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ARCHITECTS and EARTHQUAKES

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... buildings and their components; and (5) to encourage further in-depth study by the architectural profession into the areas of building performance and seismic response. The primer begins with a discussion of basic geological and seismic phenomena that cause earthquakes. Types of structural systems and materials performance and interactions under earthquake forces are discussed. Following are discussions of how these basic structural movements translate into forces acting on building components, how these are likely to fail and what can be done. The final section discusses how these relatively simple technical design issues quickly broaden into very complicated social-economic-political issues.

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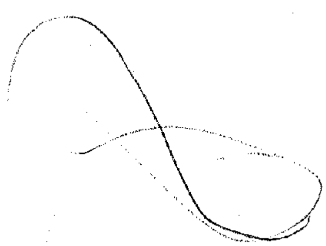
"The final measure of a well-constructed building is the safety and comfort that it affords its occupants. If, during the earthquake, they must exit through a shower of falling light fixtures and ceilings, maneuver through shifting and toppling furniture, stumble down dark corridors and stairs, and then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

*From Ayres, Sun and Brown's report on the analysis of nonstructural damage to buildings resulting from the 1964 Alaska earthquake.



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FOREWORD

AIA RESEARCH CORPORATION
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31 October 1975

Dear Reader:

Welcome to the beginning steps of a new venture. This "primer" is an introduction to the subject. It's a primer in the classic sense that it is a small introductory book. But, we would also like to think of it in the sense of "priming a pump"—a primer to start architects thinking about this subject of earthquakes as *architects.* We ought to know how our engineering colleagues view the structural design issues for earthquake resistance, but we don't need to know how to do the complex calculations that result from this point of view—unless we are actually involved in designing a building's structural system. We are planning to develop a new body of knowledge (based on the fundamentals outlined in this primer) and we want to do so *with* the architectural profession.

We think there are clear implications for architectural licensing exams and building code requirements in what we will be discovering that are different from the traditional engineering concerns with these areas. We welcome your participation in this effort and look forward to a continuing dialogue as this work develops.

Sincerely,

John P. Eberhard
President

This primer's basic purposes are:

a. To develop a national awareness among the members of the architectural profession that earthquakes can and do occur east of the Sierra Nevada Mountains; how life can be threatened; and that buildings can be significantly damaged by earthquakes.

b. To help architects further understand the nature of earthquakes and the basic response of buildings to these unique forces.

c. To emphasize how architectural planning and design affects the performance of buildings under earthquake conditions.

d. To provide architects from geographical regions of varying degrees of seismic activity with a vocabulary with which to talk to their clients and engineers about seismic resistance of buildings and their components.

e. To encourage further indepth study on the part of the architectural profession into the areas of building performance and seismic response.

INTRODUCTION

In the United States, two of the most severe earthquakes did not happen on the West Coast, but in the East and the Midwest. One of these was in Charleston, South Carolina in 1886 [Fig. 1]; the other was a series of three shocks in New Madrid, Missouri, a small town in the Mississippi River Valley, in 1811 and 1812. New Madrid was completely destroyed; the town site, formerly 25 feet (7.6 meters) above river level, subsided 13 feet (4 meters). The "felt area" was 2,000,000 square miles (5,200,000 square kilometers).

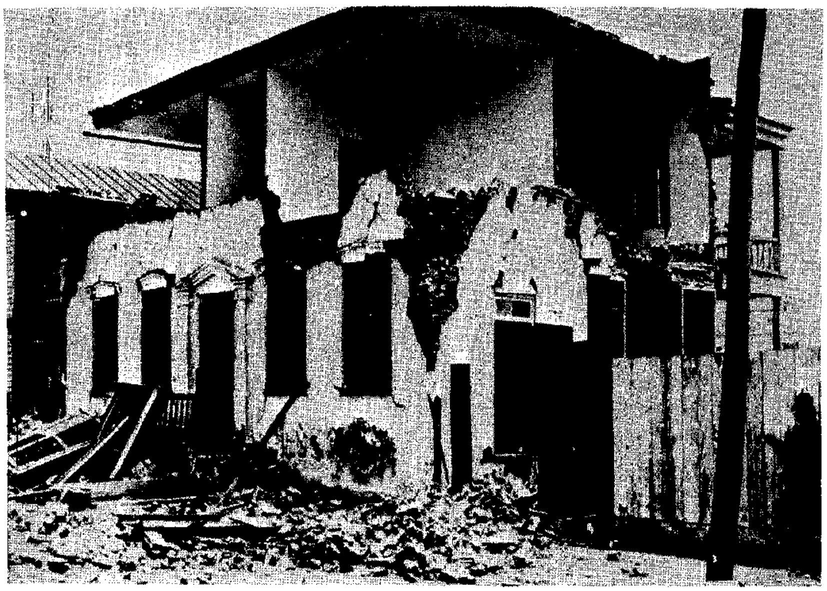


Fig. 1. A House on Tradd Street

. . .the most severe earthquakes did not happen on the West Coast, but in the East. . . One of these was in Charleston, South Carolina in 1886.

A severe earthquake is one of nature's most terrifying and devastating events. The major earthquake in Alaska in 1964 released an amount of energy equivalent to 100 nuclear explosions of 100 megatons each. It is sobering to realize that some of the most heavily populated regions in the world, such as Japan, Central and South America, China, Turkey, Iran, the United States, and nations around the Mediterranean are located in areas exposed to the most violent of earthquakes. Recent studies by the Federal Disaster Assistance Administration (FDAA) and National Oceanic and Atmospheric

Administration (NOAA) conclude that a repetition of the 1906 San Francisco earthquake could cause over 10,000 deaths and over 40,000 injuries, and could result in several billions of dollars in property damages. A similar event in the Los Angeles Basin could result in over 21,000 deaths and 82,000 injuries. In other seismic areas where there is little control over design and construction, the consequences can be staggering. (See Table I, loss of life in selected world earthquakes and Table II, property damage estimates in selected United States' earthquakes.)

Given the potential magnitude of seismic forces and general level of construction practices, it is not surprising that when an earthquake occurs, people are often safer in an open field than they are in buildings that are supposed to shelter them. Earthquakes rarely kill people directly, but buildings do—unless specific precautions are taken. If the architect ignores seismic activity, a primary duty is neglected by not responding to specific environmental site conditions. Particularly during the planning stages, the architect's decisions about earthquake protection have critical implications for life safety.

TABLE I. DEATHS IN SELECTED EARTHQUAKES AFTER 1900

Year	Locality	Deaths
1905	India, Kangra	20,000
1906	San Francisco, California	700
1908	Italy, Messina	75,000
1923	Japan, Tokyo-Yokohama	143,000
1932	China, Kansu	70,000
1935	Pakistan, Quetta	60,000
1939	Chile, Chillan	30,000
1939	Turkey, Erzincan	23,000
1949	Ecuador, Pelileo	6,000
1957	Northern Iran	2,500
1960	Morocco, Agadir	12,000
1963	Yugoslavia, Skopje	1,100
1964	Prince William Sound, Alaska	131
1967	Venezuela, Caracas	236
1970	Northern Peru	66,794
1971	San Fernando, California	65
1972	Nicaragua, Managua	10,000

Source: U.S. Department of Commerce; OEP data for 1971 earthquake.

To date, code requirements essentially deal with the structural integrity of a building as it affects life safety. Less attention is given to the performance of nonstructural or "architectural" components during an earthquake. No consideration is given to the basic architectural form of buildings which can dramatically affect seismic resistance and can adversely affect the possibility of structural survival. These factors generally have remained ignored so long as structural collapse was a primary factor—the architectural mistakes were, literally, buried. But with much-improved structural design methods, building collapse has become less prevalent. This in turn has made architectural (nonstructural) elements more vulnerable to damage. These weaknesses are being bared to the public and to the building owner, who to his great consternation, finds that he has not bought an "earthquake-resistant" building—only one which might stand up under some circumstances.

TABLE II. DAMAGE IN SELECTED U.S. EARTHQUAKES AFTER 1900

Year	Locality	Damage Loss in Millions*	Damage Loss 1958 Dollars****
1906	San Francisco, California	**$524.0	$2,500.0
1918	Puerto Rico	***$4.0	$7.5
1933	Long Beach, California	$40.0	$89.0
1935	Helena, Montana	$4.0	$8.5
1944	Cornwall, Canada/Massena, New York	$2.0	$3.5
1946	Hawaii	***$25.0	$37.0
1949	Puget Sound, Washington	$25.0	$30.0
1954	Wilkes-Barre, Pennsylvania	$1.0	$1.0
1959	Hegben Lake, Montana	$11.0	$11.0
1960	Hilo, Hawaii	***$25.5	$24.5
1964	Prince William Sound, Alaska	$500.0	$462.5
1965	Puget Sound, Washington	$12.5	$11.5
1966	Dulce, New Mexico	$0.2	$0.2
1971	San Fernando, California	$553.0	$313.0

* Dollar value at time of event. Use of these figures requires a critical examination of reference materials since the basis for the estimates varies.

** Includes $500,000,000 losses due to fire following earthquake.

*** Losses due to tsunami following distant earthquake.

**** In millions. Use of these figures requires a critical examination of reference materials since the basis for the estimates varies.

Source: U.S. Department of Commerce; OEP data for 1971 earthquake. 1958 dollars: Coffman, Jerry L., *Earthquake Investigation in the United States,* U.S. Department of Commerce, C&GS Special Publication No. 282, 1969.

Severe earthquake damage does not necessarily imply total destruction of the building's structural systems. But it can result in a severe hazard to occupants and the adjacent public and render a building useless. During the 1964 Alaska Earthquake, multistory buildings suffered damages totalling as much as 40 percent of their replacement value even though the structures remained standing. Surveys taken after the San Fernando and Managua earthquakes revealed that dollar loss associated with nonstructural damage could reach exorbitant proportions.

Social costs can be equally staggering. Although not technically destroyed in the sense of structural collapse, many buildings become functionally inoperative due to damage to architectural components, and disruption of services and utilities.

Failures of service systems [Fig. 2] and emergency facilities can precipitate secondary disasters (most of the 1906 San Francisco loss was caused by fire resulting from damage due to ground shaking which severed the water supply system) [Fig. 3]. Even in the absence of such consequences there still can be serious consequential losses such as business interruption, displacement of families, the possibility of looting, rioting, and other social disasters. Further, where major interruptions occur in critical facilities such as hospitals, utilities and communication centers, the ability of the community to recover from the primary disaster may be drastically reduced.

Fig. 2. Firetruck under Collapsed Structure

Failures of service systems and emergency facilities can precipitate secondary disasters.

Damage to architectural components is not a trivial issue in either economic or social terms. Such damage cannot be taken lightly by the architect, who holds the basic responsibility for decisions on what should be done for each building, in a particular area, whether or not such considerations are required by code, client or any other influence. The purpose of this "primer" is to make these problems and responsibilities clear to the architectural and planning community.

The primer begins with a discussion of basic geological and seismic phenomena that cause earthquakes, including discussions of the mechanics of earthquakes, ground movement, and other characteristics. The primer continues to show how ground motion in earthquakes causes movement or displacement of buildings, and describes the kinds of movement that occur. Types of structural systems and materials performance and interactions under earthquake forces are discussed. Following that are discussions of how these basic structural movements translate into forces acting on building components, how these are likely to fail and what can be done. Then, to alert the reader to the danger that any single solution cannot be relied upon to resolve this problem, the final section discusses how these relatively simple technical design issues quickly broaden into very complicated social-economic-political issues in the real world. The architect has a role here as well—to contribute thought and knowledge in those areas where these issues are to be acted upon. It is toward increasing the architect's ability to act

Fig. 3.

"Most of the 1906 San Francisco loss was caused by fire resulting from damage due to ground shaking which severed the water supply system."

knowledgeably that this primer also is directed.

If architects are to effectively communicate with the engineering profession and the public it is necessary that they understand the basic language of earthquake resistant design. It is toward this end that a glossary of terms, some of which are used in the text, follows this introduction. Terms are phrased in nontechnical language wherever possible; however, technical terms are used wherever appropriate. The glossary is not exhaustive.

GLOSSARY OF TERMINOLOGY

Accelerogram—The record from an accelerograph showing acceleration as a function of time.

Accelerograph—A strong motion earthquake instrument recording ground (or base) acceleration.

Aftershock—An earthquake, usually a member of an aftershock series often within the span of several months following the occurrence of a large earthquake (main shock). The magnitude of an aftershock is usually smaller than the main shock.

Amplification—An increase in earthquake motion as a result of resonance of the natural period of vibration with that of the forcing vibration.

Amplitude—Maximum deviation from mean or center line of a wave.

Aseismic Region—One that is relatively free of earthquakes.

Attenuation—Reduction of amplitude or change in wave due to energy dissipation over distance with time.

Axial Load—Force coincident with primary axis of a member.

Base Shear—Total shear force acting at the base of a structure.

Bilinear—Representation by two straight lines of the stress versus strain properties of a material, one straight line to the yield point and the second line beyond.

Brittle Failure—Failure in material which generally has a very limited plastic range; material subject to sudden failure without warning.

Compression and Dilatation—(rarefacation)—Used in connection with longitudinal waves, as in acoustics. They refer to the nature of the motion at a given point, usually a recording station. When the ray emerges to the surface, displacement upward and away from the hypocenter corresponds to compression, the opposite to dilatation.

Convergence Zone—A band along which moving tectonic plates collide and land area is lost either by shortening and crustal thickening or by subduction and destruction of crust.

Core—The central part of the earth below a depth of 2,900 kilometers. It is thought to be composed of iron and nickel and to be molten on the outside with a central solid inner core.

Creep (along a fault)—Very slow periodic or episodic movement along a fault trace unaccompanied by earthquakes.

Crust—The lithosphere, the outer 80 kilometers of the earth's surface made up of crustal rocks, sediment and basalt. General composition is silicon-aluminum-iron.

Damping—A rate at which natural vibration decays as a result of absorption of energy.

Critical Damping—The minimum damping that will allow a displaced system to return to its initial position without oscillation.

Deflection—Displacement of a member due to application of external force.

Depths of Foci—Earthquakes are commonly classed by the depth of the focus or hypocenter beneath the earth's surface: shallow (0-70 kilometers), intermediate (70-300 kilometers), and deep (300-700 kilometers).

Diaphragm—Generally a horizontal girder composed of a web (such as a floor or roof slab) with adequate flanges, which distributes lateral forces to the vertical resisting elements.

Divergence Zone—A belt along which tectonic plates move apart and new crust is created.

Drift—In buildings, the horizontal displacement of basic building elements due to lateral earthquake forces.

Ductility—Ability to withstand inelastic strain without fracturing.

Dynamic—Having to do with bodies in motion.

Elasticity—The ability of a material to return to its original form or condition after a displacing force is removed.

Elastoplastic—Total range of stress, including expansion beyond elastic limit into the plastic range.

Energy Absorption—Energy is absorbed as a structure distorts inelastically.

Energy Dissipation—Reduction in intensity of earthquake shock waves with time and distance, or by transmission through discontinuous materials with different absorption capabilities.

Epicenter—The point on the earth's surface vertically above the focus or hypocenter of an earthquake.

Failure Mode—The manner in which a structure fails (column buckling, overturning of structure, etc.).

Fault—Planar or gently curved fracture in the earth's crust across which relative displacement has occurred.

Normal Fault—A fault under tension where the overlying block moves down the dip or slope of the fault plane.

Strike-Slip Fault (or lateral slip)—A fault whose relative displacement is purely horizontal.

Thrust (Reverse) Fault—A fault under compression where the overlying block moves up the dip of the fault plane.

Oblique-Slip Fault—A combination of normal and slip or thrust and slip faults whose movement is diagonal along the dip of the fault plane.

Faulting—The movement which produces relative displacement of adjacent rock masses along a fracture.

Fault Zones—Instead of being a single clear fracture, the zone is hundreds or throusands of feet wide; the fault zone consists of numerous interlacing small faults.

Flexible System—A system that will sustain relatively large displacements without failure.

Felt Area—Total extent of area where an earthquake is felt.

Focal Depth—Depth of the earthquake focus (or hypocenter) below the ground surface.

Focus (of an earthquake)—The point at which the rupture occurs; synonymous with hypocenter. (It marks the origin of the elastic waves of an earthquake.)

Frames:

Moment Frame—One which is capable of resisting bending movements in the joints, enabling it to resist lateral forces or unsymmetrical vertical loads through overall bending action of the frame. Stability is achieved through bending action rather than bracing.

Braced Frame—One which is dependent upon diagonal braces for stability and capacity to resist lateral forces.

Frequency—Referring to vibrations; the number of wave peaks which pass through a point in a unit of time, usually measured in cycles per second.

Fundamental Period—The longest period (duration in time of one full cycle of oscillatory motion) for which a structure or soil column shows a response peak, commonly the period of maximum response.

Graben (rift valley)—Long, narrow trough bounded by one or more parallel normal faults. These down-dropped fault blocks are caused by tensional crustal forces.

Ground Failure—A situation in which the ground does not hold together such as landsliding, mud flows and liquefaction.

Ground Movement—A general term; includes all aspects of motion (acceleration, particle velocity, displacement).

Ground Acceleration—Acceleration of the ground due to earthquake forces.

Ground Velocity—Velocity of the ground during an earthquake.

Ground Displacement—The distance which ground moves from its original position during an earthquake.

Hypocenter—The point below the epicenter at which an earthquake actually begins; the focus.

Inelastic Behavior—Behavior of an element beyond its elastic limit.

Intensity—A subjective measure of the force of an earthquake at a particular place as determined by its effects on persons, structures and earth materials. Intensity is a measure of effects as contrasted with magnitude which is a measure of energy. The principal scale used in the United States today is the Modified Mercalli, 1956 version.

Isoseismals—Map contours drawn to define limits of estimated intensity of shaking for a given earthquake.

Lateral Force Coefficients—Factors applied to the weight of a structure or its parts to determine lateral force for aseismic structural design.

Liquefaction—Transformation of a granular material (soil) from a solid state into a liquefied state as a consequence of increased pore-water pressure induced by vibrations.

Lumped Mass—For analysis purposes, assumed grouping of mass at specific locations.

Macrozones—Large zones of earthquake activity such as zones designated by the Uniform Building Code map.

Magnification Factor—An increase in lateral forces at a specific site for a specific factor.

Magnitude—A measure of earthquake size which describes the amount of energy released.

Mantle—The main bulk of the earth between the crust and core, varying in depth from 40 to 3,480 kilometers.

Microregionalization—Breaking up of macrozones into much smaller zones of specific earthquake intensity and activity.

Modal Analysis—Determination of design earthquake forces based upon the theoretical response of a structure in its several modes of vibration to excitation.

Modified Mercalli—See Intensity.

Mud Flow—Mass movement of material finer than sand, lubricated with large amounts of water.

Natural Frequency—The constant frequency of a vibrating system in the state of natural oscillation.

Higher Modes of Vibration—Structures and elements have a number of natural modes of vibration.

Mode—The shape of the vibration curve.

Period—The time for a wave crest to traverse a distance equal to one wave length or the time for two successive wave crests to pass a fixed point; the inverse of frequency.

Nonstructural Components—Those building components which are not intended primarily for the structural support and bracing of the building.

Normalization—A method of standardizing characteristics of vibration.

Out of Phase—The state where a structure in motion is not at the same frequency as the ground motion; or where equipment in a building is at a different frequency from the structure.

Period—See Natural Frequency.

Plate Tectonics—The theory and study of plate formation, movement, interaction, and destruction; the theory which explains seismicity, volcanism, mountain building and paleomagnetic evidence in terms of plate motions.

Resonance—Induced oscillations of maximum amplitude produced in a physical spectrum when an applied oscillatory motion and the natural oscillatory frequency of the system are the same.

Response—Effect produced on a structure by earthquake ground motion.

Return Period of Earthquakes—The time period (years) in which the probability is 63 percent that an earthquake of a certain magnitude will recur.

Richter Magnitude Scale—A measure of earthquake size which describes the amount of energy released. The measure is determined by taking the common logarithm (base 10) of the largest ground motion observed during the arrival of a P-wave or seismic surface wave and applying a standard correction for distance to the epicenter.

Rift—A fault trough formed in a divergence zone or in other areas in tension. (See Graben)

Rigidity—Relative stiffness of a structure or element. In numerical terms, equal to the reciprocal of displacement caused by a unit force.

Sag Pond—A pond occupying a depression along a fault. The depression is due to uneven settling of the ground or other causes.

Scarp—A cliff, escarpment, or steep slope of some extent formed by a fault or a cliff or steep slope along the margin of a plateau, mesa or terrace.

Seiche—A standing wave on the surface of water in an enclosed or semi-enclosed basin (lake, bay or harbor).

Seismic—Pertaining to earthquake activities.

Seismicity—The world-wide or local distribution of earthquakes in space and time; a general term for the number of earthquakes in a unit of time, or for relative earthquake activity.

Seismograph—An instrument which writes or tapes a permanent continuous record of earth motion, a seismogram.

Seismoscope—A device which indicates the occurrence of an earthquake but does not write or tape a record.

Shear Distribution—Distribution of lateral forces along the height or width of a building.

Shear Strength—The stress at which a material fails in shear.

Shear Wall—A wall designed to resist lateral forces parallel to the wall. A shear wall is normally vertical, although not necessarily so.

Simple Harmonic Motion—Oscillatory motion of a wave, single frequency. Essentially a vibratory displacement such as that described by a weight which is attached to one end of a spring and allowed to vibrate freely.

Soil-Structure Interaction—The effects of the properties of both soil and structure upon response of the structure.

Spectra—A plot indicating maximum earthquake response with respect to natural period or frequency of the structure or element. Response can show acceleration, velocity, displacement, shear or other properties of response.

Stability—Resistance to displacement or overturning.

Stiffness—Rigidity, or the reciprocal of flexibility.

Strain Release—Movement along a fault plane; can be gradual or abrupt.

Subduction—The sinking of a plate under an overriding plate in a convergence zone.

Time Dependent Response Analysis—Study of the behavior of a structure as it responds to a specific ground motion.

Trench—A long and narrow deep trough in the sea floor; interpreted as marking the line along which a plate bends down into a subduction zone.

Torsion—Twisting around an axis.

Tsunami—A sea wave produced by large areal displacements of the ocean bottom, the result of earthquakes or volcanic activity.

Vibration—A periodic motion which repeats itself after a definite interval of time.

Wave:

Longitudinal Wave—Pure compressional wave with volume changes.

Love Wave—Transverse vibration of seismic surface wave.

Rayleigh Wave—Forward and vertical vibration of seismic surface waves.

P-Wave—The primary or fastest waves travelling away from a seismic event through the earth's crust, and consisting of a train of compressions and dilatations of the material.

S-Wave—Shear wave, produced essentially by the shearing or tearing motions of earthquakes at right angles to the direction of wave propagation.

Seismic Surface Wave—A seismic wave that follows the earth's surface only, with a speed less than that of S-waves.

Wave Length—The distance between successive similar points on two wave cycles.

CHAPTER ONE
EARTHQUAKES—CAUSES AND EFFECTS

General Theory of Earth Movement: Plate Tectonics

Development of the theory of plate tectonics over the past two decades has greatly increased our understanding of earthquake occurrence. This explanation of how continents and oceans form has been made possible by advances in oceanographic and geophysical research, and by the development of accurate seismic recording devices which give precise data about the oceanic terrain and the crust and subcrust under continents and oceans.

The theory of plate tectonics asserts that the crust and upper mantle of the earth are made up of six major and six or more minor internally rigid plates (or segments of the lithospere) which slowly, continuously and independently slide over the interior of the earth. These plates meet in "convergence zones" and separate in "divergence zones." Plate motion is thought to create earthquakes, volcanoes, and other geologic phenomena [Fig. 4].

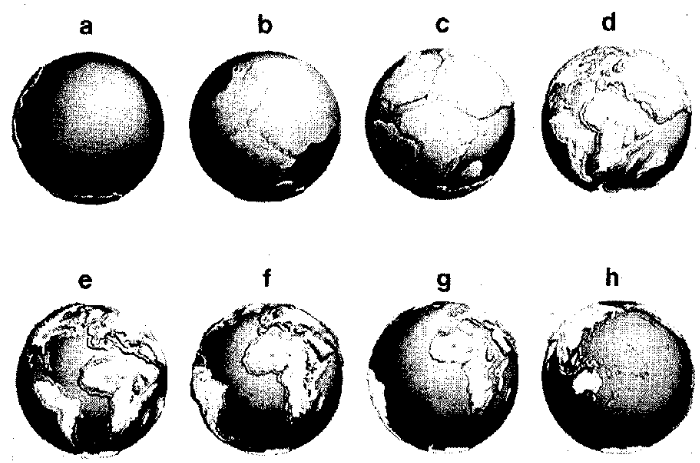


Fig. 4. Evolution of the Continents

The theory of plate tectonics asserts that the crust and upper mantle of the earth are made of. . . internally rigid plates which slowly, continuously and independently slide over the interior of the earth. [Globes depict how a single ocean and single land mass (a&b) 200 million years ago broke up and became the five continents of today (f); (g&h) represent the situation that is predicted 50 million years from now]

At *zones of divergence* molten rock from beneath the crust surges up to fill in the resulting rift and forms a ridge. This has occurred at mid-ocean locations as exemplified by the Mid-Atlantic Ridge and East Pacific Rise. The Red Sea is an example of a young spreading ridge.

At *zones of convergence* subduction occurs—one plate slides under the other forming a trench, and returns material from the leading edge of the lower plate to the earth's interior. The Aleutian Trench is an example of a subduction zone. The subcontinent of India colliding with the Asian continent, thrusting under the Himalayas, and the Nazca plate in the Pacific Ocean underthrusting the Andes Mountains on the South American plate, exemplify mountain building in a subduction zone where the resisting force of the overlying plate forces the folding and piling up of the subducting plate edge.

Plates also can slide past each other laterally as well as rotate, since one or both plates move relative to the other. For example, the Pacific plate, which borders the West Coast of the United States, is moving northwesterly past the North American plate along the San Andreas Fault in California at the rate of 2.5 inches (6.4 centimeters) per year [Fig. 5].

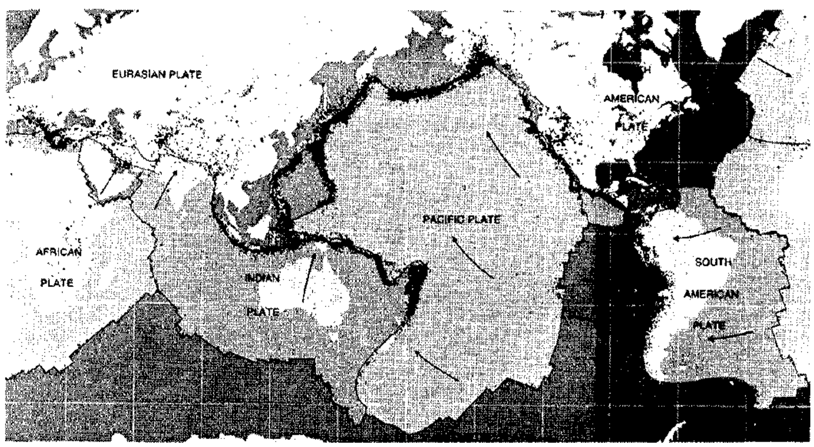


Fig. 5. Zones of Divergence at the Major Plate Boundaries

Zones of divergence. . .exemplified by the Mid-Atlantic Ridge (A) and East Pacific Rise (P). . . .the Nazca plate in the Pacific Ocean under-thrusting the Andes Mountains on the South American plate is an example of subduction where plates collide. The Pacific plate is moving northwesterly past the North American plate along the San Andreas Fault in California, at the rate of 2.5 inches (6.4 centimeters) per year.

Earthquakes at Plate Boundaries

Ninety percent of all earthquakes occur in the vicinity of plate boundaries [Fig. 6]. Where plates push into one another and one slides beneath the other, shallow to deep-seated earthquakes occur. Deep-seated earthquakes are uncommon where plates slide past each other.

Since seismic activity is more frequent on the West Coast (but not necessarily more severe), American scientists have concentrated efforts there, where data is more readily available on a continuous basis. Their concern is two-fold: to learn about earthquakes, and hopefully, to learn how to predict them.

Earthquakes Within Plates

The other ten percent of earthquakes occur at faults located within plates. They are much less frequent than those at plate boundaries, and their causes are less well understood.

Earthquakes in the Midwest and Eastern United States are in this category. Two such earthquakes (New Madrid, Missouri, in the

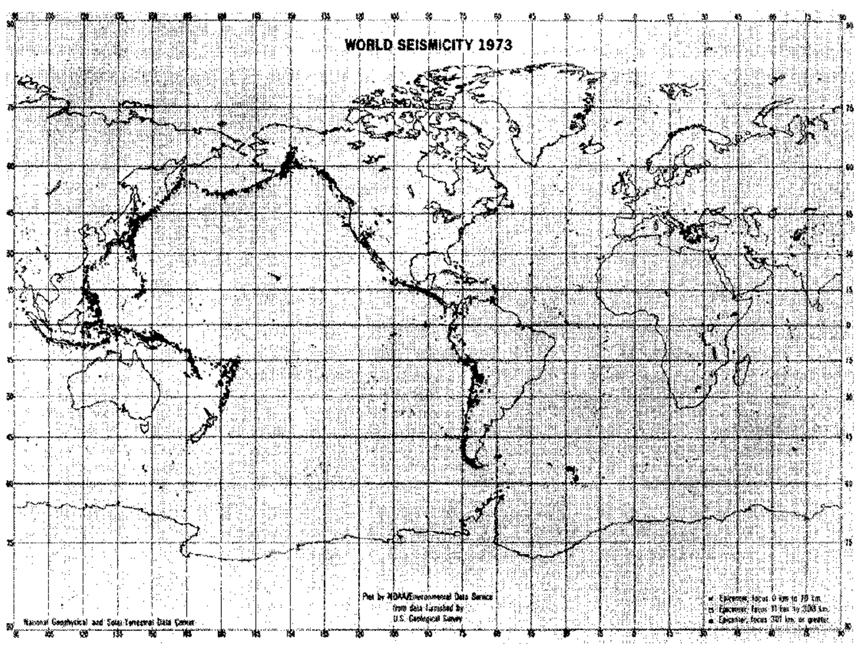


Fig. 6. World Seismicity Map, 1973

Ninety percent of all earthquakes occur in the vicinity of plate boundaries.

Mississippi Valley in 1811-12, and Charleston, South Carolina, in 1886) were equivalent in intensity (probably in magnitude also) to some of the greatest earthquakes recorded in California. The New Madrid shocks were among the greatest in U.S. history. In addition, 25 potentially damaging earthquakes have been listed in New York and New England alone since 1638, averaging one every 13 or 14 years [Fig. 7].

Eastern earthquakes are extremely difficult to predict. Historical data, which might provide a basis for prediction, has been collected only since the mid 1800's. The difficulty in prediction is made greater by the absence of ground rupture associated with these earthquakes. However, research is being done in the East to identify faults and predict earthquakes [Fig. 8].

Table III compares large Eastern earthquakes with West Coast events, and shows the extent to which energy was dissipated in the East.

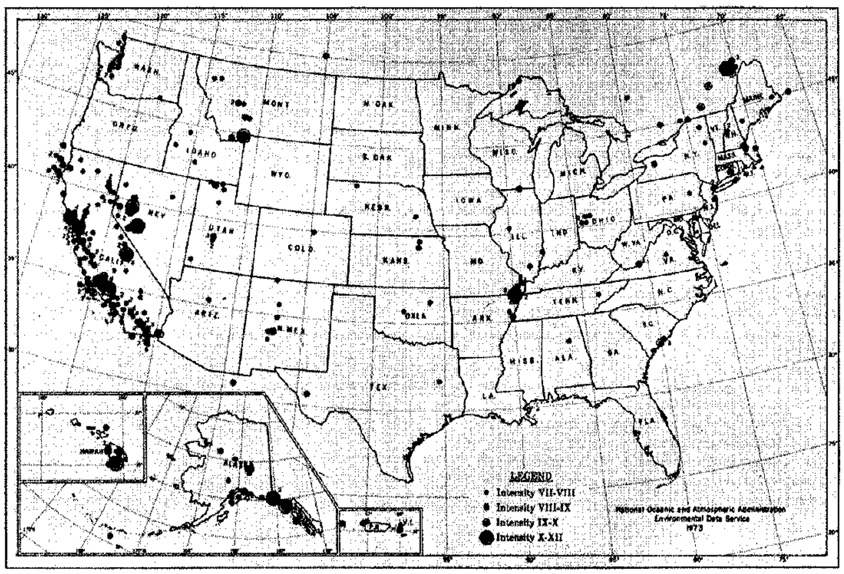


Fig. 7. U.S. Earthquake Intensity VII and Above through 1973

The other ten percent of earthquakes occur at faults located within plates.

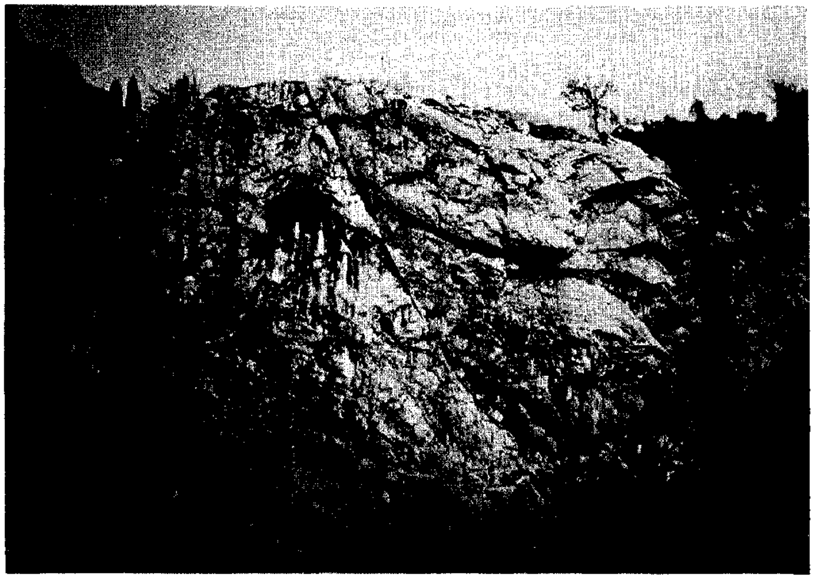


Fig. 8. Thrust Fault Located Near Oak Ridge, Tennessee

The difficulty in prediction is made greater by the absence of ground rupture associated with Eastern U.S. earthquakes. (A rare exposure: Whiteoak Mountain fault system, Paleozoic Age—about 275 million years old.)

TABLE III. COMPARISON OF LARGE U.S. EARTHQUAKES

Location	Magnitude	Peak Intensity	Felt Area
New Madrid (1811, 1912)	7.1, 7.2, 7.4+	XII	2,000,000 sq. mi.
Charleston (1886)	around 7	IX-X	2,000,000 sq. mi.
San Francisco (1906)	8.3	XI	375,000 sq. mi.
Alaska (1964)	8.3	IX-X*	700,000 sq. mi.

+ Nuttli estimates the total energy released by the three largest earthquakes to be equivalent to a magnitude 8.0.

* The epicenter was at sea, so the stronger shaking may have occurred in the epicëntral area.

Source: From John Anderson, Lamont-Doherty Geological Observatory

Fault Types/Resulting Land Forms

The geological fault represents the plane along which earth movement takes place and is the source of the ground shaking characteristic of an earthquake. Several fault types exist in the earth's crust, some of which are related to plate boundary action. Not all fault planes break through the surface of the crust to be visible to the eye. Fault planes occur to varying depths, and hypocenters (foci of earthquakes) may occur at any depth along these planes [Fig. 9].

In *normal faults* [Fig. 10], rocks on either side of the fault zone tend to pull apart creating tension at the fault. When the tension is sufficient to cause rupture, the overlying block moves down the fault line. Some normal faults occur along plate boundaries as plates pull apart.

In *thrust* or *reverse faults* [Fig. 11], the rocks on either side of the fault zone tend to push together creating compression at the fault. When the compression is great enough to cause rupture, the overlying block moves up the slope ("dip") of the fault plane. Some thrust faults occur along plate boundaries as plates collide, as in the Alps.

In *lateral slip (strike slip* or *transform faults)* [Fig. 12], movement is sideways along a nearly vertical fault plane. In some lateral slip faults two plates are sliding past each other, as in the San Andreas Fault.

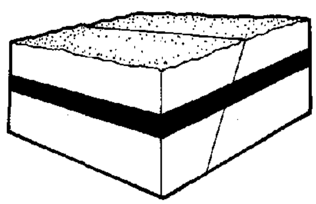


Fig. 9. Quiescent Fault

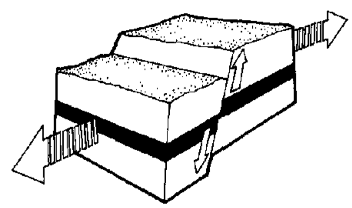


Fig. 10. Normal Fault

Fig. 9. Quiescent Fault

The geological fault represents the plane of earth movement which creates the ground shaking characteristic of an earthquake.

Fig. 10. Normal Fault

Rocks on either side of the fault zone tend to pull apart creating tension at the fault—a divergence zone.

Combinations of *normal and slip* or *reverse and slip faults* occur when movement is diagonal to the principal forces [Fig. 13].

When one or more normal faults run parallel to each other, earth movement can create a "graben" or a "horst" [Fig. 14, 15]. A graben is a long, narrow trough caused by tensional crustal forces, thus causing fault blocks to drop between parallel faults. A horst is a ridge or plateau caused by fault blocks which are elevated in relation to parallel, outward-dipping normal faults.

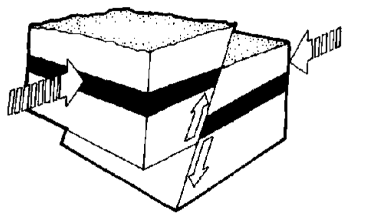


Fig. 11. Thrust or Reverse Fault

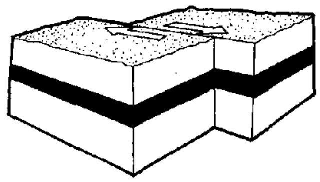


Fig. 12. Lateral Slip, Strike Slip or Transform Fault

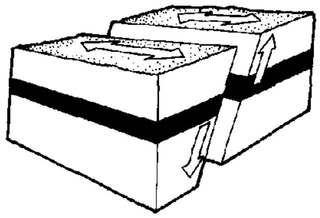


Fig. 13. Normal and Slip Fault Combination

Fig. 11. Thrust or Reverse Fault

Rocks on either side of the fault zone tend to push together creating compressions at the fault—a convergence zone.

Fig. 12. Lateral Slip, Strike Slip or Transform Fault

Sideways movement along a nearly vertical fault plane.

Fig. 13. Normal and Slip Fault Combination

Combinations of faults occur when movement is diagonal to the principal forces.

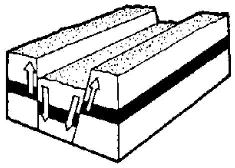


Fig. 14. Graben

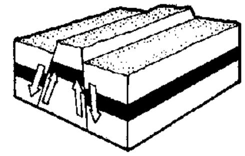


Fig. 15. Horst

Fig. 14. Graben

A long, narrow trough caused by tensional crustal forces, causing fault blocks to drop between parallel faults.

Fig. 15. Horst

A ridge or plateau caused by fault blocks which are elevated in relation to parallel, outward-dipping normal faults.

Causes of Earthquakes

Earthquake theory is generally based on the "elastic rebound theory," proposed by Professor H. F. Reid following the 1906 San Francisco earthquake. In Reid's words:

> *It is impossible for rock to rupture without first being subjected to elastic strains greater than it can endure. We conclude that the crust in many parts of the earth is being slowly displaced and the difference between displacements in neighboring regions sets up elastic strains, which may become larger than the rock can endure. A rupture then takes place and the strained rock rebounds under its own elastic stresses, until the strain is largely or wholly relieved. In the majority of cases, the elastic rebounds on opposite sites of the fault are in opposite directions.*

As parts of the earth tend to move with respect to each other, the result may be very slow movement, or creep, along a fault zone. Such movement has been observed, measured and related to gradually increasing offsets in curbs, fences, streams, and even buildings astride faults [Fig. 16].

However, when a portion of a fault is "locked" so that creep is negligible or nonexistent for that portion, an accumulation of stress builds up until it exceeds the strength of the locked section. Rupture results. This abrupt slippage is accompanied by the sudden release of tremendous amounts of stored energy, producing the vibrations of the earthquake.

Actual fault breaks may be deep-seated and not observable on the surface of the earth. However, for most shallow earthquakes actual fault traces can be found and measured. In the 1906 San

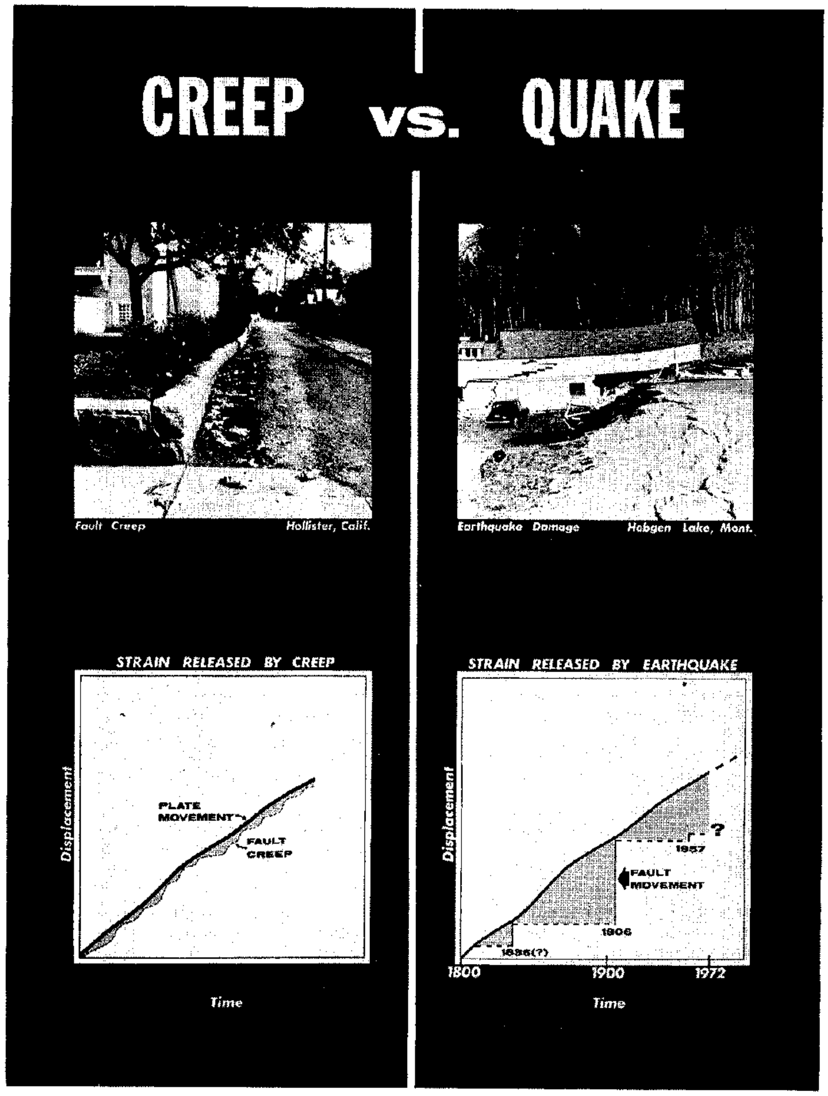


Fig. 16. Creep versus Quake

As parts of the earth tend to move, the result may be very slow movement, or creep, along a fault zone. However, when a portion of a fault is "locked" so that creep is negligible or nonexistent for that portion, an accumulation of stress builds up until it exceeds the strength of the locked section.

Francisco earthquake, the fault ruptured along the surface for a distance of 200 miles (320 kilometers), with a maximum horizontal offset of 21 feet (6.4 meters) observed in Marin County, California, north of San Francisco.

When a fault ruptures, releasing its stored energy, it produces vibrations or seismic waves emanating in all directions from the source [Fig. 17]. Although the initial source of rupture is usually identified as the focus or hypocenter, faulting may extend for many miles from the focus, releasing energy along the entire distance. Thus, seismic waves initiate not from a point source, but all along a fault.

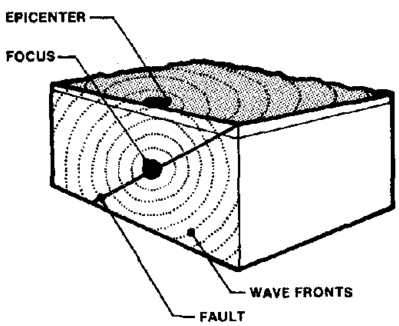


Fig. 17. Focus and Epicenter of Earthquake

When a fault ruptures, it produces seismic waves emanating in all directions from the source.

While the pattern of seismic waves is complex, wave motion is generally (and simplistically) explained in terms of two types of waves: body waves and surface waves [Fig. 18]. Body waves are of two types—compressional, primary or P-waves and shear or S-waves. P-waves are longitudinal waves which tend to compress the material in front of them. They travel nearly 15,000 miles (24,000 kilometers) per hour and are the first waves to be observed. S-waves produce a sideways motion of earth particles; they travel at about one-half the speed of the P-waves. The center of the earthquake can be determined by timing the arrival of the P-waves and S-waves at various seismograph stations around the world.

The arrival of P-waves and S-waves is followed by that of surface waves. Surface waves are created when body waves strike a sharp boundary of discontinuity such as between rock and alluvium, or rock and air at the earth's surface. As the name implies, surface waves are propagated along the surface of the earth. They travel much more slowly than body waves and generally produce the strongest vibrations.

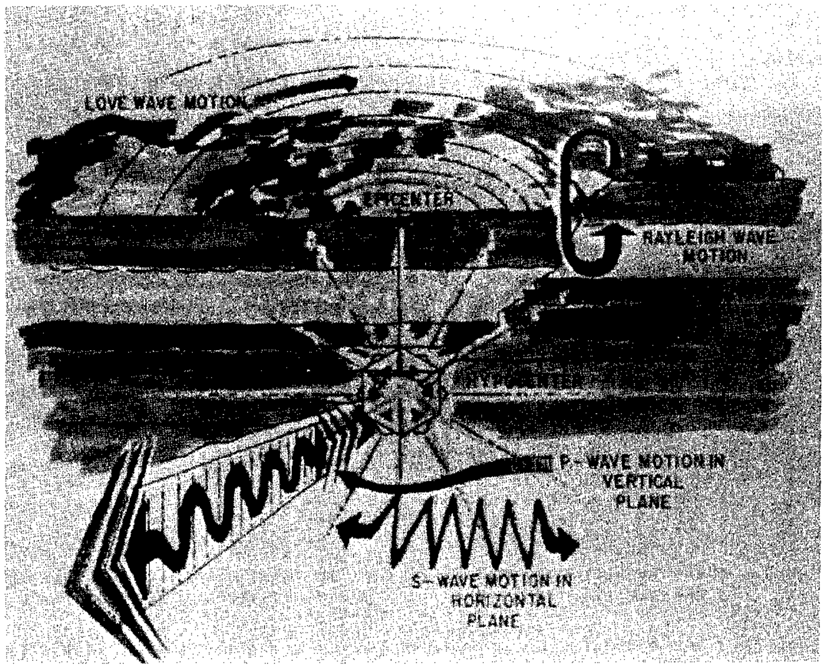


Fig. 18. P-Wave and S-Wave Motion

Wave motion is generally explained in terms of two types of waves: body waves and surface waves.

Effects of Earthquakes

The physical effects of earthquakes depend upon many parameters, including magnitude of earthquake, geologic conditions, location and depth of focus, intensity and duration of ground shaking, and the design and construction of buildings and other man-made structures. Sociologic effects are dependent upon factors such as density of population, time of day of the earthquake and community preparedness for the possibility of such an event.

Four basic causes of earthquake-induced damage are: ground rupture in fault zones, ground failure, tsunamis, and ground shaking.

1. Ground Rupture in Fault Zones

An earthquake may or may not produce ground rupture along the fault zone. If a rupture does occur, it may be very limited or may extend over hundreds of miles, as in the 1906 San Francisco earthquake [Fig. 19]. Ground displacement along the fault can be horizontal, vertical or both, and may be measured in inches or several feet as previously mentioned. It can occur along a sharp line or can be distributed across a fault zone.

Fig. 19. San Andreas Fault, California

If a rupture does occur it may. . .extend over hundreds of miles.

An illustration shows the horizontal offset in a fence near the town of Olema, California, resulting from the 1906 San Francisco earthquake. Another shows the vertical offset which took place in Nevada from the Dixie Valley earthquake of 1954. In both photos, note the proximity of wood-framed structures which appear to have survived with very little damage. Obviously, a structure directly astride such a break will be severely damaged [Fig. 20, 21].

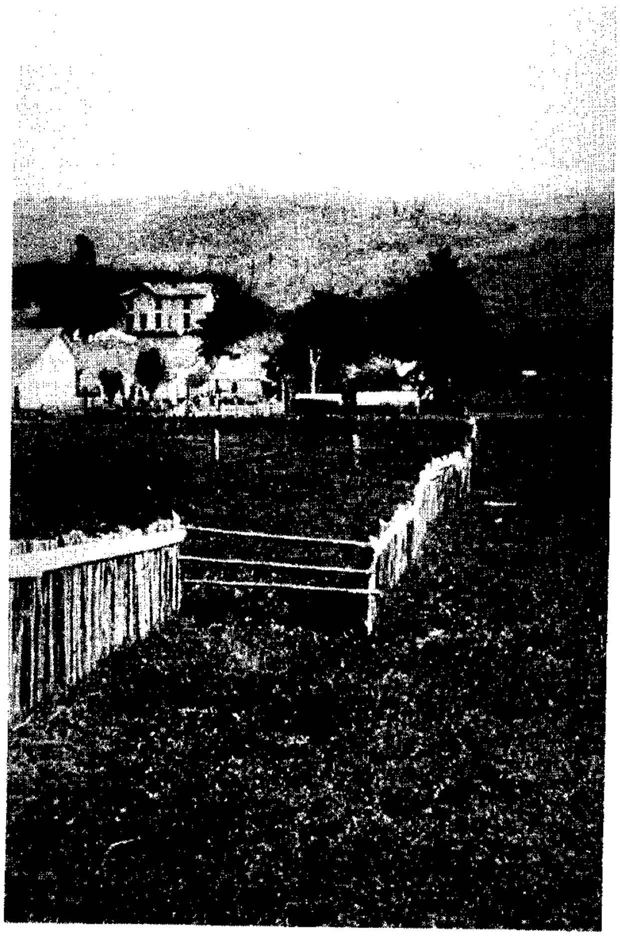


Fig. 20. Horizontal Displacement

The horizontal offset in a fence near the town of Olema, California, resulting from the 1906 San Francisco earthquake.

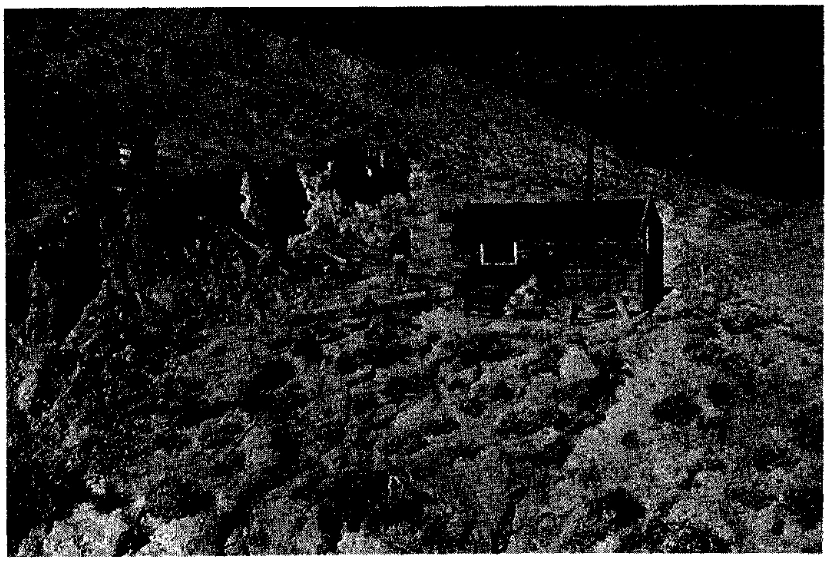


Fig. 21. Vertical Offset

Vertical offset took place in Nevada from the Dixie Valley earthquake of 1954.

It should be pointed out that "proximity" to a fault does not necessarily carry a higher risk than location at some distance from the fault; the point is only that damage from ground rupture is certain to occur only when the structure is astride the fault break.

2. Ground Failure

Earthquake induced ground failure has been observed in the form of landslides, settlement and liquefaction. Ground failures can be the result of vibration induced densification of cohesionless soils or loose back fills, flow slides of earth masses due to liquefaction of underlying material, landslides in clay soils, sloping fills and liquefaction of saturated sands [Fig. 22, 23, 24, 25, 26].

The phenomenon of liquefaction can occur in sands of relatively uniform size when saturated with water. When this material is subjected to vibration, the resulting upward flow of water can turn the material into a composition similar to "quicksand" with accompanying loss of foundation support. The most dramatic example of liquefaction occurred in Niigata, Japan during the earthquake of 1964 [Fig. 27]. Several apartment buildings tipped completely on their back while remaining otherwise intact. It was this action of liquefaction of thin sand lenses that contributed to the Turnagain Heights landslide in Anchorage [Fig. 28].

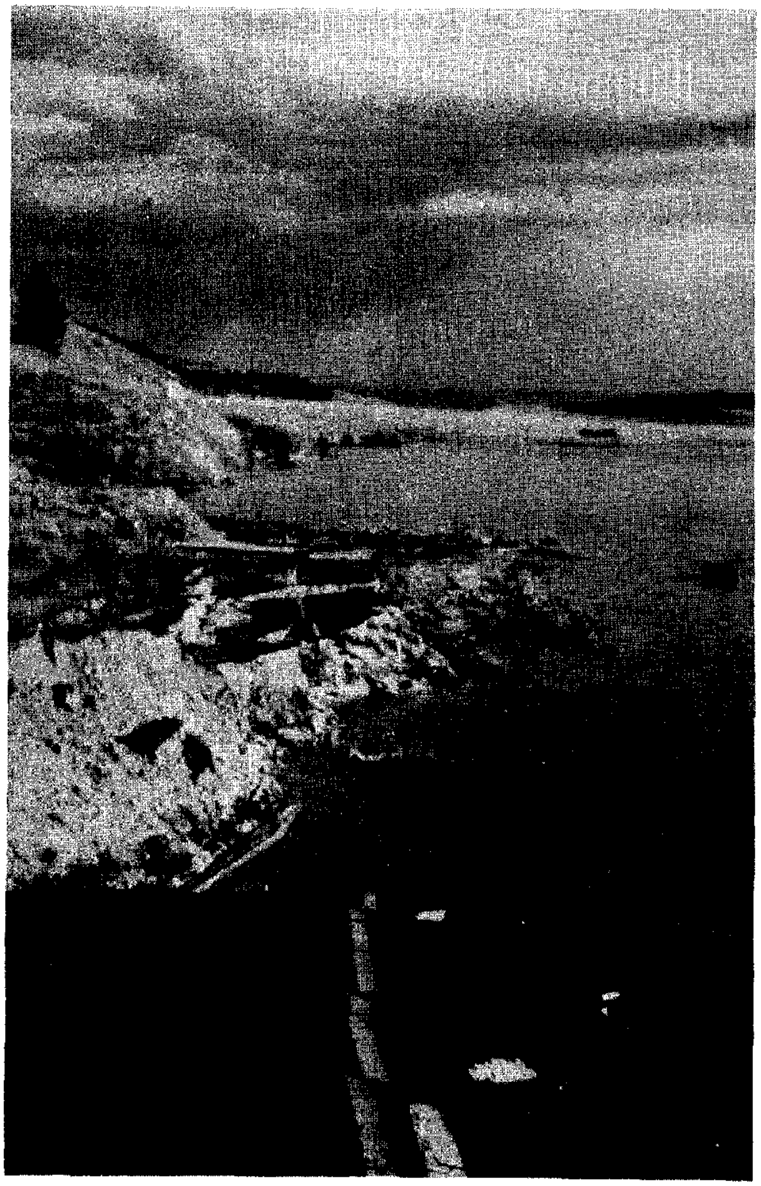


Fig. 22. Settlement due to Landslide

Earthquake induced ground failure has been observed in the form of settlement from landslides. (Hegben Lake, Montana, 1959)

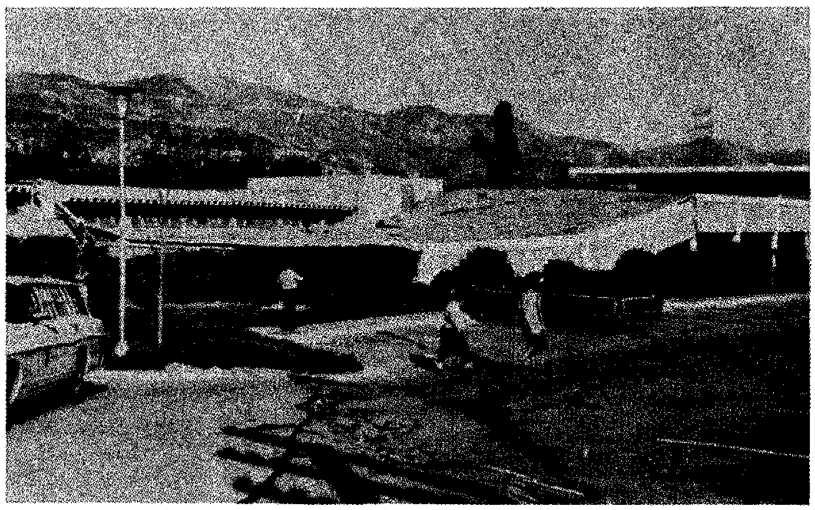


Fig. 23. Liquefaction Induced Settlement

Earthquake induced ground failure has been observed in the form of settlement from liquefaction induced landslides. (San Fernando, California, 1971)

Fig. 24. Interior Damage

Interior damage from ground failure in the form of landslides. (San Fernando, California, 1971)

Fig. 25. House in Anchorage, Alaska, 1964

Earthquake induced ground failure has been observed in the form of landslides in clay soils.

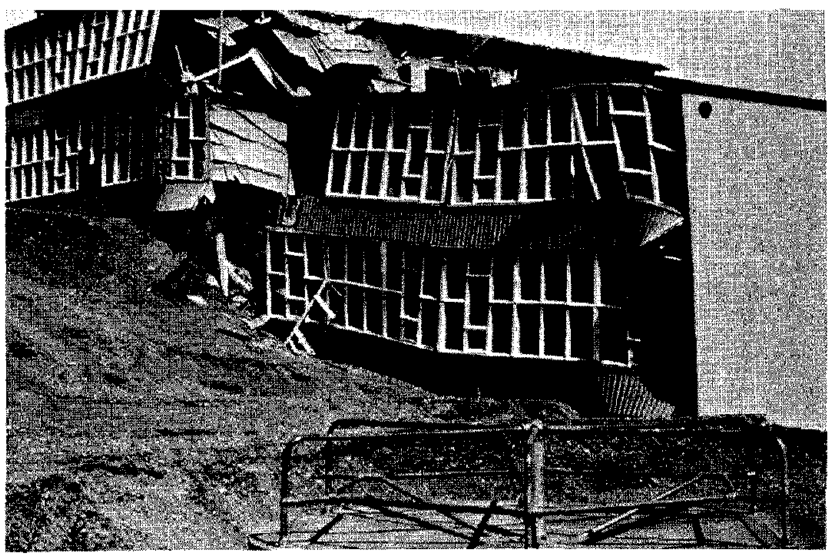


Fig. 26. School in Anchorage, Alaska, 1964

Earthquake induced ground failure has been observed in the form of landslides in clay soils.

Fig. 27.

The most dramatic example of liquefaction occurred in Niigata, Japan during the earthquake of 1964. Several apartment buildings tipped completely on their backs while remaining otherwise intact.

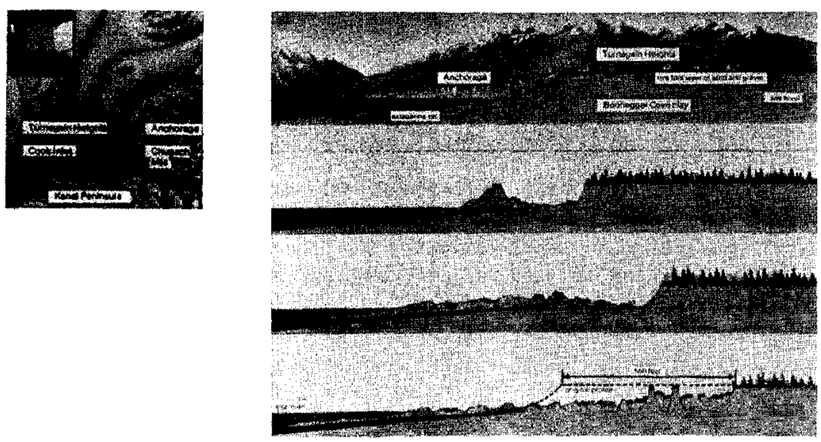


Fig. 28. Turnagain Heights Diagrams

Liquefaction of thin sand lenses contributed to the Turnagain Heights landslide in Anchorage.

Ground failures are particularly damaging to support systems such as water lines, sewers, gas mains, communication lines, and transportation facilities. Loss of these systems after an earthquake has serious effects on both health and life safety (causing fires and reducing the ability to fight them, spreading disease, etc.) [Fig. 29].

3. Tsunamis

A tsunami or seismic seawave is produced by abrupt movement of land masses on the ocean floor. Tsunamis are very high velocity waves with long periods of oscillation. Their low wave height gives little evidence of their existence in the open sea. However, as the waves approach land, their velocity decreases and their height increases. Inundation heights of 20 to 30 feet (6 to 9 meters) have been observed during tsunamis. Clearly, tsunamis can be devastating to coastal areas.

4. Ground Shaking

The effect of ground shaking on structures is a principal area of consideration in the design of earthquake resistant buildings. As the earth vibrates, all elements on the ground surface, whether natural or man-made, will respond to that vibration in varying degrees. Induced vibrations and displacements can destroy a structure unless it has been designed and constructed to be earthquake resistant [Fig. 30, 31]. Whereas static vertical loads (dead and live) can be reasonably

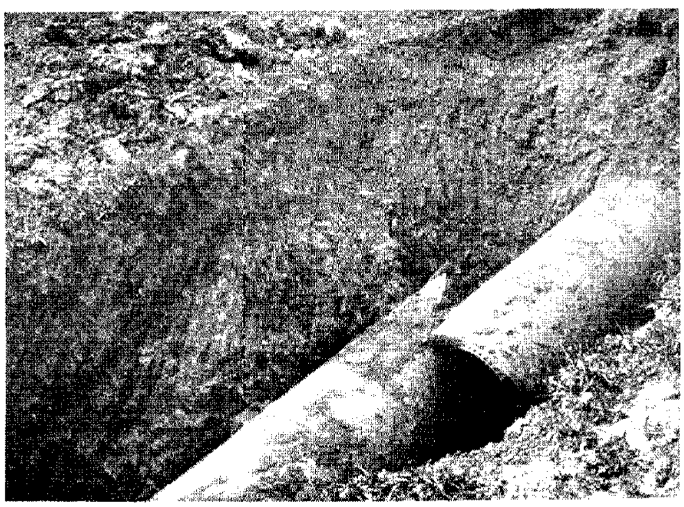


Fig. 29. Damage to Utility Systems

Ground failures are particularly damaging to support systems such as sewers.

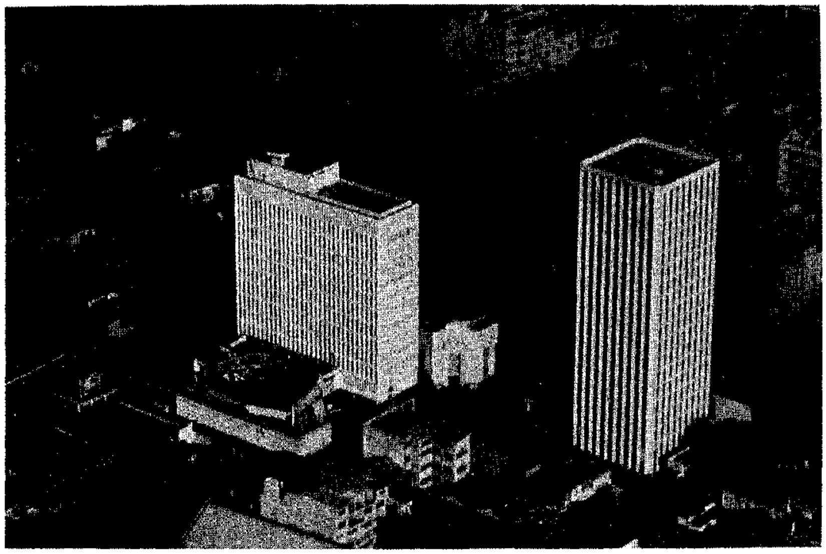


Fig. 30. Surviving Buildings in Managua, Nicaragua

As the earth vibrates, all elements on the ground surface will respond to that vibration in varying degrees. (Two tall structures left standing after 1972 Managua, Nicaragua earthquake; Banco Central on the left suffered extensive architectural damage)

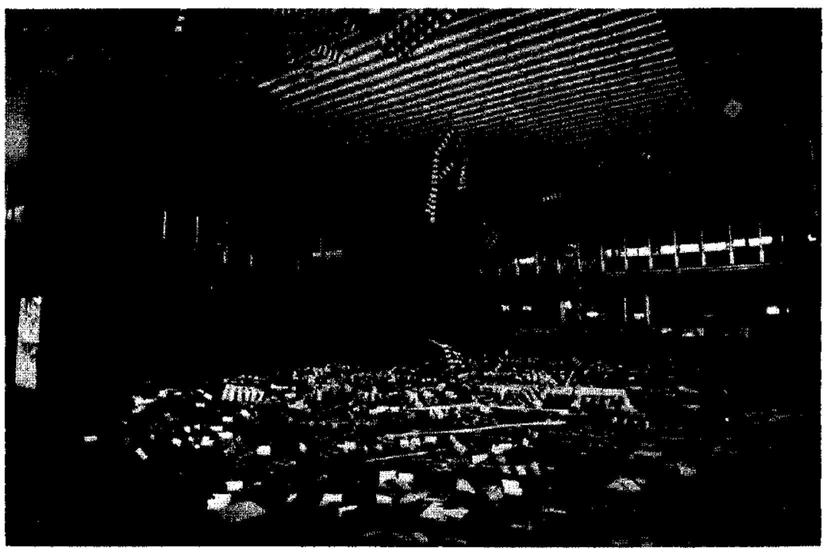


Fig. 31.

Main lobby of the Banco Central. (Managua, Nicaragua, 1972) and accurately determined, the violent and random nature of dynamic conditions due to earthquakes makes the determination of seismic design loads extremely difficult. However, experience has shown that reasonable and prudent practices can mitigate life safety hazards under earthquake conditions.

Ground Shaking Factors

Earthquake location and depth of focus are significant factors in ground shaking. The depth of focus affects the amount of energy that reaches the surface, and hence the severity of shaking. Most damaging earthquakes are associated with a relatively shallow depth of focus less than 20 miles (32 km) deep. The energy released from a shallow earthquake may be expended over a relatively small area. In contrast, seismic energy from deep-seated shocks travels greater distances. Clearly, this will affect the resultant ground shaking.

The length of a fault break will also significantly affect ground shaking since it is a major determinant in creating the duration and "magnitude" of the earthquake.

While total earthquake energy may dissipate with distance from the epicenter, it is misleading to believe that this results in less risk to life or property. Short-period ground motions tend to die out more rapidly with distance than do longer period motions. Long-period vibrations tend to coincide with the longer natural periods of vibration of tall structures, causing resonance [Fig. 32]. Low-rise buildings have shorter natural periods of oscillation, tall buildings have longer natural periods of oscillation. Therefore, the resonance effect is very significant among the damaging effects on buildings. For example, during the 1964 Prince William Sound, Alaska earthquake, tall buildings in Anchorage (80 miles—130 km—away from the epicenter) suffered significant damage.

Local soil conditions also have a significant effect on ground shaking. Basic rock motion has certain characteristics of frequency, acceleration, velocity and amplitude. These characteristics are affected by local geologic and soil conditions. Rock motion is modified by the depth of soil overburden, which increases the amplitude of motion and emphasizes longer dominant periods of vibration. The total effect depends upon the type of material in each stratum of the ground, the depth of each type, and the total depth to bed rock.

Experience in the 1906 San Francisco earthquake indicated the most severe shaking took place in areas of deeper, softer overburden, near the bay and along previously marshy areas, as compared to rock out-croppings. Areas near Santa Rosa and the Santa Clara Valley, California, both having deep alluvium over bed rock, were also severely shaken during the San Francisco earthquake (and Santa Rosa again by an earthquake in 1968).

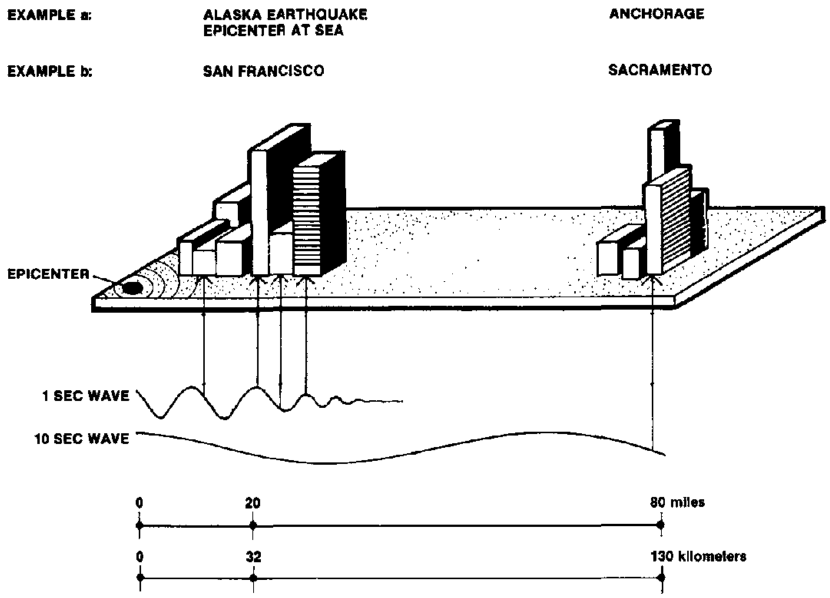


Fig. 32. Relative Wave Motion Effects

Short-period ground motions tend to die out more rapidly with distance than do longer period motions. (Lower period waves oscillate at the same frequency as lower buildings, affecting such buildings nearer the epicenter, while longer period waves which oscillate at the same frequency as taller buildings travel farther and can affect such buildings at relatively great distances)

The effects of deep alluvium were much in evidence in the 1967 Caracas, Venezuela earthquake. The most significant damage occurred to tall buildings (10 to 20 stories) in the Los Palos Grandes district of the city [Fig. 33]. Conditions may have been affected by the shape of the bed rock as well as by the depth of the alluvium overburden.

Thus, experience in these earthquakes suggests that small, rigid, well-designed buildings may perform better on soft ground, whereas taller, flexible buildings on the same ground that are more "in tune" with the lower frequency ground vibrations may experience greater movement. Conversely, on rock or firm ground, the more rigid buildings may respond to the higher frequency vibrations, while the taller buildings may not be so severely affected. Current opinion leans toward the inclusion of a site-structure resonance factor in the formula for the determination of earthquake forces. This factor relates the fundamental period of the structure to the characteristic period of the site.

Fig. 33. Failure of Hollow Tile Facade

In the 1967 Caracas, Venezuela earthquake the most significant damage occurred to tall buildings.

Measuring and Mapping Earthquakes

"Richter magnitude," named after its developer, Charles F. Richter, is the most commonly used term in describing the size of an earthquake. The Richter scale is based on the motion of a standard seismograph located 62 miles (100 kilometers) from the epicenter. Adjustments are made for seismographs of other types or when a seismograph is located other than 62 miles from the epicenter. The amplitude of the largest wave recorded by the standard seismograph at the standard distance is measured in terms of microns. The logarithm (base 10) of that number is defined as the Richter magnitude. It must be emphasized that because the scale is logarithmic, the increase of recorded motion from one whole number to the next is ten-fold. Thus, a "Richter 6" records ten times the amplitude of a "Richter 5," a "Richter 7" 100 times as much as a "Richter 5," and so forth.

Approximate correlations have been developed between an earthquake's total energy and Richter magnitude, with a one unit increase in magnitude approximating a 30-fold increase in energy release [Fig. 34a, 34b].

Energies of Earthquakes (Richter Magnitude 1.0-9.0)

Earthquake magnitude	Approximate earthquake energy	
1.0	6 ounces	T.N.T.
1.5	2 pounds	T.N.T.
2.0	13 pounds	T.N.T.
2.5	63 pounds	T.N.T.
3.0	397 pounds	T.N.T.
3.5	1,990 pounds	T.N.T.
4.0	6 tons	T.N.T.
4.5	32 tons	T.N.T.
5.0	199 tons	T.N.T.
5.5	1,000 tons	T.N.T.
6.0	6,270 tons	T.N.T.
6.5	31,550 tons	T.N.T.
7.0	100,000 tons	T.N.T.
7.5	1,000,000 tons	T.N.T.
8.0	6,270,000 tons	T.N.T.
8.5	31,550,000 tons	T.N.T.
9.0	199,000,000 tons	T.N.T.

Energies of Some Major Earthquakes

Location	Date	Richter Magnitude	Energy (tons of T.N.T.)
Anchorage, Alaska	1964	8.5	31,550,000
San Francisco, California	1906	8.2	12,550,000
Kern County, California	1952	7.7	1,990,000
El Centro, California	1940	7.1	250,500
Long Beach, California	1933	6.3	15,800
San Francisco, California	1957	5.3	500

Fig. 34a.

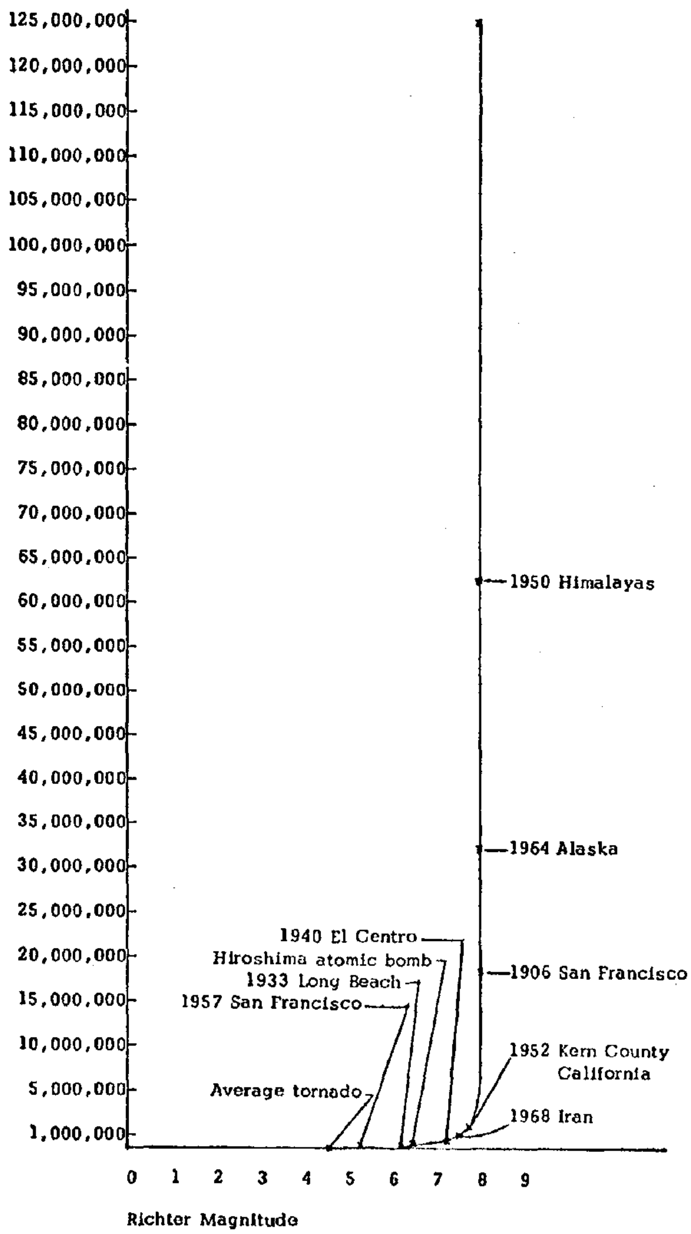


Fig. 34b. Source: Mineral Information Service, May 1969, p. 76.

Fig. 34a.
Fig. 34b. Richter Magnitude Scale Comparisons

Approximate correlations have been developed between an earthquake's total energy and Richter magnitude.

The Prince William Sound, Alaska, earthquake of 1964 had a magnitude of 8.4, while San Francisco in 1906 experienced an 8.3 magnitude. The New Madrid, Missouri, earthquakes of 1811-12 have been assigned magnitudes of greater than 8, based upon observed effects. The damaging California earthquakes in San Fernando (1971), Long Beach (1933) and Santa Barbara (1925) had Richter magnitudes of 6.6, 6.3 and 6.3 respectively. Significant damage to earthquake-resistant buildings may be generally slight for earthquakes with a magnitude less than 5.5 to 6.

While the Richter magnitude gives a reasonable guide for estimating the total energy released in an earthquake, it is not sufficient for describing the local effects of an earthquake. A number of intensity scales have been devised to describe effects of ground motion at a given location.

The generally accepted intensity scale in the United States is the Modified Mercalli Intensity Scale [Fig. 35]. Although the scale of intensity is determined and assigned by a trained observer, the observer is still very dependent upon subjective reactions and personal descriptions gathered from residents of the locale. Intensity scales of one type or another have been used throughout history; but relating these recorded intensities to today's occurrences is difficult because of changes in construction techniques, building design, people's perceptions, etc.

Following an earthquake, an isoseismal map can be prepared. These maps note intensities in various areas around the earthquake. Drawing a line which connects points of equal intensity produces an isoseismal map [Fig. 36]. The maps show that intensity decreases with increasing distance from the epicenter, a result of the attenuation of earthquake energy with distance [Fig. 37, 38, 39].

Attempts have been made to relate earthquake intensity with postulated earthquakes of varying Richter magnitudes along particular faults in an attempt to devise a seismic risk map. The assumptions necessary for such a projection are necessarily rather gross and lead to results that are at best subjective and approximate.

Current efforts are being made to establish earthquake design levels based on recorded history and probabilities. The term "return period" has been coined. It is a probabilistic term which is not meant to imply that earthquakes of any given size will return in accordance with any set pattern. Since recorded seismic history is extremely short, random occurrence must be expected. No one can say, with the present state-of-the-art, when the 1812 New Madrid earthquake might recur.

THE MERCALLI INTENSITY SCALE

(As modified by Charles F. Richter in 1956 and rearranged)

If most of these effects are observed	*then the intensity is:*
Earthquake shaking not felt. But people may observe marginal effects of large distant earthquakes without identifying these effects as earthquake-caused. Among them: trees, structures, liquids, bodies of water sway slowly, or doors swing slowly	I
Effect on people; Shaking felt by those at rest, especially if they are indoors, and by those on upper floors	II
Effect on people: Felt by most people indoors. Some can estimate duration of shaking. But many may not recognize shaking of building as caused by an earthquake; the shaking is like that caused by the passing of light trucks	III
Other effects: Hanging objects swing. *Structural effects:* Windows or doors rattle. Wooden walls and frames creak	IV
Effect on people: Felt by everyone indoors. Many estimate duration of shaking. But they still may not recognize it as caused by an earthquake. The shaking is like that caused by the passing of heavy trucks, though sometimes, instead, people may feel the sensation of a jolt, as if a heavy ball had struck the walls. *Other effects:* Hanging objects swing. Standing autos rock. Crockery clashes, dishes rattle or glasses clink. *Structural effects:* Doors close, open or swing. Windows rattle	V
Effect on people: Felt by everyone indoors and by most people outdoors. Many now estimate not only the duration of shaking but also its direction and have no doubt as to its cause. Sleepers wakened. *Other effects:* Hanging objects swing. Shutters or pictures move. Pendulum clocks stop, start or change rate. Standing autos rock. Crockery clashes, dishes rattle or glasses clink. Liquids disturbed, some spilled. Small unstable objects displaced or upset. *Structural effects:* Weak plaster and Masonry D * crack. Windows break. Doors close, open or swing	VI
Effect on people: Felt by everyone. Many are frightened and run outdoors. People walk unsteadily. *Other effects:* Small church or school bells ring. Pictures thrown off walls, knicknacks and books off shelves. Dishes or glasses broken. Furniture moved or overturned. Trees, bushes shaken visibly, or heard to rustle. *Structural effects:* Masonry D * damaged; some cracks in Masonry C *. Weak chimneys break at roof line. Plaster, loose bricks, stones, tiles, cornices, unbraced parapets and architectural ornaments fall. Concrete irrigation ditches damaged	VII

Source: Mineral Information Service, May 1969, p. 77.

If most of these effects are observed — *then the intensity is:*

Effect on people: Difficult to stand. Shaking noticed by auto drivers.

Other effects: Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Furniture broken. Hanging objects quiver.

Structural effects: Masonry D * heavily damaged; Masonry C * damaged, partially collapses in some cases; some damage to Masonry B *; none to Masonry A *. Stucco and some masonry walls fall. Chimneys, factory stacks, monuments, towers, elevated tanks twist or fall. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off............ VIII

Effect on people: General fright. People thrown to ground.

Other effects: Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes. Steering of autos affected. Branches broken from trees.

Structural effects: Masonry D * destroyed; Masonry C * heavily damaged, sometimes with complete collapse; Masonry B * is seriously damaged. General damage to foundations. Frame structures, if not bolted, shifted off foundations. Frames racked. Reservoirs seriously damaged. Underground pipes broken IX

Effect on people: General panic.

Other effects: Conspicuous cracks in ground. In areas of soft ground, sand is ejected through holes and piles up into a small crater, and, in muddy areas, water fountains are formed.

Structural effects: Most masonry and frame structures destroyed along with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes and embankments. Railroads bent slightly.................. X

Effect on people: General panic.

Other effects: Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land.

Structural effects: General destruction of buildings. Underground pipelines completely out of service. Railroads bent greatly.................... XI

Effect on people: General panic.

Other effects: Same as for Intensity X.

Structural effects: Damage nearly total, the ultimate catastrophe XII

Other effects: Large rock masses displaced. Lines of sight and level distorted. Objects thrown into air.

* Masonry A: Good workmanship and mortar, reinforced, designed to resist lateral forces. Masonry B: Good workmanship and mortar, reinforced. Masonry C: Good workmanship and mortar, unreinforced. Masonry D: Poor workmanship and mortar and weak materials, like adobe.

Fig. 35. Modified Mercalli Intensity Scale

The generally accepted intensity scale in the United States is the Modified Mercalli Intensity Scale.

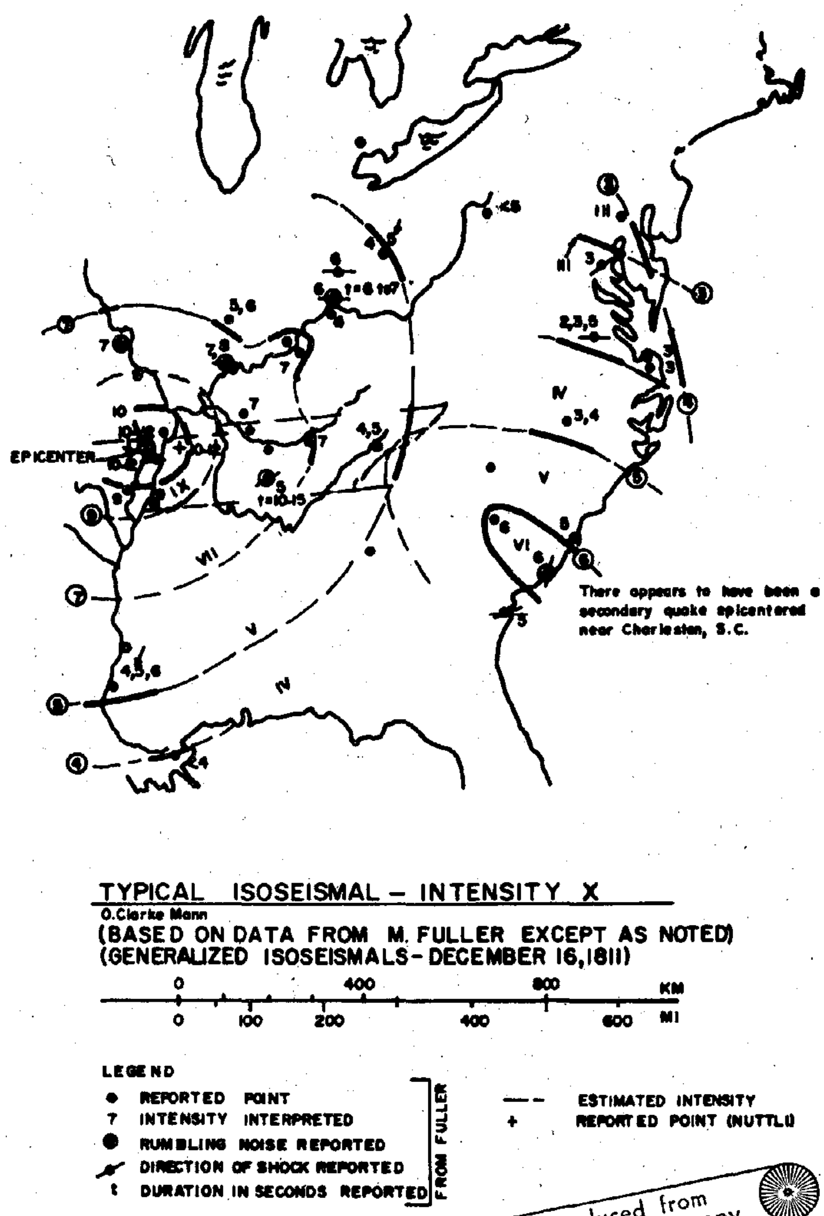


Fig. 36. Isoseismal Mapping

Drawing a line which connects points of equal intensity produces an isoseismal map. (New Madrid, Missouri earthquake, 1811)

Fig. 37. Isoseismal Map of Charleston, South Carolina Earthquake of 1886

These maps show that intensity decreases with increasing distance from the epicenter.

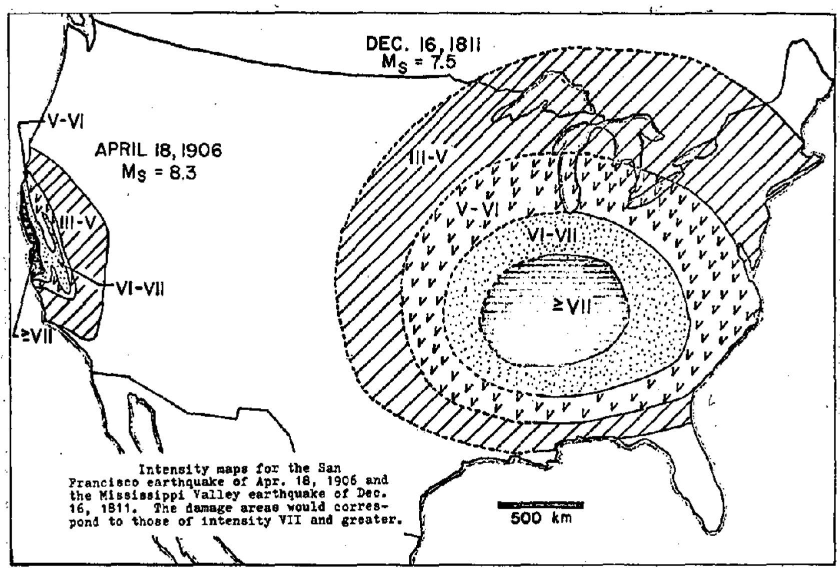


Fig. 38. Intensity Map

Intensity map comparing 1906 San Francisco and 1811 New Madrid, Missouri earthquakes.

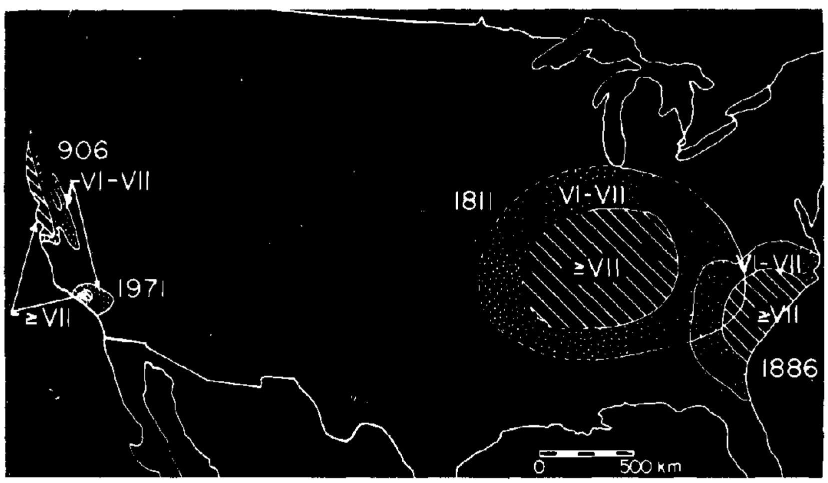


Fig. 39. Intensity VII Areas in the U.S.

Map comparing intensities VII—areas which could expect damage—for 1906 San Francisco and 1971 San Fernando earthquakes on the West Coast with the 1811 New Madrid and 1886 Charleston earthquakes in the East.

CHAPTER TWO

EFFECTS OF EARTHQUAKES ON STRUCTURES

Earthquake forces in structures result from the erratic omnidirectional motions of the ground. These vertical motions have customarily been neglected in building design because most structures have considerable strength in the vertical direction because of the force of gravity. However, the effects of vertical accelerations are under continued study.

Response of Buildings to Ground Motion

Ground motions are normally described in terms of acceleration, velocity and displacement of the ground at a particular location. These all vary with time as the ground vibrates. The longer the time involved, the more cycles of displacement the structure will have to experience and the greater the need for absorption of the energies involved. Earthquakes vary from only a few seconds of ground shaking to several minutes. Therefore, the building should be able to undergo these extended periods of ground shaking without failure [Fig. 40].

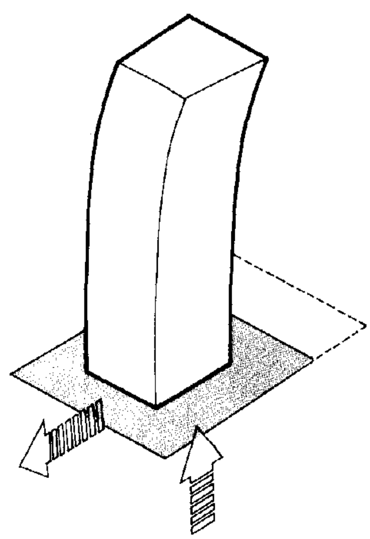


Fig. 40.

The building should be able to undergo extended periods of ground shaking without failure.

Strong motion earthquake instruments (seismographs) have been developed to record actual earthquake vibrations in terms of ground acceleration. Although many records were obtained during the 1971 San Fernando earthquake, prior to that time very few instruments were located near the sites of significant earthquakes. The record of the 1940 El Centro, California, earthquake was used for many years as the "model" for studies since it was the best record available. Figure 41 shows the north-south component of the recorded accelerogram from that earthquake along with the variation with time of the ground velocity and the ground displacement. These latter characteristics were determined by integration of the acceleration plot.

Structures that are fixed to the ground in a more or less rigid manner respond to the ground motions [Fig. 42]. As the base of the structure moves, the upper portions tend to lag behind due to inertia. The resultant force is represented by the force F. The force F is equal to M (mass) times A (acceleration); hence, the higher the acceleration, the greater the resultant force on the structure.

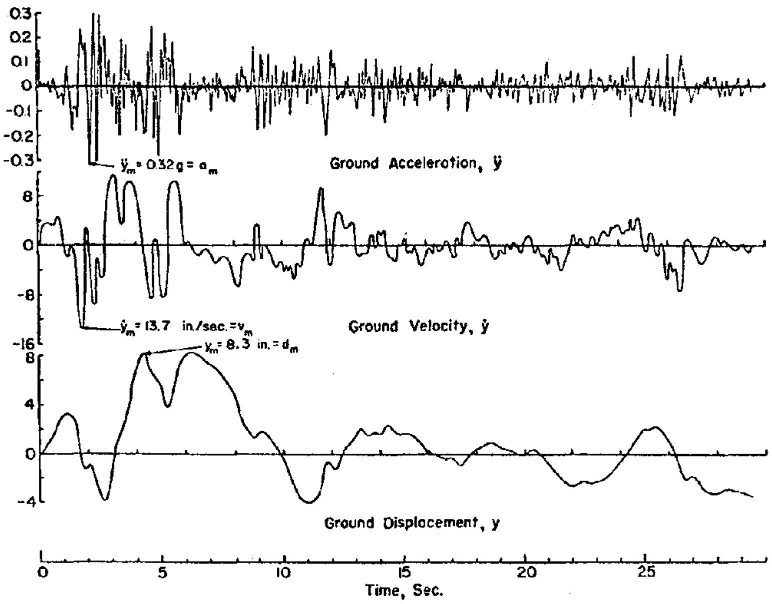


Fig. 41. Earthquake Accelerogram

The north-south component of the recorded accelerogram from the 1940 El Centro, California earthquake is shown, along with the variation with time of the ground velocity, and the ground displacement.

Imagine that the ground, having accelerated in one direction and having moved out from under the structure, suddenly stops. The structure, being somewhat flexible, will spring back to the vertical or upright position, providing that the initial shock has not exceeded the strength of the structure and caused collapse. However, the upper portion of the structure will build up momentum as it returns, and actually will travel past the vertical, bending in the opposite direction due to inertia. This process of bending back and forth produces swaying in taller structures and continues until the energy imparted to the building by the initial shock is dissipated. In short, the building acts as a pendulum with respect to the ground, with the rate and frequency of the swing (i.e., the swaying) a function of building height, mass, cross-sectional area, and numerous other factors [Fig. 43].

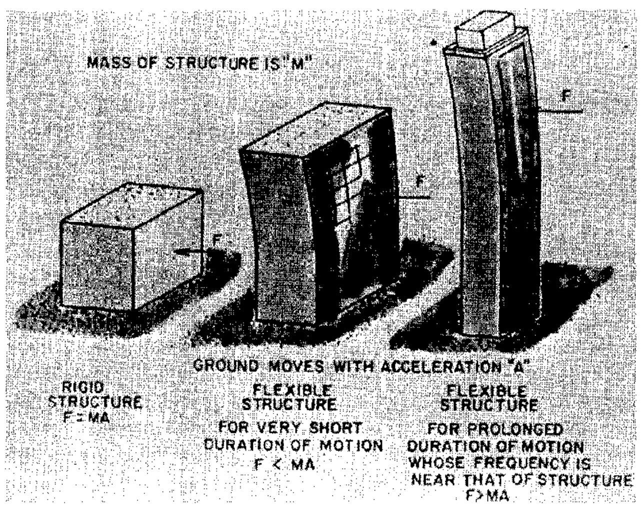


Fig. 42. Resultant Forces on Structures

Structures that are fixed to the ground in a more or less rigid manner respond to the ground motions.

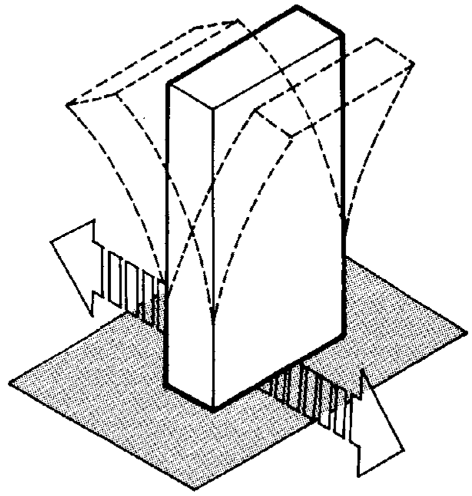


Fig. 43. Pendulum Action

The building acts like a pendulum with respect to the ground.

Relation of Wave Motion to Structural Behavior

The rate of oscillation, or "natural period" of a structure, is an extremely important factor because earthquakes do not result in ground movement in only one direction, as assumed in the example above. In fact, the ground oscillates back and forth, in all directions. Consider what would happen if, at the same time that the upper part of the structure begins to move to catch up with the initial displacement, the ground motion reverses itself. Complex deflections may result as the building vibrates in all its modes of vibration in response to ground motion [Fig. 44]. The ground motion may coincide with the natural period of the building, resulting in resonance.

It is therefore extremely important in basic seismic design that the probable frequency of ground motion as well as the natural period of the structure be considered. In early design theory, design was based on the concept of simple harmonic motion in earthquakes, i.e., wave motions of uniform frequency and intensity. Clearly, predictions about failures in design would depend upon the assumptions of the frequency of motion, as well as building form. However, experience shows that earthquakes are dominated by more or less random motions of varying frequencies. As a result, M. A. Biot proposed in 1933 that a "spectrum" of frequencies be used for evaluation of earthquake designs that would more adequately evaluate the response of different structures to various kinds of ground motion.

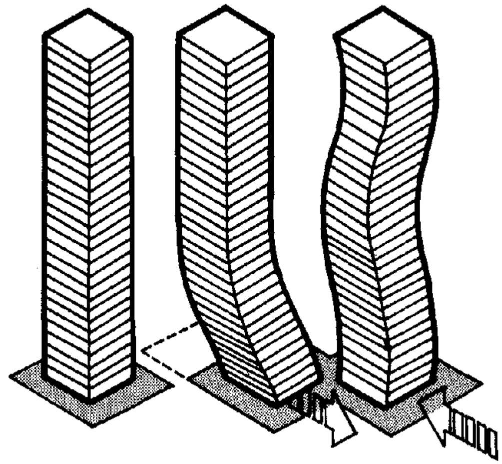


Fig. 44. Effects of Cyclic Reversals of Ground Acceleration

At the same time that the upper part of the structure begins to move to catch up with the initial displacement, the ground motion reverses itself.

It is important at this point for the architect to understand that these same forces and motions are transmitted to each and every component of the structure; and the component's response is governed in part by the same laws of physics that govern the overall structure's response. Understanding the origins of these forces is vital for dealing with them in the design of nonstructural components.

Obviously, a building is not a simple pendulum. It is generally conceived as a series of masses at each floor level that will respond with several modes of vibration. The theoretical response of the structure will depend on the input motion, the periods of vibration of the various modes, the masses at the various floor levels, and damping.

It is not possible to cover all of the variables affecting structural design in this primer. Readers interested in pursuing structural phenomena in depth should seek any of several excellent references listed at the end of this primer. However, it is useful to discuss certain additional aspects of structural behavior that relate to initial architectural design decisions.

Methods of Dealing with the Earthquake Forces

The way the structure absorbs or transfers the energy released by an earthquake will determine the success or failure of the building's seismic resistant design and construction. The energy transfer and energy dissipation mechanisms involved should be such that no damage would occur. The desired flexibility is illustrated by a thin flagpole that can sway considerably without fracture or permanent displacement [Fig. 45]. The opposite situation is represented by a stack of unreinforced bricks whose movements result in permanent displacement of each brick when a horizontal force is applied. The stack is quickly toppled. If the bricks were cemented together with epoxy, or heavily reinforced and tied to the base so as to act as a single mass of bricks rather than as single bricks, then the stack would be very rigid and would resist displacement forces until the mass fractured [Fig. 46].

In design, one must deal with structural systems that fall between the flagpole and the stack of bricks; that is, between an infinitely limber building versus one lacking in flexibility. The flexible building system is one that will bend in several parts when earthquake forces are applied. The bending takes force to accomplish, and therefore, the structural members absorb or temporarily store some of the earthquake energy imparted to the structure. This capacity for the storage or absorption of energy depends on whether the material operates in its elastic or inelastic range.

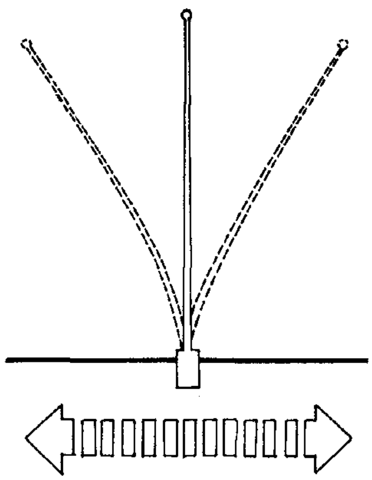


Fig. 45.

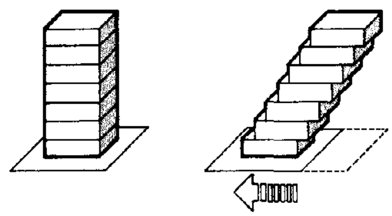


Fig. 46.

Fig. 45. Flexibility

Illustrated by a thin flagpole that can sway considerably without fracture or permanent displacement.

Fig. 46.

The opposite situation is represented by a stack of unreinforced bricks whose movement results in permanent displacement of each brick when a horizontal force is applied.

When the structure can deform, and retain the ability to return to its original state without permanent deformation, the material has stayed within its elastic range of deformation. The range of deformation past the elastic range is referred to as the inelastic range or the plastic range. In the plastic range, energy is absorbed and additional applied forces result in greater and greater permanent deformation.

Once the elastic range is exceeded fracturing of certain structural building components may occur, such as in concrete and masonry or in brittle steel connections, or in the example of the stack of bricks [Fig. 47]. The designer should be aware that structural members may fracture before the building experiences maximum energy impact, thus residual energy absorbing mechanisms should be provided in the structure.

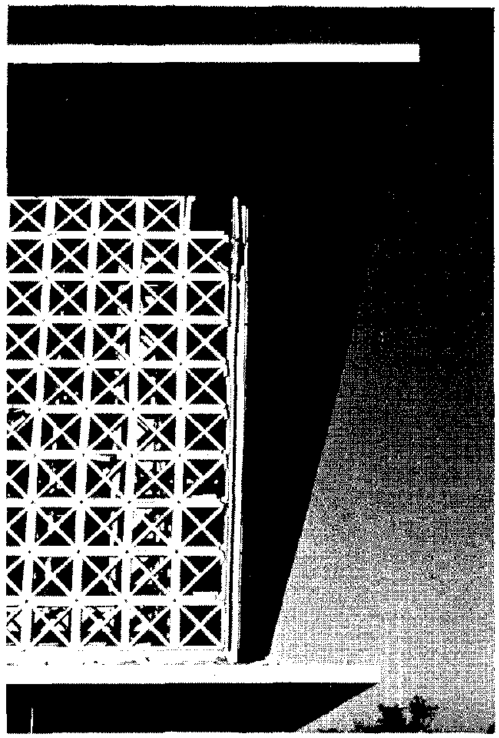


Fig. 47. Decorative Concrete Screen Failure

Once the elastic range is exceeded fracturing of building components may occur.

Impact of Architectural Form on Stiffness and Flexibility

Nearly all buildings combine some elements that are "flexible" with other elements that are fundamentally "stiff." The improper combinations of such elements may create problems in building performance under earthquake loading. These combinations can result in designs that not only have highly variable behavior in earthquakes, but also can aggravate the effects of earthquakes on the building. A classic example of this condition is the use of masonry wall infill between moment resisting frame members when the wall is not designed as a component of the frame. Since most of these problems derive from basic architectural decisions as to the plan and form of the building, it is extremely important for the architect to understand them.

Effect of Building Shape on Response to Seismic Forces

One of the most critical decisions regarding the ability of buildings to withstand earthquakes is the choice of basic plan shape and configuration. Given that earthquake forces at a site can come from any and all directions, and act upon all elements of the building virtually simultaneously, the obvious "best choice" is a building which is symmetrical in plan and elevation, and therefore equally capable of withstanding forces imposed from any direction.

However, given other constraints such as shape of site and functional requirements, rarely can the architect satisfy this demand. Therefore, an understanding of how variations in plan and elevation symmetry can affect performance is important.

Consider a building with an irregular shape, such as an "L" or "T" configuration. The wings might experience different movements depending upon their orientation relative to the direction of earthquake force [Fig. 48, 49]. For example, in a N-S directed earthquake, the N-S wing of an L- or T-shaped building will be relatively stiffer since its long axis is parallel to the earthquake motion; it would not move significantly. On the other hand, the E-W wing is shallow in the direction of the earthquake motion. Unless designed to have adequate capacity to absorb and dissipate the forces it can suffer greater damage, particularly at the point where the wings connect.

10½ Picas TO BIND

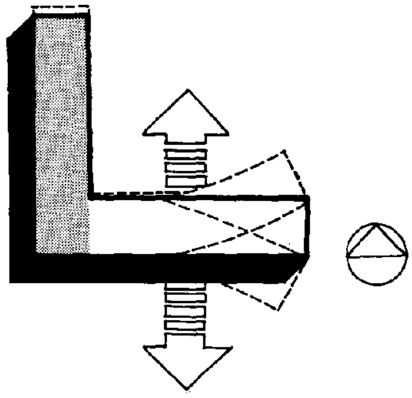


Fig. 48. Stiffness of Structure Related to Building Plan

The N-S wing of an L-shaped building will be relatively stiffer since its long axis is parallel to the earthquake motion. . .the E-W wing is shallow in the direction of the earthquake motion, and unless designed to have adequate capacity to absorb and dissipate the forces it can suffer greater damage.

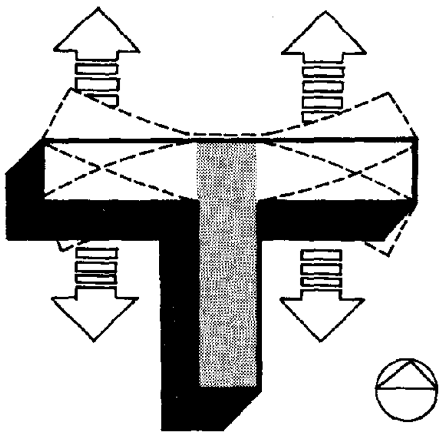


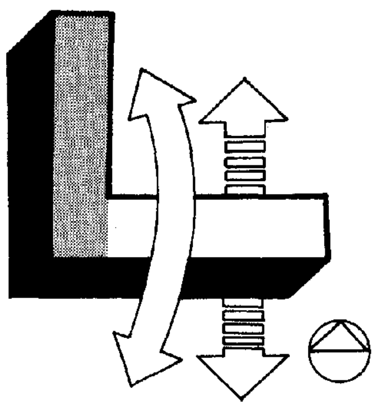
Fig. 49.

The N-S wing of a T-shaped building will be relatively stiffer since its long axis is parallel to the earthquake motion. . . the E-W wing is shallow in the direction of the earthquake motion, and unless designed to have adequate capacity to absorb and dissipate the forces it can suffer greater damage. (Plan)

Since the structure is a unit, torsional movements are created by the earthquake. Torsion is the result of rotation of an eccentric or a less rigid mass about the basic or the more rigid mass of the building. Under earthquake motion, it can cause rotation of the mass of an E-W wing relative to the mass of a N-S wing [Fig. 50].

Torsion can also occur in regular shaped buildings whenever the relative stiffness of one part of the structure is different from another. For example, in a rectangular building with a very stiff off-center core area, and the remainder of the structure flexible, torsion will develop in the flexible portion around the stiffer core [Fig. 51]. Regular shaped buildings with balanced stiffness elements therefore avoid the secondary effects of torsion and differential movement.

It also should be noted that irregular shapes that can experience torsional effects are not solely limited to irregularities in the plan or section of the building. Differences occurring in building shapes, such as where upper stories of a tall structure have greater floor area than those below, can result in similar torsional problems because of vertical accelerations [Fig. 52]. There will also be an increase in the differential displacements between the tower and the extended portion of the building due to greater stiffness provided by the increased floor size.



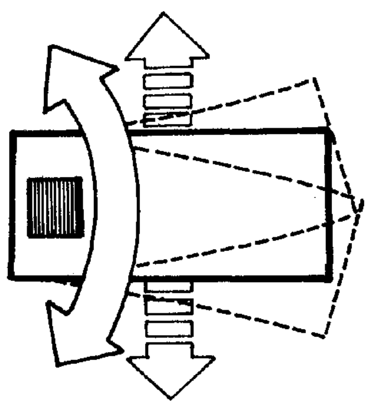


Fig. 50. Torsion Effect on Building Plan

. . . rotation of the mass of an E-W wing relative to the mass of a N-S wing.

Fig. 51. "Regular" Plan Building with Asymmetrical Stiffening

In a rectangular building with very stiff off-center core area, and with the remainder of the structure flexible, torsion will develop in the flexible portion around the stiffer core.

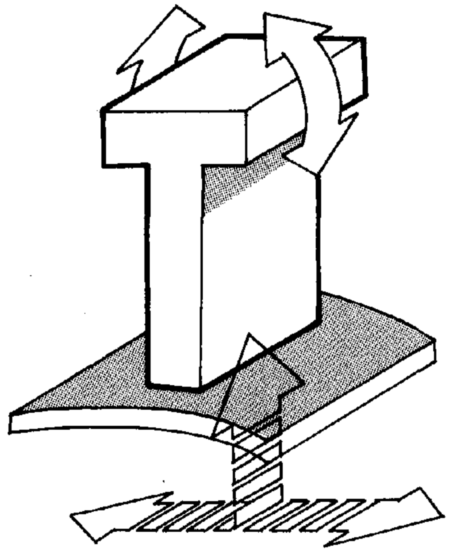


Fig. 52. Oblique View of Vertical Torsion Effect

. . .where upper stories of a tall structure have greater floor area than those below, torsional problems can result because of vertical accelerations.

Effect of Seismic Forces on Building Systems

Ideally, a building should be designed either with infinite stiffness or with all its elements capable of absorbing deflections; in other words, an infinitely flexible but stable system. Since buildings rarely fit either ideal system, the designer must fully understand the seismic performance of the system employed.

Most buildings are designed with a mixture of stiff and flexible concepts. Some of these combinations when used unwisely may cause serious damage and collapse of structures. The "open first floor" concept commonly used today—placement of a rigid upper structure on a flexible column system—exemplifies this problem. The flexible columns are expected to resist exaggerated and concentrated forces, yet may not be designed to take these loads [Fig. 53].

Another similar problem is created when the designer inadvertantly weakens a stiff wall (shear wall) with many openings. For instance, even if the openings are rather narrow, flanked by wall segments, the result may no longer be a truly stiff wall, but rather a series of thin, wide columns. If these wall segments are not then designed as columns, they may well fail under seismic forces.

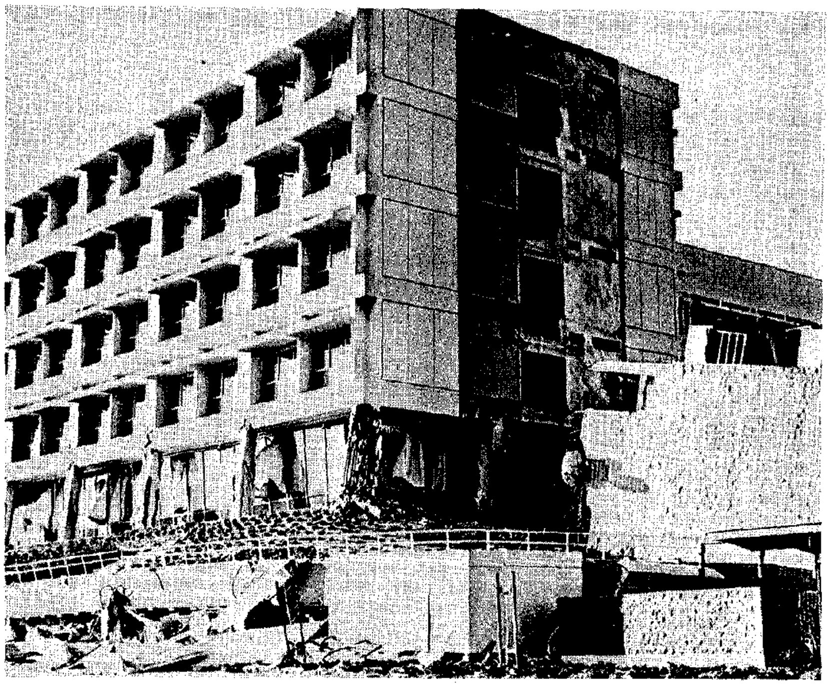


Fig. 53. "Open First Story" Failure; Columns Crushed

The placement of a rigid upper structure on a flexible column system may be the cause of serious damage and collapse. (Olive View Hospital, San Fernando earthquake, 1971)

Materials

Different materials react differently with respect to inelastic behavior. Ductile materials, such as steel, have an extended inelastic range in which they can undergo permanent deformation without rupture [Fig. 54]. On the other hand, brittle materials such as brick display almost no inelastic behavior under loading, and experience sudden failure at or near the elastic limit. The same is true, relatively speaking, of glass, unreinforced concrete and a variety of other common building materials.

Ductility, an important characteristic of materials, refers to the ability of a material to absorb energy while undergoing inelastic deformation without failure, particularly when the direction of the forces involved changes several times.

In brittle materials cracking may have occurred, and therefore, more and more displacement occurs with continued applied force, so the strength deteriorates. On the other hand, ductile materials can

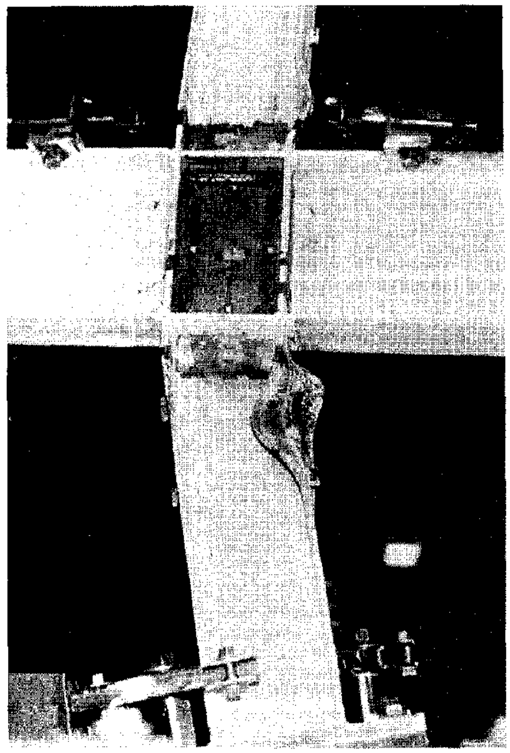


Fig. 54. Laboratory Testing Showing Results of Cyclical Loading

Ductile materials, such as steel, have an extended inelastic range in which they can undergo extended permanent deformation without rupture.

undergo many cycles of loading with the same large energy absorbing capability. Without proper reinforcement, concrete and other brittle materials have low ductility values.

Ductile building systems include steel frames, ductile concrete frames and wood diaphragm construction. Where the connections of the system used are ductile and numerous, the overall performance is improved considerably. Ductility can be thought of as providing a quality of toughness which, to a large extent, determines a building's survival under seismic conditions.

Architectural Design Concept and its Effect on Building Seismic Performance

As has been stated before, the shape chosen by the designer for the structure will determine its response to seismic forces, including the development of torsional effects as well as differential movements of parts of the building [Fig. 55]. The extent of glazing, the number of glazed facades, the size of spandrel elements, and the location of the exterior column line are among the architectural design factors which directly affect a building's seismic performance.

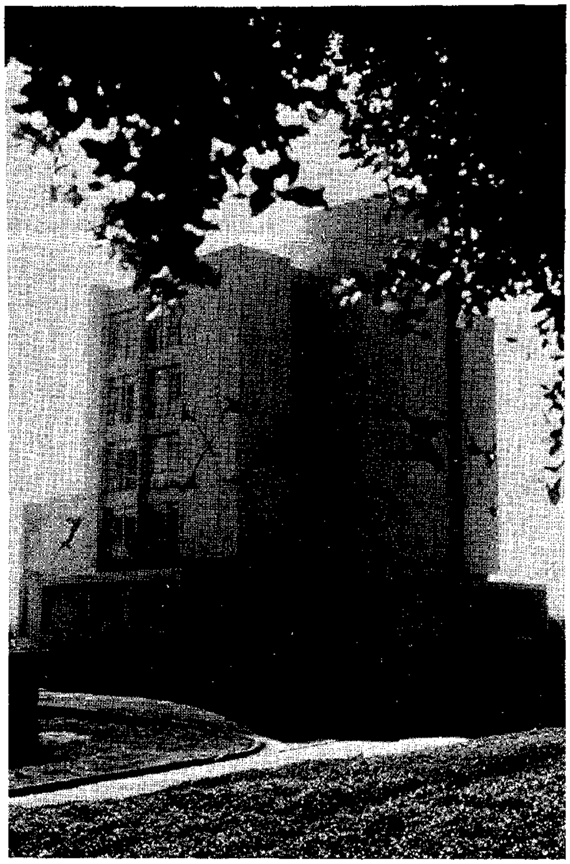


Fig. 55. "X" or Shear Cracks on Complexly Shaped Building

The shape chosen by the designer for the structure is one element in determining its response to seismic forces. (Managua, Nicaragua, 1972)

Both the architect and the engineer have to recognize and understand how design decisions may create serious seismic effects on a structure [Fig. 56, 57]. For example, the architect who desires to design an open first story must take into account the problem raised by placing a rigid structure over the open story. Similarly, if a shear wall structure is proposed, the architect must understand that numerous openings will affect the seismic performance of such a wall.

Fig. 56.

The architect who desires to design an open first story must take into account the problem raised by placing a rigid structure over the open story. (Olive View Hospital, San Fernando, 1971)

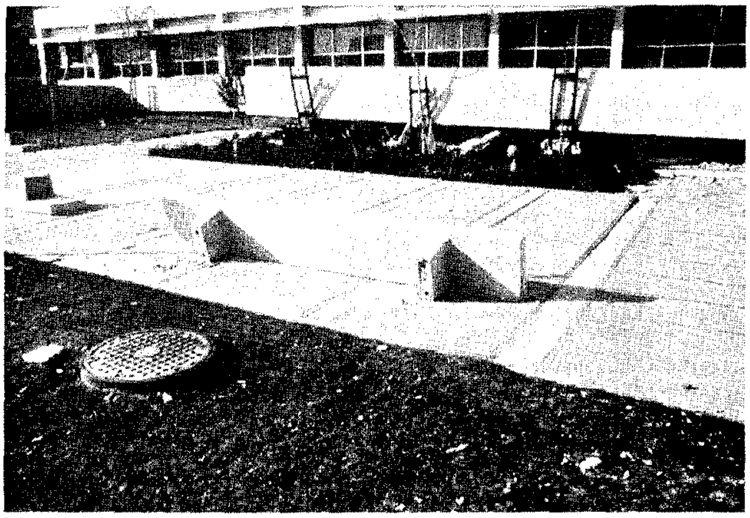


Fig. 57.

Fig. 58.

Fig. 57. First Floor Columns Completely Crushed under Upper Floor

The architect who desires to design an open first story must take into account the problem raised by placing a rigid structure over the open story. (Psychiatric Unit, Olive View Hospital, San Fernando, 1971)

Fig. 58. Collapsed Sunscreen

Sunshades must be structurally designed with sufficient capability to resist seismic forces. This horizontal concrete sunscreen supported on thin columns collapsed in Caracas, killing several people, in 1967.

Cantilevered balconies, cornices, parapets, railings, sun-shades, statues, signs and planters must be structurally designed with sufficient capability to resist seismic forces. Also the weight of materials chosen can increase or decrease the required design loads [Fig. 58, 59].

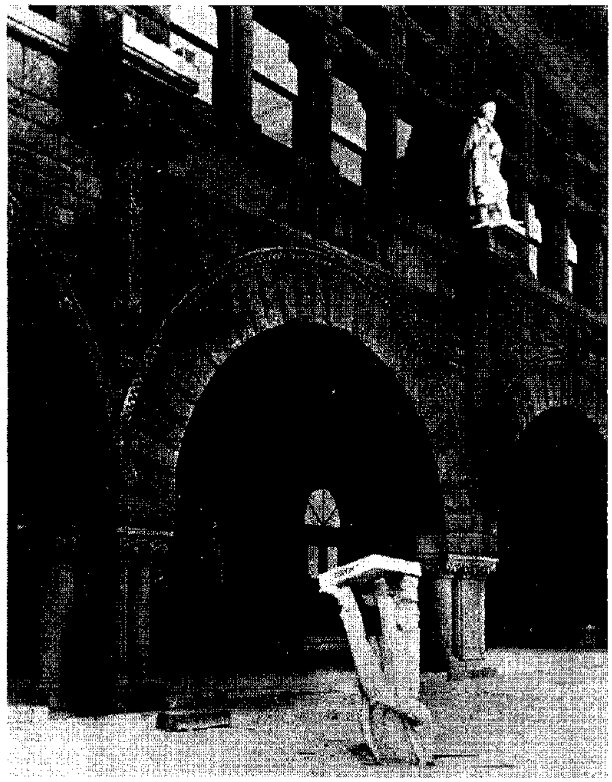


Fig. 59.

Statues must be properly anchored to resist seismic forces. (Louis Agassiz fell from his perch on Stanford University campus, 1906 San Francisco earthquake.)

Relationship to Adjoining Buildings

The architect must consider how a building is sited relative to other structures. Adequate separations must be provided to avoid "banging" since individual structures do not have identical modes of response. During an earthquake, each building will attempt to swing like a complex pendulum with its fundamental period of response. The amount of horizontal movement of a building from its original vertical position is called drift. If the clearance between two buildings of different periods is not at least equal to the sum of the calculated drift values of each structure, the buildings, acting as two pendulums, will bang together causing considerable damage [Fig. 60].

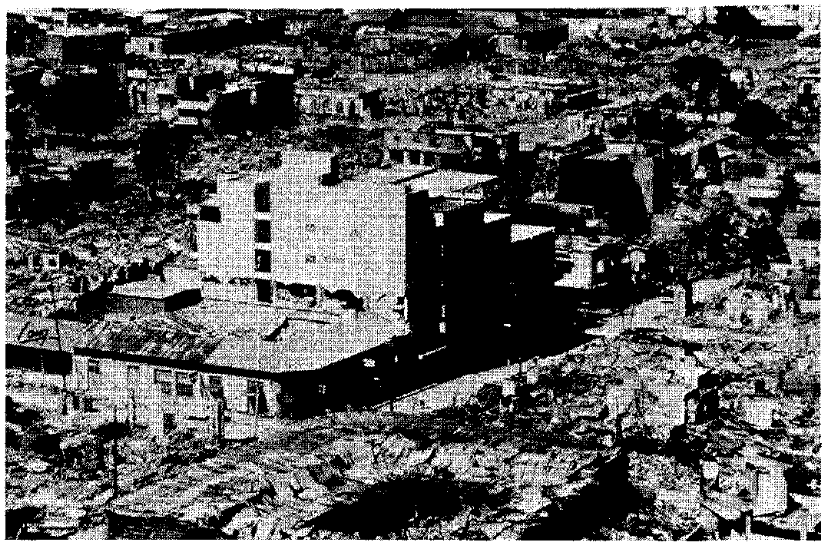


Fig. 60. Exterior Wall Failure at Floor of Building Subjected to Banging by Adjacent Lower Building

If the clearance between two buildings of different periods is not at least equal to the sum of the calculated drift values of each structure, the buildings will act as two pendulums and bang together during an earthquake causing considerable damage. (Managua, Nicaragua earthquake, 1972)

Critical Need to Tie Structural System Together

Since seismic forces affect all parts of a building, the building must act as a unit to resist these forces. If the structure is not tied together to respond as a unit, the separate elements or components of the building will respond individually and failure can occur beginning at the weakest element or component. The result would be a shift in load carrying or resisting ability of other elements which then also can fail due to overloading [Fig. 61].

Fig. 61. Inadequate Anchoring of House to Foundation

If a structure is not tied together to respond as a unit. . .failure can occur beginning at the weakest element.

The nature and completeness of the connections will determine the ability of the structural system to perform. Typical connection conditions which can fail include the use of brittle rather than ductile connections, or the spacing of fasteners at too close intervals so that connecting members fail. In addition, reinforcement bars may not be adequately anchored or spliced to develop the full strength of the connection. For example, the beam-column intersection in ductile concrete construction may not be fully developed to carry the seismic loads through the necessary reversals it may undergo.

In masonry construction, if the floor systems are not properly tied to the walls, under seismic forces the walls may move independently of the floors causing either the walls to fail or the floors to drop. This is also true wherever the design requires that the building components bear specific relationships, one to the other, in order to perform. Only by assuring adequate ties, proper detailing and careful construction can the design assumptions be carried out [Fig. 62].

Fig. 62. "Pancaking"

Under seismic forces a building not adequately tied together for toughness may have a tendency to "pancake". (Top four floors of the 11-story reinforced concrete Mansion Charaima collapsed in 1967 Caracas, Venezuela earthquake, causing 42 deaths.)

Dissimilarity of Wind and Earthquake Loads

For many years, most building codes have referred to designing for wind or for earthquakes in similar terms, and, for many years, architects and engineers have failed to recognize the important differences between these forces.

According to Charles G. Culver and H. S. Lew of the Center for Building Technology, National Bureau of Standards,

> *There is fundamental difference in the way in which lateral loads are transmitted to a building from earthquake and wind. In the case of earthquake, the load is transmitted to the building from its base. Thus, the entire building as well as the building contents will experience the force. In general, the magnitude of this force which individual members experience is proportional to their mass. On the other hand, in the case of wind, the load is transmitted to the building through its envelope. Thus the cladding and its supporting members experience the initial effects of the wind load. Except for the structural members, the interior of the building including its contents will not experience the wind loads directly as long as the envelope remains intact.*

Furthermore, excluding tornado effects, wind forces quantified by the code are usually conservative and generally all that is required is adequate stiffness in tall buildings to prevent excessive swaying.

However, earthquake resistant design is another matter entirely. Despite recent advancements in recording of earthquakes, dynamic analyses, computer applications, etc., it still is impossible to "define" a maximum design earthquake force with absolute confidence. In essence, it is important to recognize that our evaluation of earthquake design forces is at this moment just a good working approximation. But it does give the architect and engineer a basis for design which should be adequate if the nature of earthquakes and earthquake resistant design is understood.

In designing for wind forces, it is expected that buildings will resist the design wind loads without damage of any kind. The building is expected to perform entirely within the elastic limit of its materials. However, in earthquake resistant design, due to the far greater magnitude of the forces and displacements involved, it is expected that some components of the structure may exceed the elastic limit in responding to significant earthquakes and therefore some damage may occur under these conditions.

This difference in design concept must be recognized. Whereas many buildings with brittle materials and brittle connections have survived wind loads for many, many years, they would not stand a chance in a significant earthquake. Earthquake resistant buildings must be “tied together” in all respects and contain the ductility and toughness which are necessary properties if they are to survive the omnidirectional violent actions of an earthquake.

CHAPTER THREE
INTERACTION OF BUILDING COMPONENTS

General

Nonstructural components necessarily must be properly integrated with or effectively isolated from the basic structural frame if excessive damage to the building and the incumbent threat to life under earthquake induced movements are to be avoided.

The interaction between nonstructural components and structural systems can be divided into two basic relationships. These relationships are: the effect of the nonstructural components on the structural system; and the structural system's effect on components.

1. The effect of most nonstructural components on the performance of the structure is in most cases neutral, and generally does not cause undue problems when this interaction is overlooked. However, in certain cases significant modifications to the building's structural response can occur under seismic loading as a result of nonstructural-structural interaction. These modifications of response generally occur when the nonstructural component has some degree of rigidity and/or mass that causes an unexpected stiffening effect on portions of the structure. Classic examples of this are non-bearing masonry walls and firewalls, spandrels, and stair framing and other vertical shaftways, particularly when intermediate landings are tied to columns [Fig. 63]. All of these cause a stiffening of the structure, a consideration which the design team must include in their basic design considerations.
2. The second action is the effect of the basic structure movement on the nonstructural components. It is with this latter action that the bulk of this chapter will deal.

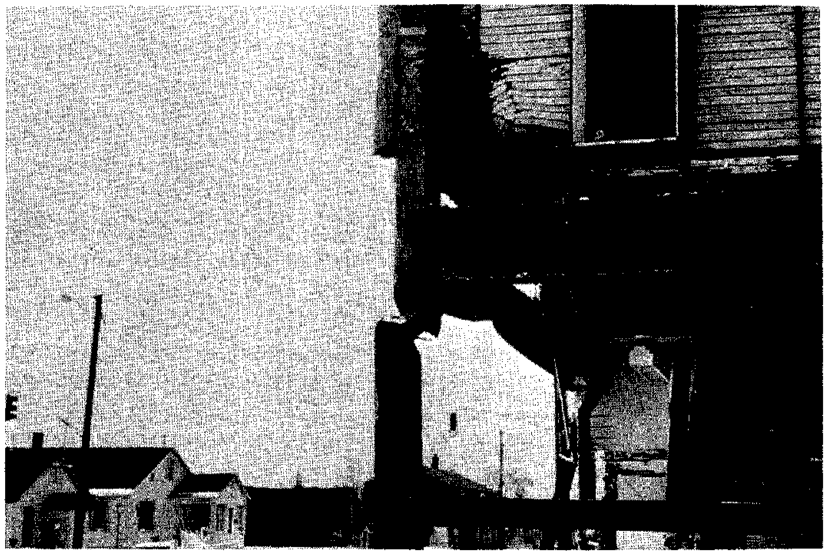


Fig. 63. Column Failure at Stairwell

. . . in certain cases significant modifications to the structural response can occur under seismic loading as a result of nonstructural-structural interaction. The column failed because stair construction stiffened the column so that it absorbed much higher forces than other columns. (Cordova Building, Anchorage, Alaska, 1964 earthquake)

Building Drift

The horizontal displacement of basic building elements is usually most critical to nonstructural components. All floors do not drift at the same rate or time, and this action causes a horizontal displacement between floors. This action, while usually cumulative, does rapidly change direction due to the earthquake forces acting at the base of the structure, and in a relatively tall building, can result in some floors of the building tending to move in one direction while floors above or below these are tending to move in the opposite direction [Fig. 64, 65]. This differential movement between floors can and does affect all full-floor height elements of a building.

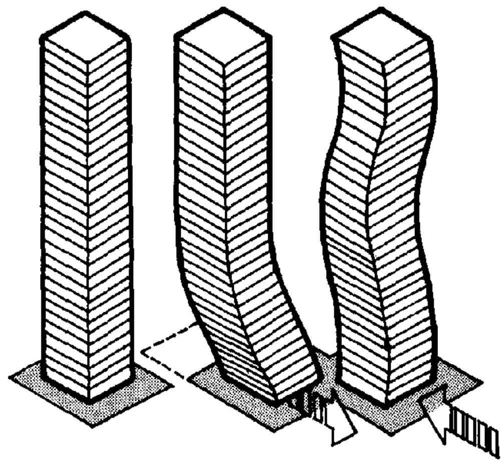


Fig. 64.

. . . some floors of the building tend to move in one direction while floors above or below these tend to move in the opposite direction in a relatively tall building.

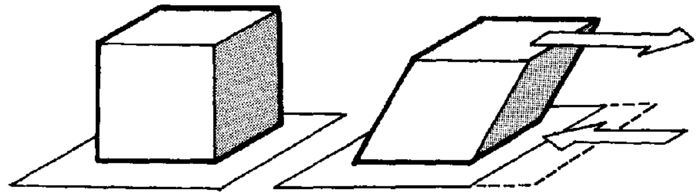


Fig. 65.

Drift diagram showing lateral displacement and resulting foreshortening.

The accumulation of drift affects only those nonstructural components that are continuous over more than one floor. Even here the effect is dependent upon the detailing of the component. For example, an exterior curtain wall that spans floor-to-floor in a simple span is seldom affected by cumulative action [Fig. 66]. However, the exterior curtain wall that is anchored at each floor slab and is cantilevered both up and down can be severely affected. Unless properly designed, the imposed racking of the elements can result in major failures of the wall system.

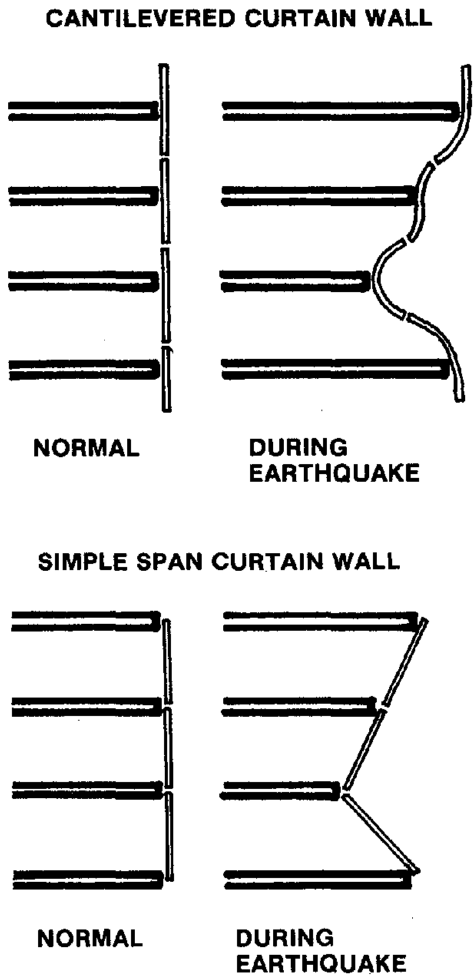


Fig. 66. Effect of Cantilevered Exterior Walls vs. Simple Span

The exterior curtain wall that is anchored at each floor slab and is cantilevered both up and down can be severely affected.

Simple shearing or racking action due to drift can be imposed on all floor-to-floor and some floor-to-ceiling components by the differential lateral movement between adjacent floor systems. In some cases bending occurs because the movement is perpendicular to the component [Fig. 67].

Problems also develop for components fitted tightly against columns due to the deflection action of the column. Under severe drift conditions, the resulting foreshortening of the relative floor-to-floor height can cause crushing. The design team should always expect that these forces will not run exactly parallel to the component and therefore, the actual movement will produce combined effects of shear, bending and, possibly if the elements are restrained, crushing.

Fig. 67. Lintel over Door Racked by Shearing Forces

Simple shearing or racking action due to drift can be imposed on all floor-to-floor and some floor-to-ceiling components by the differential lateral movement between adjacent floor systems. (Anchorage Westward Hotel, 1964 earthquake)

Building Torsion

This action, usually brought about by the eccentric lateral resistance or mass of the basic structure, causes the building to twist vertically. It should be noted that torsion in a building sometimes results from the stiffness of rigid or massive nonstructural components such as in-fill walls. The basic effects of torsion on components are quite similar to drift and will result in the same problems as those produced by drift.

Displacement of Cantilevered Members

Due to their unique nature, cantilevers tend to exaggerate the joint rotation of the structural frame [Fig. 68]. Under seismic loading cantilevers must receive special consideration. The unrestrained end condition can result in vertical displacement of a considerable magnitude. It is further quite realistic to expect this vertical displacement to be in opposite directions on adjacent floors. Since a high percentage of cantilever construction involves exterior walls, these conditions can create a significant hazard to life safety because of glass breakage and falling wall elements.

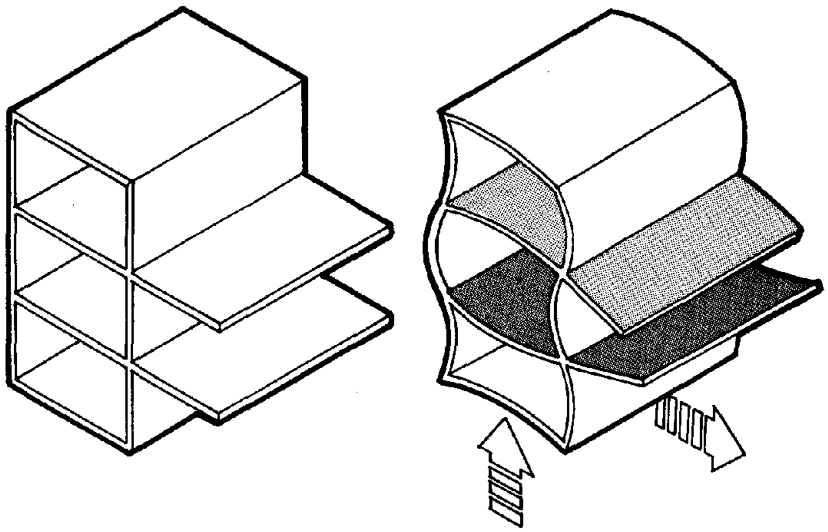


Fig. 68.

Cantilevers tend to exaggerate the joint rotation of the structural frame. . .vertical displacement can be in opposite directions on adjacent floors.

Other Factors

An additional factor should be considered in this area; that is, seismic forces are a time process in addition to a force process. As such, the various components of a building will not necessarily move as a unit even within a single floor. Therefore, the designer can expect maximum movements to occur at various components at various times and must act accordingly.

Most importantly, the reader must clearly understand that all of the above actions may commonly take place simultaneously and produce movements between the nonstructural and structural components that are quite complex.

Essentially, it is the deformation of the structural elements that controls the magnitude of relative movements between the basic structure and the nonstructural components. As has been repeatedly stressed, structure is but one factor in determining how the building responds to seismic forces. The magnitude of relative movements is determined by the complex interaction of overall building form, plan, structural systems, mass, materials, details and subsystems design. As such, the overall design of the building under consideration will totally control the magnitude of movement involved. The more monolithic and rigid the building, the less relative movement. On the other hand, in many cases flexibility is a desirable feature from a structural point of view; therefore, these alternate approaches must be coordinated in the final design.

Design Strategies for Components

Basically, two design concepts can be utilized in the approach to nonstructural component design: the deformation approach, and the detached approach.

The deformation approach is most useful when the structure is rigid, and expected movements are small. The designer may choose to rely on the ability of materials to respond to stress through their inherent elastic response. In a rigid basic structure this is usually not too difficult to achieve. Most nonstructural component materials will equal or exceed the basic structural material in allowable deformation. However, consideration must be given to component shapes and connection details. The architect must also take into account those materials or components that do not readily deform, such as glass; these brittle materials must be isolated properly to protect them.

In the detached approach the designer relies on the nonstructural components' detailing to keep them relatively free from the movement of the basic structure and thus avoid direct stresses. This method of design utilizes the extensive use of hinges, slip joints and resilient edge conditions. In the utilization of these tools the architect must remember to consider rotation and three-directional movement in order to avoid any binding action that will negate the effective action of these details.

The architect should also give consideration to combining the above approaches in the more flexible buildings. It is not unreasonable to design systems that will allow for usual seismic deflections in the detached approach and then expect that under excessive seismic movement the inherent flexibility of the component material will provide the additional resiliency needed to avoid damage to the component.

Another facet of proper seismic design that may be overlooked by the architect is the interworkings of one nonstructural component with another. In addition to being able to effectively respond to the basic structural movement, the components must be able to respond to each other. This can become somewhat tricky at intersections, and when a composite approach is being used. Classic examples of failure in this area are:

1. Rigidly fastened duct work or sprinklers penetrating a non-laterally braced suspended ceiling may move, tearing off sprinkler heads, ductwork, and/or ceiling parts [Fig. 69].
2. Suspended ceilings that rely on partitions for their lateral resistance, or partitions relying on the ceiling for their lateral resistance, may "all fall down."

Most nonstructural components are in effect small scale structures and, as such, have mass, shape and different materials just as buildings do. As such, each of these components is subject not only to external forces but to its own internal reactions to seismic forces. Therefore, these nonstructural components must have their own integrity if they are to survive severe earthquakes. In many cases, for nonstructural components such as plaster walls, ductwork and conduits, their normal integrity is usually adequate to resist seismic forces, provided they are properly connected to the building.

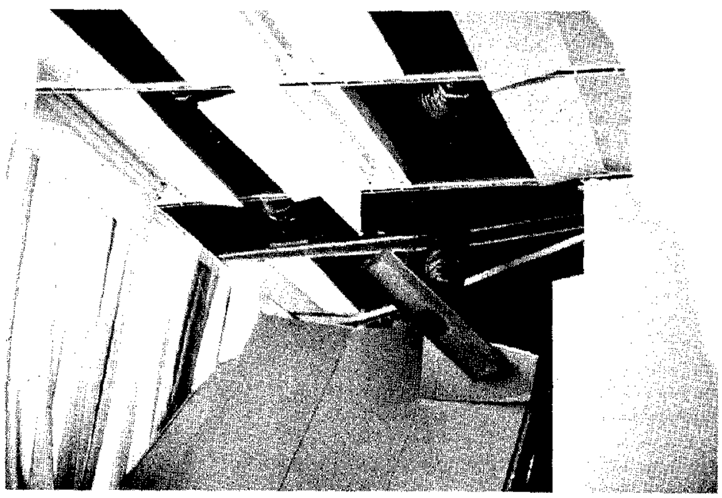


Fig. 69.

Rigidly fastened duct work or sprinklers penetrating a non-laterally braced suspended ceiling may move, tearing off ductwork and/or ceiling parts.

Certain nonstructural components are, however, extremely vulnerable to damage. These components usually fall into the category of having thin sections accompanied by heavy mass. Some typical examples are:

1. Non-bearing masonry walls [Fig. 70, 71]
2. Parapets
3. Light-weight metal curtain walls with thick or insulating glass

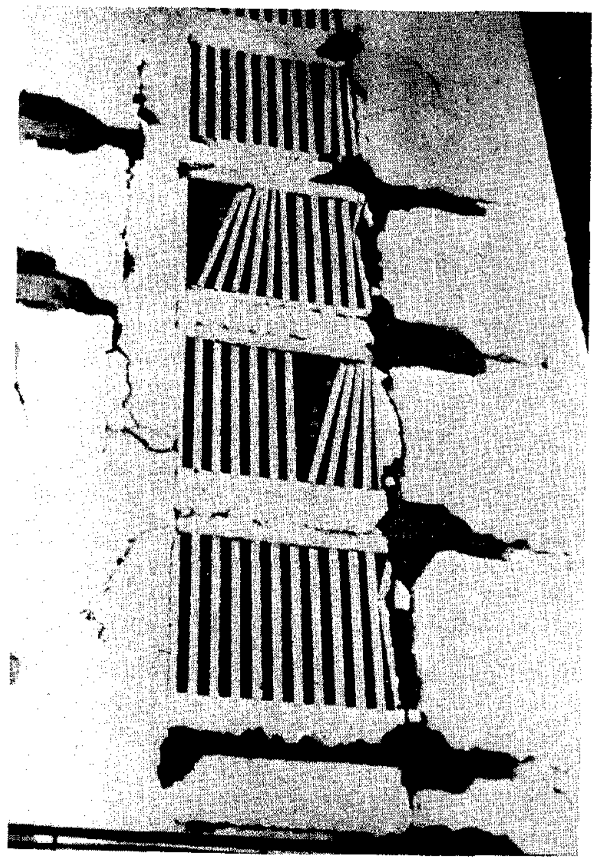


Fig. 70. Building Facade in Caracas

Certain nonstructural components are extremely vulnerable to damage as shown by these non-bearing masonry walls. (Caracas earthquake, 1967)

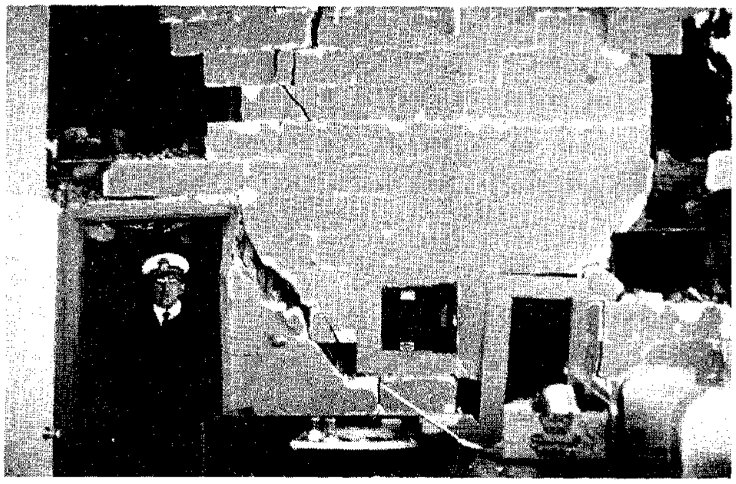


Fig. 71. Unreinforced Masonry Interior Wall Failure

Certain nonstructural components are extremely vulnerable to damage: non-loadbearing walls.

Importance of Connections and Fastenings

By and large, connections are the weakest links in seismic design [Fig. 72, 73]. This is true both in the fastening of nonstructural components to the structure, and in the basic structural system. A careful review of nonstructural component failures has shown that many occur at points of connection. At these points stresses tend to concentrate or change direction and thus often exceed the limits of the design [Fig. 74]. Some considerations of causes of these excessive stresses in nonstructural components are discussed below.

Inadequate tolerances for seismic movement will transmit impact loads to adjacent parts. Tolerances for movement must be provided in addition to normal construction tolerances.

Too often the designer fails to take into account the limitations of bearing pressures on fastenings. This is particularly true in threaded fastenings where the threads cause a sizable reduction in cross-section as well as bearing area of members.

Another critical area is in light gauge material, particularly aluminum. Excessive bearing pressure will cause yield in hole size and then "pull out." One such area of concern is the use of screws in extruded slots. These connections are extremely weak and should be avoided in critical elements.

Fig. 72. Failure of Brick Veneer

. . . the weakest links in seismic design are connections. (Several bricks pulled loose from First Presbyterian Church facade, San Fernando earthquake, 1971)

Fig. 73.

All bricks were removed from the above church facade when the absence of any fasteners was discovered.

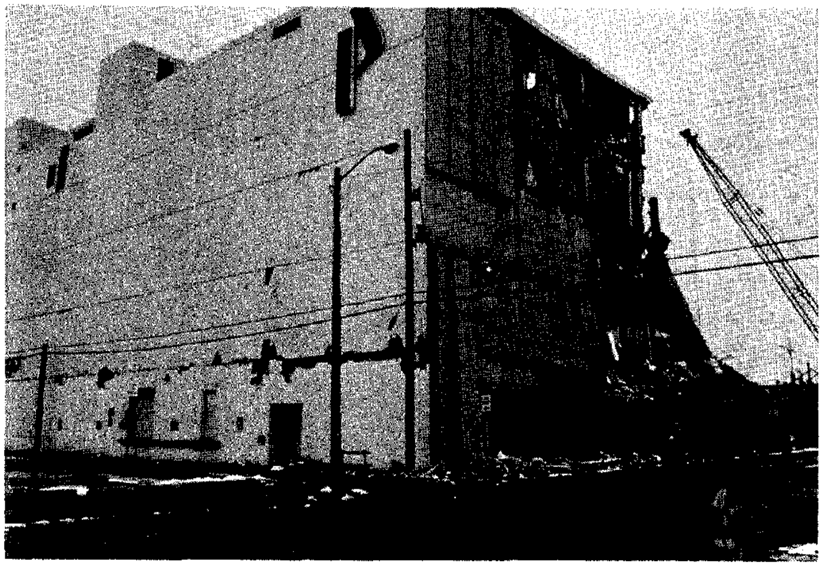


Fig. 74. Precast Concrete Facade Connection Failure

Many nonstructural component failures occur at points of connections. (Precast concrete facade panels fell from J.C. Penney building during the 1964 Anchorage, Alaska earthquake)

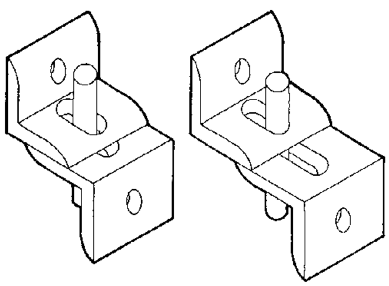


Fig. 75. Connection of Double Clip Angles

Often the connection is considered in its normal position and not in its extended position which is the critical condition when subjected to stresses.

Some connections for the attachment of components use various adjustable connections such as the double clip angle. In usual practice these are drawn in their normal position with construction tolerances not indicated [Fig. 75]. Often the connection is considered in its normal position and not in its extended position which is the critical condition when subjected to stresses.

Welding is being used more frequently in today's construction. In many cases a weld should be considered as a brittle connection, requiring special attention. Three areas of concern are:

1. Welding builds up local internal stresses, particularly at end points. These residual stresses can increase the chance of failure when the connection is further stressed due to seismic action.

2. Light gauge welding often results in burn through, particularly when light gauge material is connected to heavy structural shapes. A further concern in light gauge welding is with regard to galvanized material. The action of the zinc coating in the welding process causes gas pockets in the weld bead and can reduce the effective value of the weld. Both of these conditions seriously reduce the ability to resist seismic forces.

3. The heating of aluminum to approximately 600° F. will cause a considerable reduction in its modulus of elasticity. Thus, when aluminum is welded, care must be taken to insure that the basic member is not over stressed. This factor also must be considered when welding steel adjacent to aluminum.

Architects are urged to give very careful consideration to the design of connections since their importance cannot be overemphasized. Careful attention to this phase of design often can make the difference between success and failure under seismic loading.

At the present time, many of the details and connections in buildings may be dictated by local custom and practice in the construction industry, and not by consideration of seismic loading conditions. The need for basic research and professional education is perhaps as great in this area as in any area of research related to seismic design.

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CHAPTER FOUR
CONSIDERATIONS IN DESIGN

To this point, the primer has discussed how earthquakes generate forces, how structures respond to those forces, and some design considerations to withstand such forces. Unfortunately, this leaves the impression that the major problem is structural design, which is not the case. Certainly, the structural design is critical, for if the structure fails little else is of consequence. The purpose of this chapter is to show why the scope of earthquake design should be extended beyond structural considerations alone.

In an earlier chapter, it was demonstrated that motion in the structure is transmitted to the nonstructural components in a variety of ways. Lateral motion of the building due to ground acceleration was given as the predominant factor. Ground motion causes the building to move, with relative story drift occurring, which in turn creates stresses and forces on nonstructural components. The movement of one floor relative to another creates shear forces on the walls that are tightly fitted between them. If the deflection is large, a reduction in vertical height will occur, causing crushing of the wall.

Both shearing and crushing forces can be transmitted internally through one component into another; by this process the racking wall stresses the window frame which crushes the glass and so on. Connections also can fail.

It would be possible, but not fruitful, to go on at length describing the ways in which basic structural movement is transmitted through the structure to various components with the end result being possible failure of the components. It does not take much exploration along these lines to realize one important fact: when the structure starts moving, anything that is attached to that structure, directly or indirectly, is subject to damage or destruction unless properly designed. Literally every part of the building and everything within the building requires attention [Fig. 76].

The most curious realization is that without proper design it would be possible for the structure to behave in such ways that nearly *all* the architectural components are damaged or destroyed, while the structure remains standing.

Indeed, in recent experience, this has been the case. So-called earthquake-resistant buildings (buildings that were designed in accord with the latest structural theory) survived strong earthquakes in Anchorage, Managua, and elsewhere. The buildings remained standing; yet the total damage was assessed at up to 70 percent of replacement costs, related mainly to damage of nonstructural parts. In addition, hazards to life safety were increased dramatically by failure of these components.

Fig. 76. Apartment House in Los Angeles

. . . when the structure starts moving, anything that is attached to that structure. . .is subject to damage or destruction. . .(San Fernando earthquake, 1971)

Design responsibilities are such that architectural considerations are beyond the normal boundaries of responsibility of the structural engineer; the responsibility for examining the problems of architectural damage lies with the architect.

The question immediately arises: What should the architect do? How should the designer approach this problem? What actions should be taken?

One possible and natural response is to view the problem of architectural component damage as a natural extension of the engineering problem. Given that motion is the principal cause, and given that the ultimate result is a form of failure in the component (crushing, breaking, tearing, etc.), it is very natural to assume that damage can be reduced or eliminated by better design of components.

This is not an unreasonable assumption, but it's not without problems. The first problem that arises is: Can everything be adequately designed to withstand earthquake stresses? Certainly, as demonstrated in previous chapters, basic principles of design can be developed that will accommodate expected forces. For example, crushing forces can be offset by developing varieties of slip joints for components that absorb structural deflection without transmitting stress to the components themselves. This principle applies to a variety of situations ranging from floor-to-ceiling partitions to the design of sashes, frames and glazing.

A second problem relates to the economic ramifications of arriving at satisfactory solutions. In some cases, a solution to a problem may require extensive bracing, or perhaps the development of new components, which may involve additional costs. In other cases, the architect may be able to simply design new ways to assemble components to accomplish the desired result with no additional cost.

Both of these problems lead to a single pertinent understanding: because of cost consideration, technical feasibility, or perhaps simply because sooner or later an earthquake will occur which exceeds our design assumptions, it is probably not possible to design an earthquake damage-free or zero risk building. Hence we say "earthquake-resistant", not "earthquake-proof".

If, on the one hand, we know that every part of the building is susceptible to earthquake damage, but on the other hand, know that it is not practical to expect totally earthquake-proof buildings, then where should the architects concentrate their attention? Obviously, their attention should be directed to the "important" issues. But what are they, and how should they be defined?

In considering various ways of classifying the importance of design issues, one arrives at the realization that damage and destruction are important because they have profound effects on our lives. This rather obvious deduction is the basis for a meaningful life safety approach to earthquake design from the architect's point of view. Earthquake damage to buildings is critical because it disrupts vital functions; it represents economic losses for families and businesses; and, most importantly, it threatens injury and death to building occupants and people in the vicinity of buildings. Therefore, our criteria for earthquake design should center around mitigating these consequences, not simply ensuring the survival of the structural frame. In short, architects can begin to set meaningful priorities in earthquake design by first stating what it is that we wish to accomplish:

1. The expected performance of the building as it affects life safety and property damage
2. Establishment of basic planning and design parameters (form, shape) that will best meet the performance criteria
3. Proper integration of the various building components within the basic planning and design parameters, giving attention to appropriate life safety criteria

To apply this basic design strategy, let us now consider some basic, broadly defined performance requirements and discuss aspects of this design process specifically.

Requirement #1: Protection of occupants within, and the public adjacent to, a building during an earthquake.

During an earthquake, the greatest immediate hazard to persons in or near a building is the danger of being hit by falling objects [Fig. 77]. During the ground shaking, occupants are safest finding shelter under a desk, table or counter.

Assuming that the basic structure does not collapse, the dangers to which occupants still are exposed during a severe earthquake include toppling of free standing furniture, equipment and storage systems such as filing cabinents and bookshelves [Fig. 78, 79]. Wall mounted objects such as clocks and artwork are shaken loose and flung around the room. Suspended ceiling components may pop out, bringing snapped-off lighting fixtures, mechanical diffusers, sprinkler heads and other components down with them. Hazards from flooding and live wires may then be present. Door frames may be bent by racking partitions, and may jam the doors shut. Partitions may be crushed or may collapse. If the partitions contain utility lines, these may be broken, creating secondary hazards such as electric shock and fire. Racking walls bend window frames, causing glass to shatter and sending dangerous shards into the room or to the outside. Sashes may shear from their fastenings and may fall into or cascade outside the building [Fig. 80].

Persons outside a building can be hit by falling parapets, facade panels or elements, glass or other debris [Fig. 81, 82].

In order to protect persons from such hazards, building components and systems must be designed with the potential dangers in mind. Population densities of buildings also are included in these critical design considerations.

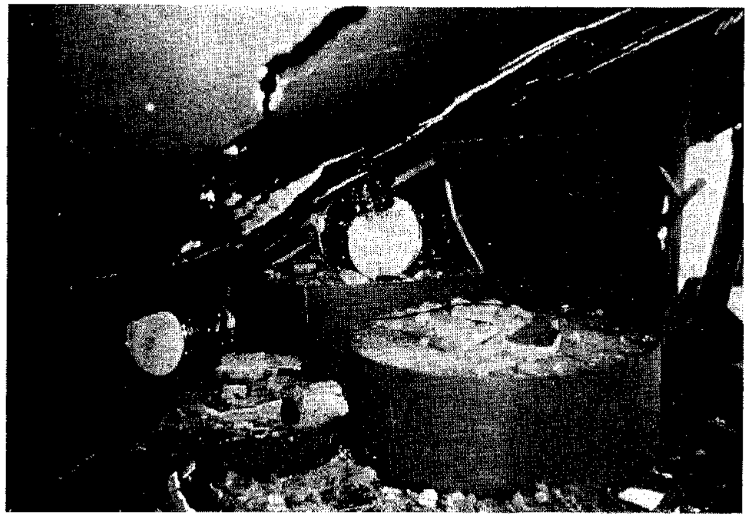


Fig. 77. Interior Destruction

During an earthquake, the greatest immediate hazard to persons in a building is the danger of being hit by falling objects. (Nightclub in Managua after the 1972 earthquake)

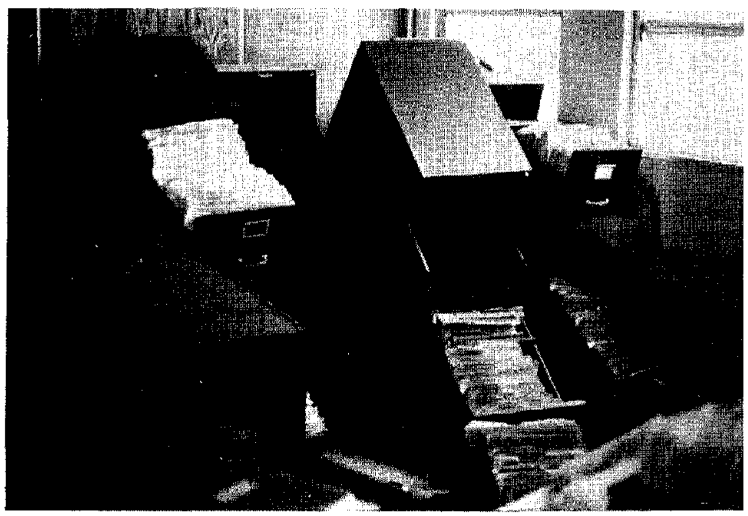


Fig. 78.

. . . the dangers to which occupants are exposed include toppling of free standing furniture, equipment and storage systems such as filing cabinets. (San Fernando, California, 1971)

Fig. 79.

Collapsed, unanchored storage racks and book shelves. (San Fernando, 1971)

Fig. 80. Racked Glazing Frames

Racking walls bend window frames, causing glass to shatter and sending dangerous shards into the room or to the outside. (Olive View Hospital, San Fernando, 1971)

Fig. 81. Van Sliced In Two by Piece of Facade Panel

Persons outside a building can be hit by falling facade panels. (Caracas, Venezuela, 1967)

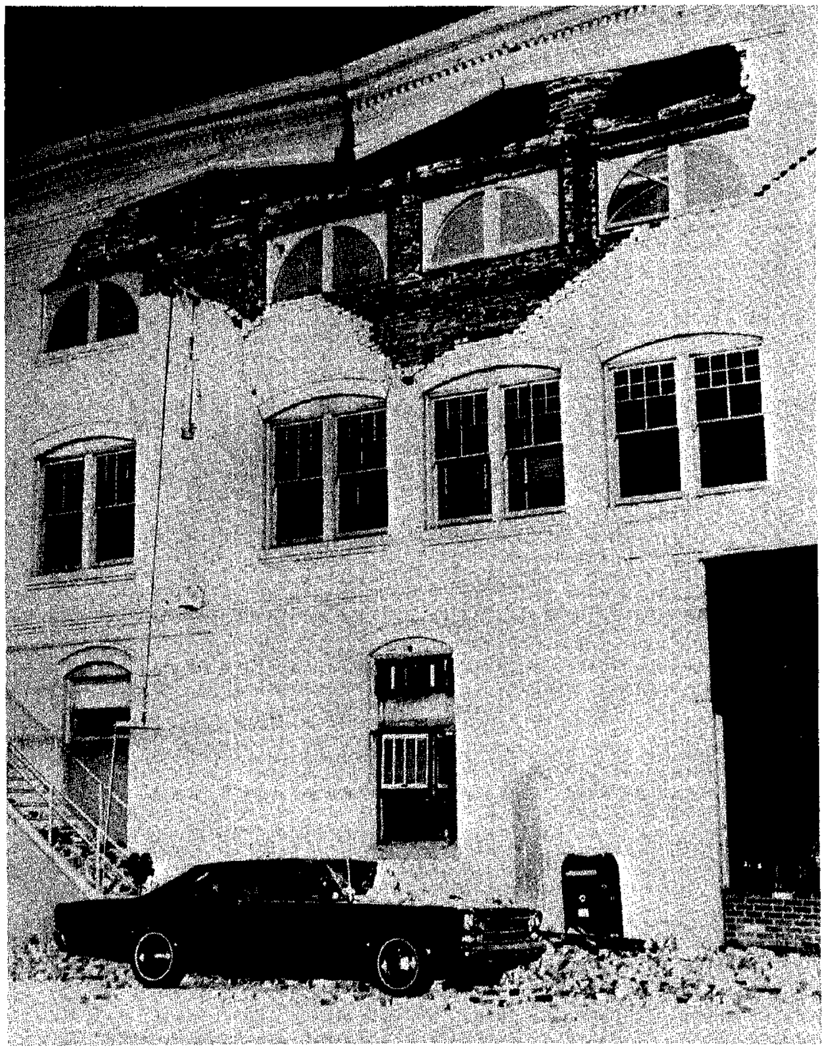


Fig. 82.

This broken cornice sent facade bricks falling onto parked car during the 1971 earthquake in San Fernando, California.

Requirement #2: Disaster control and emergency subsystems must remain operable after an earthquake.

Designers must consider the prospect that there will be casualties within buildings and people will be unable to escape [Fig. 83]. These people and the building itself will be subjected to secondary hazards caused by earthquake damage. Among the most critical are:

1. Fire: Fires can begin at a variety of locations during an earthquake, such as in mechanical rooms, kitchens, laboratories; that is, wherever fuel or electric lines rupture.
2. Electrical hazards: Collapse of ceilings or partitions or dislocation of electrical appliances may leave wiring exposed which creates danger of shock, or results in sparking which can lead to fire or explosion.
3. Flooding: Broken water pipes or sanitary lines may lead to flooding of various parts of the building.

Fig. 83. Office Interior

. . . people unable to escape . . . will be subjected to secondary hazards caused by earthquake damage. Among the most critical secondary disasters is fire. (Managua, Nicaragua, 1972)

As noted, fire protection devices can be damaged or destroyed when sprinkler heads are snapped off by collapsing ceilings. Flooding is an immediate consequence. Hoses can be torn off and fire extinguishers may be damaged when ripped off their mountings or crushed in wall encasements. They may be inaccessible or blocked by debris. Alarm systems are subject to both mechanical and electrical failures. Water supplies for fire fighting may be cut off by broken standpipes and mains inside or outside the building. Fire escapes may be blocked by debris or may have sheared completely off the building.

In order to prevent such secondary disasters, control and emergency systems such as the fire protection system should be designed to remain intact after the earthquake.

Requirement #3: Occupants must be able to evacuate a building quickly and safely after an earthquake when it is safe to do so.

While it may be an instinctive reaction for occupants to attempt to evacuate a building during an earthquake, it is the most dangerous action to take due to falling objects. Once ground shaking ceases, evacuation can begin. Quick and orderly evacuation should be accomplished because of the possibility of potentially hazardous secondary disasters such as explosions and fires, or aftershocks.

Considerable hazards can be encountered during evacuation. In an exit corridor or on a stairway, the occupant may encounter debris from ceilings, partitions and fixtures, making walking hazardous or impossible [Fig. 84]. If the lighting system fails and the occupants cannot see the way out, they may fall over obstacles. The danger is especially acute in interior stairways, where darkness makes it impossible to see missing stairs and railings, debris and other hazards.

History indicates that elevators have been extremely vulnerable to damage in earthquakes [Fig. 85]. As the building shakes, counterweights and other equipment may be torn from their connections and tossed around, striking the elevator cabs and causing guide rails and other systems to fail. Entire elevator shafts and stairwells which are attached to the building exterior, when improperly designed, may experience shearing forces that cause them to break away completely from the building [Fig. 86].

Upon reaching the exit, the occupant may find the doorway blocked by collapsed upper story walls, fallen parapets, balconies, cornices or pieces of roofing. Broken glass hinders safe passage. The door itself may not open if the frame has been bent out of alignment.

Once outside, the evacuee also risks being struck by loosened debris falling from the building's exterior [Fig. 87].

These potential hazards to life safety should be mitigated through careful consideration by the design team.

Fig. 84. Debris Filled Corridor

In an exit corridor, the occupant may encounter debris from ceilings, partitions and fixtures making walking hazardous or impossible. (Managua, Nicaragua earthquake, 1972)

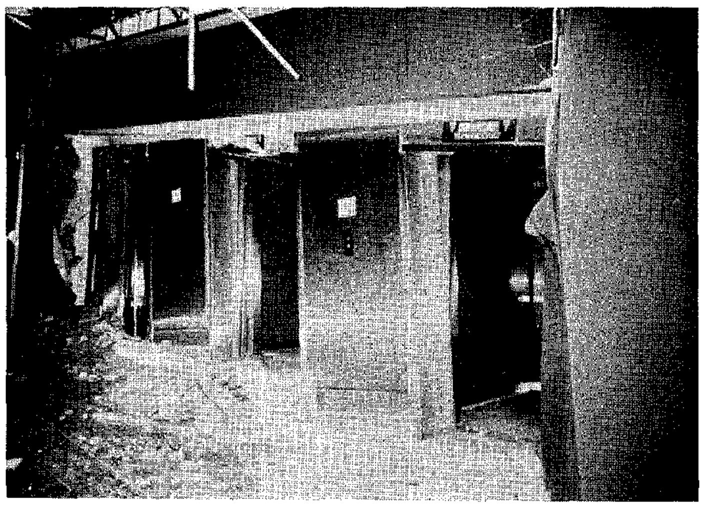


Fig. 85. Elevator Damage

Elevators are extremely vulnerable to damage in earthquakes. (San Fernando earthquake, 1971)

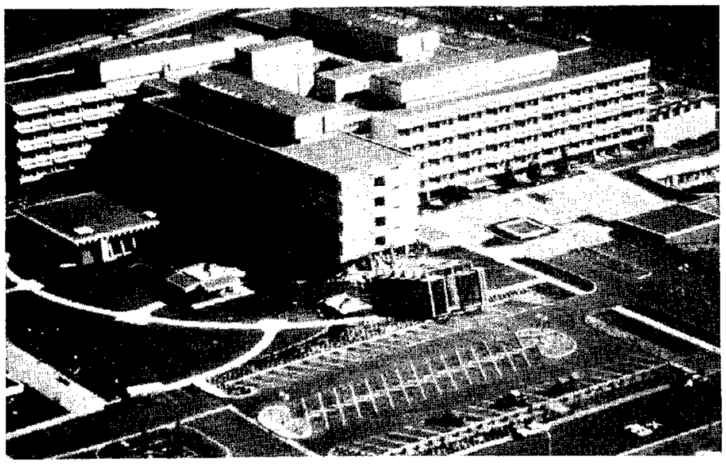


Fig. 86. Complete Stairwell Failure

Olive View Hospital. (San Fernando earthquake, 1971)

Fig. 87.

Once outside, the evacuee also risks being struck by loosened debris falling from the building's exterior. This vehicle was demolished during the Caracas, Venezuela earthquake, 1967.

Requirement #4: Rescue and emergency workers must be able to enter the building immediately after an earthquake, encountering minimum interference and danger.

After an earthquake, access to and passage within a building can be blocked to rescue and emergency workers for the same reasons that movement within and egress from the building is hindered for occupants. Review the hazards listed in Requirement #3, above [Fig. 88].

Rescue and emergency personnel need clear passageways to remove casualties. They need to find control and emergency subsystems operable in order to cope with fire and flooding.

Fig. 88. Debris Filled Stairwell

Access to and passage within a building after an earthquake can be blocked to rescue and emergency workers for the same reason that movement within and egress from the building is hindered for occupants. (Managua, Nicaragua earthquake, 1972)

Requirement #5: The building must be returned to useful service as quickly as possible.

The total "cost" of any earthquake is measured in at least two parts—the direct consequences of bodily injury or death and property damage, and the costs of social disruption and economic losses related to the inability of a city to function at full capacity after an earthquake. The latter costs—costs of interruption of social and economic processes—have two components as well. The more obvious one is the loss of business activity and revenues. The less obvious one is the cost of having to divert many resources to repair and restore services and buildings. Clearly, it is desirable to minimize these costs by minimizing damage and disruption.

This minimization is perhaps the most difficult task for the architect to undertake since virtually every component in a building is subject to earthquake damage and loss. Since it is not practical to prevent damage to all components, it must be decided which of the subsystems are the most critical to continued functioning in the building after an earthquake, and concentrate upon preventive design for these subsystems. Certainly among the most important are:

1. Sewage disposal and potable water supply: These subsystems are important in larger buildings and especially in critical facilities such as hospitals. Vertical piping systems are particularly subject to damage due to horizontal forces and over-stressing of connections and joints.
2. Electric power: Many important functions in all types of buildings are critically dependent upon the availability of electrical power, including lighting, communications, heating/cooling, vertical transportation, etc.
3. Mechanical systems should be sufficiently operational to provide at least minimum environmental control, particularly in critical use facilities.

The relative importance of subsystems depends a great deal on factors such as building occupancy, size, location, and climate. For example, maintenance of a communications system is more critical in a hospital or police station than in a residential building.

Requirement #6: The building and personal property within the building should remain as secure as possible after the earthquake.

One of the unpleasant facts to contemplate is that during or after any civil or natural disaster, the danger of looting and vandalism is imminent. Looting deters the quick restoration of social order. The components contributing to the security of the building should remain as intact as possible after an earthquake.

Maintaining the integrity of the exterior shell of the building may be the most difficult aspect of maintaining security. As noted in several places, glass breakage is a severe problem in any earthquake. Broken windows and doors are an obvious disruption of building security. The collapse of any part of the lower facade creates a similar problem. Therefore, reduction of property damage in general can alleviate security problems.

After the establishment of appropriate priorities and performance criteria, architects can then efficiently utilize their own and their consultants' broad range of knowledge and expertise to design realistic earthquake-resistant buildings within set parameters. Thus, in this manner, can we best serve our clients and the public.

CHAPTER FIVE

SOCIAL AND ECONOMIC IMPLICATIONS OF PUBLIC POLICY, AND PROFESSIONAL RESPONSE

We believe that in this primer enough basic knowledge has been presented to stimulate a broader involvement of the architectural community in a variety of activities pertinent to earthquake design, including research. This involvement could lead to a new approach to the consideration of seismic safety issues. In order to communicate these ideas effectively, the presentation has been kept simple and straightforward. However, the overall problems of dealing with earthquakes become complicated by social, economic, and public policy issues.

One of the most frequently asked questions about earthquake design is: "How much does it cost?" If the architectural profession and the public desire to raise the level of building performance during and after an earthquake through improved design, we must face the issue that this may result in increased construction costs. There is not complete agreement on the subject; but evidence gathered by several experts maintains that meeting current seismic safety demands may result in only a small increase in the cost of the building structural system.

If we assume it may cost something, then the question is: "How much are we willing to pay?" Clearly, part of that answer depends upon the risk involved, which is a function of the likelihood of occurrence of earthquakes, how severe they may be, and hence the probable loss of life and property damage sustained.

Assessing the trade-offs in such matters is included under the category of "risk analysis," an emerging art-science which is very quickly becoming a complicated issue. For example, among the things that must be considered in risk analysis is what value we might place on avoiding future threats to human life. The difficulty of that question is not hard to comprehend.

The profession also should realize that the design of better buildings is not the only option in dealing with earthquake hazards. Other strategies that are currently advocated include: 1) conscientious land-use planning in areas of high seismic activity; 2) possibly reinforcing the many existing buildings that have not been subject in the past to any kind of seismic design consideration; 3) improving building regulatory codes and property standards; 4) predisaster planning that prepares communities to recover quickly from the effects of earthquakes; and 5) earthquake prediction.

Each of these public concerns reinforces the strategy of seeking higher performance in terms of life safety and more durable buildings through better design. But each is itself as complex as the problem of achieving appropriate building design. In certain cases, public policy and economic considerations are emotional and highly controversial.

For example, earthquake prediction is still in a research stage. By expanding the potential of prediction capability, it is hoped that in the future it will be possible to specify the place, time, and magnitude of a single earthquake event within a sufficiently narrow time frame to permit short-term and appropriate long-term actions to save life and property. The precise nature and circumstances of prediction are difficult to foretell under current conditions. The way individuals and communities will respond is even less foreseeable at this time.

Regardless of the time in which the capability for prediction is realized, it is clear that the architectural profession will have significant pressure placed upon it to reduce potential hazards from earthquakes. The procedures and techniques applicable under this time constraint situation are, for all intents and purposes, the same as those required when no prediction is made. Thus, the responsibilities and demands placed upon the architect do not change with the advent of prediction capability.

All of these subjects are important because they must be considered as part of the range of solutions open to the designer. Architects must be prepared to deal with these issues in political and other arenas where, in coming years, they will be debated and acted upon. The discussion that each of these subjects deserves is not within the scope or purpose of this primer, and must be dealt with at another time. These few words are simply a caution that the subject of earthquake design, like most subjects today, is not a simple, clear-cut technical issue, but one which rapidly fans out in highly complex ways to embrace difficult social, economic, moral and political issues.

For the architect to be ignorant of these issues is to be disarmed in the marketplace. It is therefore important to make continuing inquiries into developments in each of these fields.

In achieving the five specific objectives of the primer outlined in the preface, recommendations to the individual architect and the profession have not been specified. Moreover, suggestions and directions, though implied and inferred, for providing seismic resistance to buildings are not indicated in the body of the text as it is not the purpose of the primer to present a "cook book" approach subject to obsolescence within a short time frame. At this point, however, a further synthesis of the elements comprising this effort is presented in order to set forth several suppositions for use as guidelines by the individual practitioner and the profession in seeking potential solutions to seismic design problems. By assuming a positive response to the issues raised in the primer, recommendations developed in this chapter are readily translated into goals for immediate action.

Also incumbent on the profession of architecture is the potential for providing leadership in advancing the state-of-the-art of design for life safety and property protection in potential seismic activity areas. We should move forward at both the individual and professional body levels. Our investigations, and experience in preparing this primer, now enable us to put forth several guidelines to be utilized by the individual architect and the profession as a whole, in approaching seismic design problems.

It is at the individual level that overall competence and credibility are achieved and displayed for quantification and evaluation by all segments of society. Though the profession as a whole can and should develop new bodies of knowledge, it is the individual architect who puts the resultant knowledge to work. On this basis the following recommendations are made and, in order to attain the objectives implied by them, it is necessary for the individual practitioner to:

1. **Set life safety priorities**—The architect must have a set of reasonable criteria for life safety and guidelines for providing life safety in buildings. Though these criteria and guidelines may be developed by the profession, they must be examined carefully and understood by each member of the entire design team. It is also helpful if appropriate governmental bodies are included in the discussion and development of criteria.
2. **Mitigate property damage**—It also is important that the architect have a set of criteria and guidelines for preventing property damage to buildings in earthquakes. These criteria and guidelines should be clearly understood by the client as well. Thus, all parties are aware of the possible risk factors involved, and rational, intelligent decisions can be made before the fact to avoid potential liability exposure to the architect after the fact.
3. **Establish a team approach**—For proper seismic design it is essential that the architect fully utilize the team approach for all aspects of design. At the outset the architect, the structural engineer, the foundation engineer and other appropriate professional consultants should confer to coordinate design efforts to avoid potential life hazards. Concurrently, the client should understand the cost/benefit analysis. The expertise of mechanical, electrical and other consultants is important for the proper integration of their systems into the whole structure. In this manner the architect has some assurance that the final product can and will survive earthquake action with a minimum of hazard to life safety.
4. **Evaluate site conditions and responses**—In many parts of the country active fault conditions are in evidence at the ground surface and can be accurately traced. In other places such conditions can only be suspected. Whatever the case, the architect should give careful consideration to known geologic

conditions in the area. Particular concern should be accorded to all geologic hazards affecting the site including, among others, potential effects of landslides and soils liquefaction induced by earthquakes. Such data should be interfaced with other planning and design considerations in conjunction with soil-foundation interaction, building configuration, framing concepts, materials of construction, and relative stiffness for damage control, to anticipate the expected fundamental response for any given structure.

5. **Above all, be professional, be competent**—Architecture is a public service profession oriented toward meeting the needs of contemporary society. Its ultimate objective is the improvement of the socio-economic climate through judicious design efforts to improve the quality of life. Life safety is an important objective in meeting these goals, and is best achieved through preventive measures. Response to natural disasters after the events is non-productive if it is the sole and typically short-lived reaction to the problems. The profession, as a corporate body, must encourage and support the development and adoption of criteria and guidelines for establishing and achieving goals related to seismic safety. On this premise, the following recommendations are enjoined for the profession to:

   A. **Develop greater basic knowledge**—In comparison to other professional engineering disciplines, the architectural profession has lagged behind in the development of basic knowledge related to seismic safety in the areas of planning and design. Now that specific issues have been identified as being a major responsibility of architects, it is important that the profession develop appropriate material for implementation. The profession as a cohesive unit must take the lead in this undertaking.

   B. **Achieve greater dissemination of basic knowledge**—Development of basic knowledge must be followed by a greater effort to disseminate substantive results to all levels of the profession. Without this dissemination of significant developments to individuals, basic knowledge in any subject is less likely to be useful. New programs must be brought to the attention of the practitioner in a manner which encourages their use and effectiveness. Interest can be stimulated and information communicated through the use of appropriate vehicles such as continuing education, publications, discussion seminars and workshops.

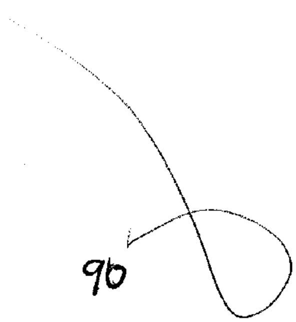
   C. **Establish greater participation in the public forum**—Many seismic safety goals, once defined, can be achieved through legislation devoted to public policy issues. In order to generate acceptance of its recommendations, the profession must have more participation in the public forum. It is here that the rewards for expended efforts will be the greatest. Any program unacceptable to the community faces failure as an invidious procedure.

D. **Consider the need for seismic design criteria on a national basis**—Historically, it has been illustrated that areas of all the 50 states are subject to seismic activity. One may be tempted to conclude from this that all areas should have severe seismic design criteria and requirements. However, it is also a fact that many areas, while they are geologically active, suffer such minor and/or infrequent earthquakes that the risk of extensive life hazard and property damage may be very low. To what degree should such areas be required to adopt strict seismic design requirements given such low risk? At what level does the risk become great enough to warrant adoption of stringent requirements? In a world of diminishing resources, how much does the adoption of such requirements cost society in terms of added building costs, if any, the cost of administering and maintaining codes, etc.? In short, how much should be invested in preventive measures given various levels of risk around the country? Is there a better way to approach the problem?

E. **Undertake a leadership role in planning and implementing programs of advanced research and development**—These recommendations are references to developing new criteria, undertaking new research and new programs of education:

As better paradigms of questions and problems are developed, new theories and directions based on the profession's expertise in planning and design must be sought out. Attempts to increase knowledge through extensions of procedural analyses of existing solutions are, at best, limited to a passive approach. Accordingly, the profession must direct its attention to all levels of basic and applied research to develop new solutions. It is here that potential "breakthroughs" in the amelioration of socio-economic models have the best chances for successful application.

Since this area of concern is new and emerging, the answers to such questions are not clear. To help clarify both the issues and the needs, the profession should take a leadership role in establishing a program that will provide knowledge pertinent to architectural concerns.



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