have major seismic deficiencies. This is because of discoveries made through study of the performance of buildings in earthquakes in the 1960s and early 1970s (notably Alaska, 1964; Caracas, Venezuela, 1967; San Fernando, California, and Managua, Nicaragua, 1971). These earthquakes were the first to test modern methods of construction and, as a result, seismic codes and construction practices have improved since the 1970s.

Although this publication is not intended to be an engineering design manual, several problems of building design should be recognized by the school owner, administrator, planner, architect, or engineer as factors that may substantially increase the earthquake risk to their building. Some of these problems are addressed in seismic building codes, but their solutions reside more in the designer's understanding of seismic-resistant design than in specific code provisions. Others, such as damage to building contents, are outside the scope of any seismic code.

The basic design problems affecting the seismic performance of schools are:

- Building form irregularities in both the horizontal and vertical planes,
- Discontinuities in strength between the major structural elements of the building,
- Inadequate diaphragms,
- Effects of nonstructural elements on the structural system,
- Deficiencies in the connections that tie the elements of the building together, and
- Damage to the nonstructural components and contents of the building.

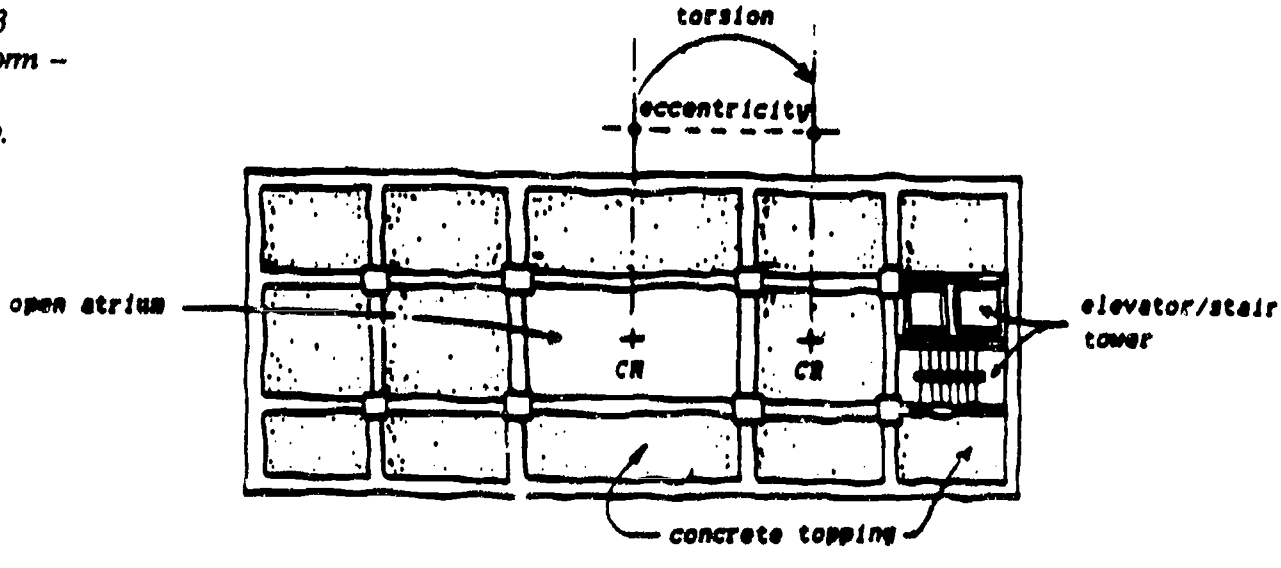
Egress complications and the disruption of post-earthquake operations are also major concerns.

Building Form Irregularities

Those who have studied the performance of buildings in earthquakes generally agree that the building's form greatly influences its performance under ground motion. This is because the shape and proportion of the building have a major effect on the distribution of earthquake forces--that is, on the relative size and nature of the forces as they work their way through the building.

A simple and symmetrical building form allows for the most even and balanced distribution of forces, but symmetry of form will not ensure low torsional effects. For instance, even in simple symmetrical rectangular buildings the location of stiff stair and elevator cores, solid and glazed walls, or other design elements that add mass in only one part of the building can result in different locations of the center of mass and the center of rigidity, and the torsion or twisting that results during an earthquakes (Figure 3) has frequently caused substantial damage.

FIGURE 3
Building form – torsional eccentricity.



A common building form that presents seismic design problems 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, H, +, or a combination of these shapes (Figure 4). These building shapes 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. Because of these characteristics, they are commonly used in school design. 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, but examples of earthquake damage to re-entrant corner type buildings are common. First noted before the turn of the century, this earthquake problem was generally acknowledged by the experts of the day in the 1920s.

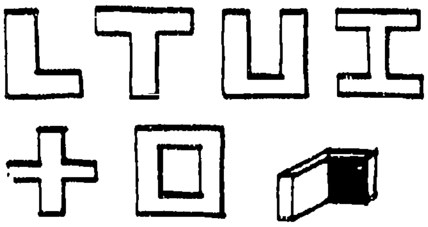


FIGURE 4
Re-entrant corner plan forms.

These shapes tend to produce variations of rigidity and, hence, differential motions between different portions of the building that result in a local stress concentration at the "notch" or re-entrant corner (Figure 5a). In addition, the wings of a re-entrant corner building often are of different heights so that the vertical discontinuity of a setback in elevation is combined with the horizontal discontinuity of the re-entrant corner in plan, resulting in an even more serious problem. The setback form--a tower on a 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 5b).

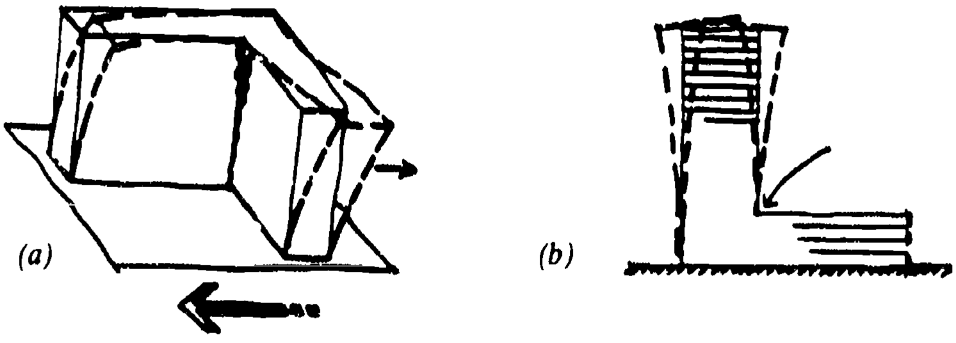


FIGURE 5
(a) movement of L-shaped building under ground motion and (b) point of stress concentration in setback building.

Typical problems with the building forms commonly used for elementary and secondary schools are as follows:

- The use of large open multipurpose spaces for functional flexibility along with smaller traditional classroom areas and relatively rigid interior walls of masonry or concrete can cause major torsional effects in the building (Figure 6a).
- The use of interconnected clusters of areas can create many re-entrant corners and consequent stress concentrations and torsional effects (Figure 6b).
- The placement of asymmetrical rigidly connected stairways within a relatively light building can cause major torsional effects (Figure 6c).
- The use of internal courtyards can cause torsional effects at the interior corners of the building (Figure 6d).
- The use of narrow wings can cause torsional effects and stress concentrations at the re-entrant corners (Figure 6e).

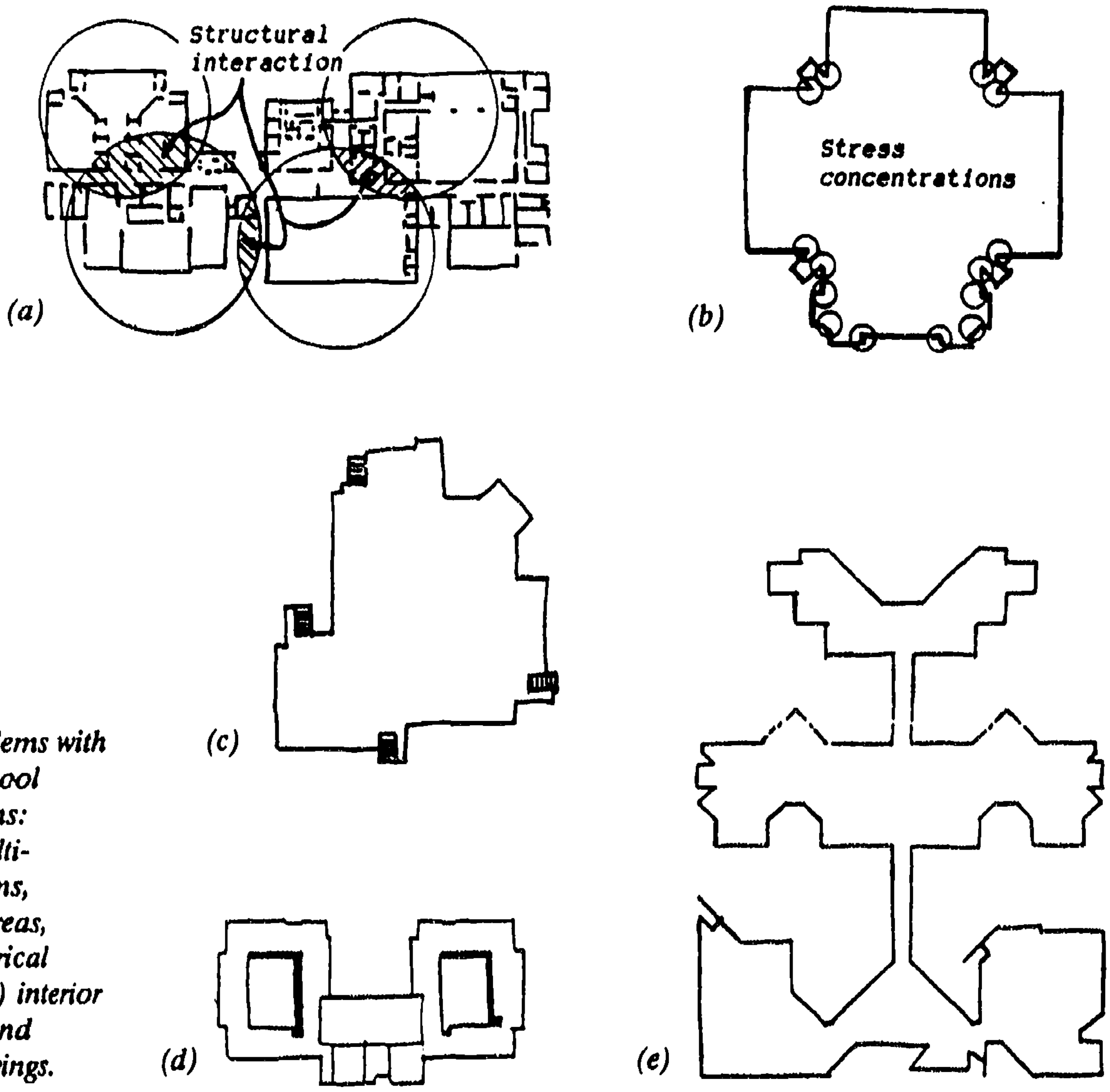
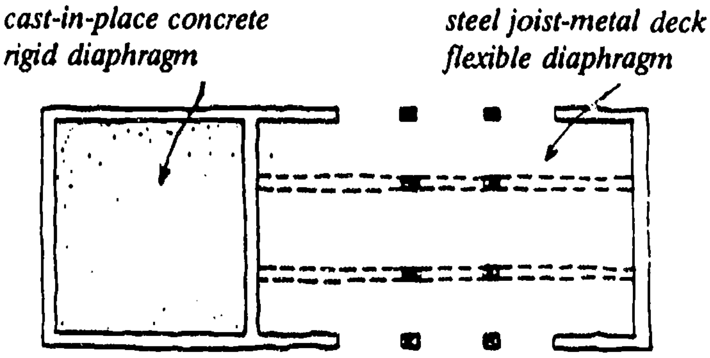


FIGURE 6
Typical problems with common school building forms:
(a) large multi-purpose rooms,
(b) cluster areas,
(c) asymmetrical stairways, (d) interior courtyards, and
(e) narrow wings.

Structural Discontinuities

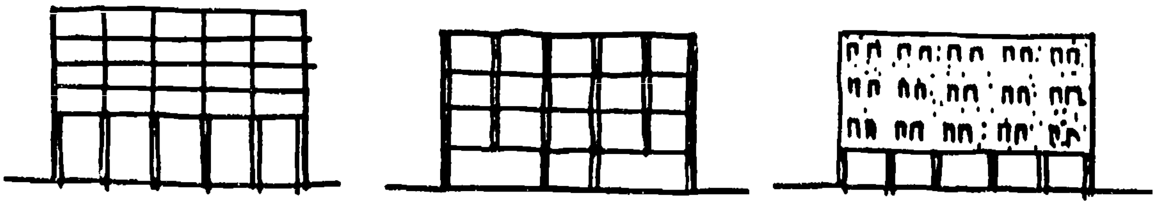
It is not generally recognized that large discontinuities (or abrupt changes) in the strength (Figure 7) or stiffness of a building can cause adverse seismic response effects. This is particularly the case where there are abrupt changes in the vertical arrangement of the structure that result in discontinuities (changes) of strength or stiffness from floor to floor.

FIGURE 7
Discontinuity in strength.



The most prominent of the problems caused by such a discontinuity is that of the "soft" first story (Figure 8), a term applied to a ground level story that is more flexible than those above. Although a "soft" story at any floor creates a problem, a stiffness discontinuity between the first and second floors tends to result in the most serious condition because forces generally are greatest near the base of a building.

FIGURE 8
"Soft" first story: (a) tall, flexible columns, (b) interrupted vertical columns, and (c) heavy superstructure over slender frame.



(a) (b) (c)

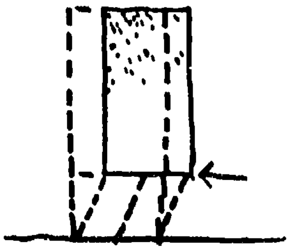
Three typical conditions create a "soft" story:

- The first occurs when there is a significant discontinuity of strength and stiffness between the vertical structure of one 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 8a).
- Discontinuity also may occur when 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 8b).

- Finally, the "soft" story may be created by an open floor that supports heavy structural or nonstructural walls above. This situation is most serious when the wall above is a shear wall acting as a major lateral force resisting element. This condition is discussed in more detail in the next chapter since it represents a very important aspect of the "soft" story problem (Figure 8c).

The basic problem with all these variations of the "soft" story is that most of the earthquake forces in the building, and any consequent structural deformity, tends to be concentrated in the weaker floor or at the point of discontinuity instead of being more uniformly distributed among all stories. The result is that, instead of the building deflection under horizontal forces being distributed equally among all the floors, it is accommodated almost entirely in the lower floors. This causes tremendous stress concentrations at the lower floor connections; failure may occur at these points and result in the collapse or partial collapse of the upper floors (Figure 9). Where earthquake forces are not an issue, the "soft" story presents no problem, but in earthquakes around the world, buildings with this condition have suffered severely.

FIGURE 9
Action of "soft" first story in ground motion.



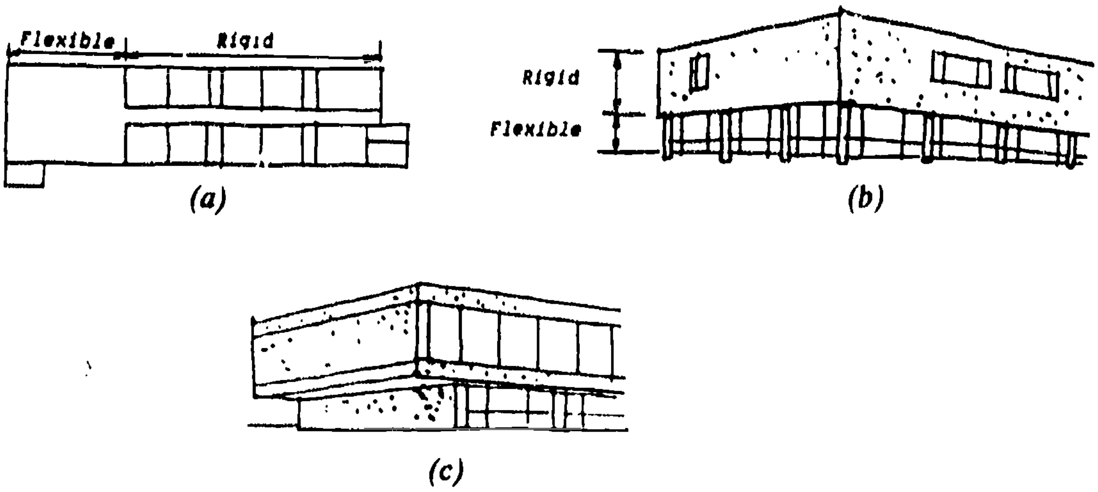
The complexity of educational facilities tends to result in vertical structural discontinuities. Among the more common situations are the following:

- The interconnection of tall, long span, flexible school areas (auditoriums, gymnasiums, cafeterias) with low, short span, rigid areas featuring shear walls (classrooms, hallways) (Figure 10a).

- The placement of stiff floors above a more flexible first floor (Figure 10b).

- Discontinuities in column or wall placement from one floor to another (Figure 10c).

FIGURE 10
Strength discontinuity: (a) plan, (b) elevation, and (c) wall-column placement.



(a)

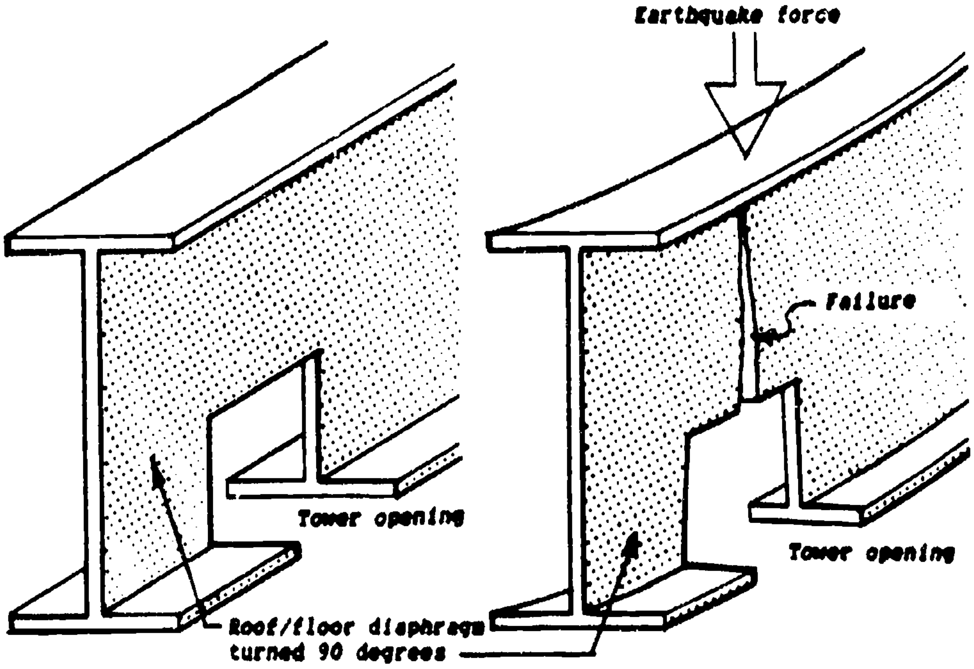
(b)

(c)

Roof and Floor Diaphragms

The earthquake loads at any level of a building will be distributed to the vertical structural elements through the roof and floor diaphragms. The roof/floor deck or slab (the horizontal diaphragm) responds to loads like a deep beam. The deck or slab is the web of the beam carrying the shear and the perimeter spandrel or wall is the flange of the beam resisting bending (Figure 11).

FIGURE 11
Openings in diaphragms.



Three factors are important in diaphragm design:

- The diaphragm must be adequate to transfer the forces and must be tied together to act as one unit.
- The collectors (members or reinforcing) must transfer the loads from the diaphragm into the shear wall.
- 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, atria, skylights) in the diaphragm create problems similar to those related to cutting a hole in the web of a beam. This reduces the natural ability of the web to transfer the forces and may cause failure in the diaphragm.

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 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.

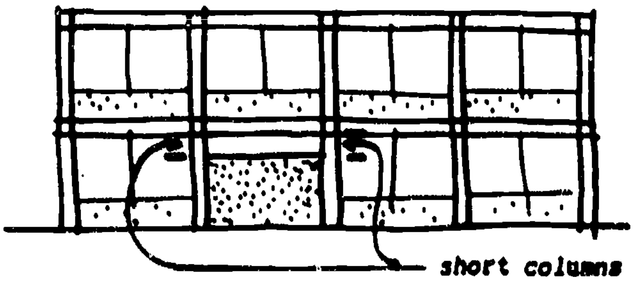
Stress or strength limitations imposed by normal design level forces occasionally may provide adequate drift control. However, the design of relatively flexible moment resisting frames and of tall, narrow shear wall buildings for seismic risk areas should be governed, at least in part, by drift considerations.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

Total building drift is the absolute displacement of any point in the building relative to the base. Adjoining buildings or adjoining wings of the same building must be considered since individual structures do not have identical modes of earthquake response and, therefore, have the tendency to pound against one another. Building separations or joints must be provided between adjoining structures to permit the different parts to respond independently to the earthquake ground motion.

Effects of Nonstructural Elements

Even in a building where discontinuities throughout the structure have been restricted, the location and design of certain nonstructural elements can actually change the effectiveness of the structural elements. For instance, the location of a rigid element (stair and elevator cores, masonry infill walls) between more flexible columns will change the "flexible" elements into rigid members. Since rigid members attract seismic forces, the columns could be subjected to forces many times greater than those for which they were designed and failure may result. (In engineering terms, horizontal forces are distributed in proportion to the rigidity of the resisting elements.) Thus, if a column designed for a full height deflection becomes a "shorter" column because of the location of a rigid infill wall, it will actually carry a larger portion of the lateral forces than assumed since horizontal forces are distributed in proportion to the rigidity of the resisting member (Figure 12).

FIGURE 12
Nonstructural infill creates short columns that attract earthquake forces.



The use of infill walls dramatically shortened the columns at the Recido School in Managua, Nicaragua (Figure 13). During the 1973 earthquake, the columns above the infill walls suffered extensive damage and barely escaped complete failure and roof collapse. Numerous other examples of damage attributed to such "shortened" columns were reported in Japanese schools following earthquakes in 1968 and 1978 (Figure 14).

FIGURE 13
Recido School after 1973 earthquake.

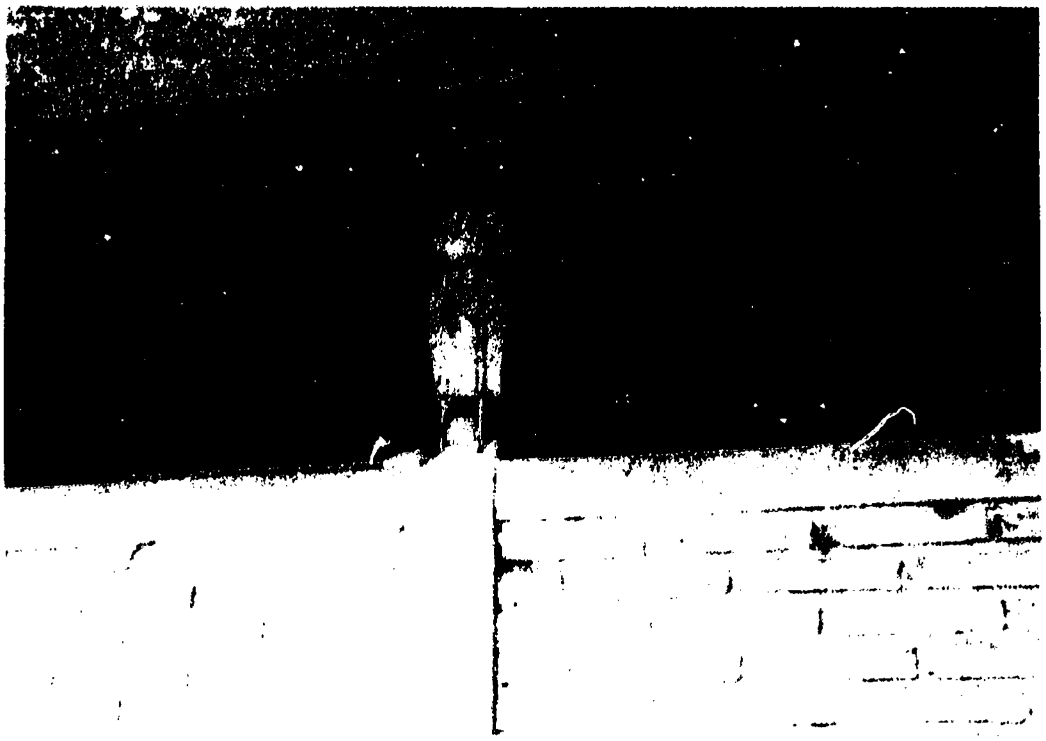
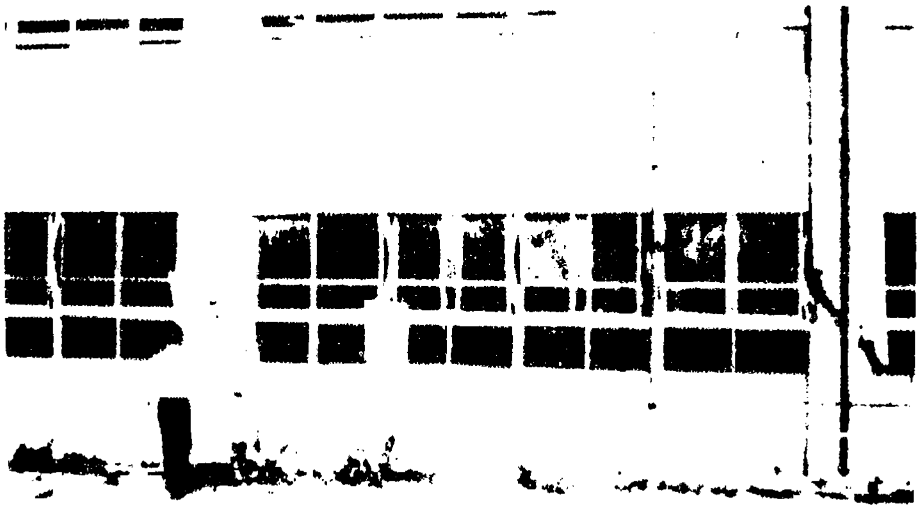


FIGURE 14
Japanese school building after 1978 earthquake.



Particular problems in terms of the effect nonstructural components can have on the structural system in schools are as follows:

- The location of rigidly connected stairs within more flexible long span spaces (multipurpose rooms) can modify the assumed deflection of the columns surrounding the cores, creating torsion and attracting a disproportionate load to the staircase structure (Figure 15).
- The use of infill walls between columns (forming windows in classrooms) can effectively stiffen the beams and shorten the columns, attracting higher loads than assumed in the design calculations (Figures 16).
- The addition of rigid infill nonstructural walls between columns separating classrooms can increase the stiffness of the columns far above what was assumed in the structural design.

FIGURE 15
Effect of stairway placement.

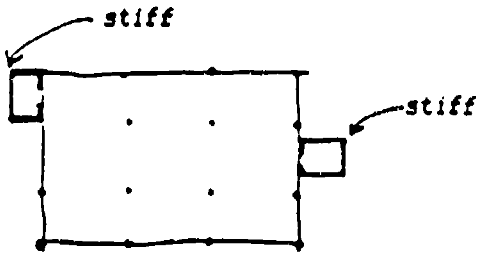
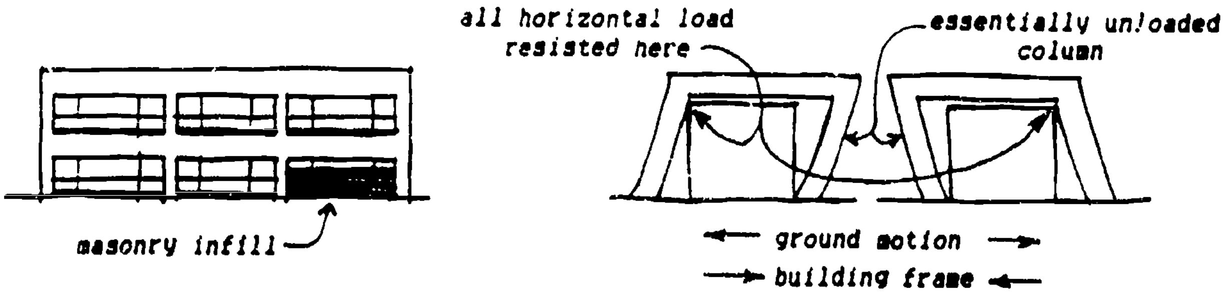


FIGURE 16
Effect of infill walls.



Connections

Structural member connections are among the most critical elements of earthquake-resistant design. Probably the most important single attribute of an earthquake-resistant building is that it is tied together to act as a unit, but no set of seismic provisions issued before the *NEHRP Recommended Provisions* (and its predecessor, the Applied Technology Council's ATC 3-06) stated this requirement. It is generally accepted by structural engineers that to develop adequate connections between structural elements is more difficult than to provide strength in the members themselves. This has been demonstrated clearly in past earthquakes where considerable damage originated at connections rather than in the structural members.

Furthermore, properly designed structural elements are usually ductile--i.e., their failure is preceded by large permanent deformations that dissipate a considerable amount of 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.

A structural element cannot transmit forces in excess of the capacity of the connections used to join the elements together. Thus, structural members and the elements that connect them should be of approximately equal strength to be fully effective. If there is a weak link, the earthquake will find it.

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.

The large open spaces common in schools often completely lack redundancy which means that every component must remain operative to ensure the integrity of the structural system under lateral loads. Thus, appropriate connections should be used and consideration should be given to the use of higher performance connections (ductile, in particular).

A public school in Melipilla, Chile, suffered severe structural and architectural damage during a 1985 earthquake (Figure 17) because the masonry facade was not properly anchored to the structural system. Collapse occurred and classrooms were showered with glass and ceiling light fixtures. Many schools of similar design also were significantly damaged in the earthquake.

Redundant characteristics can be obtained by providing several different types of seismic-resisting systems in a building; however, the designer must be careful to consider the relative stiffness and strength of the various systems in order to avoid problems. Redundancy also can be provided 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 exterior columns (a common practice) clad only in lightweight architectural curtain walls, the building may experience large deformations during an earthquake and, consequently, a great deal of interior damage.

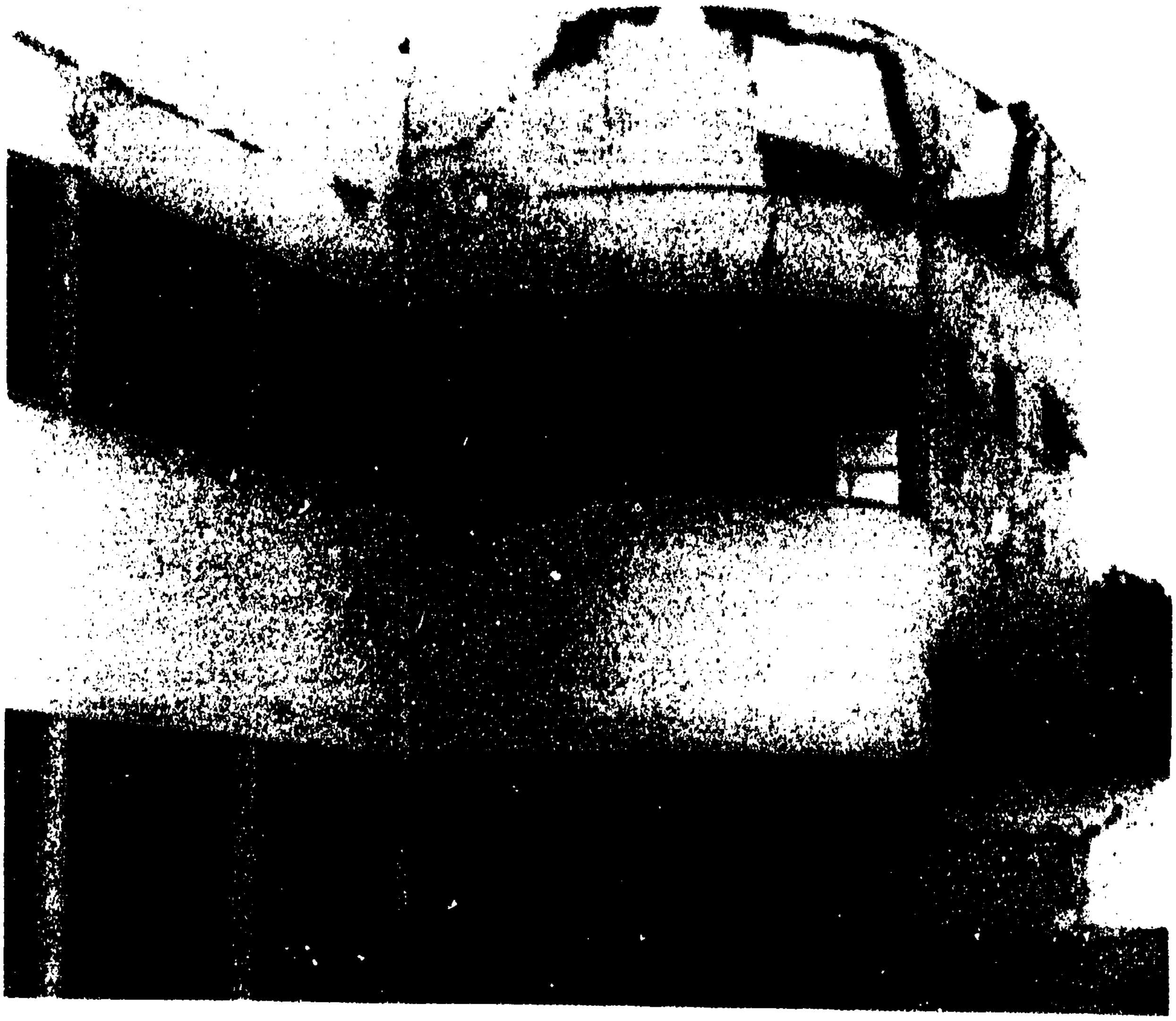
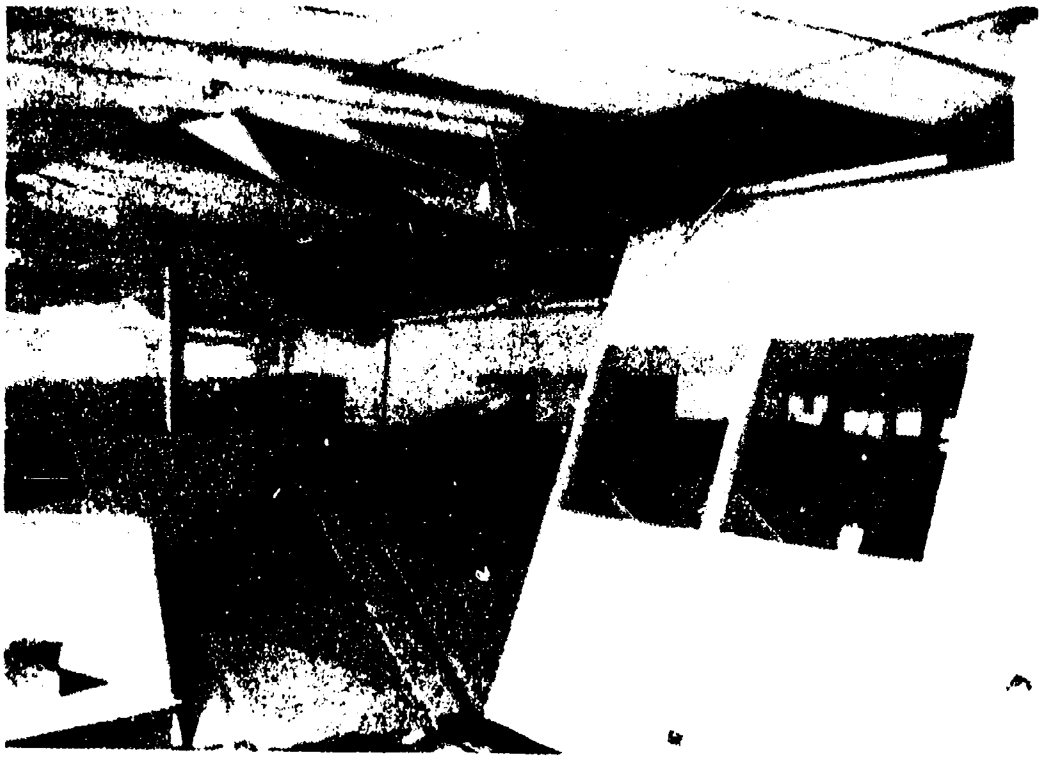


FIGURE 17
Melipilla School after 1985 earthquake in Chile.

Particular issues related to structural system redundancy in school design are as follows:

- Failure to use the large amounts of interior wall (classrooms, corridors) as redundant systems to the primary structural system and neglect of the influence of the relative stiffness of both systems (Figure 18).
- Use of limited numbers of columns (longer spans) in large open spaces (auditorium, cafeteria), causing these elements to become extremely critical.
- Discontinuity of the uniformity of the structural system through the location of large long span areas.
- Placement of openings (stacked, uniform classroom doors and windows) in the interior and exterior shear walls causing large forces to be concentrated in certain weak elements.

FIGURE 18
Collapse of interior structural partitions.



Damage to Nonstructural Components and Building Contents

Severe earthquake damage can occur even if the building structure remains essentially intact. During recent earthquakes, many buildings with no serious structural damage have suffered nonstructural damage totaling as much as 50 percent of the building replacement value. For example, the Bay Area Regional Earthquake Preparedness Project reports that the 1983 6.5 magnitude Coalinga, California, earthquake resulted in nonstructural damage totalling $2 million and that the 1987 5.9 magnitude Whittier Narrows, California, earthquake caused almost $16 million of damage, most of which was nonstructural. To understand the magnitude of the problem one need only consider that the structural system (foundation, floors, structural walls, columns, beams, etc.) constitutes only 15 to 25 percent of educational facility construction cost; therefore, the nonstructural architectural, mechanical, and electrical elements make up between 75 and 85 percent of the building's replacement value.

The nonstructural components with both life safety and major property damage consequences include exterior nonbearing walls, exterior veneers, infill walls, interior partition systems, windows, ceiling systems, elevators, mechanical equipment, and electrical and lighting equipment. All these components are subject to damage, either directly due to shaking or because of movement of the structure (which may be an intentional part of the seismic design). School occupants will be particularly vulnerable to nonstructural damage. Although school children may duck under desks and be safe from falling objects like light fixtures or glass, ceiling tile and wall finishes that fall on hallways and stairs can make movement difficult, particularly if combined with power failure and loss of lights.

Building utility systems and equipment traditionally have been designed or selected with little, if any, regard for their 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.

The Namioka Gymnasium, for example, received major ceiling and lighting damage during the 1983 earthquake in Nihon-Kai-Chobo, Japan. The gymnasium, which had been built only 3 years earlier, used hangers to support the ceiling system from steel purlins. These connections were not able to resist the major movements of the ceiling system during the earthquake and collapsed, which generated extensive debris (Figure 19).

FIGURE 19
Namioka Gymnasium after 1963 earthquake in Nihon-Kai-Chobo, Japan.

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, broken laboratory equipment, and spilled chemicals represent secondary effects of earthquakes that also are a considerable hazard to life and property. During the 1983 Coalinga earthquake in California, for example, sulfuric acid and other chemicals stored in glass containers in open cabinets in a second floor high school chemistry lab overturned and broke; the acid burned through to the first floor, and the cost of just cleaning the spill was over $50,000.

Large capacity hot water boilers, other pressure vessels, and broken distillation pipes can release fluids at hazardous temperatures. Large hot water boilers that operate at over 212 degrees pose a very serious hazard since the sudden decrease in pressure caused by a rupture of the vessel can result in instantaneous conversion of superheated hot water to steam, and the remainder of the vessel can disintegrate explosively showering the area with hot material and igniting combustible material.

Free-standing kitchen equipment and electrical equipment such as transformers, switchboards, emergency generators, and lighting fixtures can fall, causing injuries as well as fires (Figures 20-21).

FIGURE 20
Electrical equipment collapse.

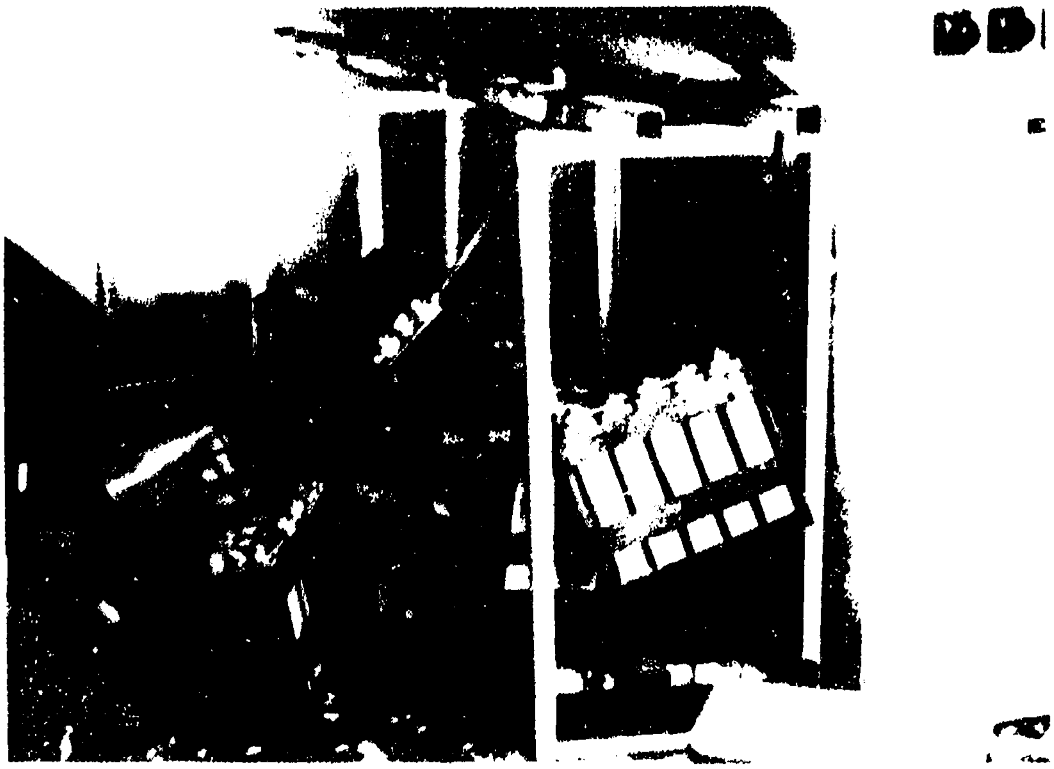
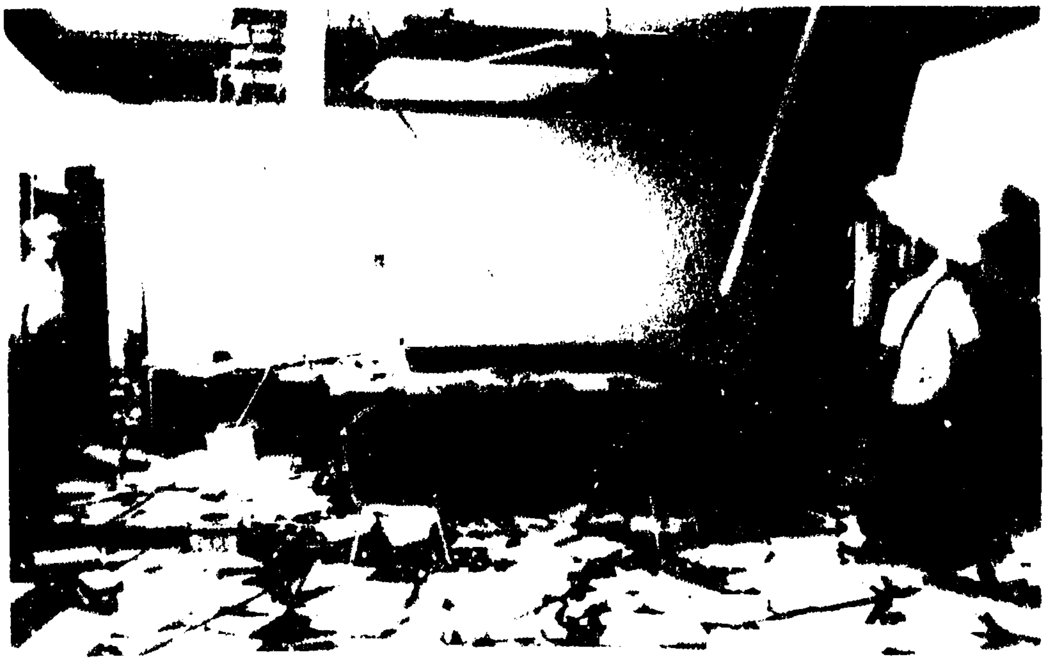


FIGURE 21
Ceiling/lighting system collapse.



Heating equipment located on roofs or hung in open spaces such as gymnasiums and auditoriums or service areas such as shops and kitchens typically is not designed for lateral forces. These pieces of equipment can easily fall and cause considerable damage or injury. Mechanical system grills and diffusers also can fall from ceilings (Figure 22).

Even such nonstructural components as glazing systems can create additional hazards. One junior high school in Coalinga, California, housed a library with an 8 by 10 foot, double height window of non-tempered glass on two walls. During the 1983 earthquake, these large windows imploded and completely littered the room with dagger-shaped pieces of glass. The floor tile and wooden furniture were gouged with flying glass, and the school superintendent believes that, had school been in session, death and serious injuries would have resulted (Figure 23).

FIGURE 22
Fallen ventilation system.

FIGURE 23
Junior high school in Coalinga after 1983 earthquake.

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, a frame that does not rack, low glass loading, and reasonably careful design and placement, good performance can be expected. Glass joint treatment also is a factor in the overall performance of a curtain wall or window unit system; if the edges are restrained, failure is likely. In this context, it also should be remembered that the sealants and gasket materials providing flexibility can lose their resiliency with age and exposure and therefore may require periodic replacement.

Post-Earthquake Egress Problems

Egress complications can be summed up by a statement made in a report on the 1964 Alaska earthquake:

> ...the final measure of a well constructed building is the safety and comfort it affords its occupants. If, during an earthquake, the occupants must exit through a shower of falling light fixtures and ceilings; maneuver through shifting and toppling furniture; stumble down dark corridors and stairs; and then be met at the street by falling glass, veneers, or facade elements...then the building certainly cannot be described as a safe building.

The problems of egress are most critical in multistory buildings and therefore, tend to apply to larger schools. Stairs are the critical means of egress out of a multistory school during and after an earthquake, but several things can happen to stairwells during an earthquake:

- Stairs tend to act as diagonal bracing between floors, and damaging loads and racking induced in them by interstory drift may result in collapse or failure.

- Stairs usually are anchored to the floors and their stiffness tends to attract forces that may cause severe damage or collapse (Figure 24).

- Masonry or concrete fire walls surrounding the stairs can fracture leaving the egress pathway littered with debris that may be impassable.

Experience indicates that doors and frames often jam in earthquakes and cannot be opened (especially by children). Heavy fire doors leading to egress routes are especially vulnerable because fire safety regulations require a heavy and tight assembly that becomes immovable when the door frame is distorted by earthquake motion.

Safe, direct, unobstructed exit routes should be planned so students and teachers can safely exit a school. Lockers, ceiling systems, lighting systems, ventilation systems, and windows that enclose these routes must be designed as critical components and be located so that their failure will not impede egress (Figure 25).

FIGURE 24
Stairway failure.

FIGURE 25
Blocked egress route.

Fire codes require school egress routes to have emergency lighting and signage; however, the anchorage of these elements in both the horizontal and vertical direction must be considered in their design. Canopies and porches at the entrances to the school are especially vulnerable if not designed for lateral loads. Their collapse may cause injuries among exiting occupants and they can become a major impediment to emergency procedures.

Disruption of Post-earthquake Operations

School buildings are often viewed by the community as local refuge, collection, or safe areas after a major disaster. This function may be formally recognized in a disaster response plan or the school may just be seen this way by neighborhood residents. And, of course, parents will want to ascertain that their children are safe as soon as possible after an earthquake. Thus, many people can be expected to converge on neighborhood schools searching for information, medical attention, or safe refuge during major power failure and inclement weather.

Disruption of regular or emergency operations can occur after an earthquake due to avoidable property damage. Some of the less critical elements (in terms of life safety and therefore codes) can cause inordinate amounts of delay in using the school as a safe refuge. Examples of these are mechanical, power, and communications system (public address or telecommunications) failure and lighting and ceiling collapse. Such damage can be minimized by designing to appropriate seismic provisions, which will save the public large sums in replacement costs.

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 such a code will ensure a basic level of safety that is difficult to obtain in any other way. Beyond the mandated requirements of a code, which set a minimum rather than a preferred standard of seismic design, the very act of designing to a seismic code requires a rational approach to design that focuses attention on those seismic issues discussed above which are not dealt with directly in code provisions.

The next chapter discusses the ways in which the *NEHRP Recommended Provisions* in particular and understanding of seismic design issues in general can work to protect elementary and secondary schools against these problems.

4

THE NEHRP RECOMMENDED PROVISIONS AND SCHOOL SEISMIC DESIGN

Achieving Good Seismic Design

In order 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 understand all the technical aspects of earthquake design, they should be familiar with 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 analysis of building response to 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 elementary and secondary schools. For a general description of some of the fundamental principles of earthquake effects and seismic design, see the BSSC's *Seismic Considerations for Communities at Risk*; technical issues are explored in the *Provisions* document itself and in the BSSC's *Guide to Use of the Provisions in Earthquake-Resistant Design of Buildings*. All BSSC publications are available free upon request.

Issues to Consider

The seismic design issues that must be considered are:

- The anticipated level of earthquake ground motion for which the school will be designed,
- The possible impacts of site geology on the performance of the building,
- The impact of the building occupancy on the seismic design of the building,
- The selection of the configuration of the building and its effect on seismic performance,
- The selection and design of the structural system of the facility and its expected performance,
- The selection and application of building materials in the design and their expected performance,
- The detailing of the structural connections,
- The design and protection of the critical functions of the facility,
- The design and protection of the nonstructural components and equipment, and
- The assurance of good construction quality.

Earthquake Ground Motion

When a seismic-resistant building is designed for a particular location, a specific level of ground motion will be assumed so that earthquake forces within the building can be calculated and the building designed to resist them. The *NEHRP Recommended Provisions* provides a basis for estimating levels of ground motion.

Obviously not all U.S. locations are subject to the same risk from earthquakes, and it would make no sense to insist that buildings in New York City be designed to resist the same earthquake forces as those in Los Angeles. How, then, is the relative risk determined and how does the *NEHRP Recommended Provisions* enable this risk to be converted into 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 motion 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 26 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, and new maps reflecting the results of these studies are being developed.

In order to determine the degree of protection to be provided the building and its occupants, a building is assigned to a Seismic Hazard Exposure Group based on its occupancy or use. The intent is for important buildings--such as hospitals or police stations--and for buildings with large numbers of occupants or where the occupants' mobility is restricted--such as auditoriums, schools, and hotels--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 III). Schools are assigned to Group II.

These two factors, effective peak velocity and Seismic Hazard Exposure Group, lead to identification of the building's Seismic Performance Category, the level of seismic performance to which the building must be designed. This is done using the following table that relates the location's effective peak velocity, A_v, to the building's Seismic Hazard Exposure Group (I-III):

Effective Peak Velocity	Seismic Hazard Exposure Group		
	I	II	III
$0.20 \le A_v$	D	D	E
$0.15 \le A_v < 0.20$	C	D	D
$0.10 \le A_v < 0.15$	C	C	C
$0.05 \le A_v < 0.10$	B	B	C
$A_v < 0.05$	A	A	A

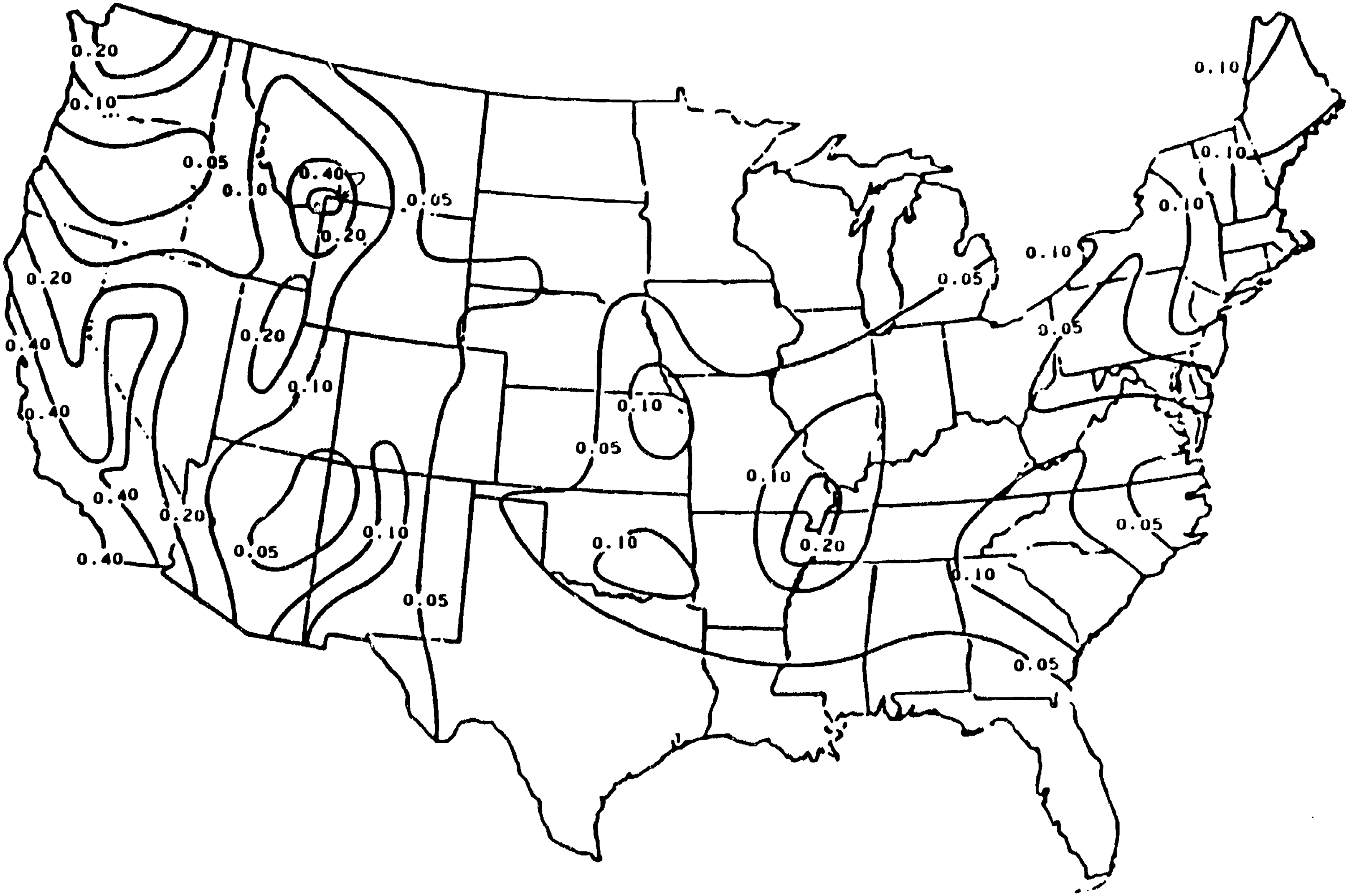


FIGURE 26

Contour map for effective peak velocity, A_v, from the 1988 Edition of the NEHRP Recommended Provisions. Contours show lines of estimated equal acceleration from 0.05g to 0.40g.

It can be seen that east of the Rockies, where A_v is nearly always less than 0.20 (Figure 26), school buildings will belong to Seismic Performance Category A, B, C, or D (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.

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 generated inertial forces caused by vibration of the building's mass. The natural tendency of any object to vibrate back and forth at a certain rate (generally expressed in seconds or fractions of a second) is its fundamental or natural period. Low- to mid-rise buildings have periods in the 0.10 to 0.50 second range while taller, more flexible buildings have periods between 1 and 2 seconds or greater. Harder soils and bedrock will efficiently transmit short period vibrations (caused by near earthquakes) while filtering out longer period motions (caused by distant earthquakes) whereas softer soils will transmit longer period vibrations.

  As a building vibrates under ground motion, its acceleration will be amplified if the fundamental period of the building coincides with the period of the vibrations being transmitted through the soil. This amplified response is called resonance. Natural periods of soil are usually in the range of 0.5 to 1.0 second so that it is entirely possible for the building and ground to have the same fundamental period and, therefore, for the building to approach a state of resonance. This was the case for many 5- to 15-story buildings in the 1985 earthquake in Mexico City. An obvious design strategy, if one can predict approximately the rate at which the ground will vibrate, is to ensure that buildings have a natural period different from that of the expected ground vibration to avoid amplification.

- The third category of earthquake effects involves ground failures. These include landslides, differential settlement, and liquefaction (sandy or silty soil that will liquefy during shaking) and they are frequent results of ground motion. Much of the damage in the 1964 Anchorage, Alaska, earthquake was the result of several landslides (Figure 27). In such a situation, proper design strategies include correcting the site conditions (soil compaction, excavation, slope elimination, water table reduction, etc.), designing for the condition (piles through the sensitive material, tie-backs, retaining walls, etc.), or avoiding sites or portions of sites that are prone to ground failures. Considerable liquefaction also occurred in San Francisco in the 1989 Loma Prieta earthquake, but the major damage in the Marina area appeared to be due more to ground motion amplification and poor design rather than to liquefaction.

FIGURE 27
Government Hill School in Anchorage after 1964 earthquake.

- The fourth category of seismic phenomena to be considered involves earthquake-induced water hazards. Tsunamis (or seismic sea waves) and seiches (waves within closed bodies of water) can be a problem for any building located on the coast of an ocean or lake. The highest recorded waves from ocean tsunamis are on the order of 50 feet but waves of about 30 feet represent a more realistic threat. These waves are generated at the source area of an underwater earthquake; they then travel long distances across the open ocean and cause destruction where they come into contact with land. By studying the location and form of the coastline, a good idea of the potential wave height can be determined, and appropriate measures can be taken (site location, fill, flood walls, elevated structures, flood shields, etc.).

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 individual buildings.

Building Occupancy

Building code occupancy classifications historically have been 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
- The degree of built-in or brought-in hazards based on the typical use of the building type.

These groupings allow for increased seismic performance requirements to be used for specific buildings when deemed necessary.

Following this approach, the *NEHRP Recommended Provisions* identifies three Seismic Hazard Exposure Groups:

- Group III includes those buildings having essential facilities that are necessary for post-earthquake recovery.
- Group II includes those buildings having a large number of occupants and those buildings in which occupants' movements are restricted or their mobility impaired.
- Group I includes all other buildings not included in Groups III and II.

As noted above, schools are assigned to Group II.

Building Configuration

One set of decisions most critical to the ability of a school building to resist earthquake damage is, as noted earlier, the choice of building configuration: its size, shape, and proportion. Since the shape of the site, functional requirements, and community aesthetic aspirations can present constraints to an optimal configuration for seismic safety, it is important to understand how the building's form affects the building's earthquake performance.

Some of the major issues were outlined in Chapter 3. The basic problem can be expressed by focusing on two conditions that have consistently caused severe damage and collapse:

- The unbalanced plan resistance of the building--Any plan configuration that has a center of rigidity (resistance) that does not approximately coincide with the center of mass (weight) will undergo significant torsional rotation during an earthquake (Figure 28).

- 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 29).

FIGURE 28
Centers of mass and resistance do not coincide causing torsion under earthquake motion.

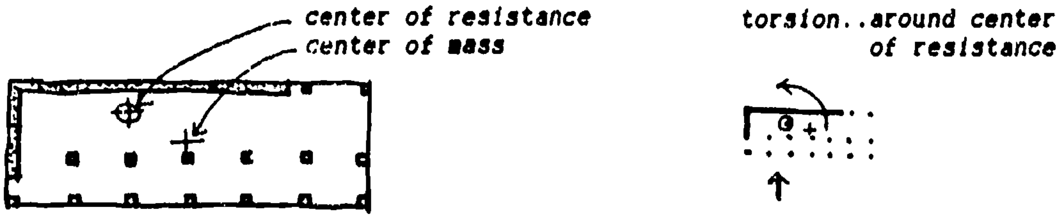
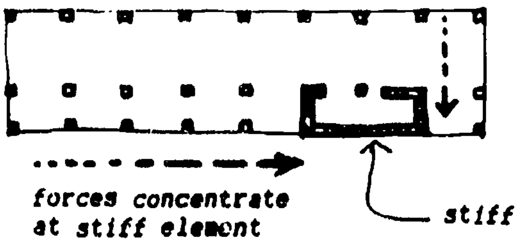


FIGURE 29
Rigid elements in plan will attract earthquake forces.



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 to prevent damage. 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 centers of mass and rigidity closer together so that the resistance systems will compensate for geometrical irregularities when ground motion occurs.

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.

Schools 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 application of the system.

Elevator cores and staircases can be designed as lightweight framed elements or detached from the surrounding structure so that they do not provide unwanted stiffness in the wrong location. Of course, a correctly designed and located core also may be effectively used as a major resistance element.

The conceptual design must be evaluated for its ability to provide balanced seismic resistance or for the possibility that unbalanced resistance or discontinuity may be inherent in the design. If found at an early conceptual stage (and it is quite easy to determine at this design stage), such a problem can be eliminated easily by modifying the structural/architectural design.

Based on the building's occupancy type and seismicity, the *NEHRP Recommended Provisions* requires that consideration be given to the potentially adverse effects that can occur when the ratio of the strength provided in any part of the building to the strength required is significantly less than that ratio for an adjacent part (i.e., where one part is weaker than another). This requirement is one way of ensuring balanced resistance throughout the building.

Structural Systems

Selecting and designing a structural system that will perform well within the range of unknowns of earthquakes is a demanding task:

- The goals for the performance of the structure must be established,
- The geological and site characteristics must be considered,
- An appropriate building form responsive to the needs of the potential users and to earthquake-resistance requirements must be developed,
- A structural system compatible with these needs must be selected and analyzed,
- The structural details must be developed, and
- The structure must be correctly constructed.

This process must be a joint effort between the three main parties involved: the building owner, the architect, and the consulting engineer.

Earthquake lateral loads are resisted by three alternative vertical structural systems: shear walls, braced frames, and moment frames. A fourth system for lateral load resistance, the so-called dual system, is a combination of moment frames and shear walls or braced frames.

Horizontal diaphragms (floors and roofs) connect the individual shear walls and frames and assist in transferring the loads to the foundation.

Each of the four vertical structural systems has certain characteristics:

- 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.

- Shear wall systems provide very stiff structures. Unless the shear walls can be confined to the exterior envelope and the communication cores, they represent an impediment to the interior planning flexibility provided by the favored open floor spaces of modern buildings.

- 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 frame system.

- In a dual system, a moment frame provides a secondary defense 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 a system for a school building requires considerable care and experience. Nevertheless, correct choice of the structural system is very important because it occurs early in the design process and is very difficult to modify or change as the design 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 difference between survival and collapse. The building should be designed so that the failure of any one supporting element will not cause the failure of the complete system.

The *NEHRP Recommended Provisions* provides information on the selection and design of a structural system appropriate for the building's seismic performance requirements. Coupling these structural concepts with building configuration and performance goals is the critical design challenge for the owner and design team. A major engineering goal in seismic design is to develop as simple and regular a design as possible, but architectural requirements may, for sound aesthetic or functional reasons, run counter to this aim. The solution requires creative collaboration between architect, engineer, and owner.

Building Materials

There are noticeable differences in the types and extent of earthquake damage observed in relation to different structural materials. As was shown by the 1987 Whittier Narrows and the 1989 Loma Prieta earthquakes as well as many earlier earthquakes, buildings constructed of unreinforced masonry perform poorly and are especially vulnerable. Buildings with steel or wood structural systems that can deform considerably before failing have a basic structural advantage, but they have suffered severe damage or failure when the elements have not been connected adequately. The combination of inherently brittle materials (masonry or concrete) with properly designed and fabricated reinforcement has led to buildings that have performed very well in earthquakes. Although the inherent properties of the structural material is important, the performance of the building depends to a great extent on the quality of the design, the detailing, and the construction. Properly executed, any combination of materials, with the exception of unreinforced masonry, can provide good seismic performance.

Steel buildings, particularly those designed according to modern seismic code requirements, generally have performed well in severe earthquakes. The structural damage that has occurred usually has involved localized failures in structural elements that creates distortion but seldom leads to collapse. However, flexible moment frames that have performed well structurally often have resulted in considerable nonstructural and contents damage, thus pointing toward the use of dual systems. The performance of poured-in-place reinforced concrete buildings in past earthquakes has ranged from very poor to excellent, depending on the type of structural system and the quality of detailing. Buildings with well designed shear walls can be expected to perform well, particularly if openings are small relative to the wall. In moment resisting frames, detailing has proven to be a critical aspect of performance. Particularly important is adequate confinement of the concrete through the use of spiral or closely spaced stirrup ties (reinforcement), which increases the system's ductility (the ability of the system or material to distort without collapsing). 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. The proper design and construction of walls and the proper connection of walls to floor and roof diaphragms are critical to the successful performance 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 sufficiently to provide the equivalent of monolithic construction. Since these systems are often used for long spans, issues of redundancy and concentration of stresses must be given serious consideration.

The *NEHRP Recommended Provisions* contains specific 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 those responsible for a school 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.

The *NEHRP Recommended Provisions* requires that all parts of the building be tied together so that defined forces can be resisted. Anchorages (which currently are not covered in the codes used in many parts of the country) are required to prevent the separation of heavy masonry or concrete walls from floors or roofs.

Functional Areas

Several school building functional areas deserve special attention because of the life-threatening situations that can develop during an earthquake.

Libraries, information centers, or any locations where stacked or concentrated loose, unrestrained materials are stored can be especially dangerous. Heavy book stacks should be adequately anchored to prevent overturning which can both endanger the safety of the students and block egress from the area (Figures 30-31). These areas usually also have more controlled exit requirements for security reasons; therefore, clear unblocked egress routes from the area should be required.

Hallways, corridors, and stairways that serve as the primary egress route from the building should be designed to be safe from falling ceilings or light fixtures and broken glass and should be kept clear of obstructions such as files or other stored items (Figure 32).

Assembly areas such as cafeterias, auditoriums, and gymnasiums should be designed to ensure that suspended mechanical systems, lighting systems, or other hanging equipment is securely fastened and will not fall. Kitchen areas should be designed to protect staff from heavy equipment and possible fire caused by broken fuel lines.

Science laboratories should be designed to protect occupants from falling heavy equipment and hazardous chemicals should be stored so that they do not fall from shelves or spill. Industrial or vocational areas should be designed to be safe by anchoring and restraining all heavy, stationary equipment. Kitchen, chemistry, and shop hoods must be properly designed and anchored to resist falling. Canopies at exits should be checked to ensure that they will not collapse, and exit routes should not adjoin exterior glass areas. The safety of staff in mechanical rooms should be evaluated and precautions taken.

FIGURE 30
Overturned book stacks.

FIGURE 31
Sylmar High School after 1971 San Fernando earthquake.

FIGURE 32
Obstructed egress area.

Nonstructural Components and Contents

In building codes, nonstructural systems and components (except for fire protection systems) are not given the same importance for life safety as the structural system and elements. However, as the Bay Area Regional Earthquake Preparedness Project indicates, for elementary and secondary schools, the protection of these elements is of great importance due to the nature of the occupants and the structure of the building:

> In well-constructed buildings, such as most public schools in California, the greatest threat to life and limb in an earthquake comes from nonstructural elements--light fixtures, ceiling tiles, windows, bookcases and filing cabinets, heating and air-conditioning ducts, flooring, pianos on rollers, hanging plants, TV monitors, aquariums, and other furnishings. Unless such elements are securely anchored, they can be dislodged or tipped by the ground shaking, becoming lethal missiles or dead weights. During an earthquake, the best response to nonstructural hazards is to get under a desk or sturdy table; in the long run, however, it is preferable to reduce such hazards in [school buildings]. Teachers and administrators in Coalinga and near Whittier wished they had done as much before comparatively moderate earthquakes raised havoc in their school buildings.
>
> The May 2, 1983, earthquake in Coalinga ... was far weaker than the major earthquakes scientists expect in large population centers of California in the not-too-distant future. Notwithstanding its size, however, the earthquake caused extensive damage in Coalinga's schools. Because it struck at 4:42 p.m., students who might otherwise have been injured or killed were not in the schools. Damage to nonstructural building elements totalled $2 million. Large windows and skylights broke, throwing glass into many rooms. Around 1,000 fluorescent bulbs fell out of fixtures, and a number of fixtures came down. Tiles and other ceiling material--some containing asbestos--were shaken loose. Some water pipes were severed where they entered buildings through concrete walls. Electrical switching mechanisms in a couple of school basements were destroyed by water and the electricity was cut off.

There were gas leakages in a number of schools, but no fires resulted. In the third-floor lab at the high school, cupboard doors flew open and chemicals spilled to the floor; they reacted with each other and burned through to the first floor. Noxious fumes--hydrogen sulfide among them--from the spilled chemicals permeated the building. Latches on file cabinet drawers did not hold and drawers "flew across the room."

Bookcases, free-standing cabinets, and shelving fell. Movie screens and maps became projectiles. Storage cabinets attached to walls with molly bolts fell over.

The 5.9 magnitude earthquake that shook areas of East Los Angeles, Whittier, and Rosemead on October 1, 1987, also struck when schools were not in session. At 7:42 a.m., no students and only a few staff members were in the approximately 100 school buildings that sustained damages. Damages in K-12 public school buildings, most of which were nonstructural, accounted for $16 million in losses. The majority of the damage to public schools consisted of cracking in plaster walls or other finish materials that were installed previous to more stringent code requirements, or failure of light fixture supports, suspended ceilings, and duct work either not designed or not constructed according to current codes. Broken window and skylight glass was substantial at a number of schools. Water and gas lines were ruptured in some places but no fires ensued. At California State University, Los Angeles, chemicals spilled and caused a fire, creating toxic fumes. Buildings had to be closed and clean-up operations took several days. Free-standing library shelves at Cal State LA swayed and buckled, and books were damaged or strewn about. Unreinforced masonry incinerator chimneys failed at several schools. Pockets of encapsulated asbestos were dislodged by earthquake shaking at some public schools, releasing airborne fibers into ventilation systems.

For relatively little cost in the design and construction of a new building (or even in the remodeling of an existing building), considerable potential injury and costly damage (including loss of function) can be avoided. The more common nonstructural elements in elementary and secondary schools that should be given special design attention include:

Appendages	Entrance canopies, overhangs, and balconies/roof-mounted mechanical units and signs/roofed walkways
Enclosures	Exterior nonbearing walls/exterior infill walls/veneer attachments/curtain wall system 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/atrium spaces and skylights/glass elevator enclosures

Lighting	Light fixtures/emergency lighting
Emergency	Structural fireproofing/emergency electrical system/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 room air conditioning or heating units/cooling towers/tanks, heat exchangers, and pressure vessels/utility and service interfaces/ducts and diffusers/piping distribution systems
Electrical	Communications systems/electrical bus ducts and primary cable systems/electric motor control centers, transformers, and switchgear
Contents	Library book stacks, filing cabinets and bookcases/computers, printers, and copying equipment/lockers/stage and curtain equipment/home economics, shop, laboratory, and food preparation equipment/laboratory supplies

The *NEHRP Recommended Provisions* establishes minimum design levels for architectural, mechanical, and electrical systems and components that recognize occupancy use, occupant load, need for operational continuity, and the interrelation of these elements. The following design strategies (Figure 33) should be evaluated to determine the correct one for protecting a particular nonstructural system or component given its physical characteristics, location, and importance:

- Increased flexibility--Improving the ability of the element to move under earthquake loading and, thus, reducing the forces on the element (e.g., using a light fixture mounting that enables it to sway safely).

- Anchorage--Providing for proper connection of the component to the building structure or other suitable element to resist slippage or upset (e.g., the anchorage of heavy tanks).

- Bracing--Properly restraining the component to resist lateral movement and possible breakage (used for pipes, ducts, ceilings).

- Increased stability--Improving the inherent geometrical resistance of an element to earthquake forces by reconfiguring it (e.g., bolting together storage racks to provide a wider base).

- Isolation--Separating the element from its support (by springs or other devices) so that floor movements are not transmitted to the component.

- Slip or control joints--Improving the ability of the element to move independently of its support and, thus, limiting the transfer of energy.

- Mass reduction--Reducing the weight of the component to reduce the inertial forces on it.
- Relocation--Changing the location of a component in order to reduce its vulnerability or threat to occupants (e.g., moving a heavy tank from roof to basement).

FIGURE 30
Earthquake strategies for nonstructural components:
o identifies possible strategies and •, strategies with high potential.

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		●		●	●			●			

Construction Quality

Building failures during earthquakes that are directly traceable to poor quality control during construction are innumerable. The literature 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.

Severe building damage and collapse have been caused by poorly executed construction joints in reinforced concrete, undersized welds in steel construction, and the 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 is expected to monitor the construction through independent special inspection to protect his own as well as the public interest.

It is essential that each party recognize its responsibilities, relationships, and procedures and be capable of carrying them out.

Concluding Note

The *NEHRP Recommended Provisions* is concerned only with those components that are directly affected by earthquake motions and whose response could affect life safety. The requirements are minimum and the school building decision-maker should give consideration to formulating an earthquake quality assurance plan that covers all other components during all phases of construction throughout the project. For elementary and secondary schools, the cost of doing this should be minimal and the potential savings in terms of increased life safety, reduced property damage, and continuing operation both during and after an earthquake could be enormous. Finally, good seismic design also provides better assurance that other types of catastrophic failure (e.g., those caused by explosions or unexpected large storms) will not occur.

5

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> **To obtain the information needed to define precisely a location's seismic situation: contact local academic institutions for geologists, geophysicists, and seismologists; 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.

DIAPHRAGM A horizontal or nearly horizontal structural element designed to transmit lateral or seismic forces to the vertical elements of the seismic resisting system.

DRIFT Lateral deflection of a building caused by lateral forces.

DUCTILITY Capability of being drawn out without breaking or fracture. Flexibility is a very close synonym.

EARTHQUAKE A sudden motion or vibration in the earth caused by the abrupt release of energy in the earth's lithosphere. The wave motion may range from violent at some locations to imperceptible at others.

EFFECTIVE PEAK ACCELERATION and EFFECTIVE PEAK VELOCITY-RELATED ACCELERATION Coefficients for determining the prescribed seismic forces shown on maps in the *NEHRP Recommended Provisions*.

ELASTIC Capable of recovering size and shape after deformation.

ELEMENTS AT RISK Population, properties, and economic activities (including public services, etc.) at risk in a given area.

EXCEEDENCE PROBABILITY The probability that a specified level of ground motion or specified social or economic consequences of earthquakes will be exceeded at the site or in a region during a specified exposure time.

EXPOSURE The potential economic loss to all or certain subsets of structures as a result of one or more earthquakes in an area. This term usually refers to the insured value of structures carried by one of more insurers.

FAULT A fracture in the earth's crust accompanied by a displacement of one side of the fracture with respect to the other and in a direction parallel to the fracture.

FRAME, BRACED An essentially vertical truss or its equivalent of the concentric or eccentric type that is provided in a building frame or dual system to resist seismic forces.

FRAME, INTERMEDIATE 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, ORDINARY 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, SPACE A structural system composed of interconnected members, other than bearing walls, that is capable of supporting vertical loads and that also may provide resistance to seismic forces.

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 complete 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-Forell 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 Giuseppe Mercalli, an Italian priest and geologist, it is an arbitrary scale of earthquake intensity related to damage produced. See the following section of this Glossary, "Measures of Earthquake Magnitude and Intensity."

PERIOD The elapsed time of a single cycle of a vibratory motion or oscillation.

RESONANCE The amplification of a vibratory movement occurring when the rhythm of an impulse or periodic stimulus coincides with the rhythm of the oscillation (period). For example, when a child on a swing is pushed with the natural frequency of a swing.

RICHTER SCALE Named after its creator, the American seismologist Charles R. Richter, a logarithmic scale expressing the magnitude of a seismic (earthquake) disturbance in terms of its dissipated energy. See the following section of this Glossary, "Measures of Earthquake Magnitude and Intensity."

SEISMIC Of, subject to, or caused by an earthquake or an earth vibration.

SEISMIC EVENT The abrupt release of energy in the earth's lithosphere causing an earthquake.

SEISMIC FORCES The assumed forces prescribed in the *NEHRP Recommended Provisions* related to the response of the building to earthquake motions to be used in the design of a building and its components.

SEISMIC HAZARD Any physical phenomenon such as ground shaking or ground failure associated with an earthquake that may produce adverse effects on human activities.

SEISMIC HAZARD EXPOSURE GROUP A classification assigned in the *NEHRP Recommended Provisions* to a building based on its use.

SEISMIC PERFORMANCE CATEGORY A classification assigned to a building as defined in the *NEHRP Recommended Provisions.*

SEISMIC RESISTING SYSTEM The part of the structural system that has been considered in the design to provide the required resistance to the prescribed seismic forces.

SEISMIC RISK The probability that social or economic consequences of an earthquake will equal or exceed specified values at a site, at several sites, or in an area during a specified exposure time.

SEISMIC ZONES Earth surface areas defined by earthquake occurrences of relatively uniform frequency, intensity, and magnitude. Such zones are defined by both global divisions and national subdivisions. They are generally large areas within which seismic design requirements for structures are constant.

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.

Measures of Earthquake Magnitude and Intensity

The following excerpt from the 1976 thesis, Seismic Design of a High-Rise Building, prepared by Jonathan Barnett and John Canatsoulis at the Worcester Polytechnic Institute explains the Richter magnitude scale and the Modified Mercalli Intensity (MMI) scale:

> There are two important earthquake parameters of interest to the structural engineer. They are an earthquake's magnitude and its intensity. The intensity is the apparent effect of an earthquake as experienced at a specific location. The magnitude is the amount of energy released by the earthquake. The magnitude is the easiest of these two parameters to measure as, unlike the intensity which can vary with location, the magnitude of a particular earthquake is constant. The most widely used scale to measure magnitude is the Richter magnitude scale. Using this scale, the magnitude, measured in ergs, can be found from the equation $\text{Log } E = 11.4 + 1.5\,M$, where M is the Richter magnitude.

> This relationship was arrived at by analysis of the amplitude of the traces of a standard seismograph located 100 kilometers from the epicenter of an earthquake and correlating this information with the radiated energy as determined through measurements of the waves released by the earthquake.... In use, the Richter scale represents an increase by a factor of 31.6 for each unit increase in the Richter magnitude. Thus, a Richter magnitude of 6 is 31.6 times larger than Richter magnitude 5....
>
> ...a problem with using the Richter magnitude is that is gives little indication of an earthquake's intensity. Two earthquakes of identical Richter magnitude may have widely different maximum intensities. Thus, even though an earthquake may have only one magnitude, it will have many different intensities.
>
> In the United States, intensity is measured according to the modified Mercalli index (MMI). In Europe, the most common intensity scale is the Rossi-Forell scale while in Russia a modification of the Mercalli scale is used.

The following excerpt from Bruce A. Bolt's 1978 book, *Earthquake: A Primer* (W. H. Freeman and Company, San Francisco, California), describes modified Mercalli intensity values (1956 version):

I.	Not felt. Marginal and long period effects of large earthquakes.
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 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 Masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; Masonry C heavily damaged, sometimes with complete collapse; Masonry B seriously damaged. General damage to foundations. Frame structures, if not bolted down, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in the ground. In alluviated areas, sand and mud ejected, earthquake fountains and sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown in the air.

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

EARTHQUAKE EXPERIENCES OF CALIFORNIA SCHOOLS

Stimulus for the Field Act

Although the magnitude of the earthquake that occurred in 1933 in Long Beach, California, was moderate (6.3), the damage to buildings was widespread. One of the occupancies to suffer the worst were the public schools (Figure A-1). Within seconds, an estimated 75 percent of the public school buildings were heavily damaged and many collapsed. It was readily apparent to responsible public officials that a horrifying number of students and teachers would have been killed and injured if the earthquake had occurred during regular school hours.

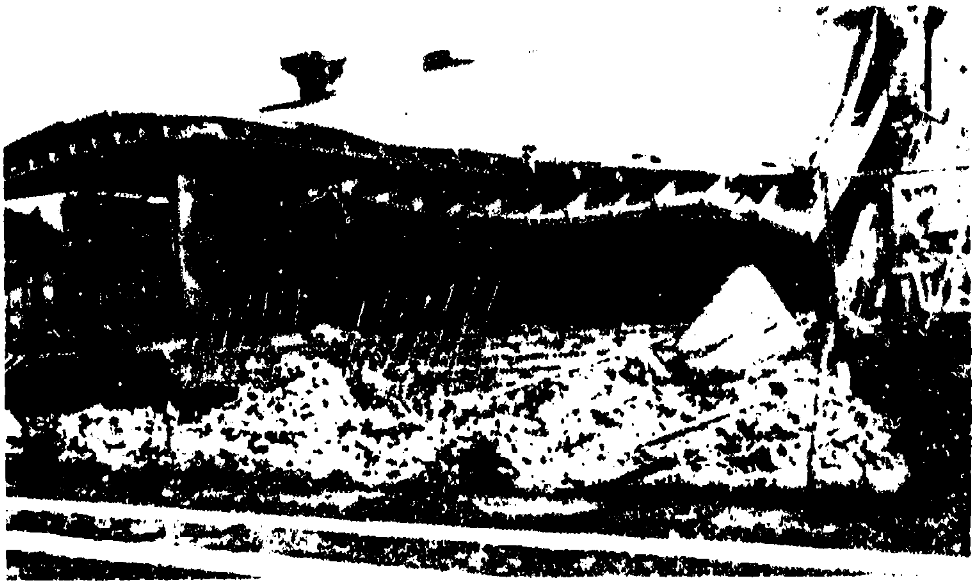
This experience resulted in a prompt legislative response to ensure that future public school buildings would be designed and constructed with sufficient earthquake resistance to protect occupants from death or injury. The history of this legislation, and its effect on building performance in subsequent earthquakes, provides some useful lessons for other areas that now find themselves confronted by the realization of an earthquake threat.

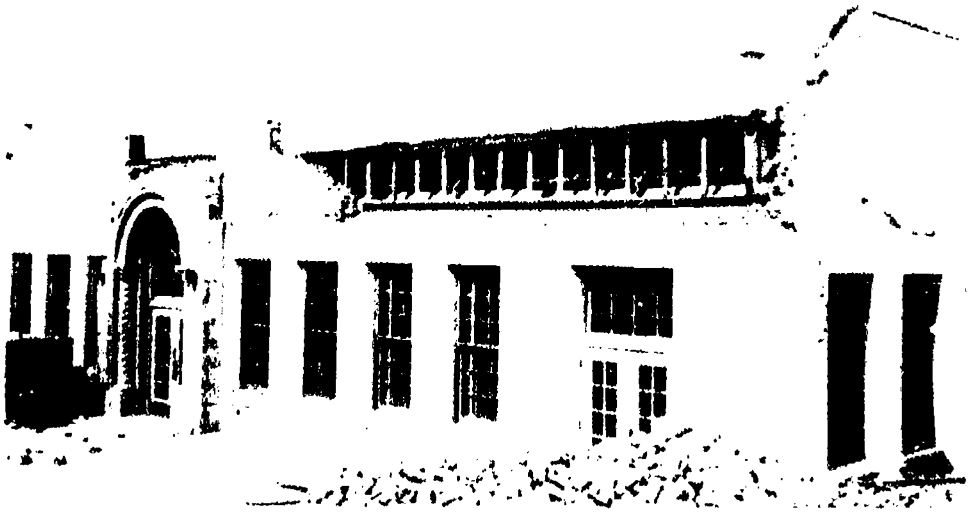
The California legislation stimulated by the Long Beach earthquake, the *Field Act*, became effective as an emergency measure one month after the earthquake. In creating this unprecedented legislation in a hurry, the drafters modeled their act on the *State Dam Safety Act*, which had been stimulated by a dam collapse in 1929. The *Field Act* applied only to the design and construction of public school buildings used for elementary, secondary, or community college purposes; private schools, the state college system, and the University of California campuses were not involved. Thus, the act related to facilities at which attendance was compulsory (with the exception of community colleges).

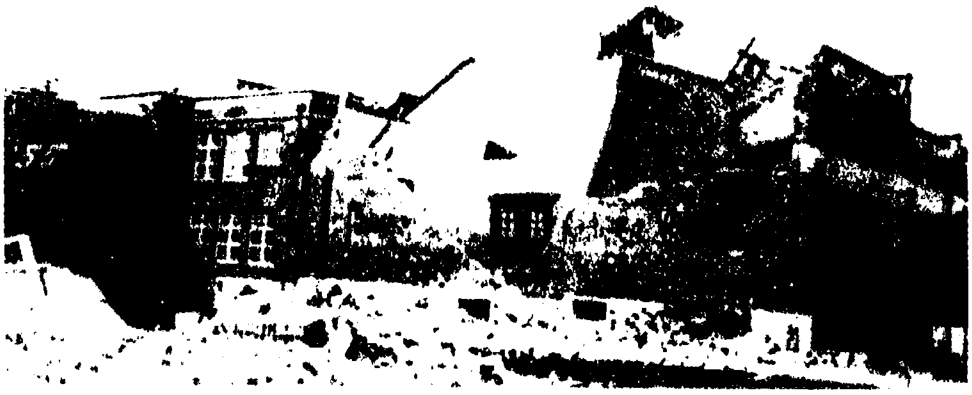
The act's principal provisions require that all construction plans be prepared by qualified persons (architects or structural engineers) and that the designs be checked by an independent state agency, which was identified as the Structural Safety Section of the Office of the State Architect. The plan checking is financed by fees, based on the cost of construction, charged against school districts submitting plans for approval.

The independent review generally is considered to be one of the most important parts of the *Field Act*. The review has always been rigorously administered by experienced designers. It is aimed at enforcing the state building code and identifying design errors and omissions and conceptual errors of judgment that might result in inadequate earthquake resistance.

FIGURE A-1
School damage in Long Beach after the 1933 earthquake.







Another very important part of the *Field Act* requires construction to be continually inspected by a qualified person approved by the designers and retained by the school board to see that all of the design requirements are carried out. This inspector is independent of the contractor or architect. All parties with assigned responsibilities, including the architect, consulting engineer, inspector and contractor, must submit verified reports stating that the construction complies with all requirements of the approved plans and specifications. The state also is authorized and required to make any inspections of the buildings and construction judged necessary to enforce the law.

The *Field Act* generally is regarded in California as immensely successful in assuring reasonable compliance with acceptable levels of earthquake resistance. It should be noted that the act was in effect during the enormous post-war expansion of population in California and correspondingly massive public school building programs. Although the seismic design review process resulted in an increase of some 2 to 3 months in plan processing and undoubtedly increased the costs of both design and construction, no substantive criticism or limitation has ever been directed at the program.

Results

Since the *Field Act* was implemented, school buildings in California have been tested in a number of earthquakes, and, to date, no students or teachers have been killed or injured in a post-*Field Act* school building during an earthquake. The damaging Kern County earthquakes of 1952 involved one earthquake of Richter magnitude 7.6 followed a month later by one of magnitude 5.8. Of 40 schools constructed prior to the *Field Act*, 40 percent suffered severe damage, 33 percent suffered moderate damage, 25 percent suffered slight damage, and 2 percent had no damage. Of the 18 schools constructed in accord with the *Field Act*, 61 percent had no damage, 33 percent suffered slight damage, and only 6 percent had moderate damage. The fact that some non-life-threatening damage was suffered by *Field Act* schools is an indication that the requirements are not too restrictive.

In December 1954, an earthquake of magnitude 6.6 occurred in the Eureka area north of San Francisco. It caused considerable minor damage to non-*Field Act* schools and no damage to post-*Field Act* schools. The San Fernando earthquake of 1971 (magnitude 6.6) caused shaking over a wide area. No *Field Act* schools received any significant structural damage although the shaking did cause some hazardous nonstructural damage to ceilings, ventilation diffusers, and light fixtures; since the earthquake occurred at 6 a.m., there were no casualties as a result of this damage. Pre-*Field Act* schools received extensive damage; many were closed and subsequently demolished. Several other pre-*Field Act* schools had been strengthened prior to the earthquake, and these performed well.

On May 2, 1983, an earthquake of magnitude 6.7 occurred in the area of Coalinga, California. Public school buildings constructed under the provisions of the *Field Act* performed quite well while some schools that were not constructed under the provisions of the act partially collapsed or were heavily damaged.

At the Coalinga junior high school, several buildings existed that had been constructed prior to the enactment of the *Field Act*. Both end spans of the roof framing of a gymnasium, which had been constructed in 1928 and converted to maintenance use after an examination declared it to be unsafe, collapsed to the floor. The building subsequently was demolished. In contrast, at West Hills College in Coalinga, the gymnasium with a 96 feet span designed under *Field Act* provisions suffered only minor damage and remained safe. Immediately after the earthquake, the building was used as a disaster center which illustrates the value of safe school buildings to post-earthquake relief efforts.

In the 1987 Whittier Narrows earthquake, damage to schools in Los Angeles was minimal and limited to nonstructural components and contents. The most serious test of school buildings was the 1989 Loma Prieta earthquake, a magnitude 7.1 event that affected the entire San Francisco Bay area. A preliminary survey of 1,544 public schools in the impacted area showed an estimated $81 million in damage. Only three schools--one in San Francisco, one in Watsonville, and one in Los Gatos--sustained severe damage. Many public school buildings were used as evacuation shelters for the earthquake victims.

The Loma Prieta school buildings in Los Gatos, close to the epicenter, were constructed in the 1950s and 1960s over hidden branches of the San Andreas fault system. At that time, there was no legislative mandate for studies of geologic hazards at school sites. Several years ago, however, it became apparent that these buildings were sited over potentially active fault traces and since then, the school system and the state have attempted to purchase a new and safer site for this school. In the Loma Prieta earthquake, one classroom wing heaved upward and the other wing suffered large cracks in the walls and sidewalks.

Early estimates set the San Francisco school district's losses at more than $45 million, a third involving the district's central administration buildings, which are not subject to the same seismic standards as school buildings. Only one San Francisco school suffered severe structural damage. This building, originally a warehouse, was purchased by the district in the 1950s and converted into a high school. Three other schools reported substantial damage: a gymnasium, a high school auditorium, and one elementary school that lost a lot of bricks. The remainder of the costs resulted from minor cosmetic damage at many facilities. Oakland's 92 schools fared better with only about $1.5 million in damage.

San Francisco's Winfield Scott School, in the heart of the Marina area, showed the effectiveness of school strengthening. The school was built in 1930 and strengthened in the 1970s. It suffered only minor cracks in the plaster and some damage to the playground even though it is located in the center of what was a severely damaged area. Its losses were estimated at less than $100,000 and it played an important role in sheltering Marina residents displaced from their dwellings.

To date, the intention of the *Field Act* appears to have been met. However, the ultimate test--a great earthquake comparable to the 1906 San Francisco earthquake of magnitude 8.3 occurring while schools are in session--has not yet been encountered. Officials in California are confident that decades of application of the *Field Act* should greatly reduce the damage and casualties resulting from such an event.

Appendix B

SEISMICITY OF THE UNITED STATES

Introduction

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. Studies of seismicity provide answers to the questions where, how big, how often, and why earthquakes occur.

The remainder of this appendix features information on U.S. seismicity produced by S. T. Algermissen of the U.S. Geological Survey in 1983 and presented in 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 a Workshop on Development of an Action Plan* (FEMA Earthquake Hazard Reduction Series No. 31).

This seismicity information is 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.

Terminology

The Modified Mercalli intensity, MMI, scale is used in the seismicity information presented here as the reference when instrumental data to define Richter and surface wave magnitudes were unavailable. Refer to the Glossary for a brief explanation of these terms.

Northeast Region

The record of earthquakes in the United States (and the Northeast) is believed to have started with the Rhode Island earthquake of 1568. Including earthquakes originating in the St. Lawrence River Valley in Canada, 16 important earthquakes have occurred in the northeast region since 1568. The distribution (number) of earthquakes with respect to the maximum MMI in the northeastern United States, excluding Canada and offshore epicenters, is as follows: V = 120, VI = 37, VII = 10, VIII = 2. The important earthquakes for eastern Canada and New England are listed below:

Date	Location	Maximum MMI (I_o)	Magnitude (Approx. M_S)
1534-1535	St. Lawrence Valley	IX-X	
June 11, 1638	St. Lawrence Valley	IX	
Feb. 5, 1663	Charlevoix zone	X	7.0
Nov. 10, 1727	New Newbury, MA	VIII	7.0
Sept. 16, 1732	Near Montreal	VIII	
Nov. 18, 1755	Near Cape Ann, MA	VIII	
May 16, 1791	East Haddam, CT	VIII	
Oct. 5, 1817	Woburn, MA	VII-VIII	
Oct. 17, 1860	Charlevoix zone	VIII-IX	6.0
Oct. 20, 1870	Charlevoix zone	IX	6.5
Mar. 1, 1925	Charlevoix zone	IX	7.0
Aug. 12, 1929	Attica, NY	VIII	5.5
Nov. 18, 1929	Grand Banks, Newfoundland	X	8.0
Nov. 1, 1935	Timiskaming, Quebec	VIII	6.0
Sept. 5, 1944	Massena, NY; Cornwall, Ont.	VIII	6.0
Jan. 9, 1982	North Central New Brunswick	V	5.7 (m_b)

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). The distribution (number) of earthquakes with respect to MMI through 1976 in the southeast region is as follows: V = 133, VI = 70, VII = 10, VIII = 2, IX = 0, X = 1. Important earthquakes of the southeast region include:

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		

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 epicentral intensities ranging from X to XII (Nuttli, 1973). Some 15 of the thousands of aftershocks that followed had magnitudes greater than 6. A distribution of earthquakes with respect to MMI through 1976 in the central region follows: V = 275, VI = 114, VII = 32, VIII = 5, IX = 1, X = 0, XI = 2, XII = 1. The important earthquakes of the central region include:

Date	Location	Maximum MMI (I_o)	Magnitude (Approx. M_S)
Dec. 16, 1811	New Madrid, MO	XI	8.6
Jan. 23, 1812	New Madrid, MO	X-XI	8.4
Feb. 7, 1812	New Madrid, MO	XI-XII	8.7
June 9, 1838	Southern IL	VIII	5.7
Jan. 5, 1843	Near Memphis, TN	VIII	6.0
Apr. 24, 1867	Near Manhattan, KS	VII	5.3
Oct. 22, 1882	West Texas	VII-VIII	5.5
Oct. 31, 1895	Near Charleston, MO	VIII-IX	6.2
Jan. 8, 1906	Near Manhattan, KS	VI-VIII	5.5
Mar. 9, 1937	Near Anna, OH	VIII	5.3
Nov. 9, 1968	Southern IL	VII	5.5
July 27, 1980	Near Sharpsburg, KY	VI	5.1

Western Mountain Region

A number of important earthquakes have occurred in the western mountain region. These include earthquakes in the Yellowstone Park-Hebgen Lake area in western Montana, in the vicinity of the Utah-Idaho border, and sporadically along the Wasatch front in Utah. The largest earthquake in the western mountain region in historic times was the 1959 Yellowstone Park-Hebgen Lake earthquake which had a magnitude (M_S) that is now believed to be in excess of 7.3. The strongest earthquake in 24 years occurred at Borah Peak in Idaho in October 1983; it had a magnitude of 7.3. The distribution (number) of historic earthquakes with respect to MMI in the western mountain region is as follows: V = 474, VI = 149, VII = 26, VIII = 22, IX = 0, X = 1. The important earthquakes of the western mountain region include:

Date	Location	Maximum MMI (I_0)	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	Near Helena, MT (Aftershock)	VIII	6.0
Nov. 23, 1947	Southwest MT	VIII	
Aug. 18, 1959	West Yellowstone-Hegben Lake	X	7.1
Aug. 18, 1959	West Yellowstone-Hegben Lake (Aftershock)	VI	6.5
Aug. 18, 1959	West Yellowstone-Hegben Lake (Aftershock)	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	Borah Peak, ID	VII est.	7.3

California and Western Nevada Region

The highest rates of seismic energy release in the United States, exclusive of Alaska, occur in California and western Nevada. The coastal areas of California are part of the active plate boundary between the Pacific and North American tectonic plates. Seismicity can be correlated with the well-known San Andreas fault system as well as many other active fault systems. A number of major earthquakes have occurred in this region. 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 (number) in California and western Nevada is as follows: V = 1,263, VI = 437, VII = 170, VIII = 41, VIII-IX = 2, IX = 8, IX-X = 3, X = 5, X-XI = 2. The important earthquakes of California and western Nevada include:

Date	Location	Maximum MMI (I_0)	Magnitude (Approx. M_S)
Dec. 21, 1812	Santa Barbara Channel	X	
June 10, 1836	Hayward fault, east of San Francisco Bay	IX-X	
June 1838	San Andreas fault	X	
Jan. 9, 1857	San Andreas fault, near Fort Tejon	X-XI	
Oct. 21, 1868	Hayward Fault, east of San Francisco Bay	IX-X	
Mar. 26, 1872	Owens Valley	X-XI	
Apr. 19, 1892	Vacaville, CA	IX	
Apr. 15, 1989	Mendocino County, CA	VIII-IX	
Dec. 25, 1899	San Jacinto, CA	IX	
Apr. 18, 1906	San Francisco, CA	XI	8.3
Oct. 3, 1915	Pleasant Valley, NV	X	7.7
Apr. 21, 1918	Riverside County, CA	IX	6.8
Mar. 10, 1922	Cholame Valley, CA	IX	6.5
Jan. 22, 1923	Off Cape Mendocino, CA	IX	7.3
June 29, 1925	Santa Barbara Channel	VIII-IX	6.5
Nov. 4, 1927	West of Pt. Arguello, CA	IX-X	7.3
Dec. 21, 1932	Cedar Mountain, NV	X	7.3
Mar. 11, 1933	Long Beach, CA	IX	6.3
May 19, 1940	Southeast of El Centro, CA	X	7.1
July 21, 1952	Kern County, CA	XI	7.7
July 6, 1954	East of Fallon, NV	IX	6.6
Aug. 24, 1954	East of Fallon, NV	IX	6.8
Dec. 16, 1954	Dixie Valley, NV (2 shocks)	X	7.3
Feb. 9, 1971	San Fernando, CA	XI	6.4
Oct. 15, 1979	Imperial Valley, CA	IX	6.6
May 2, 1983	Coalinga, CA	VIII	6.5
Oct. 1, 1987	Whittier Narrows, CA	VIII	6.1
Oct. 17, 1989	Loma Prieta, CA	Not avail.	7.1 est.

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, 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 as follows: V = 1,263, VI = 487, VII = 170, VIII-IX = 2, IX = 8, IX-X = 3. The important earthquakes of Washington and Oregon include:

Date	Location	Maximum MMI (I_0)	Magnitude (Approx. M_S)
Dec. 14, 1872	Near Lake Chelan, WA (probably shallow depth of focus)	IX	7.0
Oct. 12, 1877	Cascade Mountains, OR	VIII	
Mar. 7, 1893	Umatilla, OR	VII	
Mar. 17, 1904	About 60 km NW of Seattle	VII	
Jan. 11, 1909	North of Seattle, near Washington/British Columbia border	VII	
Dec. 6, 1918	Vancouver Island, B.C.	VIII	7.0
Jan. 24, 1920	Straits of Georgia	VII	
July 16, 1936	Northern OR, near Freewater	VII	5.7
Nov. 13, 1939	NW of Olympia (depth of focus about 40 km)	VII	5.8
Apr. 29, 1945	About 50 km SE of Seattle	VII	
Feb. 15, 1946	About 35 km NNE of Tacoma (depth of focus 40-60 km)	VII	6.3
June 23, 1946	Vancouver Island	VIII	7.2
Apr 13, 1949	Between Olympia and Tacoma (depth of focus about 70 km)	VIII	7.1
Apr. 29, 1965	Between Tacoma and Seattle (depth of focus about 59 km)	VIII	6.5

Alaska Region

The Alaska-Aleutian Island area is one of the most active seismic zones in the world. The Queen Charlotte Island-Fairweather fault system marks the active boundary in southeast Alaska where the Pacific plate slides past the North American plate. The entire coastal region of Alaska and the Aleutians have experienced extensive earthquake activity, even in the relatively short time period (85 years) for which the record of seismicity is well known. The most devastating earthquake in Alaska occurred on March 28, 1964, in the Prince William Sound. This earthquake, which has recently been assigned a moment magnitude of 9.2, also probably was the largest historical earthquake. It caused 114 deaths, principally as a result of the tsunami that followed the earthquake. The regional uplift and subsidence covered an area of more than 77,000 square miles. The distribution of earthquakes in Alaska in terms of Magnitude (M_S) is as follows: 6.0-6.9 = 344, 7.0-7.9 = 63, 8.0 = 11. The important earthquakes of Alaska include:

Date	Location	Maximum MMI (I_o)	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

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. 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 as follows: V = 56, VI = 9, VII = 9, VIII = 3, IX = 1, X = 1. The important earthquakes causing significant damage in Hawaii include:

Date	Location	Maximum MMI (I_o)	Magnitude (Approx. M_S)
Apr. 2, 1868	Near south coast of Hawaii	X	
Nov. 2, 1918	Mauna Loa, HI	VII	
Sept. 14, 1919	Kilauea, HI	VII	
Sept. 25, 1929	Kona, HI	VII	
Sept. 28, 1929	Hilo, HI	VII	
Oct. 5, 1929	Honualoa, HI	VII	6.5
Jan. 22, 1938	North of Maui	VIII	6.7
Sept. 25, 1941	Mauna Loa, HI	VII	6.0
Apr. 22, 1951	Kilauea, HI	VII	6.5
Aug. 21, 1951	Kona, HI	IX	6.9
Mar. 30, 1954	Near Kalapana, HI	VII	6.5
Mar. 27, 1955	Kilauea, HI	VII	
Apr. 26, 1973	Near northeast coast of Hawaii	VIII	6.3
Nov. 29, 1975	Near northeast coast of Hawaii	VIII	7.2
Nov. 16, 1983	Near Mauna Loa, HI		6.6

Puerto Rico and the Virgin Islands Region

The seismicity in the Puerto Rico and Virgin Islands region is related to the interaction of the Caribbean and the North American tectonic plates. The Caribbean plate is believed to be arly fixed while the North American plate is moving westward at the rate of about 2 cm/year. Earthquakes in this region are known to have caused damage as early as 1524-1528. During the past 120 years, major damaging earthquakes have occurred in 1867 and 1918; both earthquakes had tsunamis associated with them. The distribution of earthquakes affecting Puerto Rico is given below in terms of maximum MMI is as follows: V = 24, V-VI = 4, VI = 5, VI-VII = 1, VII = 6, VII = 2, VIII-X = 1. Important earthquakes on or near Puerto Rico include:

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

THE BSSC PROGRAM ON IMPROVED SEISMIC SAFETY PROVISIONS

Purpose of the Council

The Building Seismic Safety Council (BSSC) was established in 1979 under the auspices of the National Institute of Building Sciences as an entirely new type of instrument for dealing with the complex regulatory, 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 issues related to the seismic safety of the built environment could be resolved and jurisdictional problems overcome through authoritative guidance and assistance backed by a broad consensus.

The BSSC 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.

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, elected 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 types, structures, and related facilities and includes explicit consideration and assessment of the social, technical, administrative, political, legal, and economic implications of its deliberations and recommendations. The BSSC 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 (i.e., 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 or standards-promulgating role; rather, it advocates that code- and standards-formulation organizations consider BSSC recommendations for inclusion into their documents and standards.

The BSSC Program on Improved Seismic Safety Provisions has been conducted with funding from the Federal Emergency Management Agency (FEMA). It is 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.

To date, the BSSC has conducted the major projects described below to mitigate the seismic hazard to new buildings, existing buildings, and new and existing lifelines.

Improving the Seismic Safety of New Buildings

The genesis of the BSSC's new buildings effort 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; now NIST, the National Institute of Standards and Technology), the *Tentative Provisions for the Development of Seismic Regulations for New Buildings* (referred to here as the *Tentative Provisions*) was prepared by the Applied Technology Council (ATC) as 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 the ATC acknowledged that a careful assessment was needed.

Following the issuance of the *Tentative Provisions* in 1978, NBS released a technical note on the document calling for "...systematic analysis of the logic and internal consistency of [the *Tentative Provisions*]" and developed a plan for assessing and implementing seismic design provisions for buildings as its final submission to NSF. This plan called for a thorough review of the *Tentative Provisions* by all interested organizations; the conduct of trial designs to establish the technical validity of the new provisions and to predict their economic impact; the establishment of a mechanism to encourage consideration and adoption of the new provisions by organizations promulgating national standards and model codes; and educational, technical, and administrative assistance to facilitate implementation and enforcement.

During this same period, other events significant for this effort were taking place. In October 1977, Congress passed the *Earthquake Hazards Reduction Act* (P.L. 95-124) and the National Earthquake Hazards Reduction Program (NEHRP) was released by the Administration on June 22, 1978. The concept of an independent agency to coordinate all emergency management functions at the federal level also was under discussion. When this concept was effected and FEMA was created, FEMA became the implementing agency with NSF retaining its research-support role. Thus, the future disposition of the *Tentative Provisions* and the 1978 NBS plan shifted from NSF to FEMA.

The emergence of FEMA as the agency responsible for implementation of P.L. 95-124 (as amended) and the NEHRP also required establishment of a mechanism for obtaining a broad public and private consensus on both recommended improved building design and construction regulatory provisions and the means to be used in their promulgation. Following a series of meetings between representatives of the original participants in the NSF-sponsored project on seismic design provisions, FEMA, the American Society of Civil Engineers and the National Institute of Building Sciences (NIBS), the concept of the Building Seismic Safety Council was born. As the concept began to take form, progressively wider public and private participation was sought, culminating in early 1979 with a broadly representative organizing meeting at which a charter and organizational rules and procedures were thoroughly debated and agreed upon.

The BSSC provided the mechanism--in essence the forum--needed to encourage consideration and adoption of the new provisions by the relevant organizations. A joint BSSC-NBS committee was formed to conduct the needed review of the *Tentative Provisions*, which resulted in 198 recommendations for changes.

Another joint BSSC-NBS committee then developed both the criteria by which the needed trial designs could be evaluated and the specific trial design program plan. Subsequently, a BSSC-NBS Trial Design Overview Committee was created to revise the trial design plan to accommodate a multi-phased effort and to refine the *Tentative Provisions*, to the extent practicable, to reflect the recommendations generated during the earlier review.

The BSSC then initiated the effort to develop the actual trial designs which were to include low-, mid-, and high-rise residential buildings; mid- and high-rise office buildings; one-story industrial buildings; two-story commercial buildings; and the full range of typical structural systems and materials of construction.

It originally was intended that the trial design effort would be conducted in two phases that would include trial designs for 100 new buildings in 11 major cities, but financial limitations required that the program be scaled down as follows:

- During Phase I of the program, 10 design firms were retained to prepare trial designs for 26 new buildings in 4 cities with medium to high seismic risk--10 in Los Angeles, 4 in Seattle, 6 in Memphis, and 6 in Phoenix.
- During Phase II, 7 firms were retained to prepare trial designs for 20 buildings in 5 cities with medium to low seismic risk--3 in Charleston (S.C.), 4 in Chicago, 3 in Ft. Worth, 7 in New York, and 3 in St. Louis. For six of these buildings, alternative designs also were developed.

The firms participating the trial design program were ABAM Engineers, Inc.; Alfred Benesch and Company; Allen and Hoshall; Bruce C. Olsen; Datum/Moore Partnership; Ellers, Oakley, Chester, and Rike, Inc.; Enwright Associates, Inc.; Johnson and Nielsen Associates; Klein and Hoffman, Inc.; Magadini-Alagia Associates; Read Jones Christoffersen, Inc.; Robertson, Fowler, and Associates; S. B. Barnes and Associates; Skilling Ward Rogers Barkshire, Inc.; Theiss Engineers, Inc.; Weidlinger Associates; and Wheeler and Gray.

For each of the 52 designs included, a set of building requirements or general specifications was developed and provided to the responsible design engineering firm, but the designers were given latitude to ensure that building design parameters were compatible with local construction practice. The designers were not permitted, however, to change the basic structural type 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 some designers from selecting the most economical system. Each building was designed once according to the amended *Tentative Provisions* and again according to the prevailing local code for the particular location of the design.

In this context, basic structural designs (complete enough to assess the cost of the structural portion of the building), partial structural designs (special studies to test specific parameters, provisions, or objectives), partial nonstructural designs (complete enough to assess the cost of the nonstructural portion of the building), and design/construction cost estimates were developed.

This phase of the BSSC program concluded with publication of:

- A draft version of the recommended provisions, *The NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings*;
- An overview of the provisions refinement and trial design efforts; and
- The design firms' reports.

The draft provisions reflected the initial amendments to the original ATC document as well as further refinements made by the Overview Committee. They represented an interim set of provisions pending their balloting by the BSSC member organizations, which began in July 1984.

The first ballot was conducted in accordance with the BSSC Charter and was organized on a chapter-by-chapter basis. The ballot 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 explanations received with "yes with reservation" and "no" votes were compiled, and proposals for dealing with them were developed for consideration by the Overview Committee and, subsequently, the BSSC Board of Direction. The draft provisions then were revised to reflect the changes deemed appropriate by the BSSC Board and the revision was submitted to the BSSC membership for balloting again in August 1985.

As a result of this second ballot, virtually the entire provisions document received consensus approval, and a special BSSC Council meeting was held in November 1985 to resolve as many of the remaining differences as possible. The 1985 Edition of the *NEHRP Recommended Provisions* then was transmitted to FEMA for publication in December 1985.

During the next three years, a number of documents were published to support and complement the 1985 Edition of the *NEHRP Recommended Provisions*. The reports issued included: a guide to application of the *Provisions* in earthquake-resistant building design, a nontechnical explanation of the *Provisions* for the lay reader, and a handbook for interested members of the building community and others explaining the societal implications of utilizing improved seismic safety provisions and a companion volume of selected readings.

In 1987 a special two-year effort also was mounted to stimulate widespread use of the *Provisions*. Particular emphasis was placed on developing the seismic hazard awareness of building owners, developers, insurers, and investors; building and community officials; and key public interest groups.

A series of *Seismic Considerations* handbooks were developed to generate interest in seismic hazard mitigation among the owners and other decision-makers and design professionals responsible for five building types: apartment buildings, elementary and secondary schools, health care facilities, hotels and motels, and office buildings.

In developing and distributing these handbooks, the BSSC involved, to the greatest extent possible, the national organizations reflecting the interests of the identified groups. These included the Alliance of American Insurers, the American Hospital Association, the American Hotel and Motel Association, the American Institute of Architects, the American Institute for Property and Liability Underwriters, the American Insurance Association's American Insurance Services Group, the American Planning Association, the American School Boards Association, the American Society for Hospital Engineering, the Building Owners and Managers Association, the Council of Educational Facility Planners International, the Federation of American Health Systems, the Institute of Real Estate Management, the Insurance Information Institute, the International City Management Association, the National Committee on Property Insurance, the National Association of Counties, the National Governors' Association, the National Voluntary Organizations Active in Disasters, The Parent-Teacher Association, and the Public Risk and Insurance Management Association.

These specific efforts were supported by the participation of BSSC representatives in a wide variety of meetings and conferences, BSSC participation in development of curriculum for a FEMA Emergency Management Institute course on the *Provisions* for structural engineers and other design professionals, issuance of press releases, development of in-depth articles for the publications of relevant groups, and the establishment of a computer data base to permit the quick retrieval of various types of information.

The BSSC's information dissemination efforts also provide for conduct of seismic mitigation demonstration projects. The goal of these activities is to enrich the ongoing information dissemination efforts by providing tangible examples of the willingness and ability of various political jurisdictions in targeted geographic areas to consider, adopt, and implement the *NEHRP Recommended Provisions*. The first such project, being conducted by The Citadel in Charleston, South Carolina, involves development, by the U.S. Geological Survey, of a site-specific seismic risk map of the area; formulation of a set of provisions for the most common types of buildings being and expected to be constructed in the area on the basis of the *NEHRP Recommended Provisions*; and use of the resources assembled to date by the BSSC and other seismic mitigation materials in a way that targets the specific needs of the community and stimulates action on the part of influential segments of that community. In September 1989, the BSSC received funding from FEMA to initiate a second demonstration project aimed at demonstrating the usability, practicability, and technical validity of the procedure in the "Appendix to Chapter 1" of the 1988 Edition of the *NEHRP Recommended Provisions* and to document the economic impact of its utilization.

Although it is difficult to determine precisely how effective these various efforts have been, the number of BSSC publications distributed certainly provides at least one measure of the level of interest generated. In this respect, the BSSC can report that more than 30,000 publication requests were filled between December 1987 and April 1990, and this number is above and beyond those requests for BSSC documents directed to FEMA.

The need for continuing revision of the *Provisions* had been anticipated since the onset of the BSSC program and the effort to update the 1985 Edition for re-issuance in 1988 began in January 1986. During the update effort, nine BSSC Technical Committees were formed to focus on seismic risk maps, structural design, foundations, concrete, masonry, steel, wood, architectural/mechanical/electrical systems, and regulatory use. The Technical Committees (TCs) worked under the general direction of a Technical Management Committee (TMC), which was composed of a representative of each TC as well as additional members identified by the Board to provide balance. It served as the effort coordinator and was charged to deal with global issues; to provide the continuing liaison between the TCs and the BSSC Board of Direction; to consider and respond to all comments and negative votes received as 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 issues left unresolved when the 1985 Edition was published.

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 developed by the TCs and TMC and decided upon a set of 53 proposed revisions to the 1985 Edition of the *Provisions* for submittal to the BSSC membership for ballot. Approximately half of the proposals reflected new issues while the other half reflected efforts to deal with the unresolved 1985 issues.

The ballot, mailed to each BSSC member organization in February 1988 for submittal in April, was conducted on a proposal-by-proposal basis using a form that provided for four responses: "yes," "yes with reservations," "no," and "abstain." Fifty of the proposal items on the ballot passed and three failed. All comments and "yes with reservation" and "no" votes received as a result of the ballot were reviewed by the TMC. Many of the comments could be addressed by making minor editorial adjustments and these were approved by the Board. Other comments were found to be unpersuasive or in need of further study during the next update cycle (to prepare the 1991 Edition of the *Provisions*) and, consequently, no changes were made in response to these comments. Finally, a number of comments persuaded the TMC and Board that a substantial alteration of a balloted proposal was necessary, and it was decided to submit these matters (11 in all) to the BSSC membership for reballot. The reballoting began in June 1988 and concluded in July; nine of the proposals passed.

On the basis of the ballot and reballot results, the 1988 Edition of the *Provisions* was prepared and transmitted to FEMA for publication in August 1988. A report describing the changes made in the 1985 Edition and issues in need of attention in the next update cycle then was prepared and efforts began to update the complementary reports originally published to support the 1985 Edition.

By the end of 1989, almost 150 experts were at work on preparation of the 1991 Edition of the *Provisions*. Ten technical subcommittees working under the general direction of the BSSC *Provisions* Update Committee were addressing seismic hazard maps, structural design criteria and analysis, foundations, cast-in-place and precast concrete structures, masonry structures, steel structures, wood structures, mechanical-electrical systems and building equipment and architectural elements, quality assurance, and interface with codes and standards.

In late 1989, the Building Officials and Code Administrators International (BOCA) appointed an ad hoc committee to review and study the 1988 Edition of the *Provisions* with the purpose of developing a comprehensive and consistent position on code requirements for earthquake loads that will reflect technology, design practices, and national codes and standards. In addition to six building officials selected by BOCA, the committee includes six BSSC members (five of whom are Board members). Further, the Southern Building Code Congress International (SBCCI) was participating in a similar cooperative effort, and the *NEHRP Recommended Provisions* were being adapted for possible use in Standard ASCE 7 (formerly ANSI A-58).

Improving the Seismic Safety of Existing Buildings

In October 1989, with funding from FEMA, the BSSC initiated a project to provide consensus-backed approval of publications on seismic hazard evaluation and strengthening techniques for existing buildings. This effort involves:

- Identifying and resolving major technical issues in ATC-22, *Handbook for Seismic Evaluation of Existing Buildings*, and a supporting engineering report on methodologies for the seismic evaluation of existing hazardous buildings prepared by the Applied Technology Council (ATC) and in *Techniques for Seismically Rehabilitating Existing Buildings (Preliminary)*, a report on procedures for seismically retrofitting existing buildings prepared by URS/John A. Blume and Associates, Engineers (URS/Blume);

- Revising the three documents as necessary for balloting by the BSSC membership;

- Balloting the three documents in accordance with the BSSC Charter;

- Assessing the ballot results, developing proposals to resolve the issues raised, and identifying any unresolvable issues; and

- Preparing copies of the documents that reflect the results of the balloting and a summary of changes made and unresolved issues.

Basically, the consensus project is being directed by the BSSC Board and a 22-member Retrofit of Existing Buildings (REB) Committee composed of individuals representing the needed disciplines and geographical areas and possessing special expertise in the seismic rehabilitation of existing buildings. Drafts of the subject documents were received in April 1989. By April 1990, the Retrofit of Existing Buildings Committee had met three times, each committee member had conducted a detailed review of the subject documents, and subcommittees had been established to address all the comments received as a result of this review. Once committee consensus on needed changes is achieved, the modified documents will be submitted to the BSSC membership for balloting.

Earlier, the BSSC was involved in a joint venture with the ATC and the Earthquake Engineering Research Institute to develop an action plan for reducing earthquake hazards to existing buildings and it was this action plan that prompted FEMA to fund development of the ATC and URS/Blume documents.

Improving the Seismic Safety of New and Existing Lifelines

Given the fact that buildings will continue to be useful in a seismic emergency only if the services on which they depend continue to function, the BSSC conducted a program on development of an action plan for the abatement of seismic hazards to lifelines. It was expected that the resulting seismic hazard abatement action plan for new and existing lifelines would provide FEMA and other government agencies and private sector organizations with a basis for their long-range planning.

The action plan was developed through a consensus process utilizing the special talents of individuals and organizations involved in the planning, design, construction, operation, and regulation of lifeline facilities and systems. Five lifeline categories were considered:

- Water and sewer facilities
- Transportation facilities
- Communication facilities
- Electric power facilities
- Gas and liquid fuel lines

Early in 1986 a large number of individuals possessing expertise in the various technical disciplines and professions involved in the earthquake problem (i.e., geoscientists, geotechnical engineers, structural engineers, mechanical engineers, electrical engineers, architects, urban planners, lawyers, economists, social scientists, researchers, teachers, design practitioners, government policy makers, and building officials) were invited to participate in a November workshop and/or prepare papers on these topics for review and coordination prior to discussion at the workshop. Of those invited, more than 65 individuals indicated that they would participate actively and 41 issue papers were prepared.

The workshop was structured to provide for consideration of each lifeline category by a separate panel and for consideration of issues spanning the lifeline categories (i.e., political, economic, and social issues; legal and regulatory issues; and seismic risk) by overview groups composed of a chairman and a member from each of the category panels. In addition, an Action Plan Committee, composed of the chairman of each panel and each overview group, was appointed.

All issue papers were reviewed by the appropriate panel and overview group, were modified as appropriate by their authors, and were distributed to all participants prior to the workshop. At the workshop itself, each panel and overview group had the opportunity to meet as a group so that each participant would have the opportunity to contribute to action plan development. Plenary discussions permitted each panel and group to present its findings and receive meaningful contributions from those in other groups and from the workshop guests. At the conclusion of the workshop, the chairman of each panel and overview group had developed the basis of an agenda or "mini" action plan for the specific topic that had the consensus approval of the panel or group.

Following the workshop, the various participants further contributed to the agenda being developed by the panel or group to which they had been assigned and all the agendas were submitted to the BSSC Action Plan Committee in early 1987. They then were reviewed and refined and the final action plan document for FEMA was drafted and distributed once again to all workshop participants for comment. The final action plan report then was developed and transmitted to FEMA in May 1987. The workshop proceedings were published in six volumes--one covering each of the five lifeline categories and one covering political, social, economic, legal, and regulatory issues and including the general workshop presentations.

In recognition of both the complexity and importance of lifelines and their susceptibility to disruption as a result of earthquakes and other natural hazards (hurricanes, tornadoes, flooding), FEMA subsequently concluded that the lifeline problem could best be approached through a nationally coordinated and structured program aimed at abating the risk to lifelines from earthquakes as well as other natural hazards. Thus, in 1988 FEMA asked the BSSC's parent institution, the National Institute of Buildings Sciences, to provide expert recommendations concerning appropriate and effective strategies and approaches to use in implementing such a program. The effort, conducted for NIBS by an ad hoc Panel on Lifelines with the assistance of the BSSC, resulted in a report recommending that the federal government, working through FEMA, structure a nationally coordinated, comprehensive program for mitigating the risk to lifelines from seismic and other natural hazards that focuses on awareness and education, vulnerability assessment, design criteria and standards, regulatory policy, and continuing guidance. Identified were a number of specific actions that should be taken during the next three to six years to initiate the program.

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