by Christopher Arnold

4.1 INTRODUCTION

This chapter explains how various aspects of earthquake ground motion affect structures and also how certain building attributes modify the ways in which the building responds to the ground motion. The interaction of these characteristics determines the overall seismic performance of the building: whether it is undamaged; suffers minor damage; becomes un-usable for days, weeks, or months; or collapses with great loss of life.

Explanations of some characteristics of ground motion are followed by descriptions of several material, structural, and building attributes that, by interacting with ground motion, determine the building's seismic per-formance—the extent and nature of its damage.

This chapter uses the information on the nature of ground motion in Chapters 2 and 3, and applies it to structures and buildings. Chapter 5, on seismic issues in architectural design, continues the exploration of design and construction issues that, in a seismic environment, determine building performance.

4.2 INERTIAL FORCES AND ACCELERATION

The seismic body and surface waves create inertial forces within the building. Inertial forces are created within an object when an outside force tries to make it move if it is at rest or changes its rate or direction of motion if it is moving. Inertial force takes us back to high school physics and to Newton's Second Law of Motion, for when a building shakes it is subject to inertial forces and must obey this law just as if it were a plane, a ship, or an athlete. Newton's Second Law of Motion states that an inertial force, F, equals mass, M, multiplied by the acceleration, A. (Figure 4-1)

$$F = MA$$

force   mass   acceleration

Figure 4-1:

Newton's Second Law of Motion.

Mass can be assumed as equivalent (at ground level) to the weight of the building, and so this part of the law explains why light buildings, such as wood frame houses, tend to perform better in earthquakes than large heavy ones - the forces on the building are less.

The acceleration, or the rate of change of the velocity of the waves setting the building in motion, determines the percentage of the building mass or weight that must be dealt with as a horizontal force.

Acceleration is measured in terms of the acceleration due to gravity or **g** (Figure 4-2). One g is the rate of change of velocity of a free-falling body in space. This is an additive velocity of 32 feet per second per second. Thus, at the end of the first second, the velocity is 32 feet per second; a second later it is 64 feet per second, and so on. When parachutists or bungee jumpers are in free fall, they are experiencing an acceleration of 1g. A building in an earthquake experiences a fraction of a second of g forces in one direction before they abruptly change direction.

Figure 4-2: Some typical accelerations.

1 "g"   parachute team   4 "g"   roller coaster

The parachutists are experiencing 1g, while the roller-coaster riders reach as much as 4g. The aerobatic pilots are undergoing about 9g. The human body is very sensitive and can feel accelerations as small as 0.001g.

9 "g" air force display team   0.001 "g" human perception

Engineering creations (planes, ships, cars, etc.) that are designed for a dynamic or moving environment can accommodate very large accelerations. Military jet planes, for example, are designed for accelerations of up to 9g. At this acceleration, the pilot experiences 9 times the body weight pressing down on the organs and blacks out.

A commercial airliner in fairly severe turbulence may experience about 20 percent g (or 0.2g), although unbuckled passengers and attendants have been known to hit the ceiling as a result of an acceleration "drop" of over 1g. A fast moving train on a rough track may also experience up to about 0.2g.

Poorly constructed buildings begin to suffer damage at about 10 percent g (or 0.1g). In a moderate earthquake, the waves of vibration may last for a few seconds, and accelerations may be approximately 0.2g. For people on the ground or at the bottom of a building, the sensations will be very similar to those of the occupants of the plane in turbulence or passengers standing in the fast moving train: they feel unsteady and may need to grab onto something to help them remain standing. Earthquakes cause additional alarm because when the shaking starts, those experiencing it do not know whether it will quickly end or is the beginning of a damaging and dangerous quake. Short accelerations may, for a fraction of a second, exceed 1.0g. In the Northridge earthquake in 1994, a recording station in Tarzana, five miles (8 km) from the epicenter, recorded 1.92g.

4.3 DURATION, VELOCITY, AND DISPLACEMENT

Because of the inertial force formula, acceleration is a key factor in determining the forces on a building, but a more significant measure is that of acceleration combined with duration, which takes into account the impact of earthquake forces over time. In general, a number of cycles of moderate acceleration, sustained over time, can be much more difficult for a building to withstand than a single much larger peak. Continued shaking weakens a building structure and reduces its resistance to earthquake damage.

A useful measure of strong-motion duration is termed the **bracketed duration**. This is the shaking duration above a certain threshold acceleration value, commonly taken as 0.05g, and is defined as the time between the first and last peaks of motion that exceeds this threshold value. In the San Fernando earthquake of 1971, the bracketed duration was only about 6 seconds. In both the Loma Prieta and the Northridge earthquakes, the strong motion lasted a little over ten seconds, yet caused much destruction. In the 1906 San Francisco earthquake, the severe shaking lasted 45 seconds, while in Alaska, in 1964, the severe motion lasted for over three minutes.

Two other measures of wave motion are directly related to acceleration and can be mathematically derived from it. Velocity, which is measured in inches or centimeters per second, refers to the rate of motion of the seismic waves as they travel through the earth. This is very fast. Typically, the **P wave** travels at between 3 km/sec and 8 km/sec or 7,000 to 18,000

mph. The **S wave** is slower, traveling at between 2 km/sec and 5 km/sec, or 4,500 mph to 11,000 mph.

Displacement refers to the distance that points on the ground are moved from their initial locations by the seismic waves. These distances, except immediately adjacent to or over the fault rupture, are quite small and are measured in inches or centimeters. For example, in the Northridge earthquake, a parking structure at Burbank, about 18 miles (29 km) from the epicenter recorded displacements at the roof of 1.6 inches (4.0 cm) at an acceleration of 0.47g. In the same earthquake, the Olive View hospital in Sylmar, about 7.5 miles (12 km) from the epicenter, recorded a roof displacement of 13.5 inches (34 cm) at an acceleration of 1.50g.

The velocity of motion on the ground caused by seismic waves is quite slow—huge quantities of earth and rock are being moved. The velocity varies from about 2 cm/sec in a small earthquake to about 60 cm/sec in a major shake. Thus, typical building motion is slow and the distances are small, but thousands of tons of steel and concrete are wrenched in all directions several times a second.

In earthquakes, the values of ground acceleration, velocity, and displacement vary a great deal in relation to the frequency of the wave motion. High–frequency waves (higher than 10 hertz) tend to have high amplitudes of acceleration but small amplitudes of displacement, compared to low-frequency waves, which have small accelerations and relatively large velocities and displacements.

4.4 GROUND AMPLIFICATION

Earthquake shaking is initiated by a fault slippage in the underlying rock. As the shaking propagates to the surface, it may be amplified, depending on the intensity of shaking, the nature of the rock and, above all, the surface soil type and depth.

A layer of soft soil, measuring from a few feet to a hundred feet or so, may result in an amplification factor of from 1.5 to 6 over the rock shaking. This amplification is most pronounced at longer periods, and may not be so significant at short periods. (Periods are defined and explained in the next section, 4.5.1.) The amplification also tends to decrease as the level of shaking increases.

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As a result, earthquake damage tends to be more severe in areas of soft ground. This characteristic became very clear when the 1906 San Francisco earthquake was studied, and maps were drawn that showed building damage in relation to the ground conditions. Inspection of records from soft clay sites during the 1989 Loma Prieta earthquake indicated a maximum amplification of long-period shaking of three to six times. Extensive damage was caused to buildings in San Francisco's Marina district, which was largely built on filled ground, some of it rubble deposited after the 1906 earthquake.

Because of the possibility of considerable shaking amplification related to the nature of the ground, seismic codes have some very specific requirements that relate to the characteristics of the site. These require the structure to be designed for higher force levels if it is located on poor soil. Specially designed foundations may also be necessary.
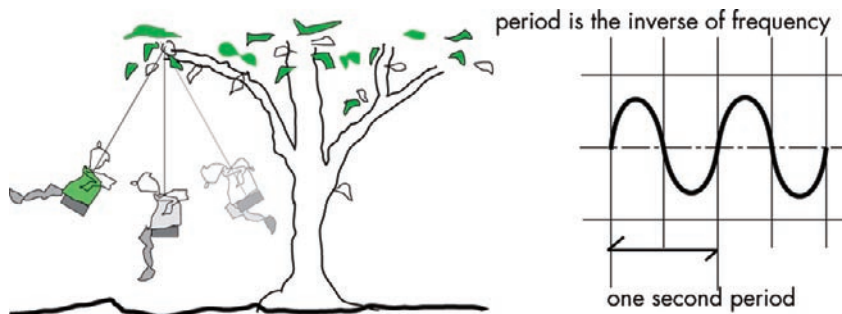
4.5 PERIOD AND RESONANCE

Figure 4-3 The Fundamental Period.

4.5.1 Natural Periods

Another very important characteristic of earthquake waves is their **period** or frequency; that is, whether the waves are quick and abrupt or slow and rolling. This phenomenon is particularly important for determining building seismic forces.

All objects have a natural or fundamental period; this is the rate at which they will move back and forth if they are given a horizontal push (Figure 4-3). In fact, without pulling and pushing it back and forth, it is not possible to make an object vibrate at anything other than its natural period.

When a child in a swing is started with a push, to be effective this shove must be as close as possible to the natural period of the swing. If correctly gauged, a very small push will set the swing going nicely. Similarly, when earthquake motion starts a building vibrating, it will tend to sway back and forth at its natural period.

Period is the time in seconds (or fractions of a second) that is needed to complete one cycle of a seismic wave. Frequency is the inverse of this—the number of cycles that will occur in a second—and is measured in "Hertz". One Hertz is one cycle per second.

Natural periods vary from about 0.05 seconds for a piece of equipment, such as a filing cabinet, to about 0.1 seconds for a one-story building. Period is the inverse of frequency, so the cabinet will vibrate at 1 divided by 0.05 = 20 cycles a second or 20 Hertz.

A four-story building will sway at about a 0.5 second period, and taller buildings between about 10 and 20 stories will swing at periods of about
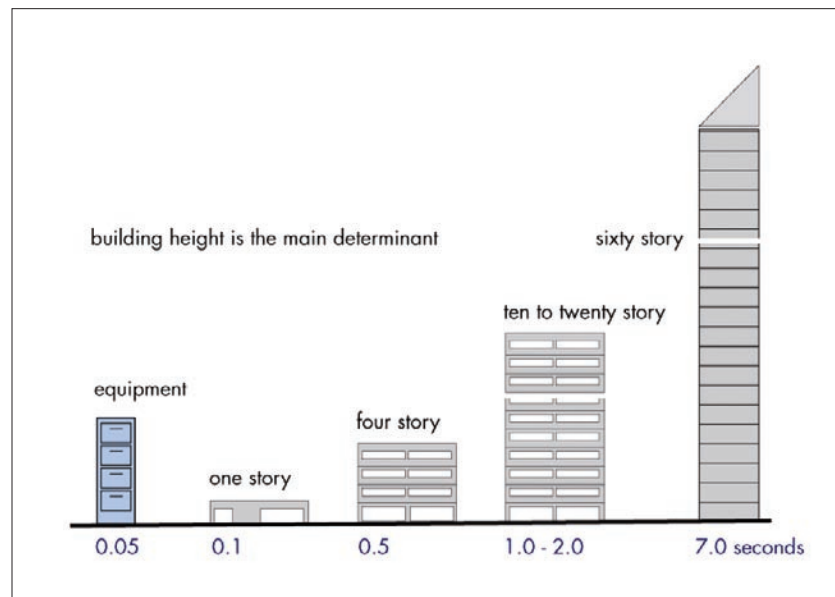

Figure 4-4: Comparative building periods, determined by height. These values are approximations: the structural system, materials, and geometric proportions will also affect the period.

EARTHQUAKE EFFECTS ON BUILDINGS

1 to 2 seconds. A large suspension bridge may have a period of around 6 seconds. A rule of thumb is that the building period equals the number of stories divided by 10; therefore, period is primarily a function of building height. The 60-story Citicorp office building in New York has a measured period of 7 seconds; give it a push, and it will sway slowly back and forth completing a cycle every 7 seconds. Other factors, such as the building's structural system, its construction materials, its contents, and its geometric proportions, also affect the period, but height is the most important consideration (Figure 4-4).

The building's period may also be changed by earthquake damage. When a reinforced concrete structure experiences severe ground shaking, it begins to crack: this has the effect of increasing the structure's period of vibration: the structure is "softening." This may result in the structure's period approaching that of the ground and experiencing resonance, which may prove fatal to an already weakened structure. The opposite effect may also occur: a steel structure may stiffen with repeated cycles of movement until the steel yields and deforms.

4.5.2 Ground Motion, Building Resonance, and Response Spectrum

When a vibrating or swinging object is given further pushes that are also at its natural period, its vibrations increase dramatically in response to even rather small pushes and, in fact, its accelerations may increase as much as four or five times. This phenomenon is called resonance.

The ground obeys the same physical law and also vibrates at its natural period, if set in motion by an earthquake. The natural period of ground varies from about 0.4 seconds to 2 seconds, depending on the nature of the ground. Hard ground or rock will experience short period vibration. Very soft ground may have a period of up to 2 seconds but, unlike a structure, it cannot sustain longer period motions except under certain unusual conditions. Since this range is well within the range of common building periods, it is quite possible that the pushes that earthquake ground motion imparts to the building will be at the natural period of the building. This may create resonance, causing the structure to encounter accelerations of perhaps 1g when the ground is only vibrating with accelerations of 0.2g. Because of this, buildings suffer the greatest damage from ground motion at a frequency close or equal to their own natural frequency.
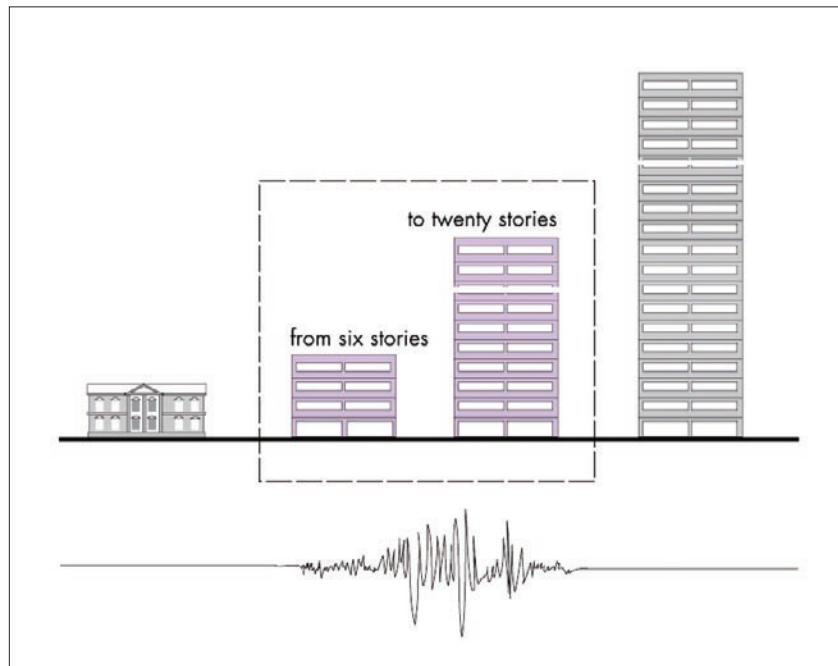
Figure 4-5: The vulnerable group: Mexico City, 1985. The periods of buildings in the 6 to 20 story range resonated with the frequency content of the earthquake.

The terrible destruction in Mexico City in the earthquake of 1985 was primarily the result of response amplification caused by coincidence of building and ground motion periods (Figure 4-5). Mexico City was some 250 miles from the earthquake focus, and the earthquake caused the soft ground in margins of the old lake bed under the downtown buildings to vibrate for over 90 seconds at its long natural period of around 2 seconds. This caused buildings that were between about 6 and 20 stories in height to resonate at a similar period, greatly increasing the accelerations within them. Taller buildings suffered little damage. This amplification in building vibration is very undesirable. The possibility of it happening can be reduced by trying to ensure that the building period will not coincide with that of the ground. Thus, on soft (long-period) ground, it would be best to design a short, stiff (short-period) building.

Taller buildings also will undergo several modes of vibration so that the building will wiggle back and forth like a snake (Figure 4-6).

However, later modes of vibration are generally less critical than the natural period, although they may be significant in a high-rise building. For low-rise buildings, the natural period (which, for common structures, will always be relatively short) is the most significant. Note, however, that the low-period, low- to mid-rise building is more likely to experience resonance from the more common short-period ground motion.
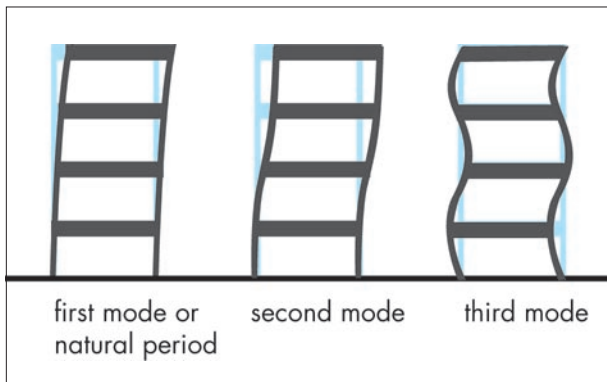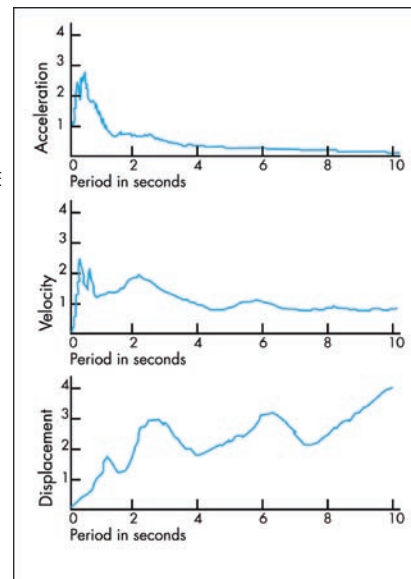

Figure 4-6

Modes of vibration.

4.5.3 Site Response Spectrum

From the above, it can be seen that buildings with different periods (or frequency responses) will respond in widely differing ways to the same earthquake ground motion. Conversely, any building will act differently during different earthquakes, so for design purposes it is necessary to represent the building's range of responses to ground motion of different frequency content. Such a representation is termed a site **response spectrum**. A site response spectrum is a graph that plots the maximum response values of acceleration, velocity, and displacement against period (and frequency). Response spectra are very important tools in earthquake engineering.

Figure 4-7 shows a simplified version of a response spectrum. These spectra show, on the vertical ordinate, the accelerations, velocities and displacements that may be expected at varying periods (the horizontal ordinate). Thus, the response spectrum illustrated shows a maximum acceleration response at a period of about 0.3 seconds—the fundamental period of a midrise building. This shows how building response varies with building period: as the period lengthens, accelerations decrease and displacement increases. On the other hand, one- or two-story buildings with short periods undergo higher accelerations but smaller displacements.

In general, a more flexible longer period design may be expected to experience proportionately lesser accelerations than a stiffer building. A glance at a response spectrum will show why this is so: as the period of the building lengthens (moving towards the right of the horizontal axis of the spectrum), the accelerations reduce. Currently our codes recognize the beneficial aspect of flexibility (long period) by permitting lower design coefficients. However, there is an exchange, in that the lower accelerations in the more flexible design come at the expense of more motion. This increased motion may be such that the building may suffer considerable damage to its nonstructural components, such as ceilings and partitions, in even a modest earthquake.

Figure 4-7

Simplified response spectra, for acceleration, velocity and displacement.

SOURCE MCEER INFORMATION SERVICE

Seismic codes provide a very simple standardized response spectrum that is suitable for small buildings (Figure 4-8). The code also provides a procedure for the engineer to construct a more accurate response spectrum for the building, based on various assumptions. For larger buildings in which a geotechnical consultant provides information on the site characteristics and an estimate of ground motions, detailed response spectra will also be provided to assist the engineer in the calculation of forces that the building will encounter.

The response spectrum enables the engineer to identify the resonant frequencies at which the building will undergo peak accelerations. Based
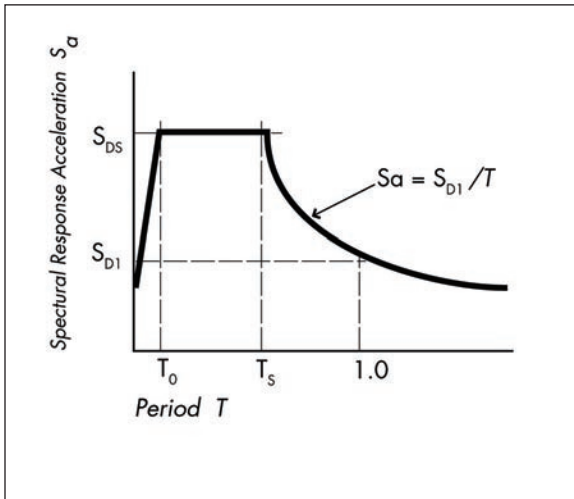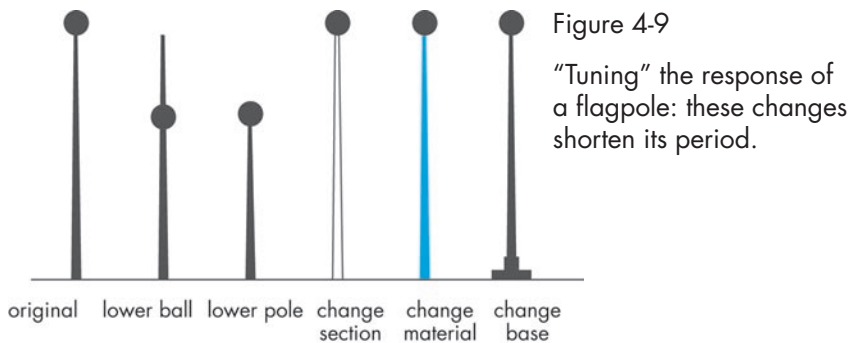
Figure 4-8

Simple response spectrum, for use in seismic codes.

SOURCE: NEHRP, 1997

on this knowledge, the building design might be adjusted to ensure that the building period does not coincide with the site period of maximum response. For the site characteristics shown, with a maximum response at about 0.3 seconds, it would be appropriate to design a building with a longer period of 1 second or more. Of course, it is not always possible to do this, but the response spectrum shows clearly what the possible accelerations at different periods are likely to be, and the forces can be estimated more accurately. Information gained from a response spectrum is of most value in the design of large and high structures.

Figure 4-9

"Tuning" the response of a flagpole: these changes shorten its period.

How does one "tune" a building, or change its period, if it is necessary to do so? One could change the natural period of a simple structure such as a flag pole by any or all combinations of the methods shown in Figure 4-9:

○ Changing the position of the weight to a lower height

○ Changing the height of the pole

○ Changing the sectional area or shape of the pole

○ Changing the material

○ Altering the fixity of the base anchorage

There are analogous possibilities for buildings, though the building is much more complex than the simple monolithic flagpole:

○ Tune the building by ensuring that the structural characteristics of a design are compatible with those of the site as the preliminary design is developed.

○ Incorporate devices in the structure that dissipate energy and change the response characteristics. These devices are discussed in Chapter 7.

○ After the Mexico City earthquake of 1985, a number of damaged buildings had their upper floors removed to lower their period and reduce their mass, thus reducing the likelihood and consequences of resonance.

4.6 DAMPING

If a structure is made to vibrate, the amplitude of the vibration will decay over time and eventually cease. Damping is a measure of this decay in amplitude, and it is due to internal friction and absorbed energy. The nature of the structure and its connections affects the damping; a heavy concrete structure will provide more damping than a light steel frame. Architectural features such as partitions and exterior façade construction contribute to the damping.

Damping is measured by reference to a theoretical damping level termed **critical damping**. This is the least amount of damping that will allow the structure to return to its original position without any continued vibration. For most structures, the amount of damping in the system will vary from between 3 percent and 10 percent of critical. The higher values would apply to older buildings (such as offices and government buildings) that employed a structure of steel columns and beams encased in

concrete together with some structural walls, which also had many heavy fixed partitions (often concrete block or hollow tile), and would have high damping values. The lower values would apply to a modern office building with a steel-moment frame, a light metal and glass exterior envelope, and open office layouts with a minimum of fixed partitions.
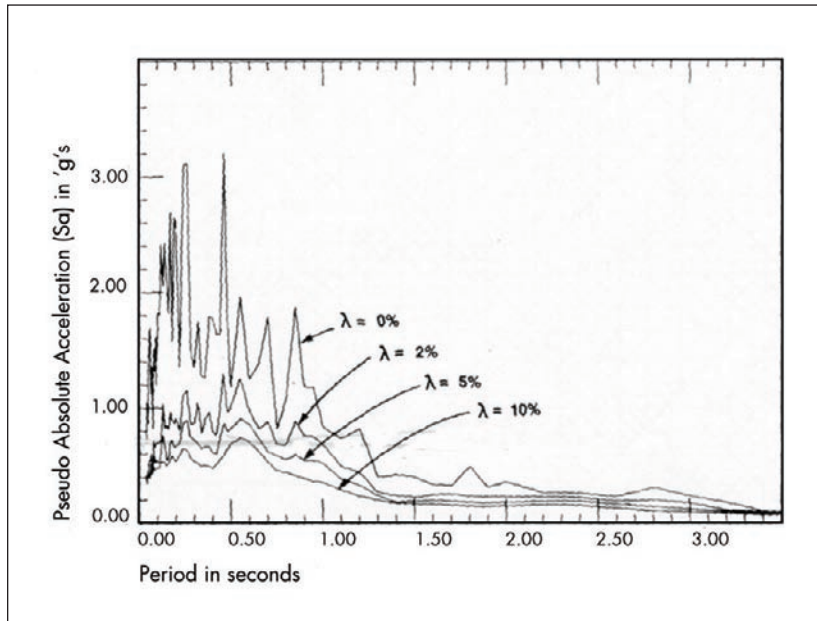

Figure 4-10

Response spectra for a number of damping values.

SOURCE: STRATTA, 1987

The main significance of damping is that accelerations created by ground motion increase rapidly as the damping value decreases. The response spectra shown in Figure 4-10 show that the peak acceleration is about 3.2g for a damping value of 0 %, 0.8g for a damping value of 2 % and a value of about 0.65g for a value of 10 %.

Tables are available that indicate recommended damping values, and the damping characteristics of a structure can be fairly easily estimated. Response spectra generally show acceleration values for 0, 2, 5, and 10 % damping. A damping value of zero might be used in the design of an simple vibrator, such as a flag pole or a water tank supported on a single cantilever column. For typical structures, engineers generally use a value of 5 % critical.

Damping used to be regarded as a fixed attribute of buildings, but in recent years a number of devices have been produced that enable the engineer to increase the damping and reduce the building response. This greatly increases the designer's ability to provide a "tuned" response to the ground motion.

4.7 DYNAMIC AMPLIFICATION

It was early observed and calculated that for most structures, the structural movement is greater than that of the ground motion. The increase of the structural movement over that of the ground motion is commonly referred to as **dynamic amplification**. This amplification is caused when energy is reflected from the P and S waves when they reach the earth's surface, which is consequently affected almost simultaneously by upward and downward moving waves (See Chapter 2, Section 2.3.2). The extent of amplification also varies depending on the dynamic properties of the structure and the characteristics of the initial earthquake ground motion encountered. The important engineering attributes of the structure are:

❍ The period of vibration of the structure

❍ The damping properties of the structure

For typical earthquake motions and for structures having the common damping value of 5 percent damping and a period range of 0.5 seconds to 3.3 seconds, the dynamic amplification factor would be about 2.5, which is a significant increase. For higher damping values, the amplification factor is reduced.

4.8 HIGHER FORCES AND UNCALCULATED RESISTANCE

Even if a building is well damped and is unlikely to resonate, it may be subjected to forces that are much higher than the computed forces for which it was designed. For those familiar with the assumptions of design for vertical loads and the large factors of safety that are added into the calculations, this may seem surprising. Why is this so?

The answer is that to design a building for the very rare maximum conceivable earthquake forces, and then to add a factor of safety of two or three times as is done for vertical loads, would result in a very expensive structure whose functional use would be greatly compromised by

massive structural members and structural walls with very limited openings: the ordinary building would resemble a nuclear power plant or a military bunker.

Experience has shown, however, that many buildings have encountered forces far higher than they were designed to resist and yet have survived, sometimes with little damage. This phenomenon can be explained by the fact that the analysis of forces is not precise and deliberately errs on the conservative side so that the building strength is, in reality, greater than the design strength. In addition, the building often gains additional strength from components, such as partitions, that are not considered in a structural analysis. Some structural members may be sized for adequate stiffness rather than for strength, and so have considerable reserve strength. Materials often are stronger in reality than the engineer assumes in his calculations. Finally, seismically engineered structures have an additional characteristic that acts to provide safety in the event of encountering forces well beyond the design threshold: this is the important property of **ductility**. Taken together, these characteristics, though not all explicit, provide a considerable safety factor or uncalculated additional resistance.

4.9 DUCTILITY

The gap between design capacity (the theoretical ability of a building to withstand calculated forces) and possible actual forces is, finally, largely dealt with by relying on the material property of ductility. This is the property of certain materials (steel in particular) to fail only after considerable inelastic deformation has taken place, meaning that the material does not return to its original shape after distortion. This deformation, or distortion, dissipates the energy of the earthquake.

This is why it is much more difficult to break a metal spoon by bending it than one made of plastic. The metal object will remain intact, though distorted, after successive bending to and fro while the plastic spoon will snap suddenly after a few bends. The metal is far more ductile than the plastic (Figure 4-11).

The deformation of the metal (even in the spoon) absorbs energy and defers absolute failure of the structure. The material bends but does not break and so continues to resist forces and support loads, although with diminished effectiveness. The effect of earthquake motion on a building

Figure 4-11: Ductility
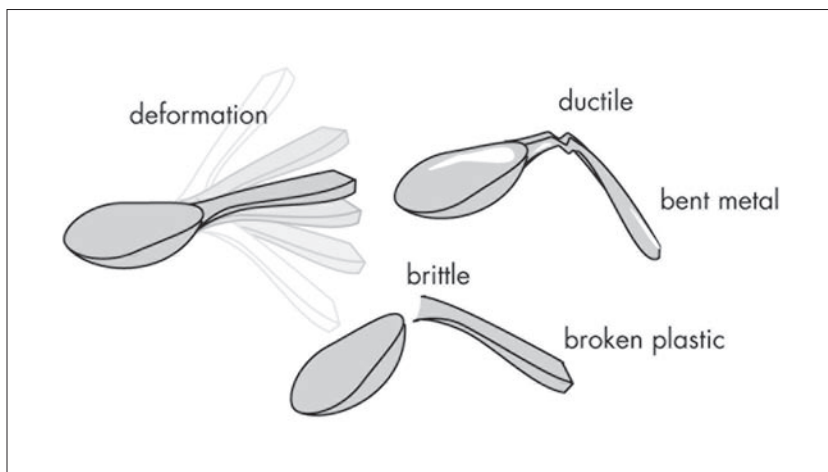
is rather like that of bending a spoon rapidly back and forth: the heavy structure is pushed back and forth in a similar way several times a second (depending on its period of vibration).

Brittle materials, such as unreinforced masonry or inadequately reinforced concrete, fail suddenly, with a minimum of prior distortion. The steel bars embedded in reinforced concrete can give this material considerable ductility, but heavier and more closely spaced reinforcing bars and special detailing of their placement are necessary.

Ductility and reserve capacity are closely related: past the elastic limit (the point at which forces cause permanent deformation), ductile materials can take further loading before complete failure. In addition, the member proportions, end conditions, and connection details will also affect ductility. Reserve capacity is the ability of a complete structure to resist overload, and is dependent on the ductility of its individual members. The only reason for not requiring ductility is to provide so much resistance that members would never exceed elastic limits.

Thus, buildings are designed in such a way that in the rare case when they are subjected to forces higher than those required by a code, the materials and connections will distort but not break. In so doing, they will safely absorb the energy of the earthquake vibrations, and the building, although distorted and possibly unusable, is at least still standing.

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4.10 STRENGTH, STIFFNESS, FORCE DISTRIBUTION, AND STRESS CONCENTRATION

4.10.1 Strength and Stiffness

Strength and stiffness are two of the most important characteristics of any structure. Although these two concepts are present in non-seismic structural design and analysis, the distinction between strength and stiffness is perhaps most critical, and its study most highly developed, in structural engineering for lateral forces.

Sufficient strength is necessary to ensure that a structure can support imposed loads without exceeding certain stress values. Stress refers to the internal forces within a material or member that are created as the structural member resists the applied load. Stress is expressed in force per unit area (for example, pounds per square inch).

Stiffness is measured by deflection, the extent to which a structural member, such as a floor, roof, or wall structure, bends when loaded. Deflection is generally expressed as a fraction of length of the member or assembly. For gravity loads, this is usually the only aspect of stiffness that is of concern. When floor joists are designed for a house, for example, it is often deflection rather than strength that dictates the size of the joists—that is, the depth of the joists is determined by how much they will bend under load rather than by whether they can safely support the floor loads. Typically, an unacceptable amount of bending (in the form of an uncomfortable "springy" feeling to occupants) will occur well before the joists are stressed to the point at which they may break because of overload.

To ensure sufficient strength and stiffness, codes such as the *International Building Code* (IBC) provide stress and deflection limits that are not to be exceeded for commonly used materials and assemblies. For example, interior partitions "shall be designed to resist all loads to which they are subjected, but not less than a force of 5 pounds per square foot applied perpendicular to the walls." In addition, "the deflection of such walls under a load of 5 pounds per square foot shall not exceed 1/240 of the span for walls with brittle finishes and 1/120 of the span for walls with flexible finishes."

Most designers are familiar with deflection in this sense, and have an intuitive feel for this quality. In seismic design, deflection of vertical structural members, such as columns and walls, is termed **drift**. Analogous to the deflection of horizontal members, limitations on drift may impose more severe requirements on members than the strength requirements. Story drift is expressed as the difference of the deflections at the top and bottom of the story under consideration: this is also often expressed as a ratio between the deflection and the story, or floor-to-floor height (Figure 4-12). Drift limits serve to prevent possible damage to interior or exterior walls that are attached to the structure and which might be cracked or distorted if the structure deflects too much laterally, creating racking forces in the member. Thus the IBC requires that drift be limited in typical buildings to between 0.02 and 0.01 times the building height, depending on the occupancy of the building. For a building that is 30 feet high, drift would be limited to between 3.6 inches and 7.2 inches depending on the building type.

Figure 4-12

Story drift ratio.
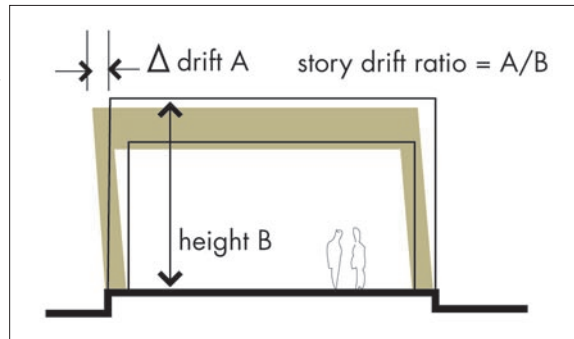
When the earthquake-induced drift is excessive, vertical members may become permanently deformed; excessive deformation can lead to structural and nonstructural damage and, ultimately, collapse.

Thus strength and stiffness are two important characteristics of any structural member. Two structural beams may have approximately equal material strengths and be of similar shape but will vary in their stiffness and strength, depending on how they are oriented relative to the load. This concept can be easily understood by visualizing the flexibility of a narrow, deep beam placed where it has to support a load: the extent of deflection will depend on whether the load is placed on the beams flat surface or on its edge (Figure 4-13).

Figure 4-13: Strength and stiffness.
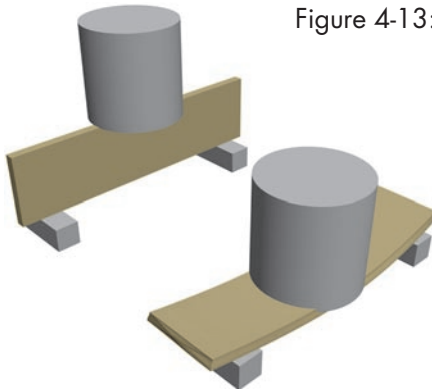
members are approximately equal in strength but their stiffnesses are different.

lateral forces are distributed in proportion to the stiffness of the resisting members.

4.10.2 Force Distribution and Stress Concentration

In seismic design, there is another very important characteristic of stiffness, besides that of deflection. The simple solution of determining the overall lateral force on the building by multiplying the building weight by its acceleration has already been discussed. But the engineer needs to know how this force is allocated to the various resisting structural elements that must be designed: each shares some proportion of this overall force. The answer is that the force is distributed in proportion to the **relative stiffness of the resisting members**. In other terms, the applied forces are "attracted to" and concentrated at the stiffer elements of the building. Thus the engineer must calculate the stiffness of the resisting elements to ascertain the forces that they must accommodate.

The relative rigidities of members are a major concern in seismic analysis. As soon as a rigid horizontal element or diaphragm, such as a concrete slab, is tied to vertical resisting elements, it will force those elements to deflect the same amount. If two elements (two frames, walls, braces, or any combination) are forced to deflect the same amount, and if one is stiffer, that one will take more of the load. Only if the stiffnesses are identical can it be assumed that they share the load equally. Since concrete slab floors or roofs will generally fit into the "rigid diaphragm" classification, and since it is unusual for all walls, frames, or braced frames to be identical, the evaluation of relative rigidities is a necessary part of most seismic analysis problems in order to determine the relative distribution of the total horizontal force to the various resisting elements.

The reason why forces are related to the stiffness of the resisting elements can be understood by visualizing a heavy block supported away from a wall by two short beams. Clearly, the thick, stiff beam will carry much more load than the slender one, and the same is true if they are turned 90 degrees to simulate the lateral force situation (Figure 4-14).

Figure 4-14

Force distribution and stiffness.

vertical load

horizontal force
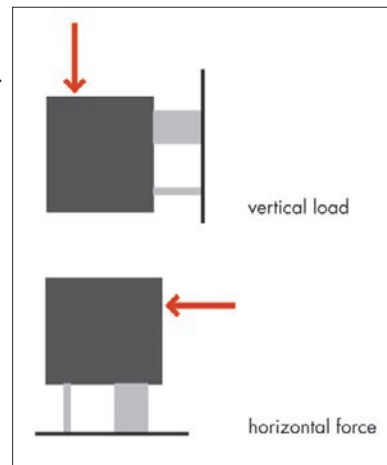
An important aspect of this concept in relation to column lateral stiffness is illustrated in Figure 4-15. In this figure the columns have the same cross-section, but the short column is half the length of the long one. Mathematically, the stiffness of a column varies approximately as the cube of its length. Therefore, the short column will be eight times stiffer (2^3) instead of twice as stiff and will be subject to eight times the horizontal load of the long column. Stress is concentrated in the short column, while the long column is subject to nominal forces.

In a building with members of varying stiffness, an undue proportion of the overall forces may be concentrated at a few points of the building, such as a particular set of beams, columns, or walls, as shown at the top of Figure 4-15. These few members may fail and, by a chain reaction, bring down the whole building. People who are in the building demolition business know that if they weaken a few key columns or connections in a building, they can bring it down. An earthquake also tends to "find" these weak links.
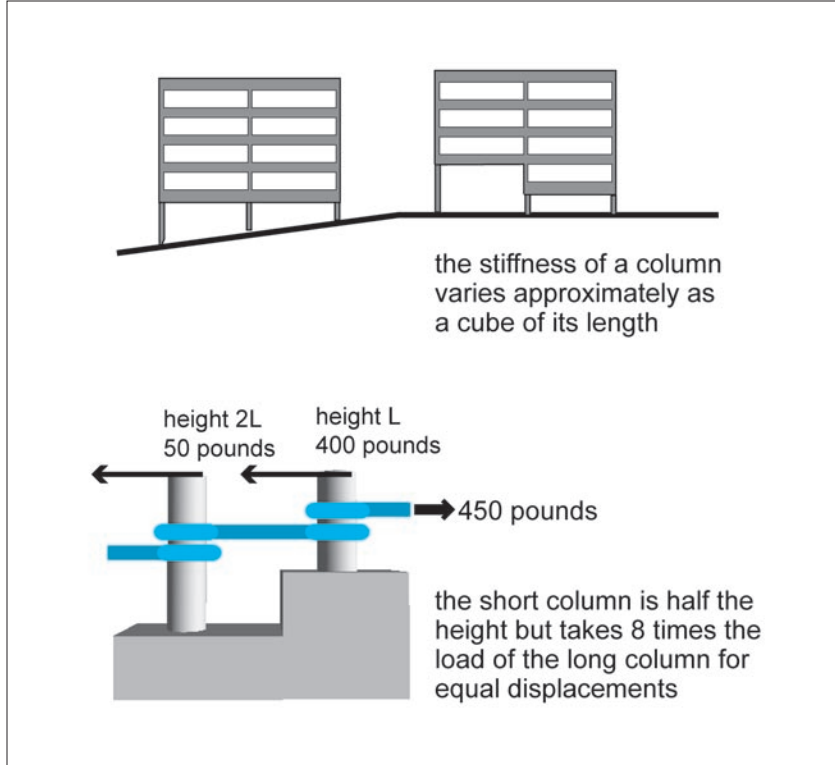
Figure 4-15: The short column problem.

This condition has serious implications for buildings with column or shear walls of different length. In designing a structure, the engineer tries to equalize the stiffness of the resisting elements so that no one member or small group of members takes a disproportionate amount of the load. If this cannot be done - if their size and stiffness vary for architectural reasons, for example – then the designer must make sure that stiffer members are appropriately designed to carry their proportion of the load.

A special case of this problem is that sometimes a short-column condition is created inadvertently after the building is occupied. For example, the space between columns may be filled in by a rigid wall, leaving a short space for a clerestory window. Such a simple act of remodeling may not seem to require engineering analysis, and a contractor may be hired to do the work: often such work is not subject to building department reviews and inspection. Serious damage has occurred to buildings in earthquakes because of this oversight (Figure 4-16).

Figure 4-16

Creation of inadvertent
short columns.

partial floor-height panel infill

short column

failure pattern
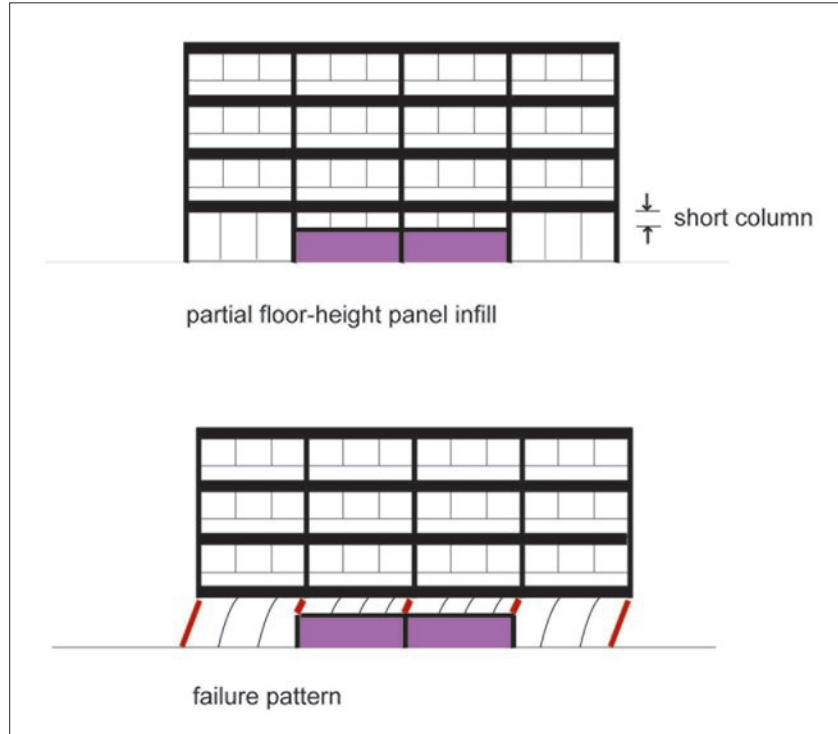
4.11 TORSIONAL FORCES

The center of mass, or center of gravity, of an object is the point at which it could be exactly balanced without any rotation resulting. If the mass (or weight) of a building is uniformly distributed (in plan), the result is that the plan's geometric center will coincide with the center of mass. In a building, the main lateral force is contributed by the weight of the floors, walls, and roof, and this force is exerted through the center of mass, usually the geometric center of the floor (in plan). If the mass within a floor is uniformly distributed, then the resultant force of the horizontal acceleration of all its particles is exerted through the floor's geometric center. If the resultant force of the resistance (provided by shear walls, moment frames, or braced frames) pushes back through this point, dynamic balance is maintained.

Torsional forces are created in a building by a lack of balance between the location of the resisting elements and the arrangement of the building mass. Engineers refer to this as **eccentricity between the center of mass and the center of resistance**, which makes a building subjected to ground motion rotate around its center of resistance, creating torsion

- a twisting action in plan, which results in undesirable and possibly dangerous concentrations of stress (Figure 4-17).

In a building in which the mass is approximately evenly distributed in plan (typical of a symmetrical building with uniform floor, wall and column masses) the ideal arrangement is that the earthquake resistant elements should be symmetrically placed, in all directions, so that no matter in which direction the floors are pushed, the structure pushes back with a balanced stiffness that prevents rotation from trying to occur. This is the reason why it is recommended that buildings in areas of seismic risk be designed to be as symmetrical as possible. In practice, some degree of torsion is always present, and the building code makes provision for this.
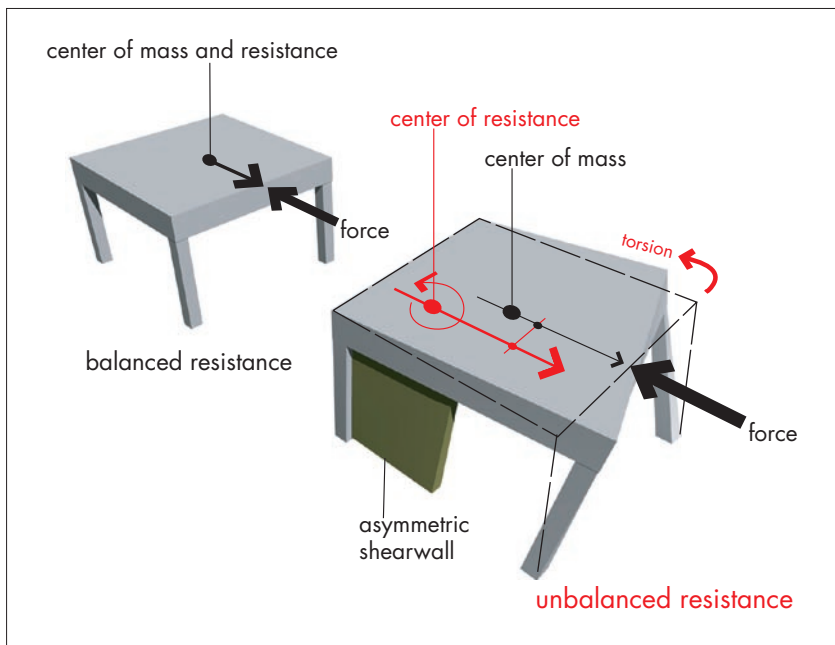

Figure 4-17

Torsional forces.

4.12 NONSTRUCTURAL COMPONENTS

For many decades, seismic building codes focused exclusively on the structure of the building—that is, the system of columns, beams, walls, and diaphragms that provides resistance against earthquake forces. Although this focus remains dominant for obvious reasons, experience
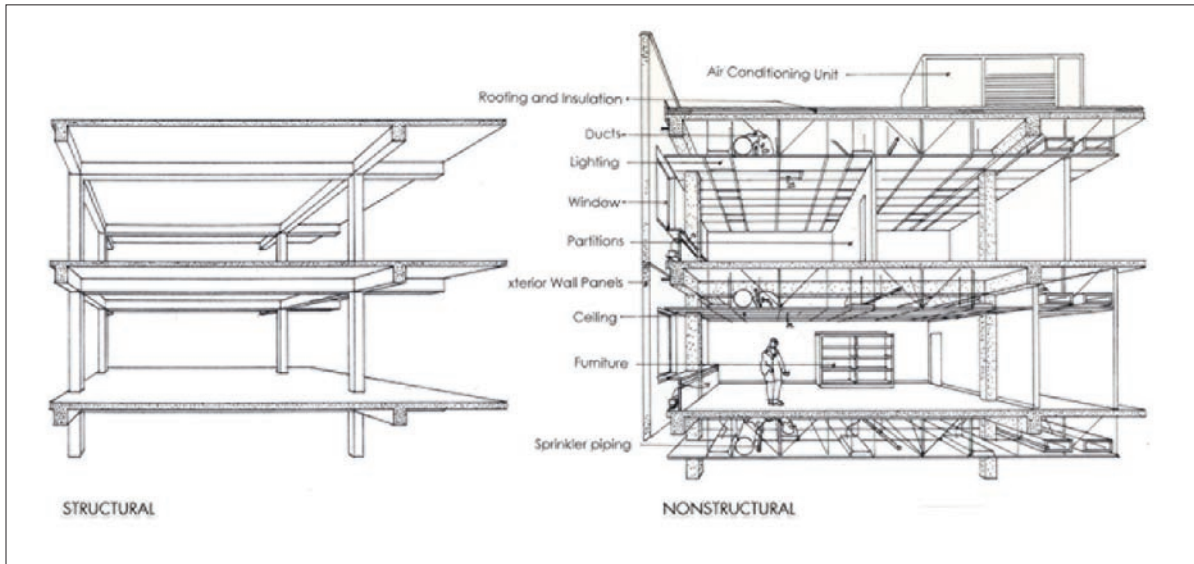
Figure 4-18: Structure (left), nonstructural components and systems (right).

in more recent earthquakes has shown that damage to nonstructural components is also of great concern. In most modern buildings, the non-structural components account for 60 to 80 percent of the value of the building (Figure 4-18). Most nonstructural components are fragile (compared to the building structure), easily damaged, and costly to repair or replace (Figure 4-19).

Figure 4-19

Typical nonstructural damage in school. Northridge earthquake, 1994.

The distinction between structural and nonstructural components and systems is, in many instances, artificial. The engineer labels as nonstructural all those components that are not designed as part of the seismic lateral force-resisting system. Nature, however, makes no such distinction, and tests the whole building. Many nonstructural components may be called upon to resist forces even though not designed to do so.

The nonstructural components or systems may modify the structural response in ways detrimental to the safety of the building. Examples are the placing of heavy nonstructural partitions in locations that result in severe torsion and stress

concentration, or the placement of nonstructural partitions between columns in such a way as to produce a short column condition, as described in Section 4.10 and illustrated in Figure 4-16. This can lead to column failure, distortion, and further nonstructural damage. Failure of the fire protection system, because of damage to the sprinkler system, may leave the building vulnerable to post-earthquake fires caused by electrical or gas system damage.

4.13 CONSTRUCTION QUALITY

One other characteristic that applies to any structure may be obvious, but must be emphasized: the entire structural system must be correctly constructed if it is to perform well. Lateral forces are especially demanding because they actively attempt to tear the building apart, whereas vertical loads (with the exception of unusual live loads such as automobiles or large masses of people) sit still and quiet within the materials of the building.

The materials of the seismically resistant structure must have the necessary basic strength and expected properties, but most importantly, all the structural components must be securely connected together so that as they push and pull against one another during the earthquake, the connections are strong enough to transfer the earthquake forces and thereby maintain the integrity of the structure.This means that detailed design and construction of connections are particularly important.

The correct installation of reinforcing steel and anchors in concrete structures; the correct design, fabrication and installation of connection members in steel structures; and correct nailing, edge clearances and installation of hold-downs in wood framing are all critical. For nonstructural components, critical issues are the maintenance of correct clearances between precast concrete cladding panels, at seismic separation joints, and between glazing and window framing, and the correct design and installation of bracing of heavy acceleration-sensitive components such as tanks, chillers, heavy piping, electrical transformers and switch gear.

Quality control procedures must be enforced at all phases of design and construction, including material testing and on-site inspection by qualified personnel. The earthquake is the ultimate testing laboratory of the construction quality of the building.

4.14 CONCLUSION

This chapter has discussed a number of key characteristics of earthquake ground shaking that affect the seismic performance of buildings. In addition, a number of building characteristics have been reviewed that, together with those of the ground, determine the building's seismic performance: how much damage the building will suffer. These characteristics are common to all buildings, both new and existing, and all locations.

The building response to earthquake shaking occurs over the time of a few seconds. During this time, the several types of seismic waves are combining to shake the building in ways that are different in detail for each earthquake. In addition, as the result of variations in fault slippage, differing rock through which the waves pass, and the different geological nature of each site, the resultant shaking at each site is different. The characteristics of each building are different, whether in size, configuration, material, structural system, method of analysis, age, or quality of construction: each of these characteristics affects the building response.

In spite of the complexity of the interactions between the building and the ground during the few seconds of shaking there is broad understanding of how different building types will perform under different shaking conditions. This understanding comes from extensive observation of buildings in earthquakes all over the world, together with analytical and experimental research at many universities and research centers.

Understanding the ground and building characteristics discussed in this chapter is essential to give designers a "feel" for how their building will react to shaking, which is necessary to guide the conceptual design of their building. The next chapter continues this direction by focusing on certain architectural characteristics that influence seismic performance - either in a positive or negative way.

4.15 REFERENCES

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4.16 TO FIND OUT MORE

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