Appendix C

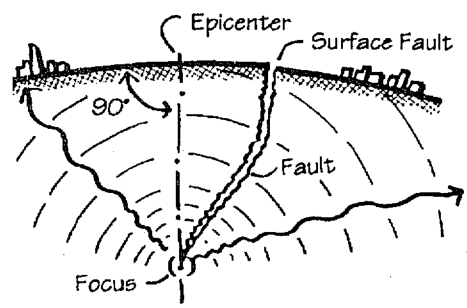
EARTHQUAKES, BUILDINGS, AND THE *NEHRP RECOMMENDED PROVISIONS*

The information that follows in this appendix has been excerpted from another book prepared for FEMA by the BSSC, *A Nontechnical Explanation of the 1994 NEHRP Recommended Provisions* (FEMA Publication 99). Those readers who find this appendix of interest and would like to learn more about how the *Provisions* treats seismic design are encouraged to order this free document from the BSSC.

THE NATURE OF EARTHQUAKE GROUND MOTION

The Origin of Earthquakes

Most earthquakes are the result of abrupt slippage along a fault zone below the surface of the earth. This slippage eventually may result in "*surface faulting*," the cracking or breaking apart on the earth's surface that typifies movie visions of earthquakes.

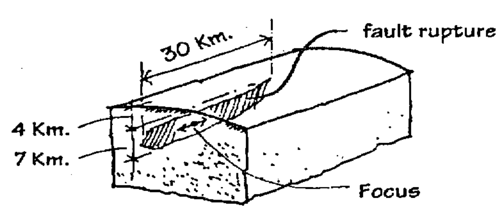


The point where the first slip on the fault occurs is called the "*focus*" or "*hypocenter*." The "*epicenter*" is a theoretical point on the earth's surface that is vertically above the focus. The earthquake starts at the focus, not the epicenter.

Faults and Waves

There are several kinds of faults but, for seismic design purposes, the concern is not what kind of fault slippage generated when the fault slips occurs, but rather what will be the nature of the ground motion to which the building will be subjected.

There is often extensive surface faulting in large earthquakes in the immediate vicinity of the fault. In the 1906 California earthquake, the fault broke the surface over a distance of over 200 miles with lateral movement of as much as 20 feet. In the 1992 Landers earthquake, east of Los Angeles, the fault broke the surface over a distance of 48 miles with lateral movements of up to 18 feet reported.



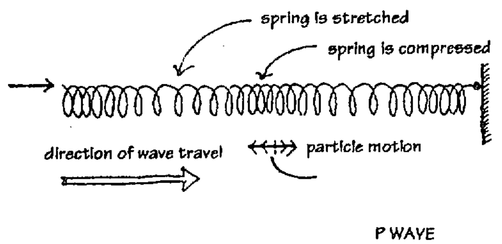
LOMA PRIETA FAULT RUPTURE

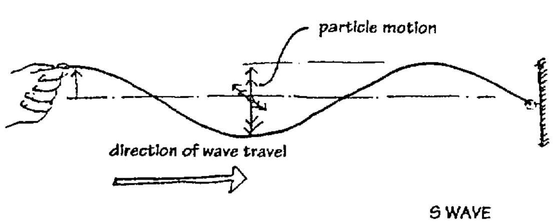
When such a large movement occurs, a building straddling the fault would be severely damaged since no building can be designed to deal with such large ruptures. However, this kind of disturbance of the ground is generally quite narrow in width to either side of the fault (in Landers, the maximum width of severely disturbed ground was about 125 feet. Beyond this area, structures are affected only by general ground shaking, and this is what seismic design is intended to deal with. Since almost all building damage is caused by ground motion rather than by fault rupture, this strategy makes sense.

Once the fault slips, the rupture spreads rapidly along the fault. The rupture creates waves of vibration deep in the earth that spread in all directions from the point of inception and along the fault. The seismic waves begin like ripples in a still pond when a pebble is thrown into it, but they rapidly become much more complex.

Because the waves spread not only from the focus but also along the length of the fault rupture as it spreads rapidly along the fault, the intensity of the ground shaking has *directivity* – that is, the waves of vibration are of greater magnitude and last longer in the direction of fault rupture. In addition, the heavy shaking tends to reduce more rapidly in the direction normal to the fault line so that the area of heavy shaking has an elongated shape when viewed from above, instead of being a circle that is centered on the focus.

Studies of recent large earthquakes, such as Landers, Northridge and Kobe, also have shown that a few large pulses of long-period energy often occur towards the beginning of the earthquake close to the fault line. Because of the directivity effect, these large pulses can cause severe and almost instantaneous damage to relatively large, long-period buildings and structures such as bridges that are located close to and along the line of the fault.





There are four main types of seismic waves: two "body" waves within the earth and two "surface" waves confined to the surface layers of the earth. All four are considered in design. First to arrive at the surface is the *P* or *primary* wave. In this wave, the ground is successively pushed and pulled along the wave front. The motion of the ground is analogous to that of a coil spring when one end of the spring is moved. Successive waves can be created that move along the spring from one end to the other, alternately stretching and compressing the coils. A point on a coil – analogous to a spot on the ground – will announce the arrival of the wave by an abrupt movement in the direction of the wave and then will move only back and forth.

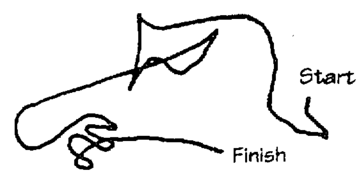
The *P* wave is followed by the *S* or *secondary* or *shear* wave, which is a motion at right angles to the wave front. This can be represented by pulling one end of a horizontal rope rapidly up and down to create waves that travel the length of the rope. A point on the rope will move only perpendicular to the direction of the rope which, for the ground, represents both lateral and vertical motion. When the wave reaches the surface, the motion is mostly horizontal. Just as the *P* wave travels faster than the *S* wave, the back and forth motion of a particle in the *P* wave is faster than the sideways motion of a particle in the *S* wave.

The *P* wave produces a jolt followed soon after by the "rolling" motion of the *S* wave. The two other waves are only at the earth's surface; the *Rayleigh* wave is an elliptical wave in the vertical plane and the *Love* wave is a surface wave that produces sideways motion similar to that of the *S* wave.

These different waves can be identified on records generated by modern strong-motion instruments and an observer some distance from the epicenter often can feel the difference between the "punch" of the primary wave and the "roll" of the secondary wave.

Within a few seconds, all the waves participate and the result is a random wave motion, predominantly in all horizonal directions but also somewhat vertical. The actual ground movement (and consequent building motion) is small, even in a major earthquake, except in the immediate vicinity of a fault rupture. The problem for a building is that the result is hundreds or thousands of tons of steel, concrete, and other materials moving back and forth a few inches in a very violent manner.

Although study of building damage after earthquakes generally shows a clear direction to the shaking (buildings will suffer varying damage depending on the orientation of their long or short sides), this seismic direction cannot be anticipated and therefore does not influence design.

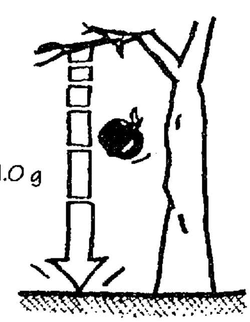


Scratch left on the floor by a kitchen range in the 1933 Long Beach, California earthquake.

Although seismic waves create ground motion that is predominately horizontal, there also often is considerable vertical motion. However, all buildings are designed to withstand vertical loads – the weight of the building and its contents – and large safety factors are used (that is, the calculated loads are multiplied by 2 or 3 to determine the loads for which the building is designed). These large safety factors mean that vertical earthquake forces are generally not a problem, but there are rare cases in which the vertical seismic forces exceed gravity, and buildings and other objects may be tossed into the air. Such was the case in the 1971 San Fernando earthquake when a fireman was tossed out of bed onto the floor and his bed fell on him. Large vertical accelerations in the Northridge earthquake also are believed to be responsible for some of the damage. In spite of these instances, however, seismic design and seismic codes focus on providing resistance to the horizontal forces that try to abruptly push buildings and objects sideways in all directions.

Forces and Gravity

The seismic body and surface waves create inertial forces within the building. These are the forces that may cause damage and are what seismic design tries to cope with. Inertial forces are created within an object when an outside force tries to make it move if it is at rest or change its rate or direction of motion if it is already 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 in motion and must obey this law just as if it were a plane, a ship, or an athlete. Newton's Second Law of Motion states, in essence, that an *inertial force, F, equals mass, M, multiplied by the acceleration, A.*



32 ft. per sec²

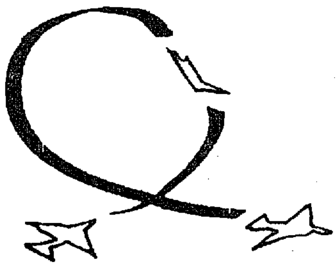
ONE "G" (NEWTON'S APPLE)

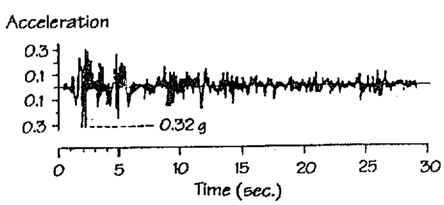
Mass can be taken as equivalent (at ground level) to the weight of the building and so this part of the law explains why light buildings, such as wood frame houses, tend to perform better in earthquakes than large heavy ones – the forces on the structure are less.

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." 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 1 "g." A building in an earthquake experiences a fraction of a second of "g" forces in one direction before they abruptly change direction.

FORCE = MASS x ACCELERATION

Engineering creations (planes, ships, cars, etc.) that are designed for this dynamic or moving environment can accommodate very large accelerations. Military jet planes, for example, are designed for accelerations of up to 9 "g." At this acceleration, the pilot experiences 9 times his body weight pressing down on his organs and blacks out. A commercial airliner in fairly severe turbulence may experience about 20 percent "g" (or 0.2g) as may a fast moving train on a rough track.


Military Jet - 9 g



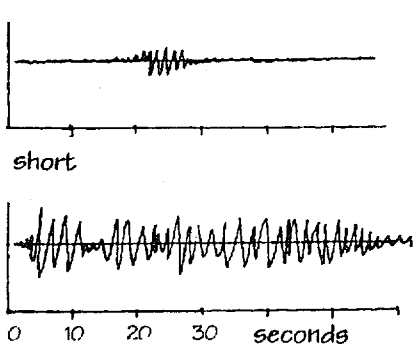
ACCELERATION

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 20 percent "g." For people on the ground or at the bottom of a building, the sensations will be very similar to those of the occupants of a plane in turbulence or passengers in the corridor of a fast moving train over a somewhat uneven track: they feel a little unsteady and may need to grab on to something to help them remain standing. In large earthquakes, the heavy shaking will last for more than a few seconds but, except for rare major events, will not reach one minute. Sustained accelerations may, for a fraction of a second, be as high as 0.6 or 0.7 "g." Acceleration "spikes" – single very short duration accelerations – that reach almost 2 "g" have been recorded by instruments but these are so rapid that they do not damage the building and are not sensed by people.


ACCELERATION "SPIKE"

Duration, Velocity, and Displacement

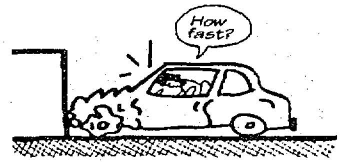
Because of the inertial force formula, acceleration is a key factor in determining the forces on a building, but other characteristics of the earthquake waves also are important.



DURATION

One of these has already been mentioned. This is *duration* – how long the heavy shaking lasts. Although those who have experienced bad earthquakes believe the shaking lasts a lifetime, in fact almost all significant earthquake shaking can be measured in a few seconds. Duration is important because continued shaking weakens a building structure and reduces its resistance to earthquake damage.

Two other measures are directly related to acceleration and can be mathematically derived from it. *Velocity,* which is measured in inches per second or centimeters per second, refers to the rate of motion at any given instant. For example, when a moving car hits an obstacle, it suddenly decelerates and, if the car occupants are not belted in and there are no airbags, they lurch forward toward the windshield. How fast, at that instant, are the occupants moving? The abrupt stop determines the extent of occupant injury and also affects the extent of damage to a structure.



VELOCITY

Displacement, measured in inches or centimeters, refers to the distance a point on the ground is moved from its initial location. Points in a building affected by shaking also will be moved to a comparable, or greater, extent so that this affects the structure (and also the comfort and security of the building occupants).

Acceleration, velocity, and displacement are mathematically and physically related and can be derived from one another.

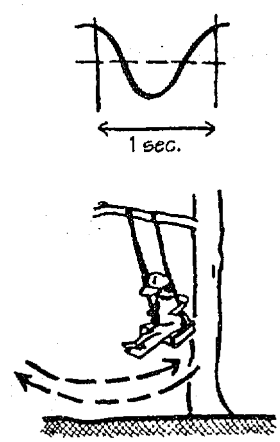
CRITICAL BUILDING CHARACTERISTICS

So far, we have been describing the *input motion* – the characteristics of ground motion that affect the building. However, there also are some important things about a building itself that, *in conjunction with* the ground motion, affect its performance and may dictate whether it collapses or survives.

Period and Amplification

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.

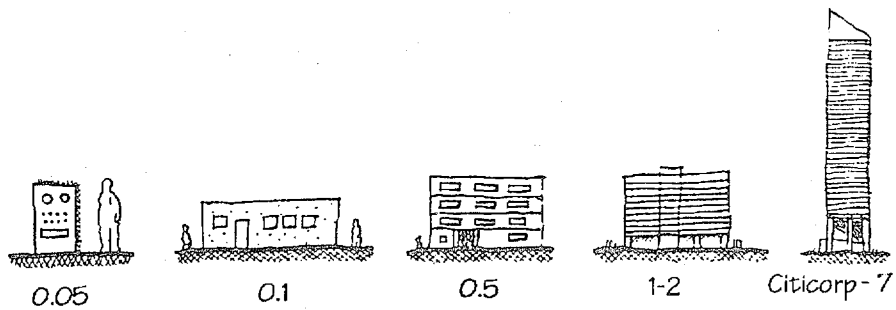
All objects have a *natural or fundamental* period; this is the rate at which they will move back and forth if they are given a horizontal push. In fact, without dragging it back and forth, it is not possible to make an object vibrate at anything other than its natural period. When a child in a swing 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.



NATURAL, or FUNDAMENTAL PERIOD

When a vibrating structure is given further pushes that are also at its natural period, the structure tends to *resonate.* 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.

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

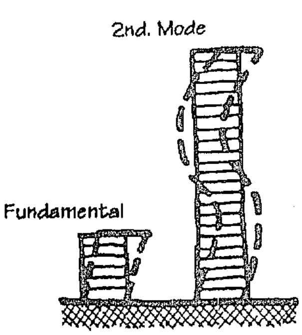


FUNDAMENTAL PERIODS

vibrate at 1/0.05 = 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 *1 to 2 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 building in New York has a 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 construction materials, which affect the stiffness of the structure, and the building's geometric proportions also affect the period, but height is the most important consideration.

Taller buildings also will undergo several *modes of vibration* so that the building will wiggle back and forth like a snake. For seismic purposes, however, the natural period generally is the most significant.

The ground, of course, also vibrates at its natural period. The natural period of ground in the United States varies from about *0.4 seconds* to *2 seconds* depending generally on the hardness of the ground. Very soft ground may have a period of up to *2 seconds* since 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 the ground gives the building will be at the natural period of the building. This may create *resonance*, causing the structure to have to deal with accelerations of perhaps *1 "g"* when the ground is only vibrating with accelerations of *0.2 "g."*

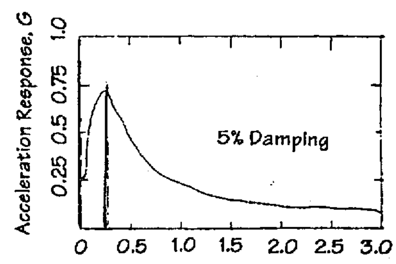


MODES OF VIBRATION

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. Mexico City was some 250 miles from the earthquake focus, and the earthquake caused the soft ground under the downtown buildings to vibrate for over 90 seconds at its long natural period of around 2 seconds. This caused tall buildings between about 10 and 20 stories to resonate at a similar period, greatly increasing the accelerations within them. 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.

There is also a more general amplification effect related to different types of ground. Earthquake ground shaking tends to be greater on soft ground than on hard ground such as rock. 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. Studies after the 1989 Loma Prieta earthquake also showed that shaking in the soft ground around San Francisco Bay was two and a half to three and a half times that of shaking in rock. 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.

To assist the engineer in determining whether there may be a problem because the period of a new building is close to that of the site, curves for the site can be drawn (based on information about the nature of the ground) that show estimates of the periods at which *maximum building response* is likely – that is, the building periods for which maximum shaking can be anticipated. Such a curve is termed the *site response spectrum*. This spectrum shows the accelerations (on the vertical ordinate) that may be expected at varying periods (the horizontal ordinate). Thus, the response spectrum illustrated shows a maximum response at a period of about 0.3 seconds – the fundamental period of a mid-rise building. Based 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 figure 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 building can then be designed accordingly.



TYPICAL SITE RESPONSE SPECTRUM

Damping

The important relationship between the building and ground motion periods was illustrated in above using a the child's swing to show how the swinging motion is amplified by an *input motion*, in this case a judicious push. However, the child's swing is a pendulum that vibrates very efficiently and continue to swing for many minutes after any assistance even though the amplitude will diminish. Buildings and other objects do not swing as efficiently as pendulums because the vibration is *damped* or reduced. The extent of damping in a building depends on the materials of construction, how those materials are connected together, and on its architectural elements such as partitions, ceilings, and exterior walls.

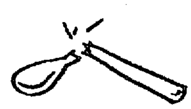
Higher Forces and Uncalculated Resistance

Even if a building is well damped and will not resonate, it may be subjected to forces that are much higher than the computed forces for which it was designed. Why is this the case? Because designing a building for the rare maximum conceivable earthquake forces and then adding 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 impeded by huge walls and columns.

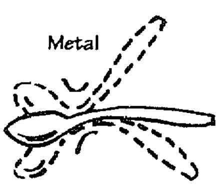
Experience shows, however, that many buildings have encountered forces far higher than they were designed to resist and yet have survived, sometimes with little damage. This phenomenon can be explained by the fact that the analysis of forces is not precise and deliberately errs on the conservative side so that the building can really survive higher forces than is apparent. In addition, the building often gains additional strength from components, such as partitions, that are not considered in an analysis. Some structural members may be sized for adequate stiffness rather than for strength. Finally, materials often are stronger in reality than the engineer assumes in his calculations. Taken together, these factors provide a considerable safety factor or uncalculated additional resistance.

Ductility

An additional property of materials is used to ensure that a building may adequately resist much more than its design ground shaking. This material property is called *ductility*. Ductility is the characteristic of certain materials – steel in particular – to fail only after considerable distortion or deformation has occurred. 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.



BRITTLENESS



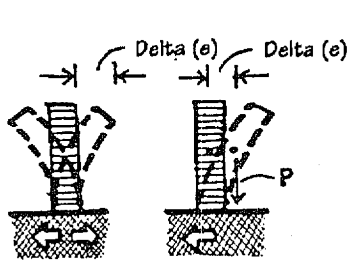
DUCTILITY

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 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 brickwork or unreinforced concrete, fail suddenly with a minimum of distortion. However, the steel contained in a well designed modern reinforced concrete structure can give the combined material the ductility that is needed for earthquake resistance.

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.

Overturning



P-DELTA

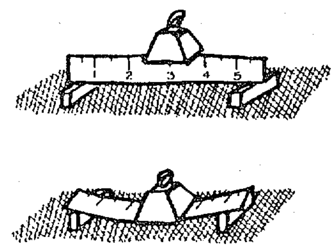
Although building mass or weight was discussed as part of the *F = MA* equation for determining the horizontal forces, there is another way in which the building's weight may act under earthquake forces to overload the building and cause damage or even collapse.

Vertical members such as columns or walls may fail by *buckling* when the mass of the building exerts its gravity force on a member distorted or moved out of plumb by the lateral forces. This phenomenon is known by engineers as the *P-e or P-delta* effect, where *P* is the gravity force or weight and e or delta is the eccentricity or the extent to which the force is offset. All objects that overturn do so as a result of this phenomenon.

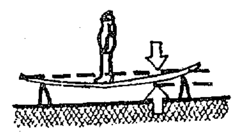
The geometrical proportions of the building also may have a great influence on whether the *P-delta* effect will pose a problem since a tall slender building is much more likely to be subject to overturning forces than a low squat one. However, in earthquakes, buildings seldom overturn. This is because structures are not homogeneous but are composed of many elements connected together; the earthquake forces will pull the components apart and the building will fall *down*, not over. Strong, homogeneous structures such as filing cabinets, however, will fall over.

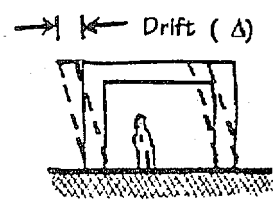
Strength, Stiffness, and Drift

Two important related characteristics of any structure are its *strength* and its *stiffness*. Two structural beams may be equally strong (or safe) in supporting a load but may vary in their stiffness – the extent to which they bend or *deflect* in doing so. Stiffness is a material property but it also is dependent on *shape*. This concept can be easily understood by visualizing the flexibility of a long ruler placed where it has to support a load; how well it supports the load will depend on whether the load is placed on the ruler's flat surface or on its edge.


STIFFNESS, STRENGTH

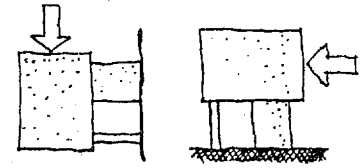
The measure of stiffness is *deflection*, the extent to which a structural element moves or bends when loaded. For vertical gravity loads, this is usually the only aspect of stiffness that is of concern. When floor joists are designed for a house, for example, it is often deflection rather than strength 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 will occur well before the joists are stressed to the point at which they may break because of the loads. (Stress refers to the internal forces within a material or member. The stress is created as the structural member resists the applied load. Stress is expressed in force per unit area – for example, pounds per square inch. Codes provide stress limits that are not to be exceeded for commonly used materials.)


DEFLECTION

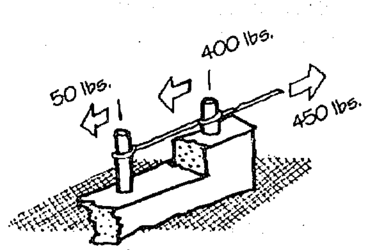


DRIFT

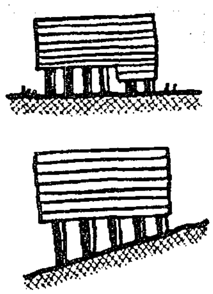
The analogous lateral force condition occurs when limitations on *drift*, the horizontal story-to-story deflection, impose more severe requirements on members than the strength requirements. Drift limits serve to prevent possible damage to interior or exterior walls that are attached to the structure and which might be cracked or distorted if the structure deflects too much laterally. The strength issue involves using a material strong enough to resist a load without exceeding a safe stress in the material while the drift issue involves preventing a structure from moving out of vertical alignment more than a given amount.



In seismic design, there is another very important aspect to stiffness. The problem of determining the overall lateral force on the building by multiplying the building weight by its acceleration has already been discussed. But how is this force distributed among the various elements of a building? The engineer needs to know this so that each member and connection can be properly designed to withstand the forces it may encounter. *Relative stiffness* enters into this issue because the applied forces are "attracted to" and concentrated at the stiffer elements of the building – in engineering terms, the forces are *distributed in proportion to the stiffness of the resisting elements.*



Why this is so 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.

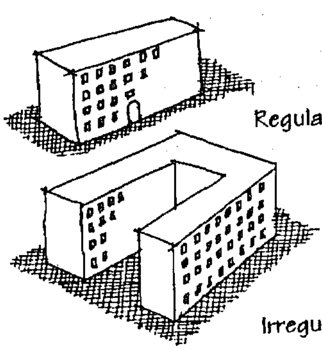

SHORT COLUMNS

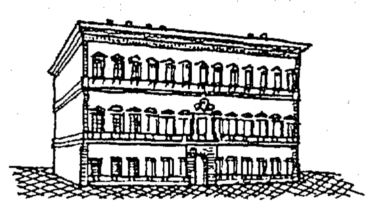
An important aspect of this for column lateral stiffness is illustrated in the next sketch. Mathematically, the stiffness of a column approximately varies as the cube of its length. In this diagram, the columns have the same cross-section but the short column is half the length of the long one. Therefore, the short column will be *eight* times stiffer (2^3) instead of *twice* as stiff and will take *eight times the horizontal load* of the long column. This concept has serious implications for buildings with columns of different lengths, and in designing a building, 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 (for architectural reasons, for example), then the designer must make sure that stiffer members are appropriately designed to carry their proportion of the load.

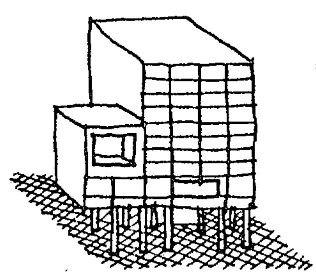
Building Size and Shape

The size, shape, and geometrical proportions of a building are termed its *configuration*. How the building configuration relates to its structural systems has a major influence on the building's ability to withstand shaking.

Many years ago when engineers first started studying the earthquake problem in a systematic way, they noticed that buildings with certain shapes and proportions seemed to be more prone to damage in earthquakes than others no matter what construction materials or structural systems had been used. In general, the more *irregular* the building – that is, the more the building deviated from a regular simple symmetrical shape – the more likely it seemed to suffer damage.



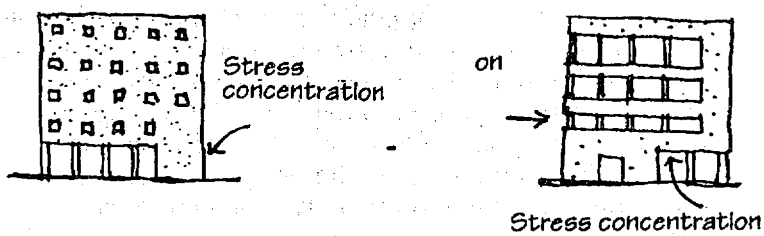

Decorated box


Modern structure

In the past, buildings tended to have simple configurations because traditional materials such as stone and brick did not allow for much more than superficial or surface decorative irregularity in design. (Sometimes, as in a medieval Gothic cathedral or a Renaissance Italian palace, this surface "irregularity" achieved the highest and most enduring form of art.) But starting in the late nineteenth century, modern steel and reinforced concrete frame construction allowed for increased structural daring and permitted architects to conceive designs that would have been impossible with traditional masonry. Configuration irregularity results in two main effects – stress concentrations and torsional forces.

Stress Concentrations

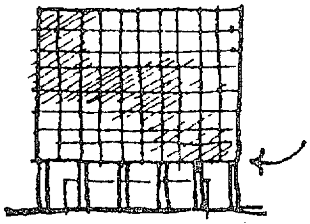
Irregularities tend to create abrupt changes in strength or stiffness that may concentrate forces in an undesirable way. These can be very difficult to deal with even in a modern structure. So, although the size of the overall force that the building must withstand is determined by the $F = MA$ equation, the way in which this is *distributed and concentrated* is determined by the configuration.



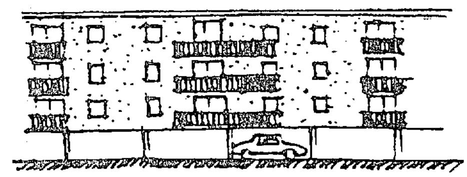
Stress concentration means that an undue proportion of the overall forces is concentrated at one or a few points of the building such as a particular set of beams, columns, or walls. These few members may fail and, by a chain reaction, bring down the whole building. Because, as has been noted, forces are attracted to the stiffer elements of the building, these also tend to be locations of stress concentration. 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."

Stress concentration can also be created by vertical irregularity. The most serious condition of vertical irregularity is that of the *soft*, or weak, story in which one story, usually the first, is significantly weaker or more flexible than those above. A high first story is often architecturally desirable to accommodate larger rooms – lobbies, banking floors, or hotel meeting rooms. The design creates a major stress concentration at the points of discontinuity and, in extreme circumstance, may lead to collapse unless adequate design is provided at such points. A common example of the soft first story occurs in apartment houses, which often allocate all or most of the first floor to parking, with widely spaced columns and a minimum of walls.

The first floor of the Northridge Meadows apartments, designed before the problem of the soft first story was fully understood, collapsed in the 1994 Northridge earthquake, with considerable loss of life. Many other similar apartments also collapsed or were severely damaged, but fortunately only automobiles were destroyed.



Soft story

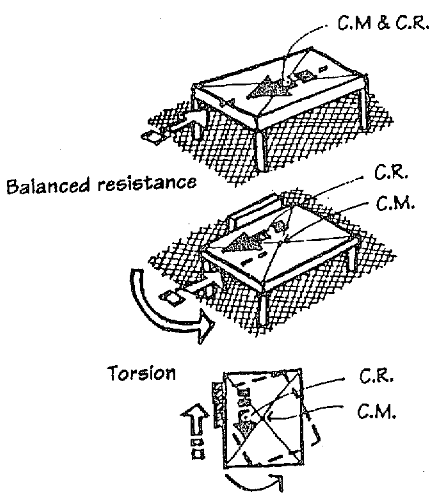


NORTHRIDGE MEADOWS APARTMENTS

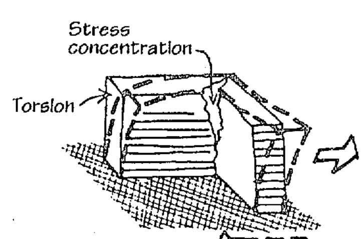
Torsional Forces

In addition to stress concentrations, irregularities, particularly in plan, may permit what are called *torsional* or twisting forces to develop, which contributes a significant element of uncertainty to an analysis of building resistance. ("Plan" refers to the horizontal layout of the building which may be a simple square or rectangular or an irregular shape with wings of different shapes and proportions.)

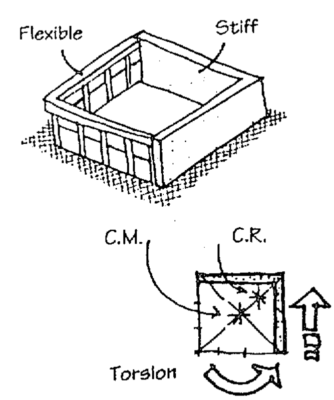
Torsional forces are created in a building by a lack of balance between the location of the resisting elements and the arrangement of the building mass. Engineers refer to this as *eccentricity* between the *center of mass* and the *center of resistance*, which tends to make the building rotate around the latter and creates torsion in the resisting elements. 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 resistance provided by walls and columns pushes back through this point (the center of resistance), then there is no torsion and balance is maintained. If not, torsion is introduced and dangerous concentrations of stress can be created. This is the reason why it is recommended that buildings in areas of seismic risk be designed to be as symmetrical as possible.



TORSION



L-SHAPED BUILDING



PERIMETER VARIATION

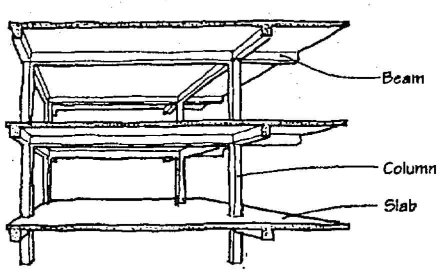
One building configuration that is most likely to produce torsion features *re-entrant corners* (buildings shaped like an L or a T for example). The wings of such buildings tend to twist and produce torsional forces. In addition, re-entrant corner buildings also tend to produce *stress concentration* at the "notch" where the wings meet because this location often is stiffer and therefore attracts a higher proportion of the forces.

Buildings that have large *variations in their perimeter resistance* on different sides of the building also tend to produce torsion. This form of variation in perimeter resistance occurs often in buildings such as stores in which side and end walls may be masonry or concrete party walls while the front wall may be largely glass. The centers of mass and resistance do not balance and, in extreme cases, the building can tear itself apart.

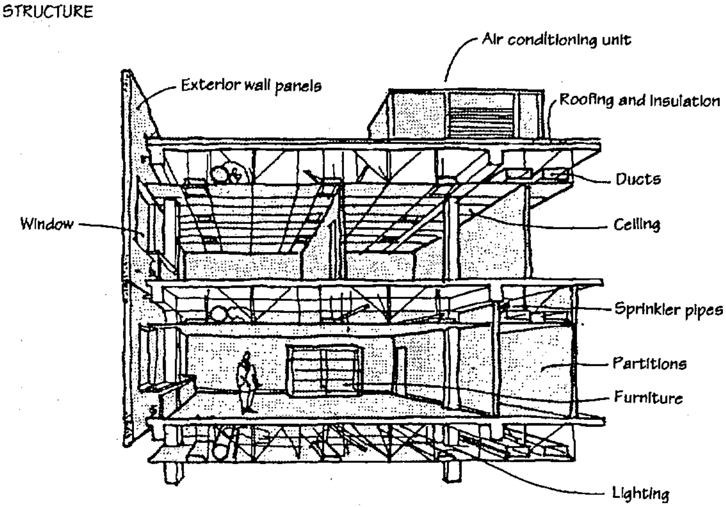
Nonstructural Components

For a long time, 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 in more recent earthquakes has shown that damage to *nonstructural components* is also of great concern. In most modern buildings, the nonstructural components account for 60 to 80 percent of the value of the building.

Nonstructural components surround us at work or at home – ceilings, partitions, light fixtures, windows, and exterior walls. They are also the components that enable the building to function – the power, heating, cooling, and elevator systems and, for buildings like hospitals, the medical equipment that maintains or saves lives. Damage to nonstructural components



STRUCTURE



NONSTRUCTURE (shaded)

can result in great economic loss, in terms of both the cost of repair and the loss of building use and business interruption while the building is closed for repair. If the building is a critical facility such as a hospital, damage to utility systems providing such things as water and power may shut the building down when it is most needed.

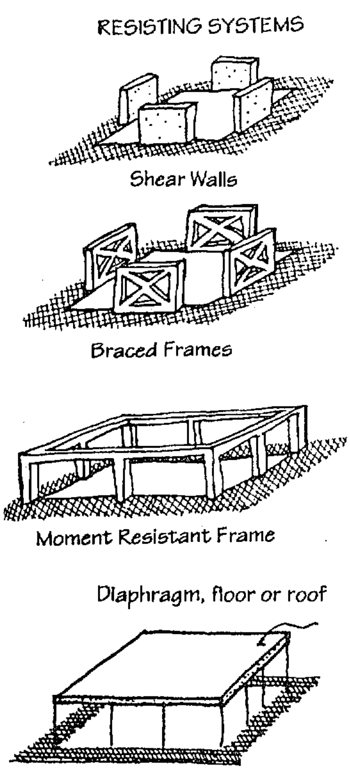
Nonstructural damage often is caused by movement of the building structure that is perfectly acceptable as far as the safety and stability of the structure is concerned. But the nonstructural components and finishes that are rigidly attached to the structure are bent and twisted in way that they cannot accommodate with the result that tiles fall off walls and plaster partitions and ceilings crack. This kind of damage is hazardous to occupants and can be difficult and expensive to repair.

Construction Quality

One other characteristic that applies to any building must be mentioned: it must be constructed well if it is to perform well. The materials from which it is constructed must have the necessary basic strength and expected properties. Most important, all the building's 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.

Framing Systems

How does an engineer design a building to resist all the forces that are produced by ground motion? Essentially, he must choose from a small set of components and then combine them in his design to form a complete resistance system.



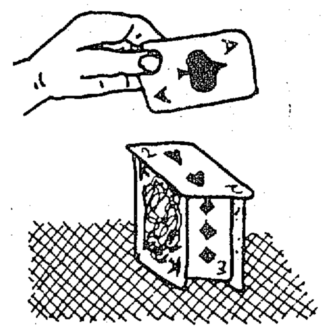
Three kinds of framing systems can resist the lateral forces generated in a building by an earthquake – *shear walls, braced frames*, and *moment resisting frames* (sometimes called rigid frames). These three types of framing system are really alternatives. Although designers sometimes mix components, using one type in one direction and another type in the other, this is inadvisable, mainly because the different systems have different stiffnesses and it is difficult to obtain balanced resistance when they are mixed.

Thus, the designer generally chooses only one type of framing system to resist the applied loads. This must be done at an early stage in the design because the different characteristics of these components have a considerable effect on the architectural design, both functionally and aesthetically. For example, if shear walls are chosen as the *seismic force resisting system*, the building will feature a pattern of permanent structural walls that run through every floor from roof to foundation. While this may be acceptable if the building is to be an apartment house or hotel, it will not work well if the building is to be a rental office building where internal space requirements will change regularly.

It should be noted that moment resistant frames sometimes are combined with one of the other systems to produce a *dual system*, in which the moment resistant frame backs up the other system. In this case, the two systems interact to share the load.

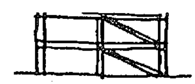
In the horizontal plane, *diaphragms,* generally formed by the floor and roof elements of the building, are necessary. (Sometimes, however, horizontal bracing systems independent of the roof or floor structure serve as diaphragms.) Diaphragms transfer the lateral forces to the vertical resistant elements – the shear walls or frames.

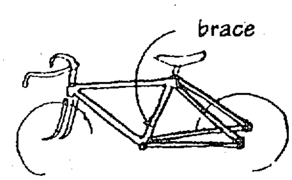
Shear walls are designed to receive lateral forces from diaphragms and transmit them to the ground. The forces in these walls are predominantly shear forces in which the material fibers within the wall try to slide past one another. A card house is a shear wall structure, and sufficient "card" walls must be placed at right angles to one another or the house will collapse. It is a very inefficient structure because the connections between the walls and between the walls and the diaphragms are nonexistent. If the walls are connected by slots or by tape, the structure is transformed into one that is very efficient for its size and weight. Similarly, the connections between the walls and floor and roof diaphragms in a building must be very strong and ductile.



Card House
- a shear wall structure

Braced frames act in the same way as shear walls; however, they generally provide less resistance but better ductility depending on their detailed design. Bracing provides lateral resistance through triangulated geometry, which prevents the frame from folding up if given a sideways push. A bicycle is a familiar example of a braced frame; without the connecting diagonal brace, the other members and connections would have to be much stronger to prevent the frame from folding up.

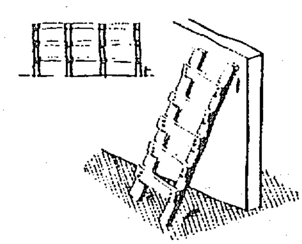




BRACED FRAME

In a building with a braced frame, lateral forces may cause the bracing to successively elongate and compress causing it to lose its effectiveness and experience large distortions that ultimately lead to collapse of the vertical structure it is trying to brace. Ductility therefore must be designed into the bracing so that it will deform but not snap.

A *moment resistant frame* is the engineering term for a frame structure in which the lateral forces are resisted primarily by bending in the beams and columns that is mobilized by strong rigid joints between columns and beams. (To engineers, a "moment" of a force about a point is the force multiplied by the distance between the point and the line of action of the force.) A simple ladder is an example of a moment resistant frame. In a building that uses a moment resistant frame, no walls or braced frames are required. The joints, however, become highly stressed and the details of their construction are very important in both steel and reinforced concrete.



MOMENT RESISTANT FRAME

As a last resort, moment resistant frames use the energy absorption obtained by ductility – that is, the permanent deformation of the structure prior to ultimate failure. For this reason, moment resistant frames generally are steel structures with bolted or welded joints in which the natural ductility of the material is an advantage. However, properly reinforced concrete frames that contain a large amount of precisely located steel reinforcing also are effective as ductile moment frames.

THE *NEHRP RECOMMENDED PROVISIONS*

This appendix has outlined the ways in which earthquake ground motion affects buildings and the ways in which building characteristics affect the response of buildings to this shaking. What the *Provisions* does is present procedures in the form of simple mathematical formulas and advisory precepts that the building designer uses as criteria for the building design. In doing this, the *Provisions* remains, however, focused the goal of providing a uniform level of safety for all building types in all areas of the United States even though there is great variability in the potential ground shaking hazard around the country.

As noted at the beginning of this appendix, readers interested in finding out more about the *Provisions* are encouraged to order FEMA Publication 99, *A Nontechnical Explanation of the 1994 NEHRP Recommended Provisions*.