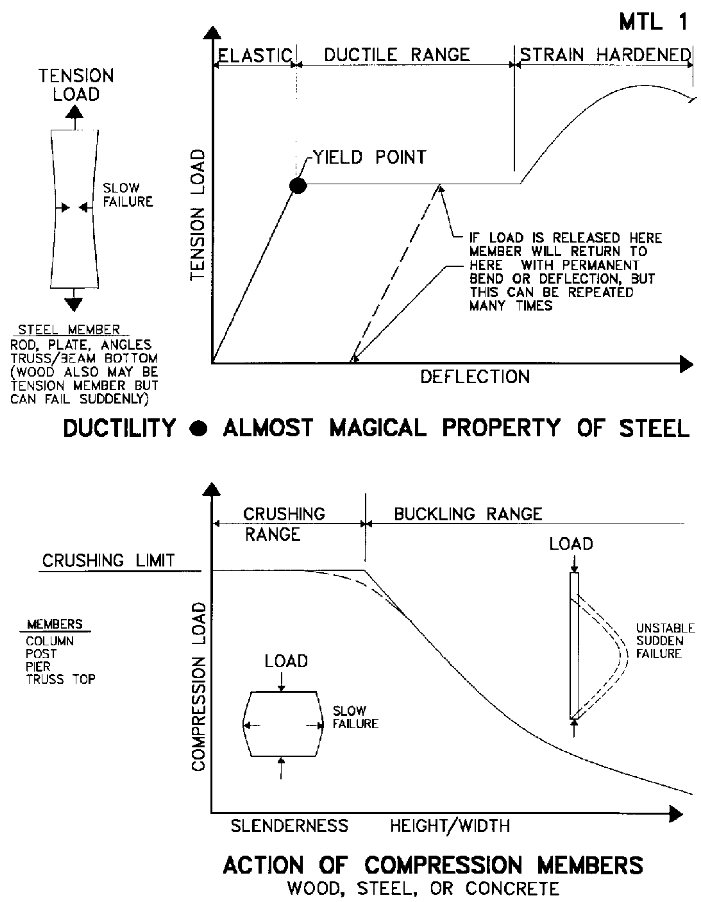
II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

MATERIAL STRESSES

It is useful to review basic stresses as they relate to failure mode in order to better identify brittle (sudden) vs. ductile failure.

Tension Stress — stretches members of steel or wood. Concrete and masonry have no reliable tension strength. The ductile action of steel in tension provides the special property of forgiveness (warning of failure) and in-elastic response which makes it especially desirable in resisting dynamic loading.

Compression Stress — can lead to crushing of material when the members are short and relatively fat, or at bearing surfaces between wood or concrete beams and columns. Long, slender members of all materials fail in buckling, which tends to occur relatively suddenly. The crushing failures tend to give more warning (i.e., local splitting of concrete and noisy, slow, compression of wood fibers).



II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

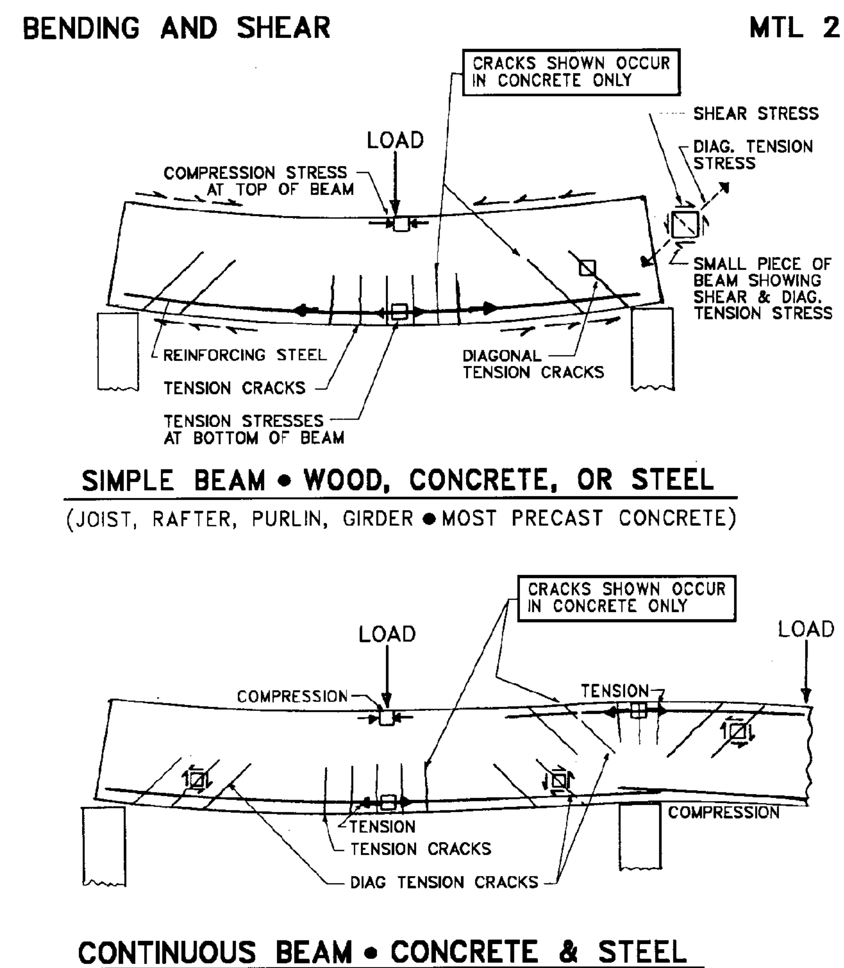
MATERIAL STRESSES (continued)

Bending Stress — the location of tension and compression extreme fiber stresses are illustrated by (MTL-2). Shear stresses are also present and these lead to different types of failure in different materials.

! Simple beams have tension stresses on the bottom, since it gets stretched, and have compression stresses at the top as it gets shorter.

! Continuous beams have alternate tension and compression, on top and bottom.

! Structural steel and reinforced concrete, moment resistant frames experience tension and compression stresses on opposite faces (similar to continuous beams). These stresses can reverse during earthquakes and high winds.

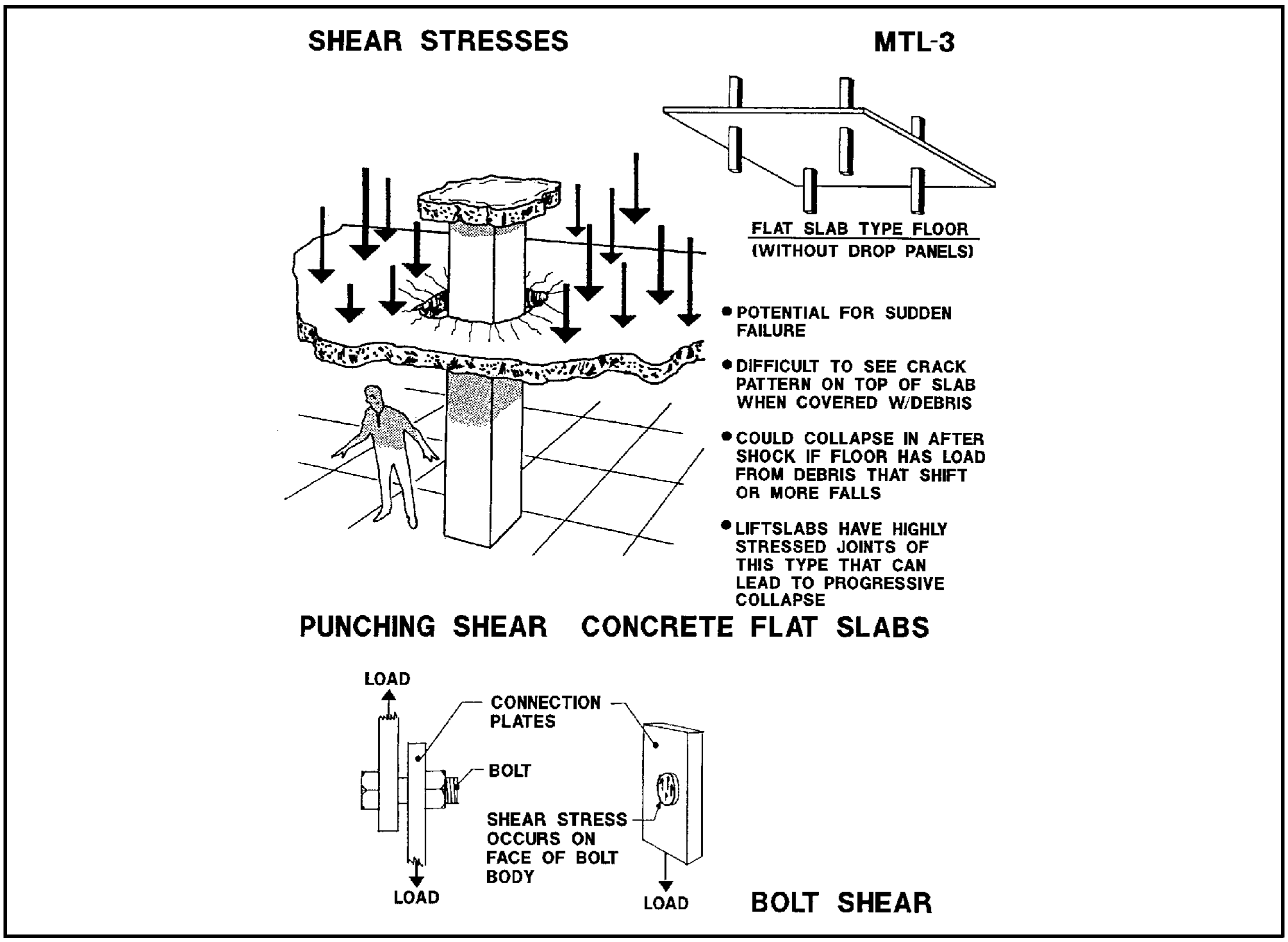


II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

MATERIAL STRESSES (continued)

Shear stresses occur in all beams, and are greatest adjacent to supports. Shear stress can be described as the tendency to spin little elements of the beam. In concrete beams these shear stresses develop diagonal tension cracks, since concrete is very weak in tension. Wood beams are strong in tension and compression, but are particularly weak in shear along the horizontal plane of the softer spring wood.

Punching Shear — occurs where a two-way concrete flat slab is connected to a column and it is the tendency of the slab to drop as a unit around the column. The column appears to punch through the slab. The cracking that indicates the over-stress leading to this type of collapse is most visible on the top surface of the slab, which is often covered by debris during US&R activities. This can only add to the difficulty of discovering this common hazard under the suspected overload conditions where it is most likely to be a problem.



II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

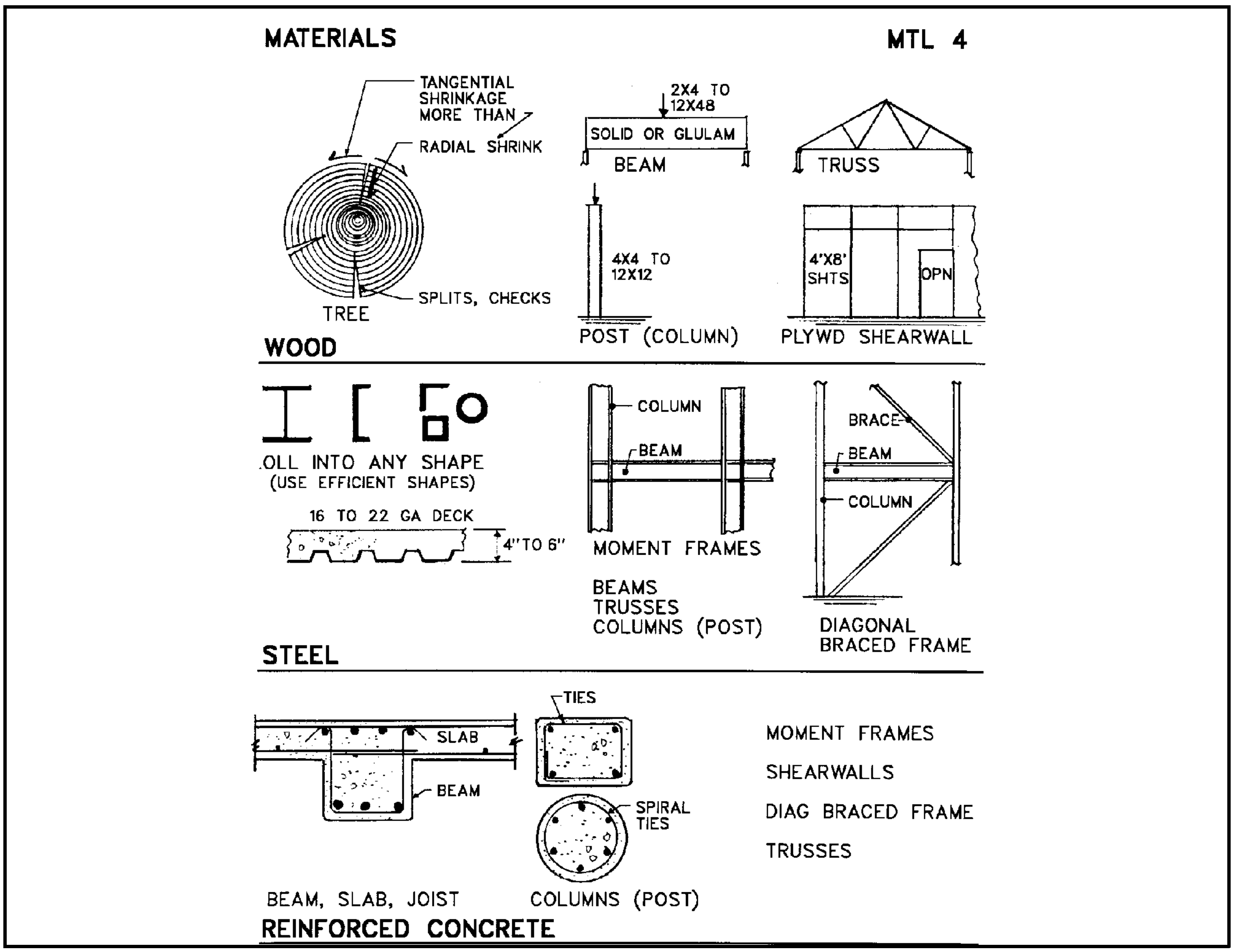
MATERIAL STRESSES (continued)

Bolt Shear — tendency of steel pin-like connector (bolt, nail, screw) to break across its cross section. This type of failure can be sudden. Nail failures in wood structures, which often involve some degree of pull-out, can occur with enough deformation to give warning.

Building Wall Shear and Overturn Stresses — lateral forces of wind or earthquake cause shear and bending stresses in walls (See MTL-7).

MATERIAL PROPERTIES

Wood
 ! Is tough, light fibrous, fire supporting, cut from living trees and graded by humans.



II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

MATERIAL PROPERTIES

Wood (continued)

! Has defects like knots, splits and non-straight grain that cause stress concentration.

! Growth pattern — fast spring wood vs. slow summer wood leads to structural problems of weak beam cross grain tension, weak parallel to grain, shear strength and shrinkage. Live wood may be as much as one half water, while older wood in a structure may contain as little as 5%. Its volume can change as much as 10% over this range.

! Shrinkage (in width/depth, not length) causes special problems in bolted connections. Splits may be formed, which allow the bolt to slip out of the joint along the split.

! Connections should feature bearing but can be bolted. Wood performs well when nailed with many connections as long as splitting is avoided

! Plywood sheathing of wood structures makes them very tough and earthquake resistant as long as it is nailed properly.

Steel

! Is tough, light, strong, ductile, formable into any shape, but needs to be fireproofed. It starts to lose strength above 700 ^{o} Fahrenheit.

! It has almost magical property of ductility. That is, it can be over stressed and severely bent, but still have enough strength to resist failure. This makes the ideal structure in that it gives warning of collapse (has forgiveness).

! It can be efficiently connected by bolting or welding (older structures used rivets instead of bolts). Welding must be properly done or it can lead to brittle failure.

! Steel beams must be laterally braced so as not to buckle about their weak axis, especially if the ductile performance required for earthquake resistance is expected.

Steel framed structures must be properly proportioned in order to avoid the over loading of columns by the great strength of beams and diagonal bracing members.

II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

MATERIAL PROPERTIES

Concrete

! Is essentially cast rock, that is strong in compression but weak in tension.

! Steel bars are cast into concrete to provide for longitudinal tension stress and enclosing type steel ties and stirrups are added for confinement and shear resistance. Sufficient steel can be added to provide adequate toughness for seismic resistance, enabling reinforced concrete to exhibit ductile properties similar to structural steel.

! Concrete can also be reinforced by adding high strength cable and small bars that are pretensioned prior to their being loaded by the structures weight (pre-stressed concrete). Structures of this type may be precast in a factory using pre-tensioned reinforcing that is bonded to the concrete when cast, or may be cast in place with draped cables included, that are post-tensioned after the concrete has cured.

! Concrete shrinks, cracks, and creeps under normal circumstances and its normal behavior needs to be differentiated from the cracking and spalling that indicate failure.

! Concrete is easily connected together if cast in place, but must be very competently connected together if it is precast. Since precast concrete members (especially prestressed precast) can be very strong, the joints that connect then must be very tough (ductile) in order to resist the very high dynamic forces generated by an earthquake.

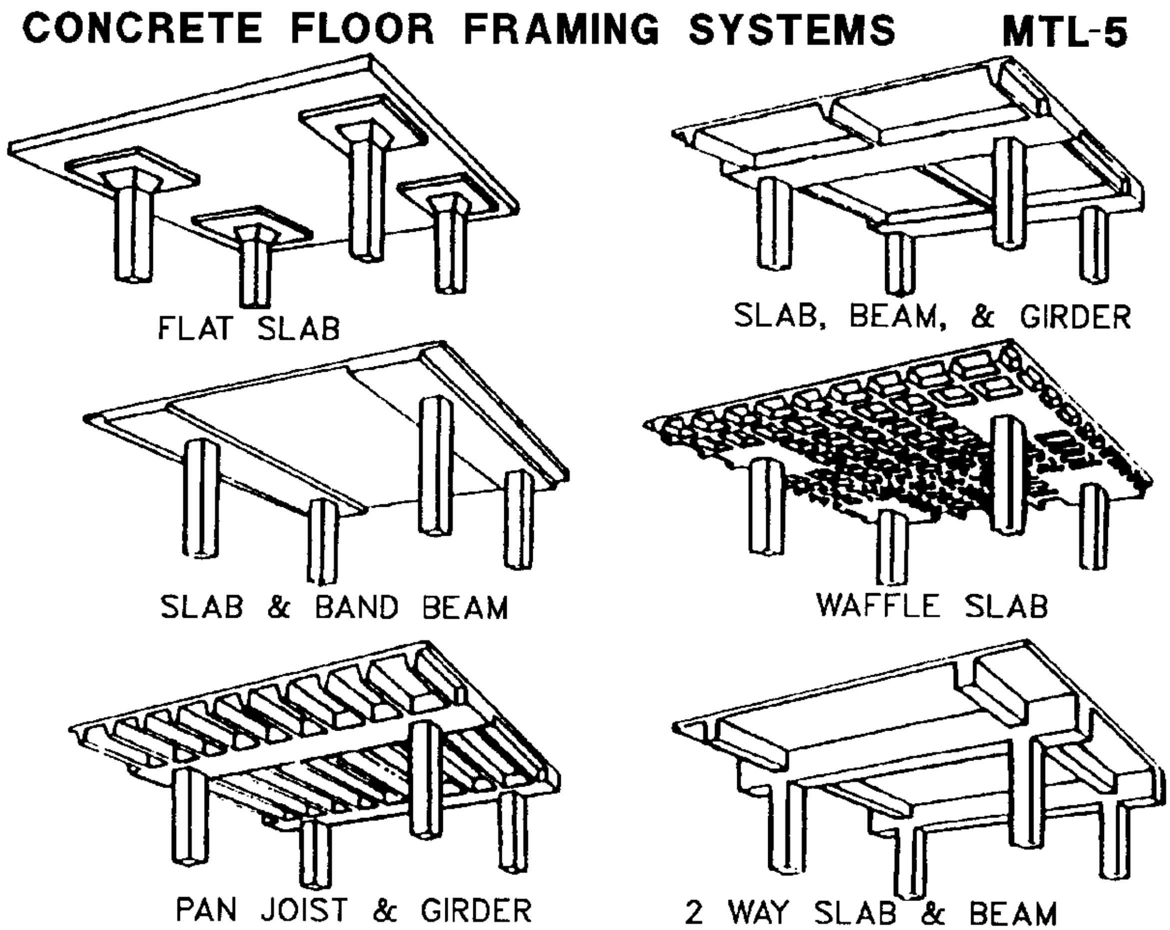
! Properly reinforced concrete can provide seismicly resistant construction if the reinforcing is proportioned such that the confining tie, hoop and stirrups are sufficient to resist the shear that can be generated by the overall structural configuration and longitudinal reinforcement. Wall like structures of cast in place and precast concrete have out performed frame type construction in most earthquakes.

! Unreinforced concrete walls can be found in structures built prior to about 1910. These perform very poorly in earthquakes, as they tend to break into large pieces defined by shrinkage cracks or original pour joints.

II. STRUCTURAL ENGINEERING SYSTEMS

A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

MATERIAL PROPERTIES



II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

MATERIAL PROPERTIES

Reinforced Masonry

! Is made from clay brick or hollow concrete blocks formed into walls using mortar joints and concrete grout filling of interior cavities in seismicly resistant construction.

! Since masonry properties are similar to concrete, reinforcing steel bars are normally added to provide tension and shear resistance. Small heavy wire ladder type reinforcing is used at the joints in some cases.

! Masonry wall construction is highly dependent on workmanship to provide adequate mortar and grout strength, since these products are often job mixed in small quantities. Adequately reinforced masonry walls can be used in seismicly resistant construction if carefully detailed and constructed.

Unreinforced Masonry

! Not currently built in seismic risk areas, but many structures with unreinforced masonry walls still exist throughout the world.

! Walls were constructed with a thickness made from three or more bricks being laid longways, side by side, for five or six layers high (courses) and then a layer was placed with the bricks at 90 degrees (header course), and so on.

! Unreinforced masonry buildings date back to the late 1800s in California and back to the 1700s in other parts of the U.S. The strength of the bricks is generally higher outside of California.

! The strength and seismic performance of unreinforced masonry is highly dependent on the mortar strength. The shear strength of mortar can vary from 15 PSI to over 150 PSI, and is determined by the proportion of lime to portland cement and the workmanship. Lime produces a nice buttery mortar, but if too much is used a low strength will result. Lime can also be leached out of the mortar by water over time.

! Decorative veneers are a special seismic problem. Veneers were often laid up with building paper between them and the URM wall, and were anchored with wire or galvanized ties. The ties normally corrode away within twenty years or so, leaving a heavy brick face, just waiting to peal off when subjected to a lateral load.

II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

STRUCTURAL MEMBERS & VERTICAL LOAD SYSTEMS

Structural members in these systems can be divided into two types, those that form horizontal (or sloped roof) planes and those that provide the vertical support for these planes.

Horizontal members support floor and roof planes and are normally loaded in bending such as:
- ! Wood; rafters, joist, purlins,beams, girders.
- ! Steel; corrugated sheets (filled with concrete), joist, purlins, beams, girders.
- ! Reinforced concrete floor systems may be of many types (See MTL-5). All have some relationship to the economy of providing adequate structural depth with available forming materials.
- ! Precast concrete floors may contain, planks, cored slabs, single or double tees, beams and girders. Most modern systems in California combine a cast-in-place overlay slab to provide adequate interconnection of individual members and overall planar stability.
- ! These individual members need to be interconnected to their supported planes in order to provide the lateral stability to resist the extreme fiber compression forces associated with bending, which occur on the top or bottom of the members.

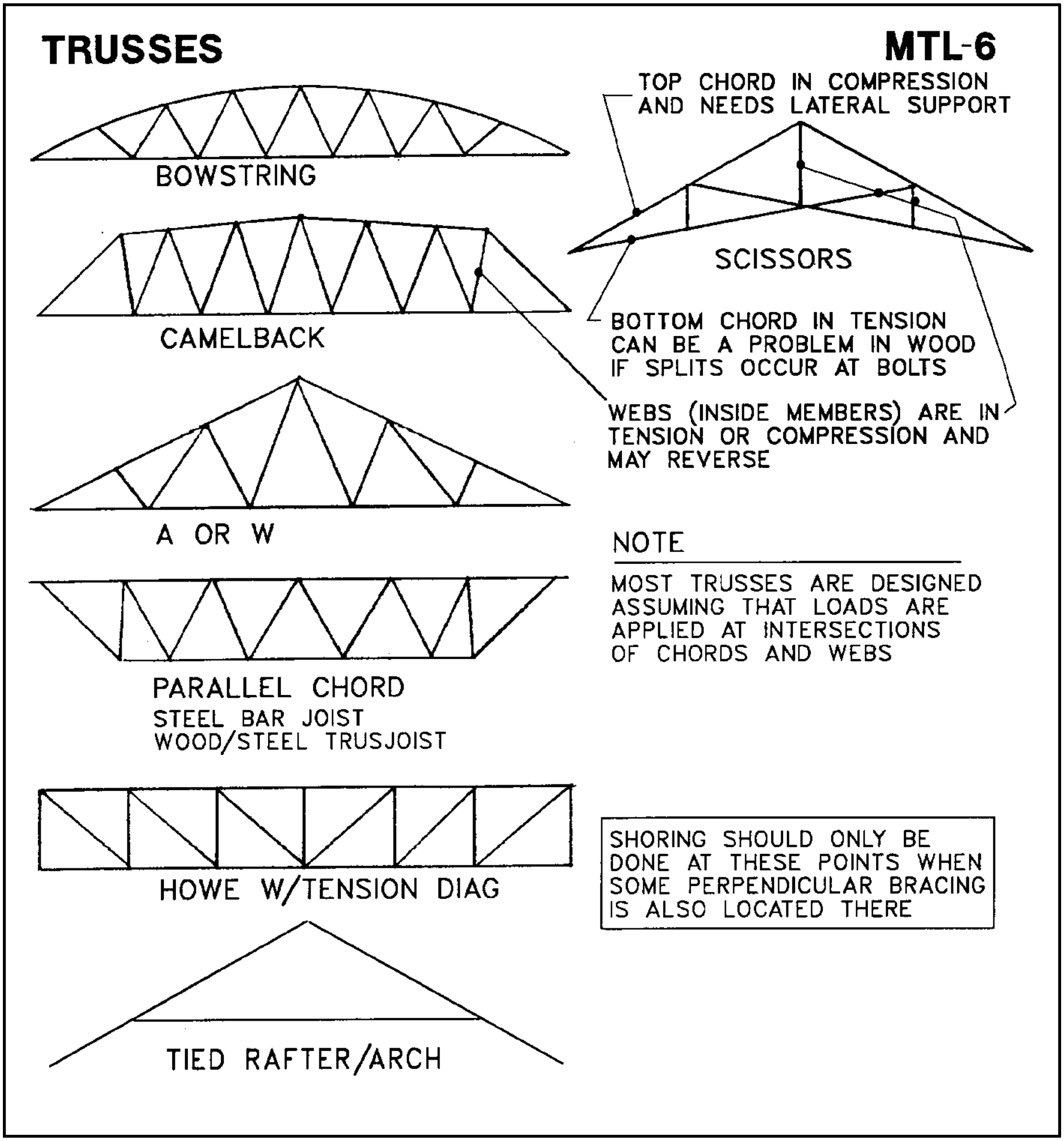
Trusses are special vertical load resistant members that use greater depth for structural efficiency, but require more positive lateral bracing of compression members (See MTL-6).
- ! Trusses are usually made from wood and/or steel, although concrete has been used for economy in some areas of the world.
- ! Individual members are stressed in either tension or compression, although stress may reverse in some members due to changes in live load (people, vehicles, rain/snow).
- ! Compression members are normally governed by buckling and tension members are normally governed by their connections.

- ! There have been many failures of wood trusses due to seasoning defects. Wood checks (splits) that occur near the ends of tension members has lead to many pull-through bolted connection failures. Overloads due to rain or snow can lead to sudden collapse, as a result of a compression member buckling or tension connection failure. The use of closely spaced trusses with gang-nail connection plates, and those using specially fabricated wood with steel pin connected bars have improved the reliability of wood trusses.

II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

STRUCTURAL MEMBERS & VERTICAL LOAD SYSTEMS (continued)

! Steel trusses have been fairly reliable , but they are also susceptible to sudden compression member failures, due to temporary overload, and loss of stability due to inadequate bracing of compression members.



II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

STRUCTURAL MEMBERS & VERTICAL LOAD SYSTEMS (continued)

! Trusses present special problems when the shoring of a hazardous structure is being considered. The support provided by the shoring must be applied so as not to cause a stability problem or overload of a small or inadequately braced individual truss member. (It's usually a bad idea to shore a truss at the bottom chord.)

Vertical Support Members — are normally configured as bearing walls or columns.

! In wood and light framed steel systems the bearing walls are made using closely spaced columns (studs at 16-24" o.c.) that must be interconnected by a skin in order to provide the lateral stability that will allow the individual members to be loaded in compression without buckling.

! Concrete and masonry bearing walls are proportioned to carry heavy vertical loads depending on their height to thickness ratio.

! Individual column (posts) normally carry large compression forces and may be made of wood, steel, or reinforced concrete. In all cases the load capacity is based on the members slenderness ratio (l/r, l/d) as well as the adequacy of the connection between the column and the horizontal system.

It is assumed in all vertical load systems that some minimum system is present to provide for lateral stability (i.e., the proper alignment of vertical load path). These lateral load systems may be capable of resisting lateral forces that are anywhere from less than one percent to more than fifty percent of the structures weight.

LATERAL LOAD RESISTANT SYSTEMS

Most structures can be grouped into two basic types of lateral load systems, shear wall/box system and frame system. Buildings may contain sections of each type. Some buildings have been designed with a dual system containing both types of lateral bracing in order to provide a more redundant system, which is highly desirable.

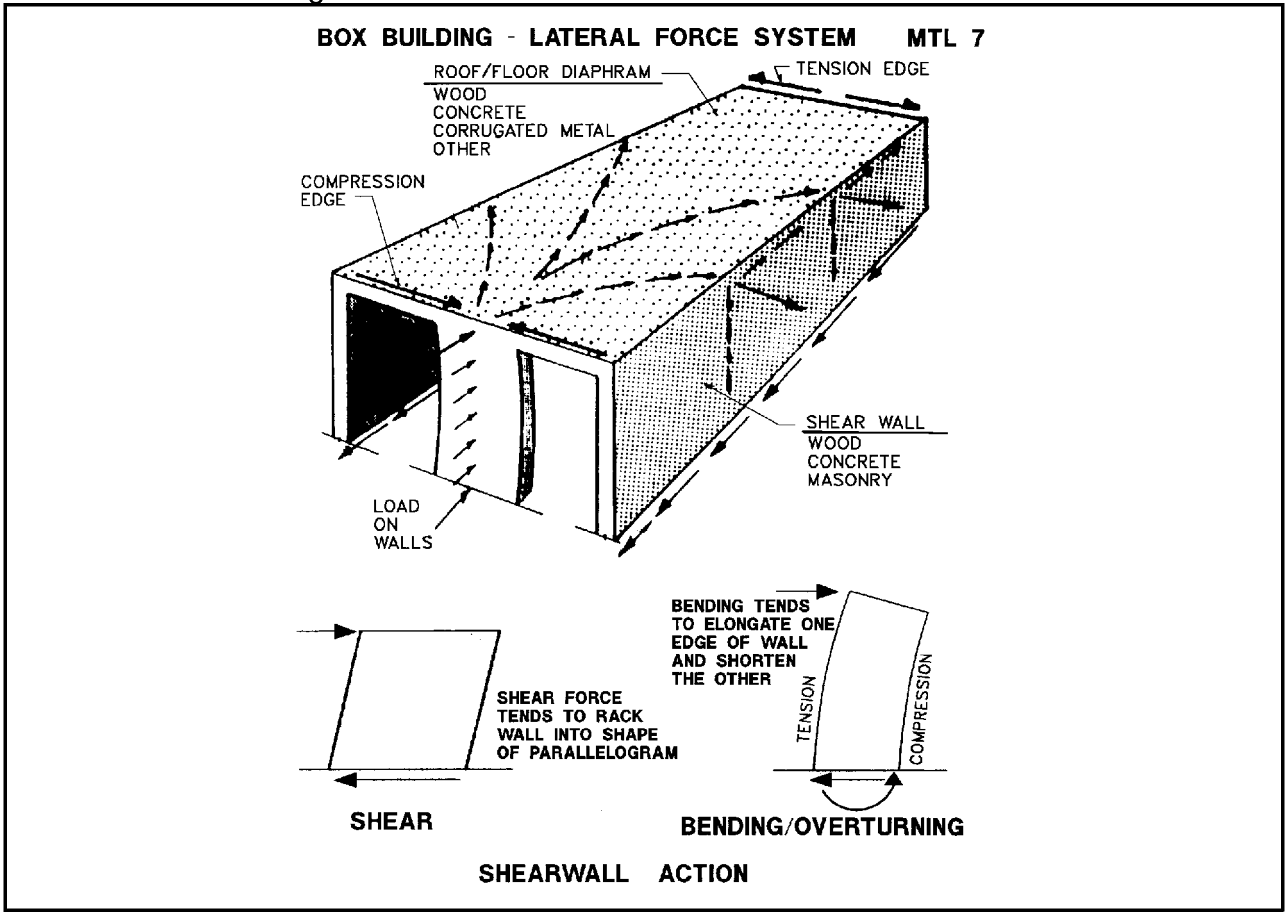
II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

LATERAL LOAD RESISTANT SYSTEMS (continued)

Shear Wall/Box Buildings

! These are buildings with exterior walls that provide bearing strength as well as seismic resistance. They may or may not have interior, structural walls. Floors, flat or sloped roof planes called diaphragms form the horizontal surfaces to complete the boxes, with the walls forming the sides.

! The typical action of a box structure subjected to the lateral loads is illustrated by MTL-7. Floor/roof planes act like giant beams as stresses in tension and compression are generated at a the edges while shear stresses are distributed through out the plane. The floor/roof planes (diaphragms), span horizontally between exterior (sometimes interior) walls which provide each horizontal plane with lateral support. The walls (shear) in turn are loaded by the floor diaphragm must be capable of resisting shear stresses plus bending stresses caused by overturning.



II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

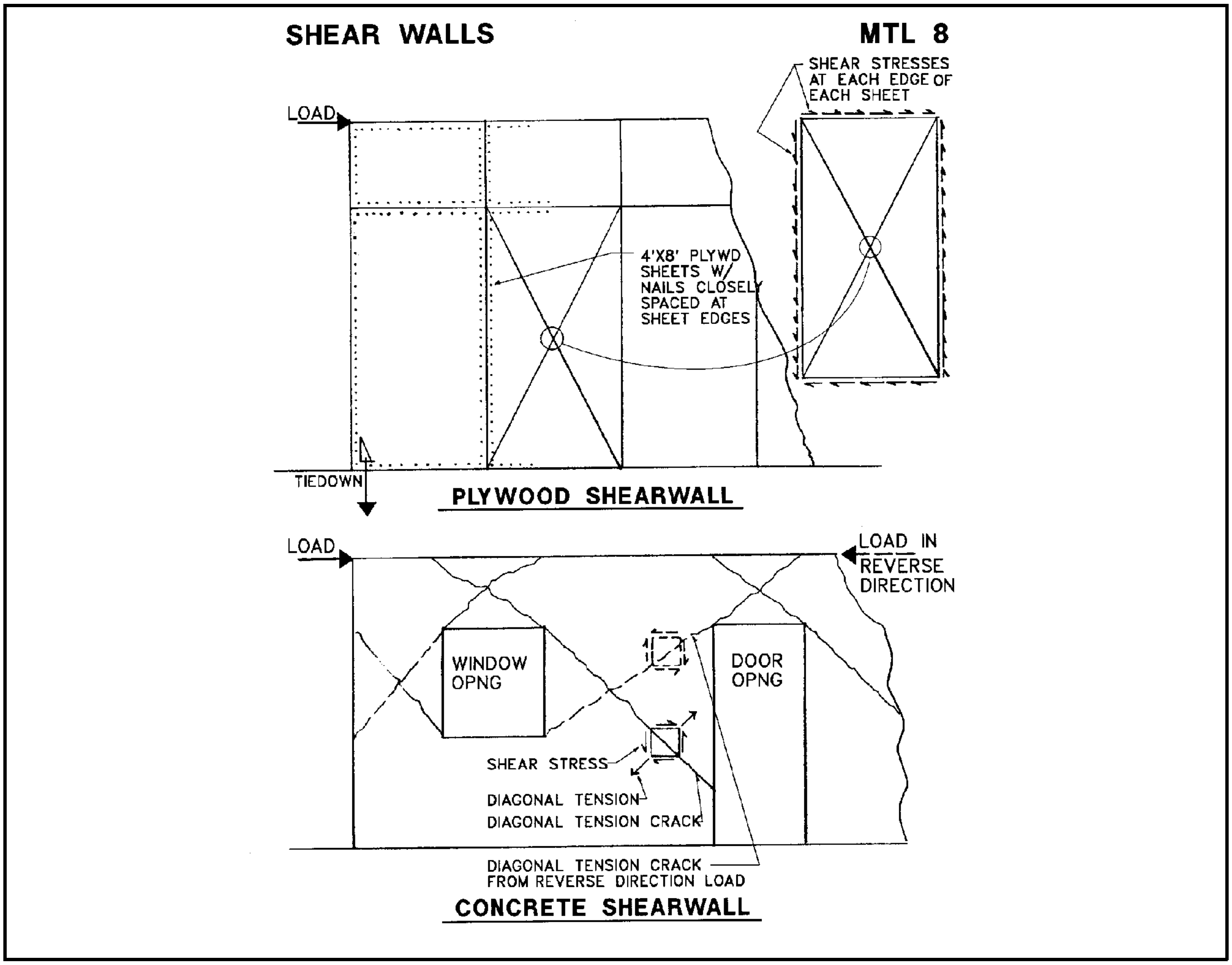
LATERAL LOAD RESISTANT SYSTEMS (continued)

Shear Wall/Box Buildings

! Floor/roof diaphragms are made of plywood, diagonal wood sheathing, corrugated metal deck (with and without concrete topping), and concrete.

! Shear walls are made of plywood and solid wood sheathing over studs, concrete, and concrete block.

! In the very light weight wood systems the skin (sheathing) carries all of the lateral shear force, but is a minor vertical support member. In concrete and concrete block systems the vertical and lateral loads are carried by the relatively heavy reinforced concrete slab and bearing walls.



II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

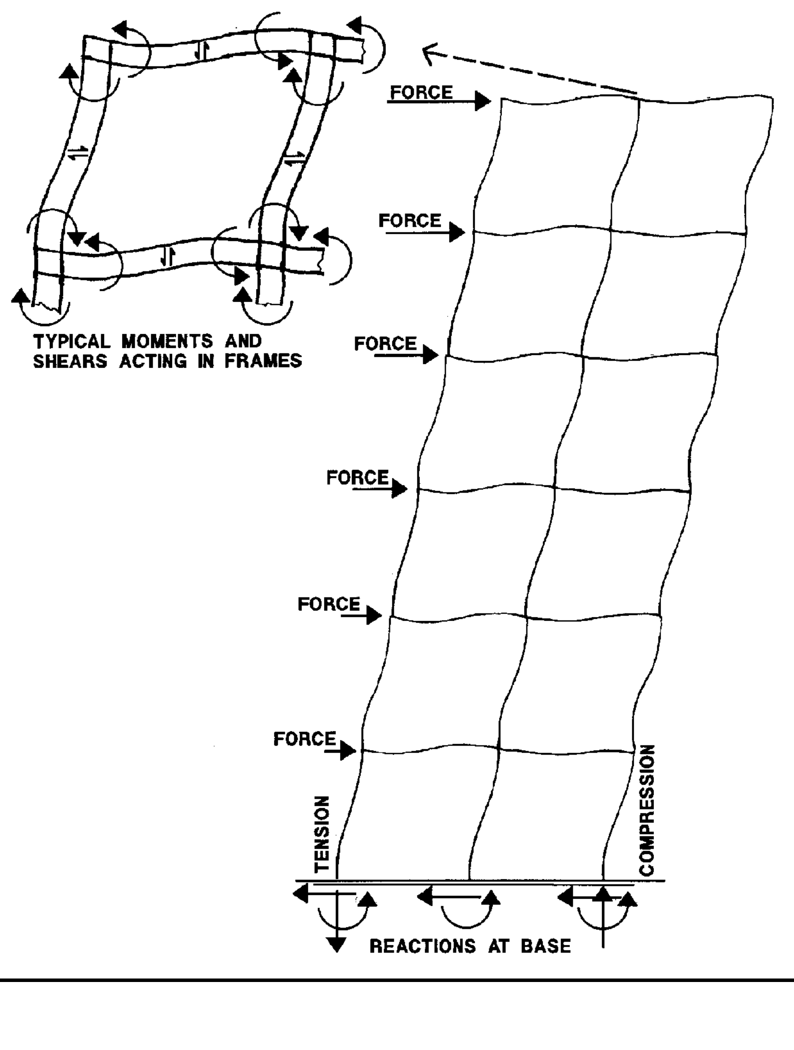
LATERAL LOAD RESISTANT SYSTEMS (continued)

Frame Buildings — Moment Resistant

! The walls for this type normally are constructed for enclosure purposes only and may be of glass, light framing with non-structural covering (plaster veneer or brick/stone, finish wood), a combination of precast concrete and glass, etc. The vertical load is carried by large evenly spaced columns of steel or reinforced concrete.

! The floor and roof diaphragms are constructed as in the box system, however, the stresses developed in the diaphragms are usually smaller since they do not have to span as far.

MOMENT FRAME - LATERAL FORCE SYSTEM MTL 9



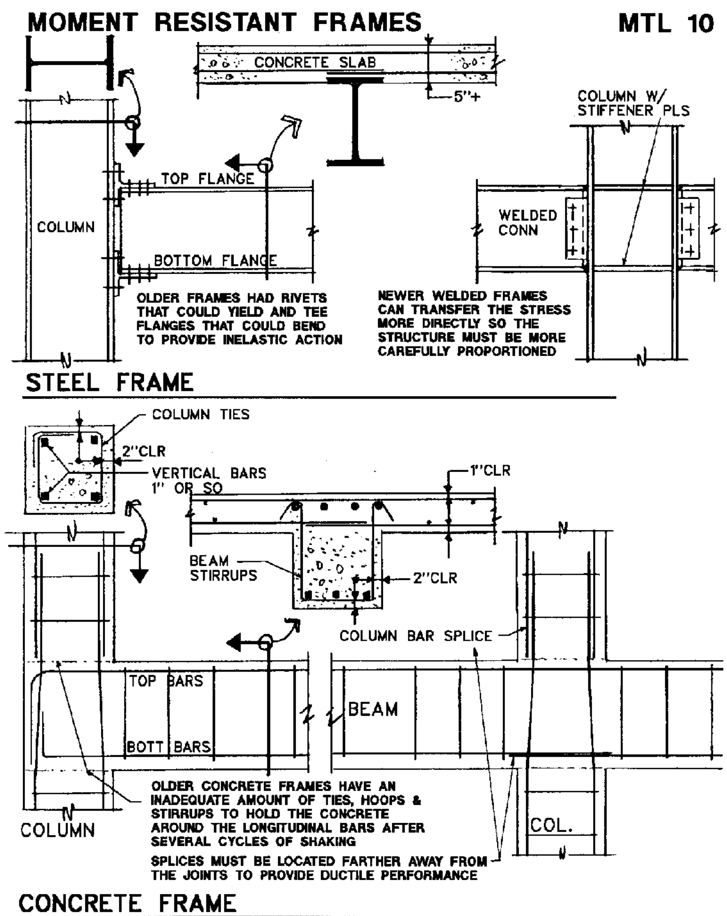
II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

LATERAL LOAD RESISTANT SYSTEMS (continued)

Frame Buildings — Moment Resistant

! The lateral load resistance is provided by the interconnection or large tough floor beams/girders and the columns. The "frame" made by the beams and columns is kept from changing into a parallelogram by making the connections as strong as the members. Structural steel or well confined heavily reinforced concrete are used today for these moment resistant frames.

! Structural toughness- the ability to repeatedly sustain reversible stresses in the inelastic range without significant degradation, is essential for a moment resistant frame. Most concrete frames built prior to 1965 in California (and other seismic zones with similar building codes) were not constructed with much structural toughness. Structural steel frames have out performed concrete frames in the past. There were examples of lightly connected steel frames that survived the San Francisco 1906 earthquake, however, they were susceptible to fire damage.

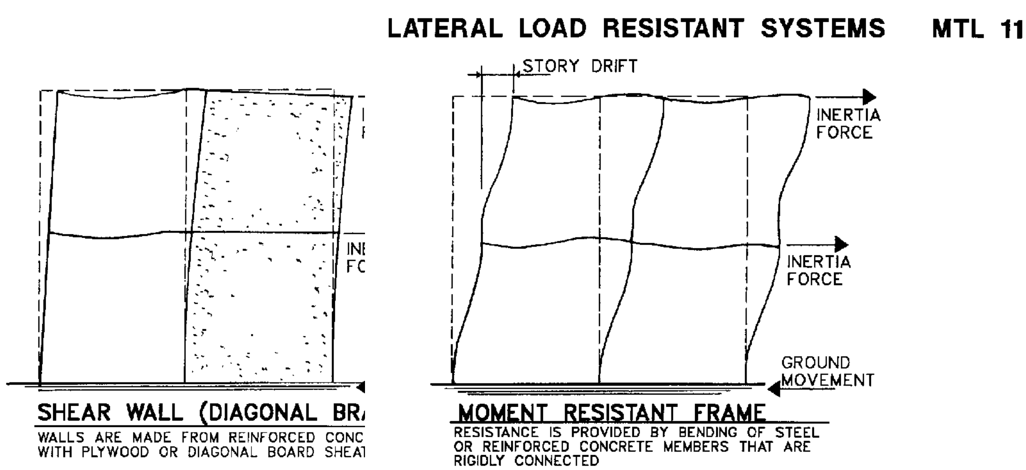


II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

LATERAL LOAD RESISTANT SYSTEMS (continued)

Frame Buildings — Moment Resistant

- ! Tall buildings with moment frames may generate significant tension and compression forces in the exterior and or corner columns. High tensions can be very detrimental to older concrete frames, since severe cracking can result in catastrophic failures when the loading is reversed and the member is also required to resist bending. High compression forces in steel frames can cause buckling of tube or wide flange columns.
- ! Modern building codes require that the columns be stronger than the sum of the connecting beams at any story, in order that when inelastic action occurs it will form plastic hinges in the beams, not the columns. Since modern steel moment frames are connected by welding, good workmanship is critical. Visual inspection and ultrasonic testing is normally required to assure quality control.
- ! Moment resistant frames can be used in combination with concrete shear walls to provide a dual system. A comparison of the action of each is shown in which must be considered in the design. Older, pre-1960, steel moment frames may be covered with cast-in-place concrete fire-proofing. (Important identification info.)



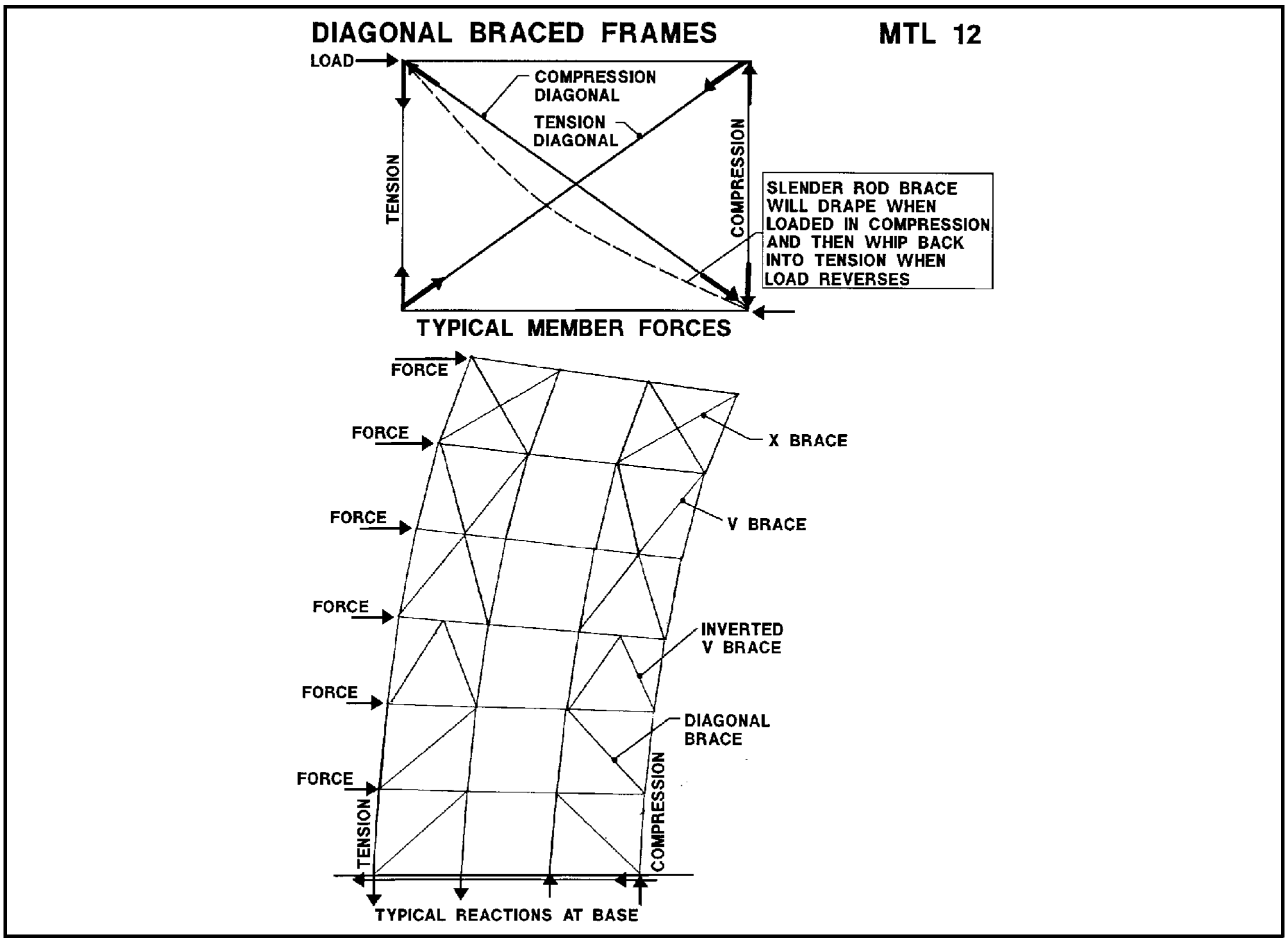
II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

LATERAL LOAD RESISTANT SYSTEMS (continued)

Frame Buildings — Diagonally Braced

! These systems are constructed similar to moment resistant frame structures. Their lateral load resistance is provided by adding diagonal members between columns to prevent lateral racking. Alternately reversing tension and compression forces are generated in the diagonal members which are usually made of structural steel, although reinforced concrete has been used (especially in Central and South America).

! Diagonal members should be able to resist both tension and compression, since the whipping action of slender rod cross-bracing can allow too much distortion. An exception is that light, steel frame, industrial buildings have performed reasonably well with slender rod cross-bracing, since corrugated metal finishes are quite flexible.



II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

LATERAL LOAD RESISTANT SYSTEMS (continued)

Frame Buildings — Diagonally Braced

- ! The columns in diagonally braced frames need to be proportioned so that they are stronger than the tension capacity of the braces that are connected to them. This is in order to assure that failure will not occur in the columns, and has only been required in recent building codes.

- ! Diagonal members are normally made from double angles or tube sections, and connections must be carefully detailed and built in order to prevent local buckling and/or other joint failure.

- ! Diagonal braced frames have been used in combination with moment resistant frames to provide a highly desirable, dual system. They also are configured as eccentric braces within a moment frame bay to provide a bracing system that combines the toughness of moment frame with the rigidity of braced frame.

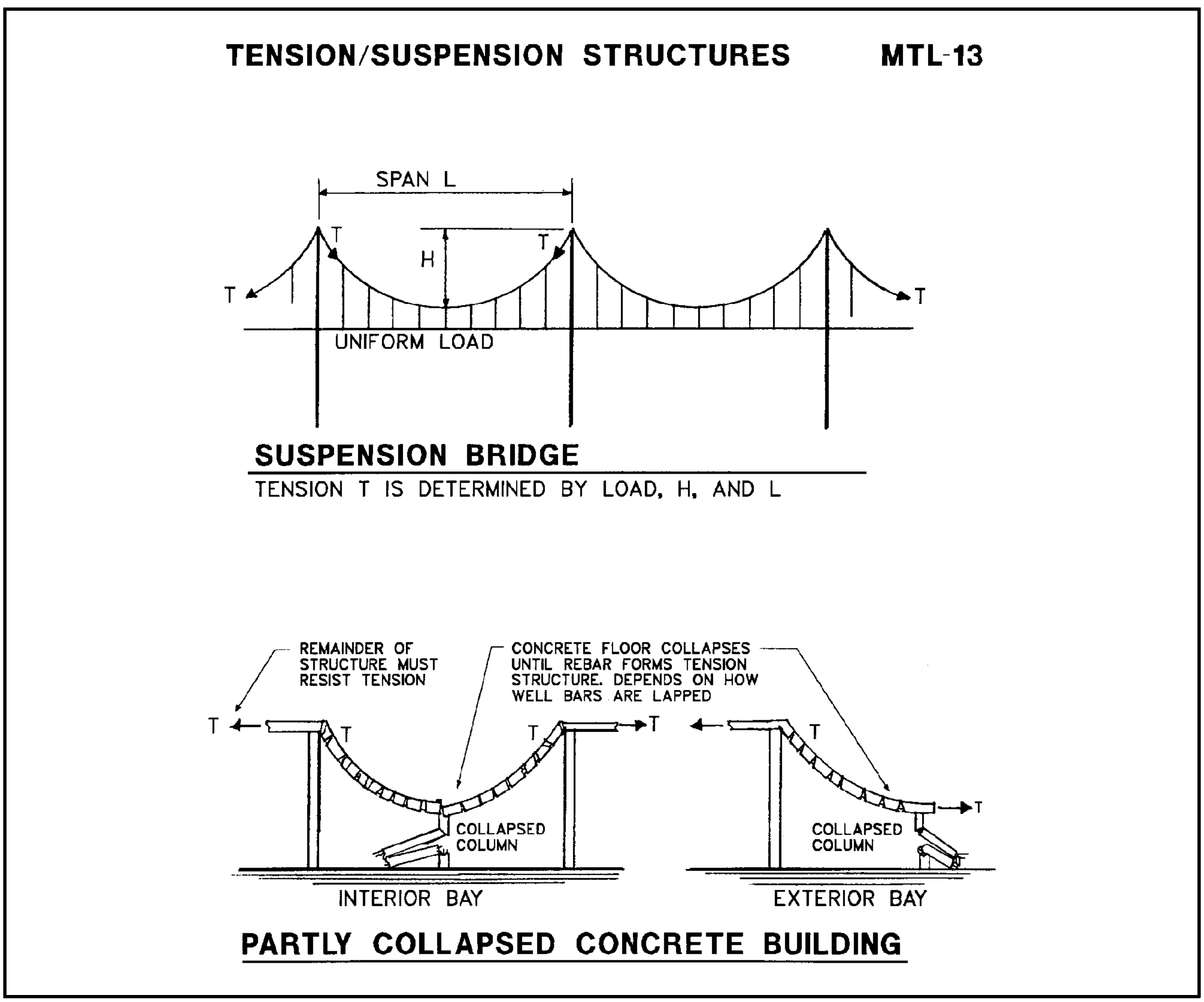
II. STRUCTURAL ENGINEERING SYSTEMS
A. BUILDING MATERIALS & STRUCTURAL SYSTEMS

LATERAL LOAD RESISTANT SYSTEMS (continued)

Suspension / Tension Structures

! Are not commonly used in building structures. These are very efficient structures that require significant height (cable drape) to span great spaces.

! Earthquake damaged, reinforced concrete slabs often form tension like structures, after failure of a vertical support. (MTL-13) This will cause unplanned tension forces in the remainder of the structure, which may cause lean-over of the remaining walls etc. However, this action can prevent complete collapse, but leaves a condition that is difficult to assess. The slabs may be hanging on reinforcing steel with unknown and/or unreliable embedment.



II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

BASIC STRUCTURAL LOADING

Earthquake — Some of the most destructive effects caused by earthquake shaking are those that produce lateral loads in a structure. The input shaking causes the foundation of a building to oscillate back and forth in a more or less horizontal plane. The building mass has inertia and wants to remain where it is and, therefore, lateral forces are exerted on the mass in order to bring it along with the foundation. This dynamic action can be simplified (in an upside down way) as a group of horizontal forces that are applied to the structure in proportion to its mass, and to the height of the mass above the ground, as shown in (BF-16).

! In multi-story buildings with floors of equal weight and relatively light walls, the loading is further simplified as a group of loads, each being applied at a floor line, and each being greater than the one below in a triangular distribution. Seismicly resistant structures are designed to resist these lateral forces through inelastic action and must, therefore, be detailed accordingly. These loads are often expressed in terms of a percent of gravity weight, and can vary from a few percent to near fifty percent of gravity weight.

! There are also vertical loads generated in a structure by earthquake shaking, but as mentioned previously, but these forces rarely overload the vertical load resisting system. Earthquake induced vertical forces have caused damage to heavy concrete structures with high dead load compared to design live load. these vertical forces also increase the chance of collapse in concrete frame buildings due to either increased or decreased compression forces in the columns. (Increased compression that overloads columns or decreased compression that reduces column bending strength.)

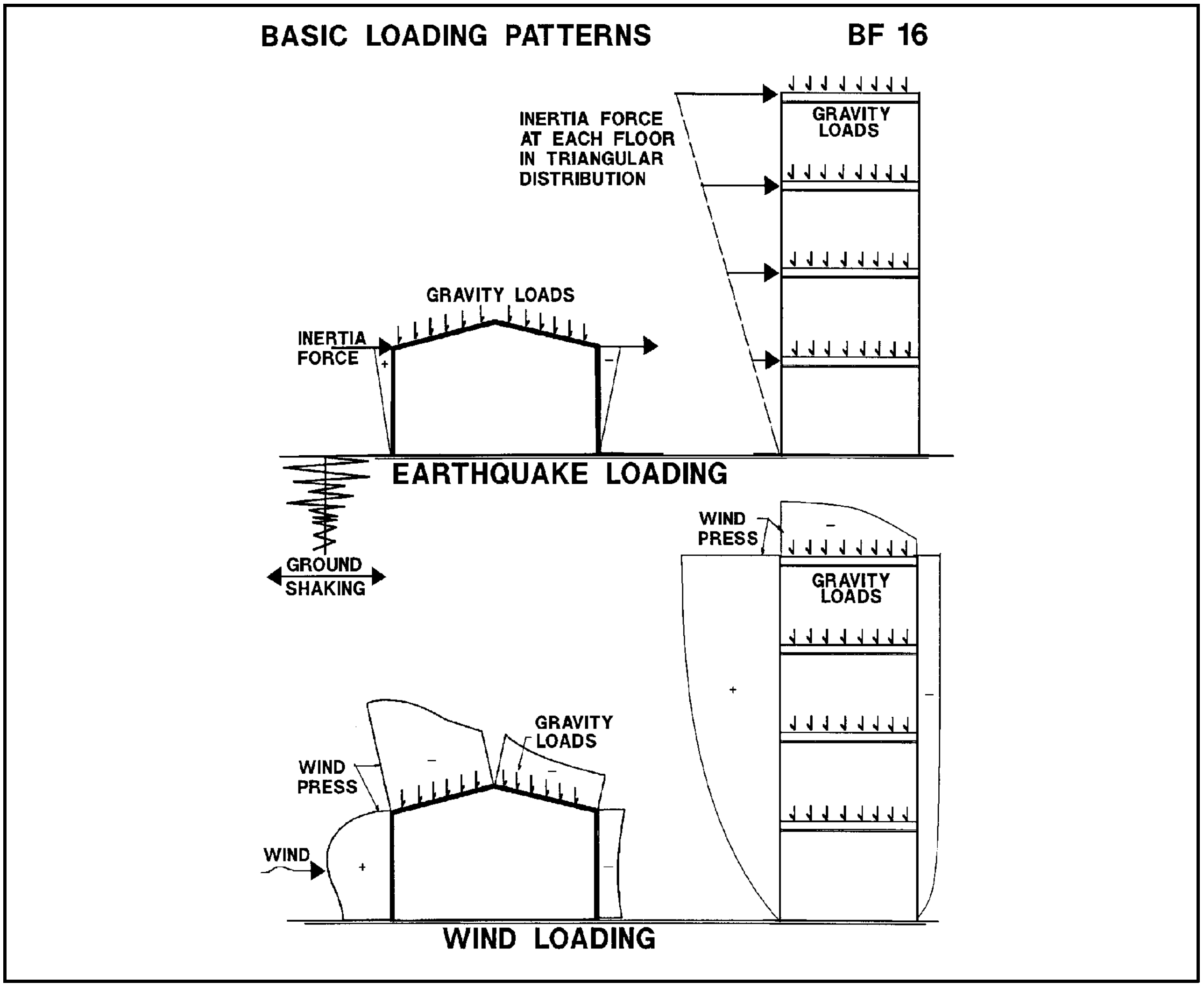
Wind — forces are generated on the exterior of the building based on its height, local ground surface roughness (hills, trees, other buildings) and the square of the wind velocity. The weight of the building, unlike the earthquake condition, has little effect on wind forces, but is helpful in resisting uplift. Unless the structure is penetrated all the forces are applied to the exterior surfaces of the building, as contrasted to earthquakes, where as an example both exterior and interior walls are loaded proportionally to their weight.

II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

BASIC STRUCTURAL LOADING

Wind (continued)

! Wind pressures act inward on the windward side of a building and outward on most other sides and most roof surfaces. Special concentrations of outward force, due to aerodynamic lift, occur at building corners and roof edges, especially overhangs. The overall structure must be designed for the sum of all lateral and uplift pressures and individual parts must be designed to resist the outward and inward pressure concentrations, and must be connected to supporting members (beams, columns, walls, foundation) to form a continuous resistance path. Forces are also generated on structures by airborne missiles that vary in size from roofing gravel to entire sections of roofs.

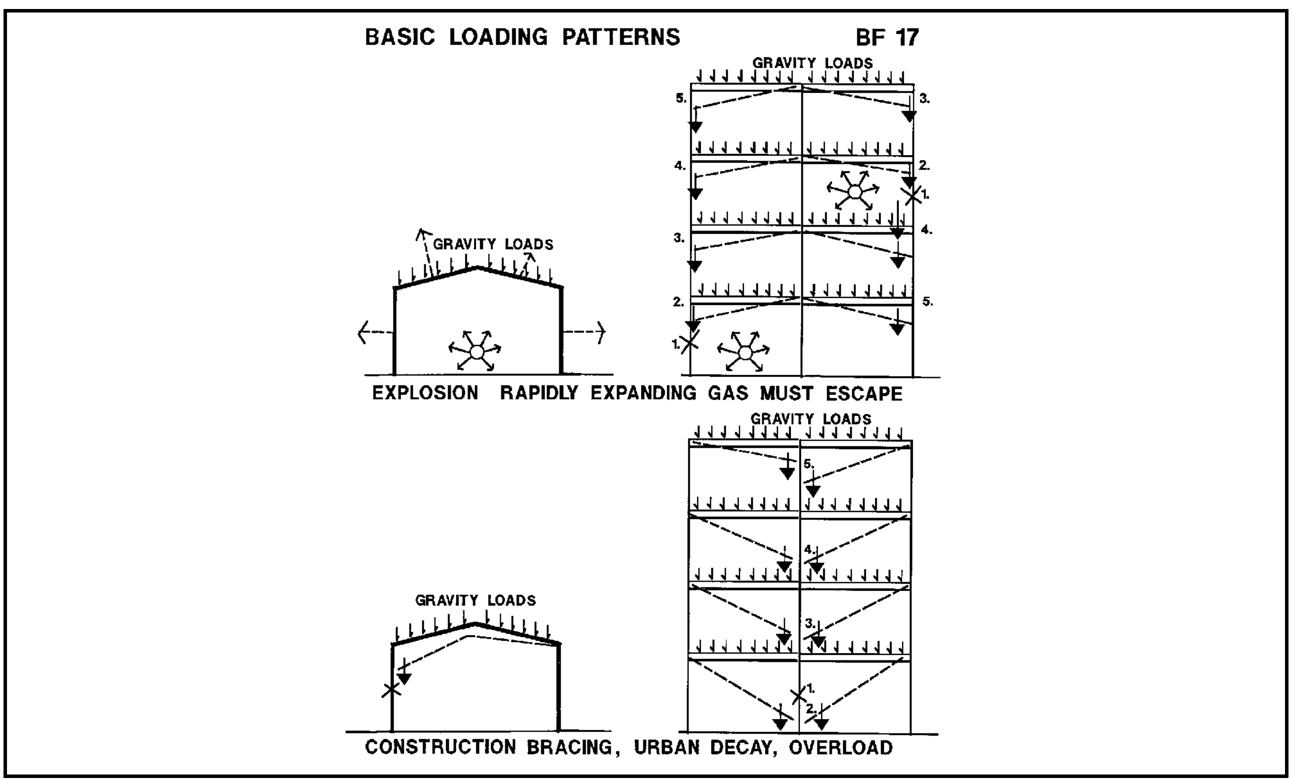


II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

BASIC STRUCTURAL LOADING (continued)

Explosion — occurs when a solid or concentrated gas is transformed into a large volume of hot gases in a fraction of a second. In the case of High Explosives, detonation (conversion of energy) occurs at a very high rate (as high as 4 miles /sec), while Low Explosives (such as gunpowder) undergo rapid burning at the rate of about 900 ft./sec. The resulting rapid release of energy consists of sound (bang), heat and light (fire ball) and a shock wave that propagates, radially outward from the source at subsonic speeds for most Low Explosives to supersonic speeds for High Explosives It is the shock wave, consisting of highly compressed particles of air that causes most of the damage to structures.

In the case of an exterior explosion from a bomb, the shock wave is initially reflected and amplified by the building face and then penetrates thru openings, subjecting floor and wall surfaces to great pressure. Diffraction occurs as the shock propagates around corners, creating areas of amplification and reduction in pressure. Finally the entire building is engulfed by the shock wave, subjecting all building surfaces to the over-pressure (BF-EXPLO) A secondary effect of the air-blast is a very high velocity wind that propels the debris (becoming deadly missiles), and in addition high intensity, short duration ground shaking (earthquake) may be induced.

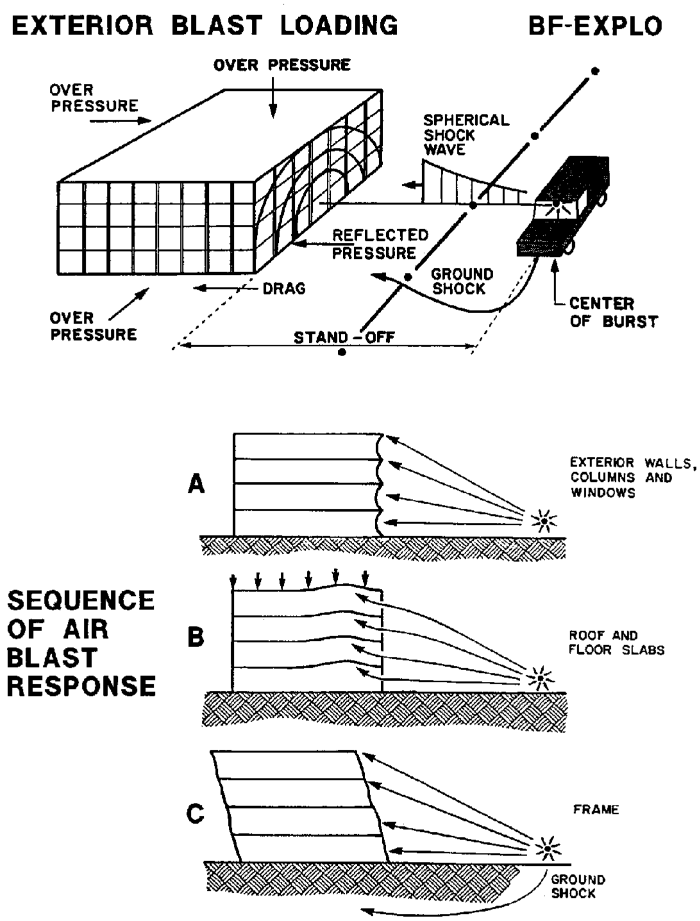


II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

BASIC STRUCTURAL LOADING (continued)

When natural gas explosions occur within structures, gas pressures can build up within confined spaces causing extensive damage. In all explosions, large, weak and/or lightly attached wall, floor, and roof surfaces may be blown away. The columns and beams in steel frame structures may survive a blast, but their stability maybe be compromised by the removal of their bracing elements (floor diaphragms, shearwalls). In large explosions concrete slabs, walls and even columns may be blown away, leading to conditions that will produce progressive collapse as illustrated by BF-18. This progressive collapse started with the initial damage due to an interior natural gas explosion, but then gravity drove the unstable braced structure to the ground.

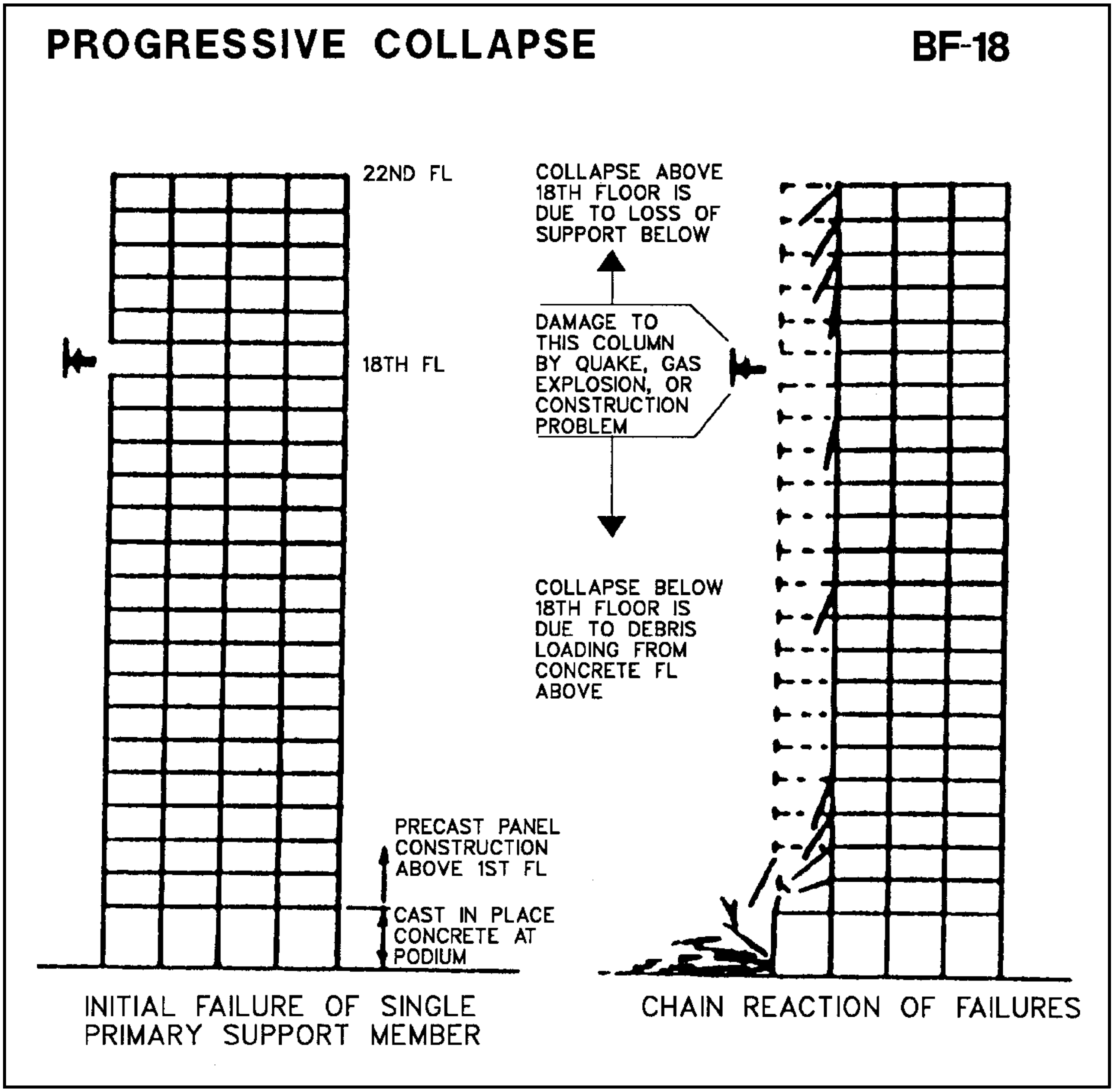
In very large explosions at close proximity to reinforced concrete surfaces, the effect can be so severe that the concrete is locally disintegrated and separated away from the reinforcing steel. Lighter wood, steel frame, and even precast concrete buildings can be leveled by explosions as the wall and floor/roof planes are blown away leading to an overall loss of stability.



II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

BASIC STRUCTURAL LOADING (continued)

Explosion (continued)



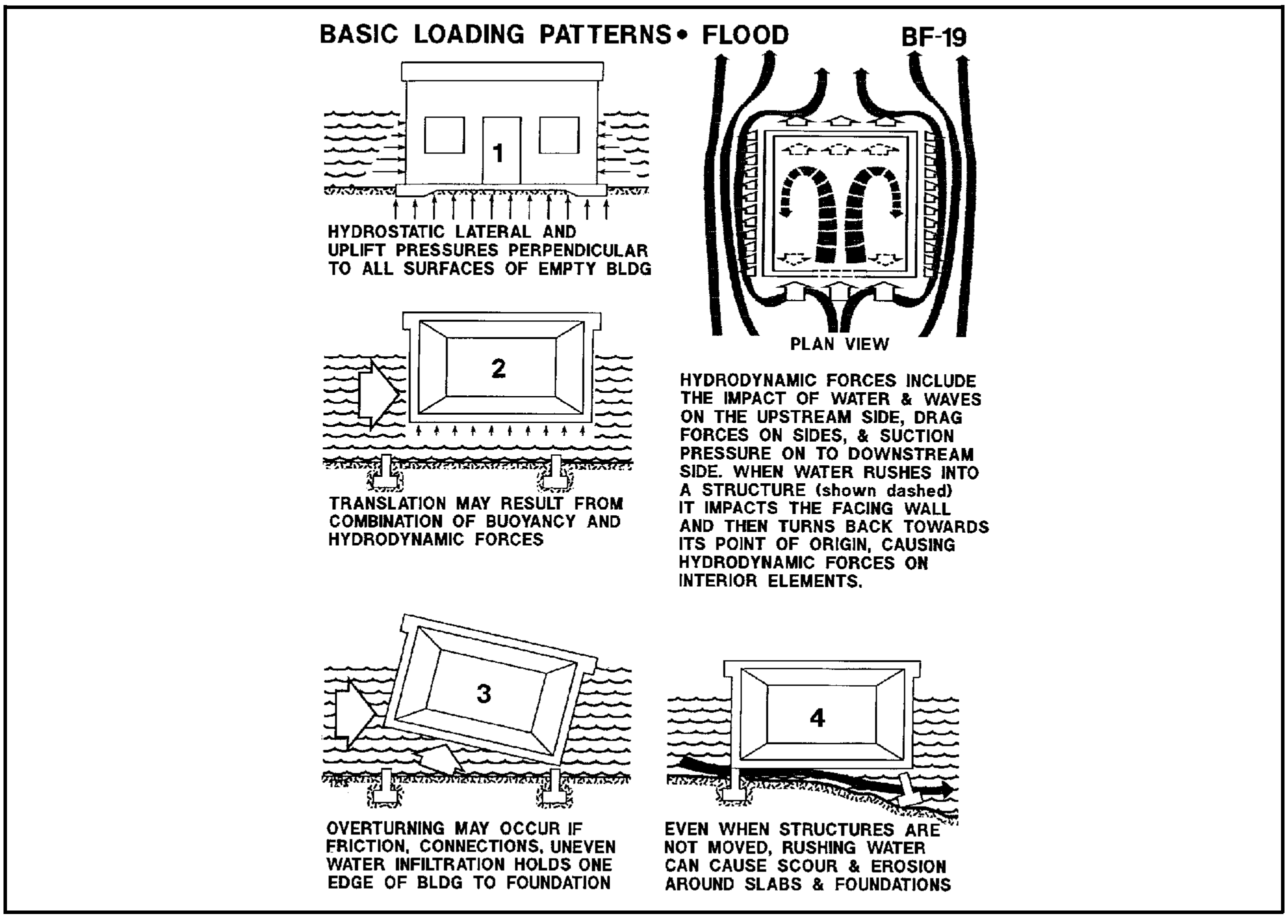
Fire — wood or metal roof/floors often collapse due to burn-through and can pull exterior masonry or concrete walls in or leave them standing in an unbraced condition. A steel structure left standing after a fire can have significantly reduced strength due to loss of the original heat treatment. A remaining concrete structure can be damaged due to spalling and shearwalls can be cracked due to expansion of floors.

II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

BASIC STRUCTURAL LOADING (continued)

Flood — Forces are generated on buildings due to hydrostatic lateral and lifting pressure, hydrodynamic forces, and debris impacts. Hydrostatic pressures can highly load foundation and basement walls and lift structures, when water level is not equalized between exterior and interior spaces. River and ocean currents will load frontal and side walls that are submerged, and ocean waves and step-up flows can produce pressures as high as 1000 PSF. Debris varying in size from floating wood pieces to floating structures can impact a building causing anything from broken windows to a total collapse.

Construction Bracing, Urban Decay, Overload — These sudden, collapses usually occur due to gravity loading when a vertical support is either inadequate, overloaded by snow, overloaded due to plugged roof drain, or reduced in capacity due to age, corrosion, or non-engineered alteration. Failures of this type occur all too frequently, but most often effect only one structure at a time. In some cases very hazardous conditions have been left standing in this type of collapse (i.e., multi-story URM walls left unsupported when wood floors pancaked).



II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

ATC-21 NOMENCLATURE

- ATC-21, Rapid Visual Screening of Buildings For Potential Seismic Hazards funded by FEMA and written by Applied Technology Council in 1988. There are twelve building types listed, and these are discussed in detail in the ATC-21 document pages 14 through 37.

- S2,C1,C3/S5,TU,PC2 and URM are expected to be most susceptible to earthquake damage. Wood residential structures have also provided a large number of failures in California , since they are, by far the most prevalent type. However, due to their relatively light weight and small size, people are seldom entrapped in wood residences. Type S3 is listed since it is very susceptible to damage by wind. Many S1 (steel frame) structures experienced cracks in their welded connections during the Northridge (L.A.) quake, which is of great concern to the engineering design profession. However, since none of these buildings were damaged to an extent that would cause even partial collapse, they are not currently considered probable for Urban Search & Rescue operations.

BF-2

STRUCTURAL BUILDING TYPES — ATC-21-1

W	Wood buildings of all types
S1	steel moment-resisting frames
S2	Braced steel frame
S3	Light metal frame
S4	Steel frames with cast-in-place concrete walls
C1	Concrete moment-resisting frames
C2	Concrete shear wall buildings
C3/S5	Concrete/steel frame with URM infill walls
TU	Tilt-up concrete wall building frames
PC2	Precast concrete frame buildings
RM	Reinforced masonry buildings

PROBLEM BUILDINGS

W	1- to 3-story houses and 2- to 4-story apartments (especially pre-1940)
URM	1- to 8-story (most less than 3 stories)
C1/C3	pre-1971 buildings (especially pre-1940)
PC2/TU	factory-built precast and tilt-up walls
S2	taller frames where column capacity doesn't exceed capacity of diagonal braces
Others	buildings with irregularities, soft first-, other-stories, open fronts.

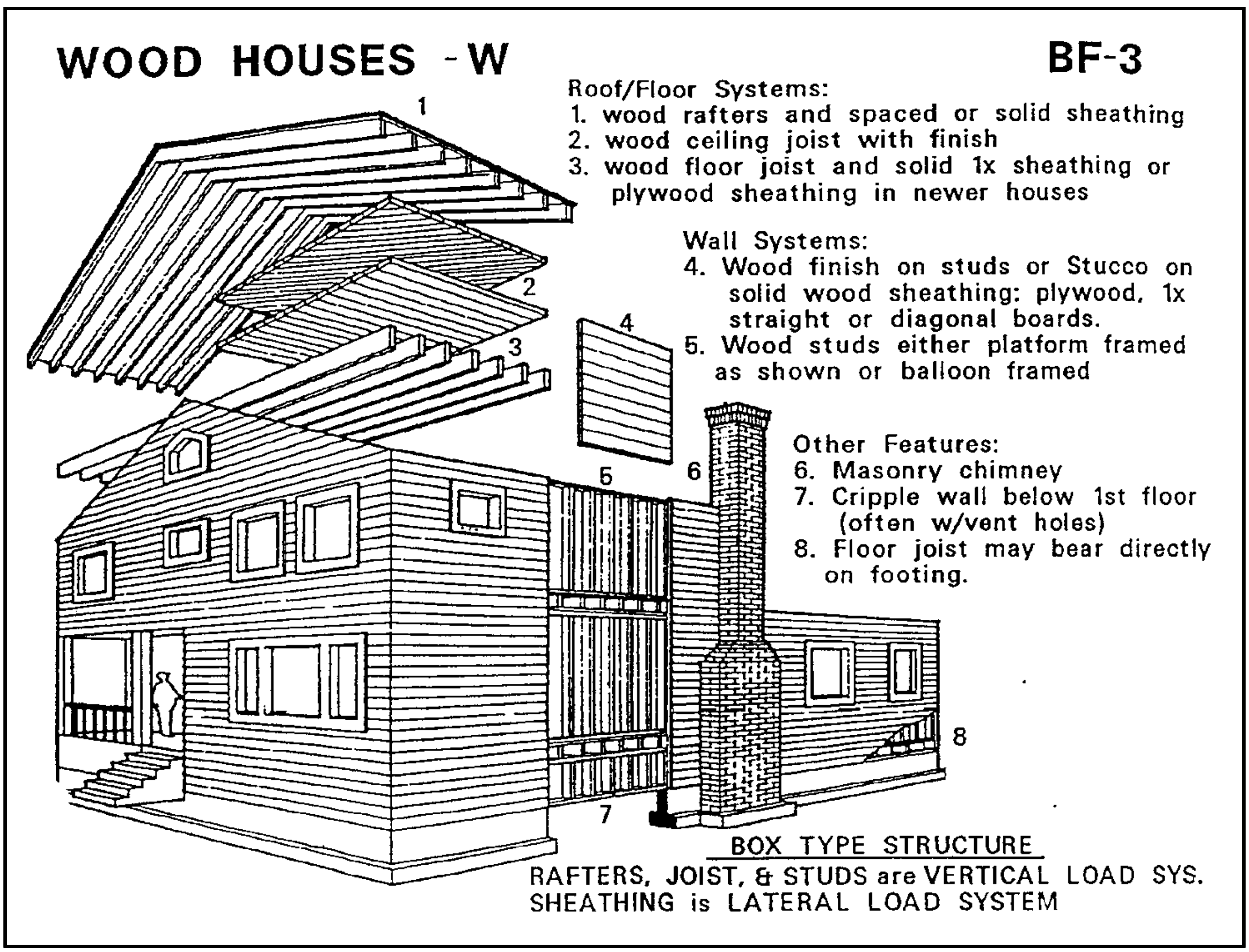
II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

PROBLEMATICAL BUILDING TYPES

Wood Frame Building — W These structures can vary from 1 to 4 stories and contain from one to tens of living units. The principle weakness may be in lateral strength of walls, or interconnection of structure especially at the foundation. Common problems in strong earthquakes are:

! Walls that are weakened by too many openings become racked (rectangles become parallelograms). This can cause a significant offset of one floor from another and in severe cases collapse has occurred.

! Relatively modern 2- and 3-story, wood apartment buildings may have walls that are braced using only plaster/gypsum board, let-in bracing, or inadequately designed plywood. These structures may experience brittle, first story failures, especially when upper story walls do not align with those in the lower story.



II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

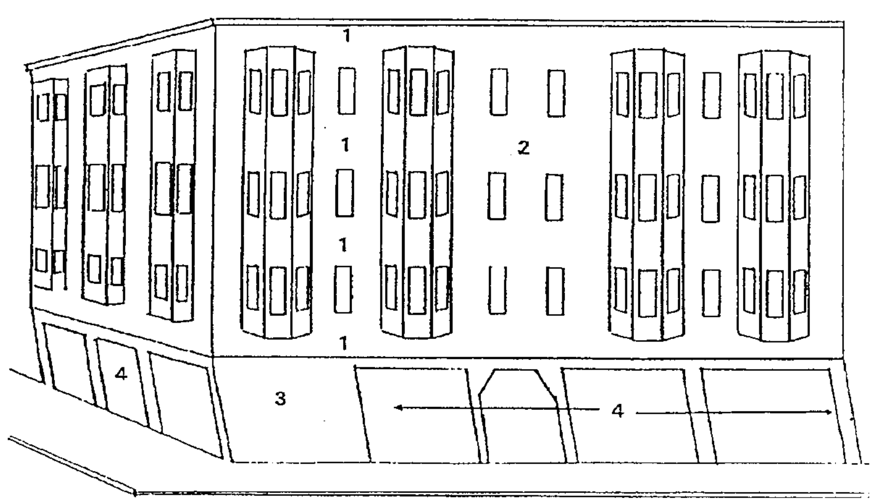
PROBLEMATICAL BUILDING TYPES

Wood Frame Building — W (continued)

! Wood houses with crawl spaces can shift or slide off their foundations.
! Masonry chimneys can crack and fall off or into the structure.
! Masonry veneers can fall off walls and shower adjacent areas with potentially lethal objects.
! Structures can separate at offsets in floor/roof levels (such as porches and split level houses).
! There is a great danger of fire in these structures due to the presence of so much fuel.

WOOD FRAME APARTMENT BUILDINGS BF-4

1. 2x wood joist at roof/floors with 1x wood sheathing or plywood (post 1945)
2. Wood studs, platform framed with wood sheathing:
   1x horizontal - pre 1935
   1x diagonal - pre 1945
   Plywood, Gypsum, or wire after 1945
3. Walls may have masonry veneer especially in first story
4. First story garage openings create a weak/soft story. This can be overcome by using properly designed shearwalls or by changing the garage to a concrete structure with strong shearwalls.

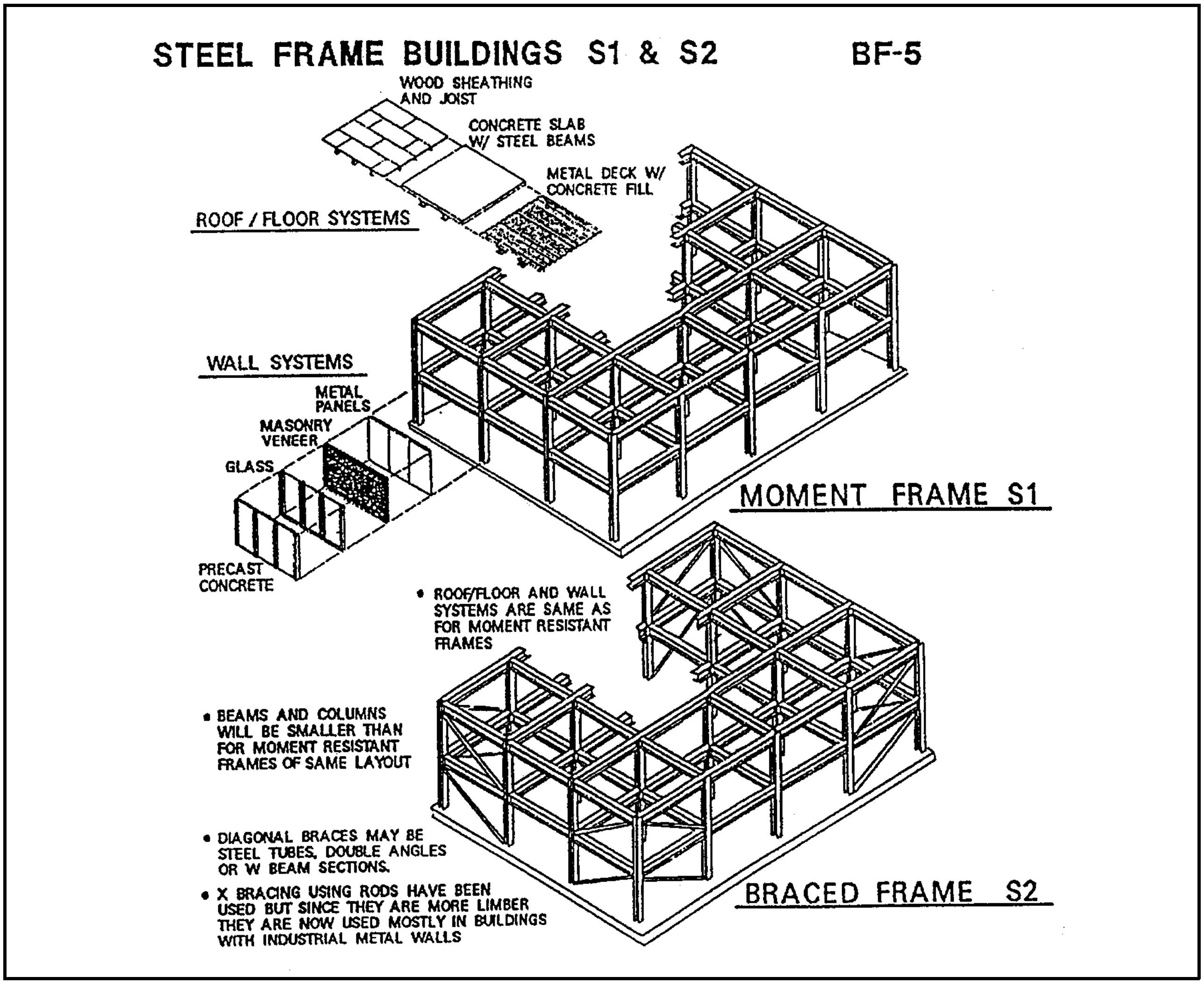


II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

<u>PROBLEMATICAL BUILDING TYPES</u> (continued)

Diagonally Braced Steel Frames — S2 may be from one- to twenty-story office buildings with glass or other non-structural exterior covering. Steel buildings in general have performed well, but those with diagonal bracing have had the following problems:

- ! Buildings that contain slender rod cross bracing may have excessive distortion (story drift) which can lead to shedding or significant damage to brittle, finish materials such as glass, masonry veneer, or precast concrete panels. Whipping action has caused some slender cross braces to break.
- ! When the braces/columns are not properly proportioned, especially in taller frames, the great tension strength of the braces can cause compression (buckling) failure of columns. This effect is attributed to the catastrophic failure of the Pino Suarez, 20-story tower in Mexico City in 1985.

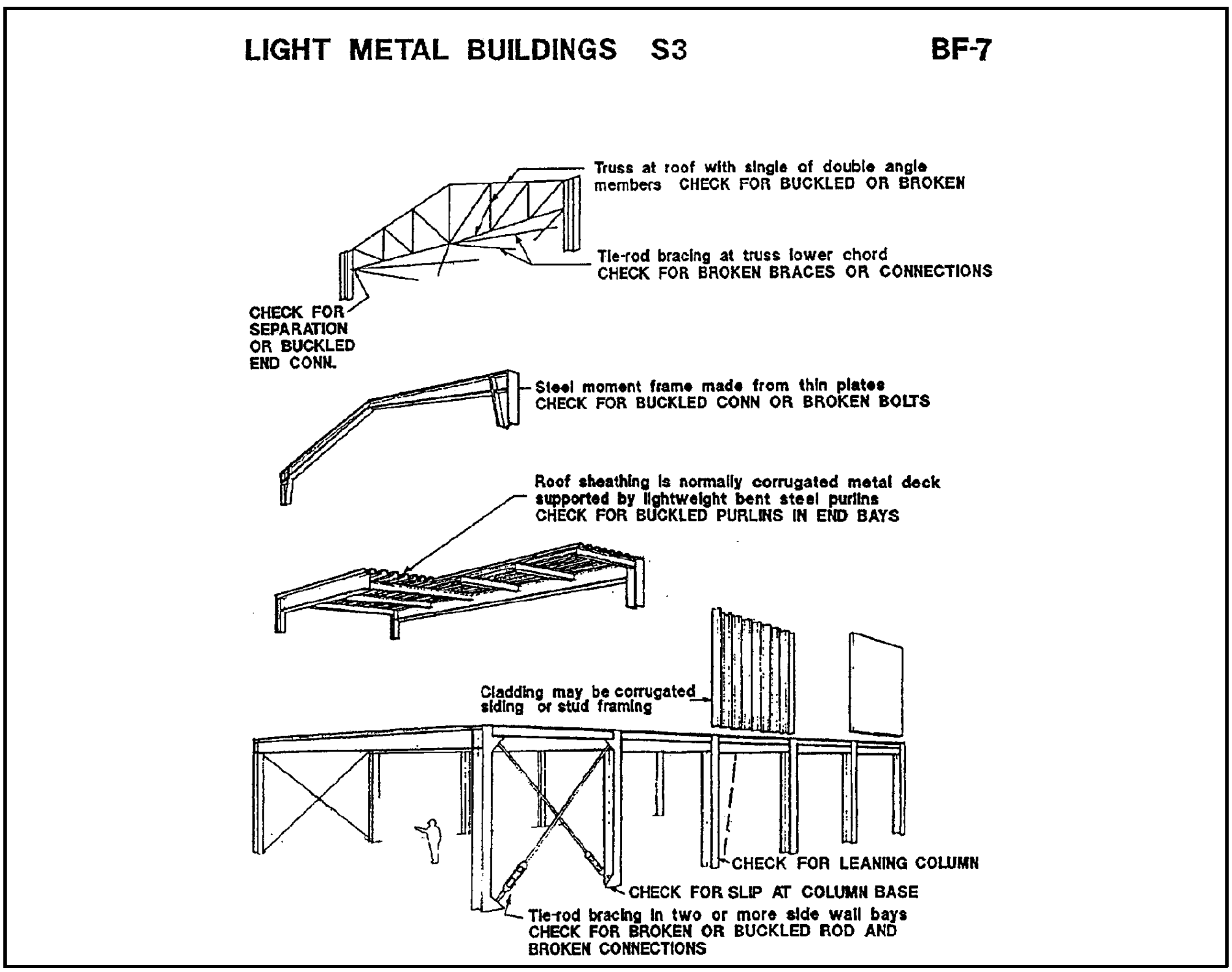


II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

PROBLEMATICAL BUILDING TYPES (continued)

- ! When tube type members are used for diagonals, sudden local crippling at cross-section corners has resulted. This can occur when cold rolled tubes are used, since high stresses are originally induced during forming.
- ! Inadequate detailing or workmanship at connections has caused local failures, such as buckling of connection plates and roll over of beams. Although collapse has not resulted from these failures, significant non-structural damage has occurred.

\# **Light Metal Buildings — S3** are normally one story pre-engineered buildings, sheathed with metal siding and roofing. These structures have been damaged during earthquakes due to poor connections and field errors such as incomplete welding of joints. However, most respond well to quakes due to their lack of mass and abundance of flexibility. During strong windstorms, however, Light Metal Structures have exhibited the following problems:



II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

PROBLEMATICAL BUILDING TYPES (continued)

Light Metal Buildings — S3

! Building walls and roof loose sheathing, purlins and girts that were braced by the sheathing will then buckle, often leading to progressive, buckling collapse of entire structure.

! Doors and windows are blown in leading to greatly increased outward pressures on leeward wall and roof, followed by shedding of sheathing, and in most severe cases, progressive collapse.

! Tie-rod bracing can be broken or stretched by whipping action. Also, rod end connections can fail by pullout, prying action, etc.

! Lower chord bracing at end walls can buckle due to wind pressure on wall.

! Since these structures have little redundancy, performance is usually governed by "WEAKEST LINK" behavior (failure of one element can lead to progressive/domino type collapse).

Concrete Frame Buildings -C1, C3 older frames are from one to thirteen stories high, and may have URM infill walls. Older frames in California had thin concrete infill walls on property lines in some cases. The most hazardous configurations include soft (high, open) first stories, open front buildings (typical of retail one- and two-story), and corner buildings (torsion problems). The common earthquake problems are:

! Columns break at intersections with floor beam. Inadequate rebar and ties don't confine the concrete when subjected to high shear and tension stresses. Failures may be driven by strong P-Delta effect.

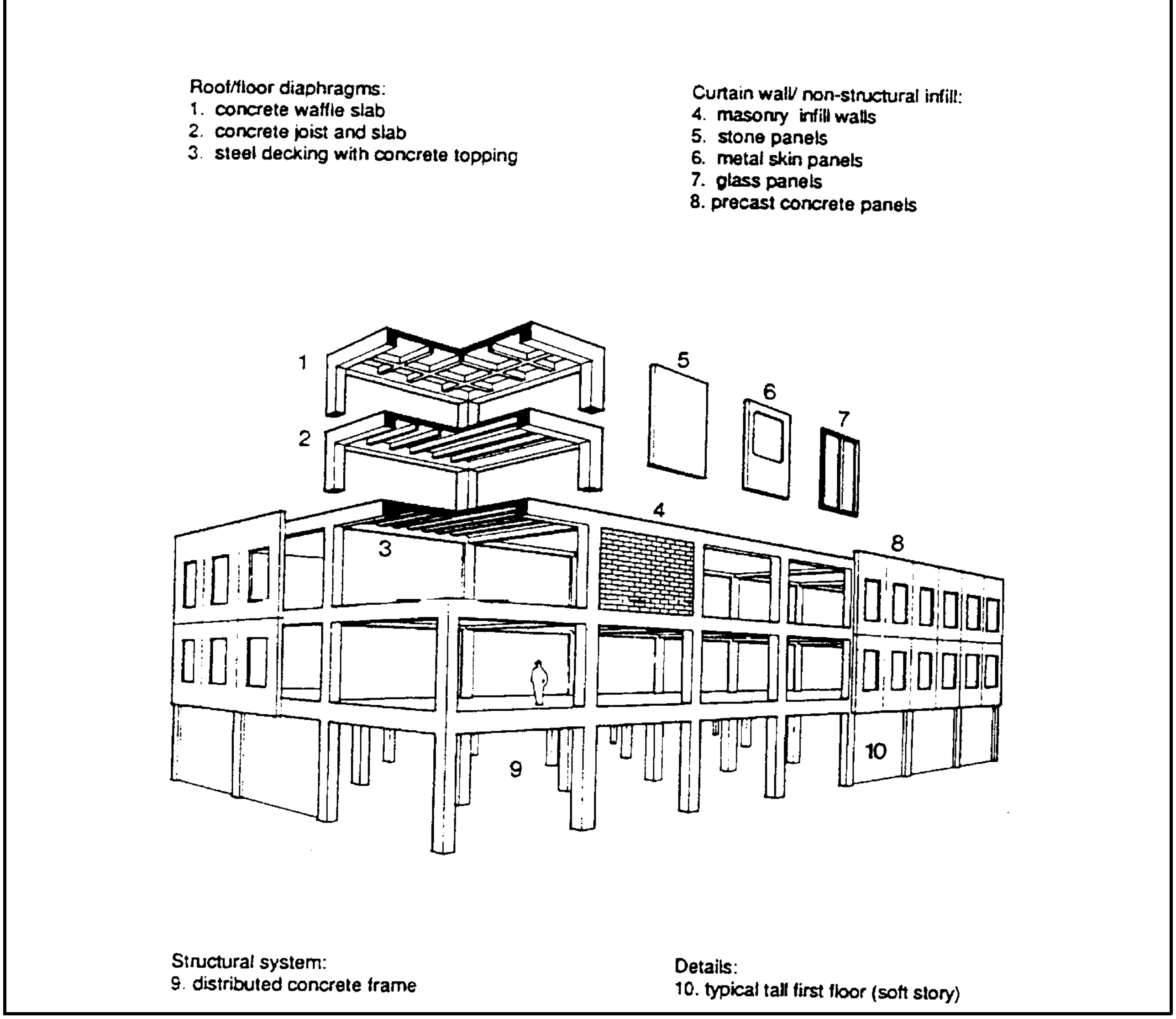
! Short columns in exterior walls get high shear and tension stresses focused into them by surrounding massive concrete.

II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

PROBLEMATICAL BUILDING TYPES (continued)

Concrete Frame Buildings — C1, C3

- ! Bending and punching shear failure at inter-sections of flat slabs (waffle etc.) and columns.
- ! URM infill can fall off, often pop out of surrounding frames. Also, URM infill can cause columns to shear off at floor line or top of URM.
- ! Weak concrete and poor construction can make all above conditions worse and more likely to lead to larger collapse.



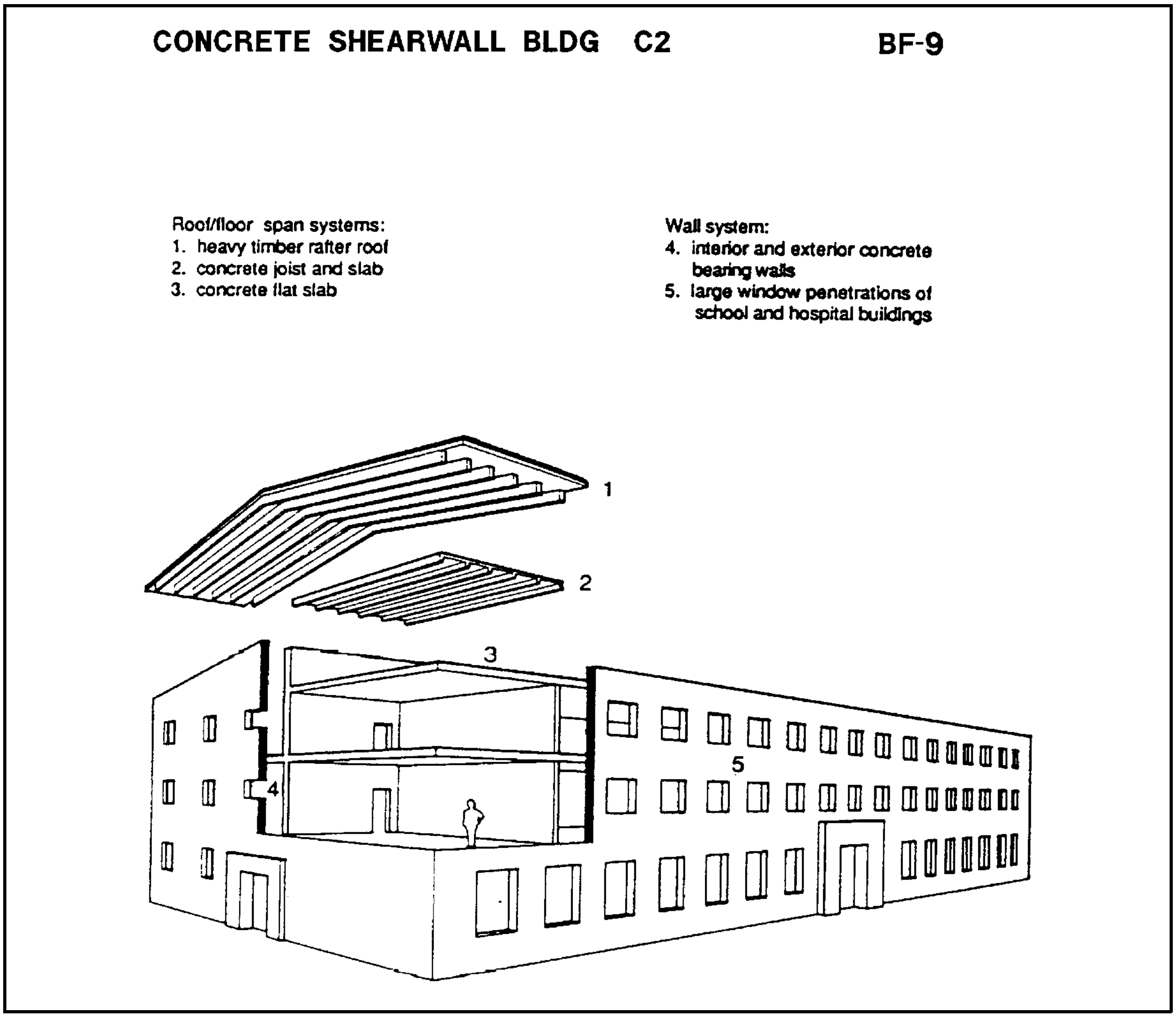
CONCRETE MOMENT RESISTING FRAME C1 BF-8

II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

PROBLEMATICAL BUILDING TYPES (continued)

Concrete Shearwall Buildings — C2 are from one- to thirteen-stories high with walls on all four sides and/or within the structure as corridor/stair or other divisions between spaces. Walls may have openings "punched in" as doors or windows, but in more modern buildings, the openings may be in groups that are placed between solid wall sections. These buildings rarely collapse in earthquakes but damage can occur, such as:

! X-cracking of wall sections between punched-in openings.
! Severe cracking of shallow wall/floor header sections that frame between solid wall sections.
! Severe cracking or collapse of columns that occur in "soft stories" of otherwise uniformly stiff shearwall buildings (soft first-story, etc.).



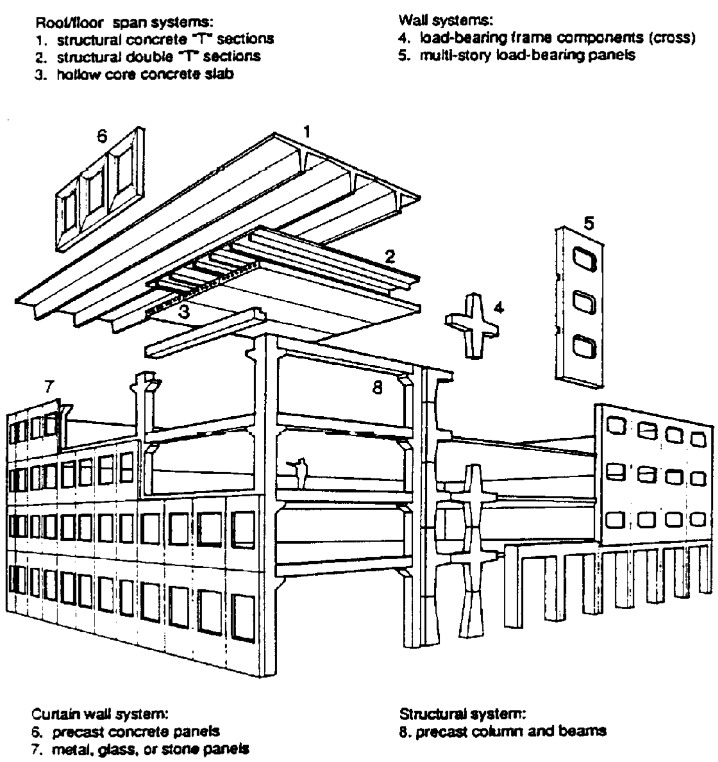
II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

PROBLEMATICAL BUILDING TYPES (continued)

Precast Concrete Frame PC2 — Usually one to ten stories tall, although precast wall panels may be used in taller buildings. Floors/roof may be tee, double tee, or hollow core concrete plank sections supported by precast girders and columns. Lateral resistance is often provided by reinforced masonry or concrete walls, but buildings that rely on moment frame resistance have performed very poorly (Armenia). The common earthquake failures are:

- ! Joint failures — joints between roof/floor and walls, between roof panels, between wall panels and joints between floor beams and columns. This can lead to complete collapse as the building breaks into very large parts.
- ! Wall panels separate from building and can fall. If panels are non bearing only local failure may be the result. In cases the floors/roof supported by the walls can also collapse.
- ! Progressive collapse can be caused by a joint failure between column and beam or slab and wall panel. This then results in failure of the structure just above, due to lack of support, and also to the structure below, due to debris loading.

PRECAST CONCRETE BUILDINGS PC2 **BF-10**



PRECAST CONCRETE FRAME W/ SHEARWALLS

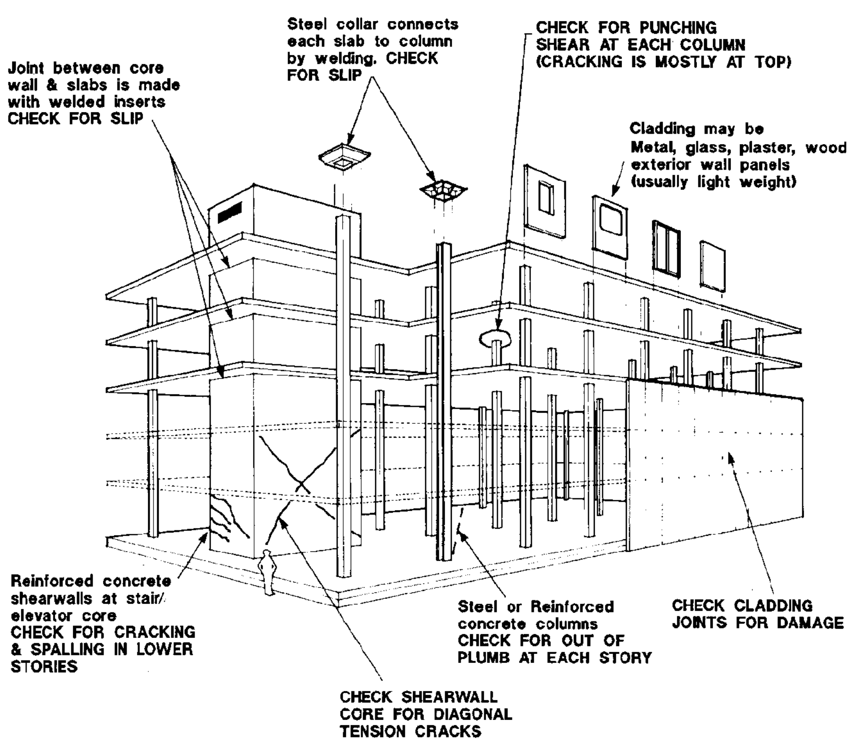
II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

PROBLEMATICAL BUILDING TYPES (continued)

Post-tensioned Lift Slabs — These are buildings from 3 to 13 stories high, made with thin (6 to 8") flat slabs poured as pancake stacks and then lifted into place on concrete or steel columns. They are laterally braced with cast in place concrete shear walls that form elevator or stair wells and/or reinforced masonry shear walls. Not listed in ATC-21, but included here since spectacular collapses have occurred.

- ! A six-story apartment building of this type collapsed in the 1964 Alaska earthquake due to overturning of the stair cores. A twelve-story building of this type collapsed during construction in 1987.
- ! The resulting collapsed structures have very closely spaced broken slabs that are essentially unreinforced concrete. The unbonded reinforcing cables become loose during collapse, leaving the concrete essentially unreinforced. The lack of projecting beams, in this type of construction, can result in very close spacing of collapsed slabs.

POST TENSIONED LIFT SLAB BUILDING BF-11



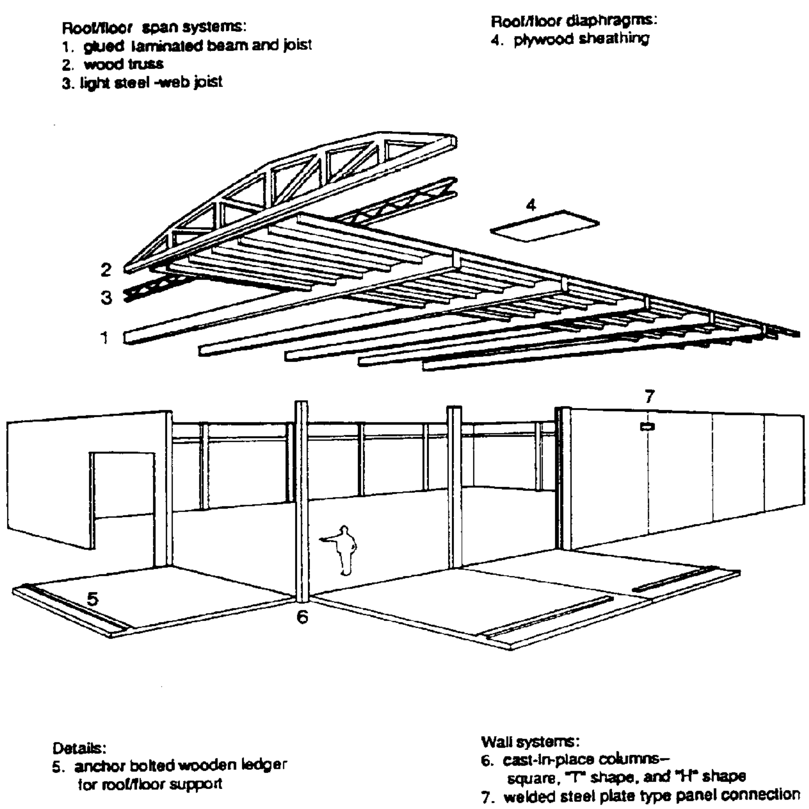
II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

PROBLEMATICAL BUILDING TYPES (continued)

Tilt Up Concrete Wall Buildings — TU Usually one-story buildings with wood roof, but may be up to three stories. May have wood floors, concrete floors, steel framing with concrete filled metal deck floors, or with up to 1½" concrete or other fill on wood floor. The common earthquake problems are:

! Walls separate from wood floors/roof causing at least local collapse of floor/roof, possible general collapse of walls and floor/roof. (Note: This problem occurred during the Northridge Earthquake to approximately 400 buildings, most of which had strap connections that were cast into walls and bolted to roof members. More substantial connections, that can resist both tension and compression, appear to be required, since it has been demonstrated that forces as high as 200% G can be generated at the mid-span of wood roof diaphragms in this type of building.)

TILT-UP CONCRETE WALL BUILDING BF-12



ONE STORY TILT-UP BUILDING (MAY ALSO BE 2 OR 3 STORY)

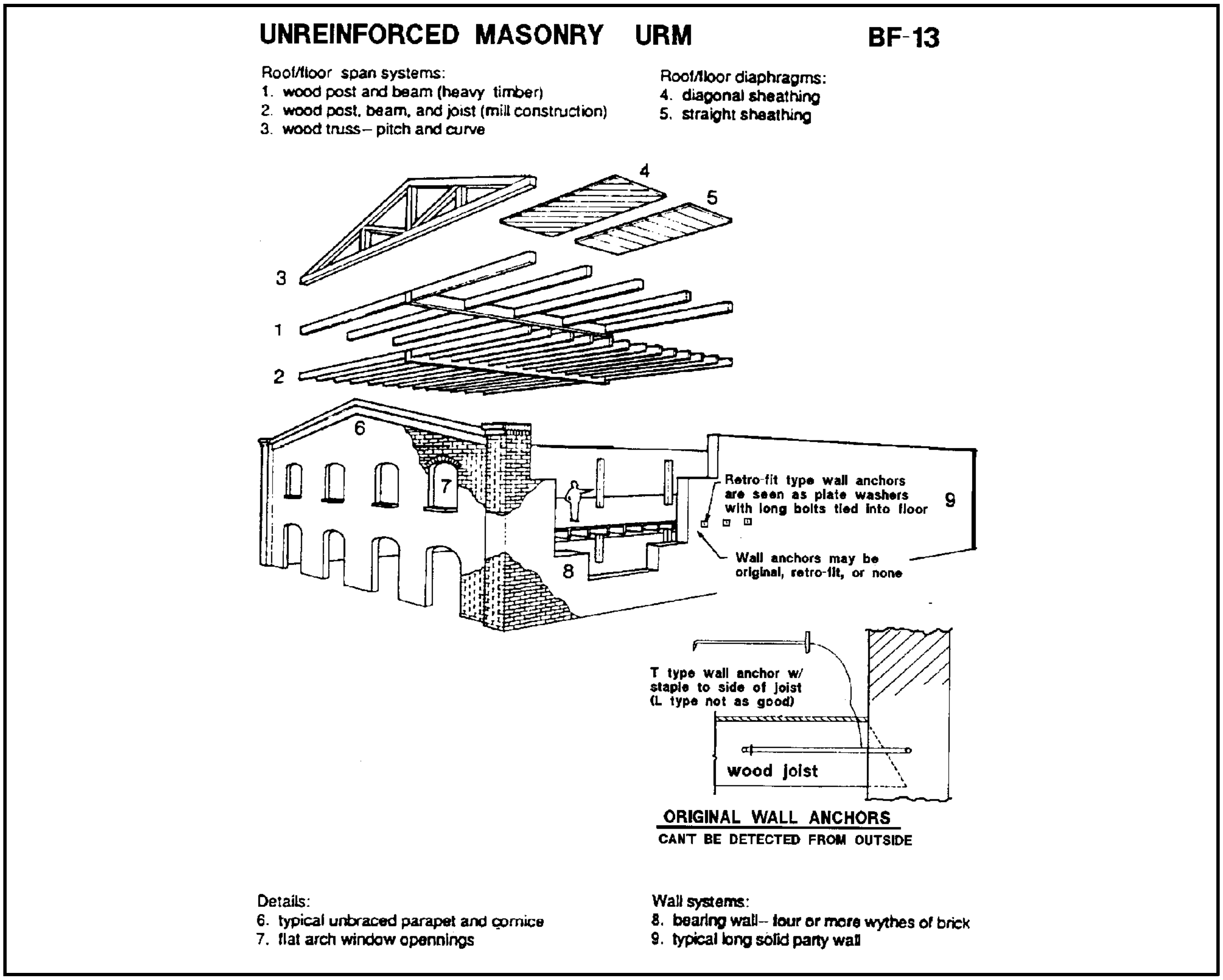
II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

PROBLEMATICAL BUILDING TYPES

 # Tilt Up Concrete Wall Buildings — TU (continued)

- ! Suspended wall panels fall off building. (Note: suspended panels could be a problem on S1, S2, C1, C2, PC2, and RM buildings.)
- ! Walls may have short, weak columns between window openings that fail due to inadequate shear strength. Large buildings that are TEE, L, or other non-rectangular plan configuration can have failures at the intersecting corners.
- ! The major weight of these buildings is normally in the walls, and most failures are limited to exterior bays of the buildings, supported by the walls.

 # Unreinforced Masonry Buildings URM



II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

PROBLEMATICAL BUILDING TYPES (continued)

Unreinforced Masonry Buildings URM Usually from one- to six-story buildings with URM bearing walls and wood floors (BF-13). There are estimated to be as many as 50,000 in California. This would include steel and concrete frames with URM infill (BF-15, 15a). In addition to these, there are unreinforced or under-reinforced hollow concrete block walls, masonry veneer on wood or metal studs, and native stone, adobe, etc., bearing wall structures. Common earthquake problems are:

! Parapets and full walls fall off buildings due to inadequate anchors.
! Multi thickness walls split and collapse or break at openings. Mortar is often weak and made with too high a lime content.
! Walls that are more heavily loaded by roof and floors tend to perform better than walls that are parallel to framing, since load of floor etc. tend to compress bricks together.
! Roof/floors may collapse if there are no interior wall supports and if the earthquake has a long enough duration.

BF-13A

TYPES OF URM BUILDINGS

1. Brick bearing wall buildings — mostly the exterior walls are URM, but floors and interior walls are wood. Usually found in downtown areas.

2. URM infill — in concrete frames and steel frames. Infill may be brick, hollow clay tile, or hollow concrete block (cinder block).

3. Unreinforced, hollow concrete block, bearing wall buildings. May have bond beams at floor and roof lines. Similar to 1.

4. Unreinforced or under-reinforced multi-thickness cavity wall buildings. Often will have insulation layer between two masonry layers or insulation in hollow unit masonry blocks. This is relatively modern construction and may be used as infill or bearing walls with bond beams.

5. Masonry veneer on wood or steel stud walls. Anchorage is all important due to interaction of brittle wall covering on flexible structure.

6. Native stone, adobe, mud, etc. bearing wall buildings.

II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

PROBLEMATICAL BUILDING TYPES (continued)

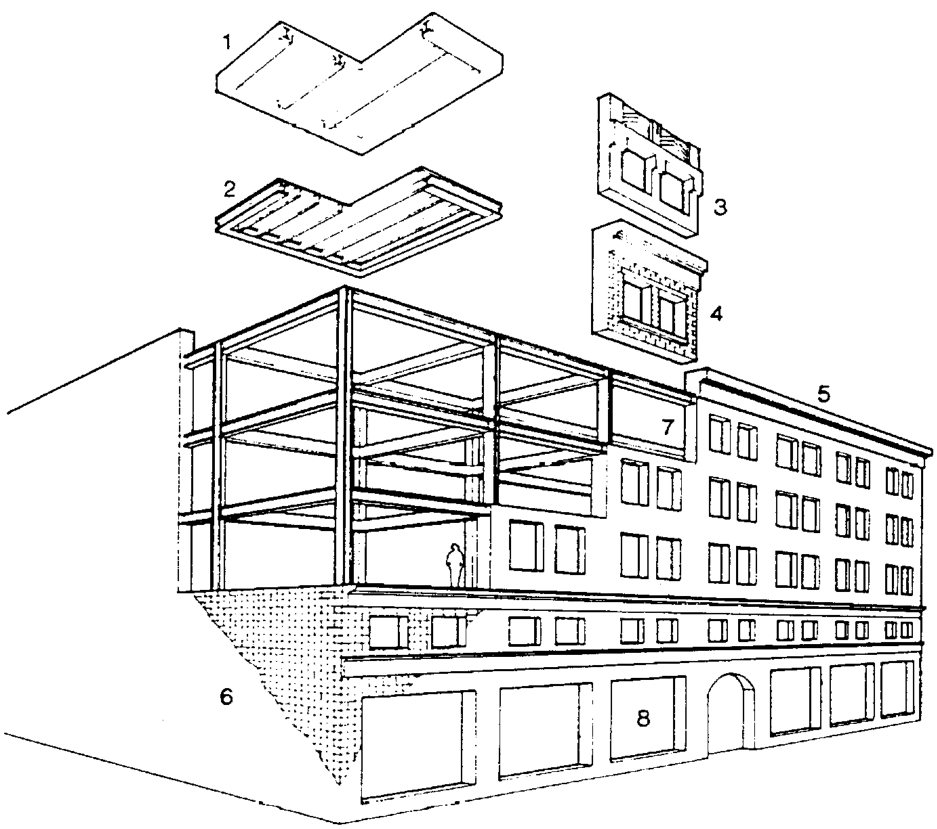
 # Unreinforced Masonry Buildings URM

- ! Cavities are usually formed by wood floors in familiar patterns of Vee, Lean-to, and complicated Pancake.
- ! Older steel frame buildings with unreinforced or lightly reinforced masonry infill, often shed this weak, brittle covering as they flex to resist the quake (BF-15).
- ! Broken bricks often line the streets where these buildings are located and people can be trapped on the sidewalk, auto, etc.

STEEL FRAME WITH URM INFILL **BF-15**

Roof/floor span systems:
1. steel framing with concrete cover
2. wood floor joist and diaphragm (diagonal and straight)

Wall systems:
3. non-load-bearing concrete wall
4. non-load-bearing unreinforced masonry cover wall



Details:
5. unreinforced and unbraced parapet and cornice
6. solid party walls

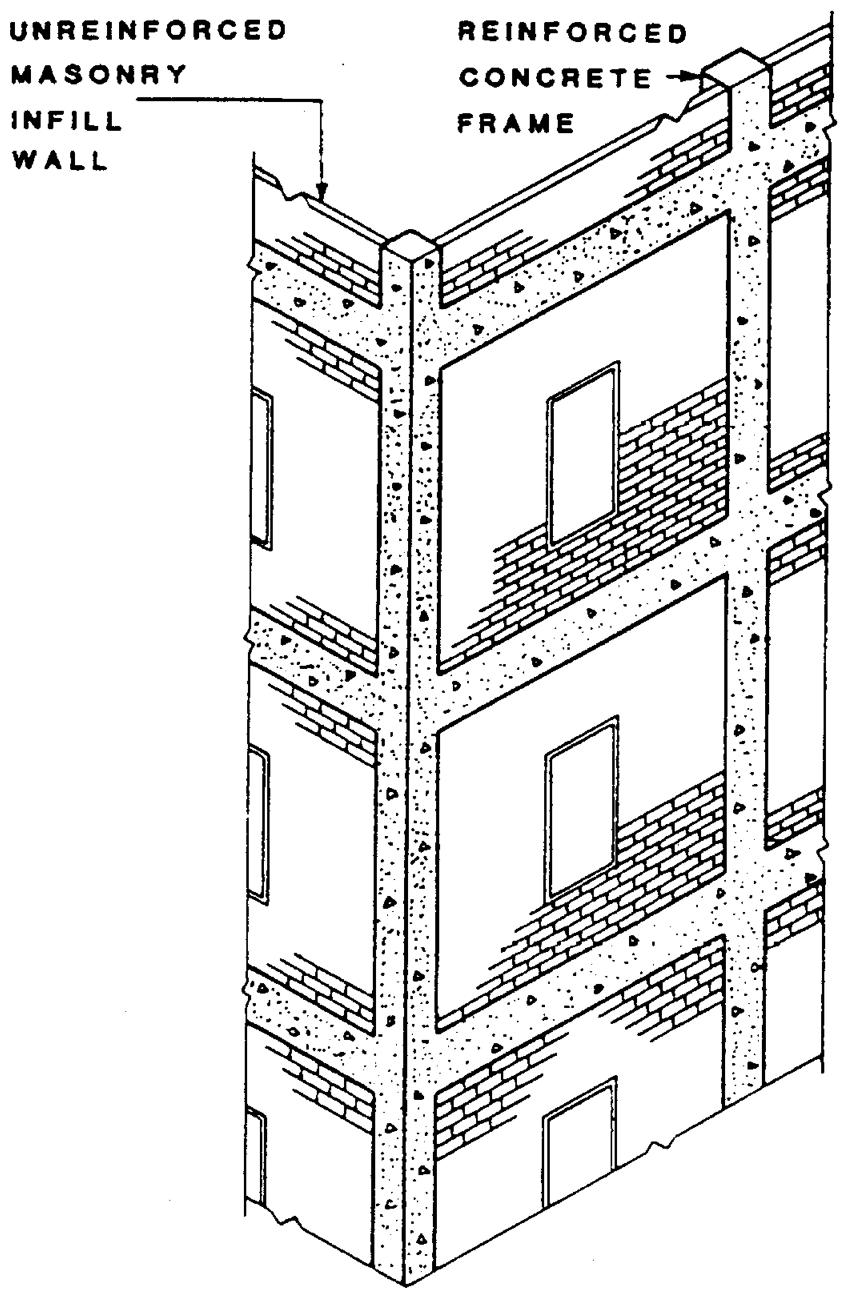
Openings and wall penetrations:
7. window penetrated front facade
8. large openings of street level shops

II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

PROBLEMATICAL BUILDING TYPES (continued)

Unreinforced Masonry Buildings URM

URM INFILL IN CONCRETE FRAME C3 **BF-15a**

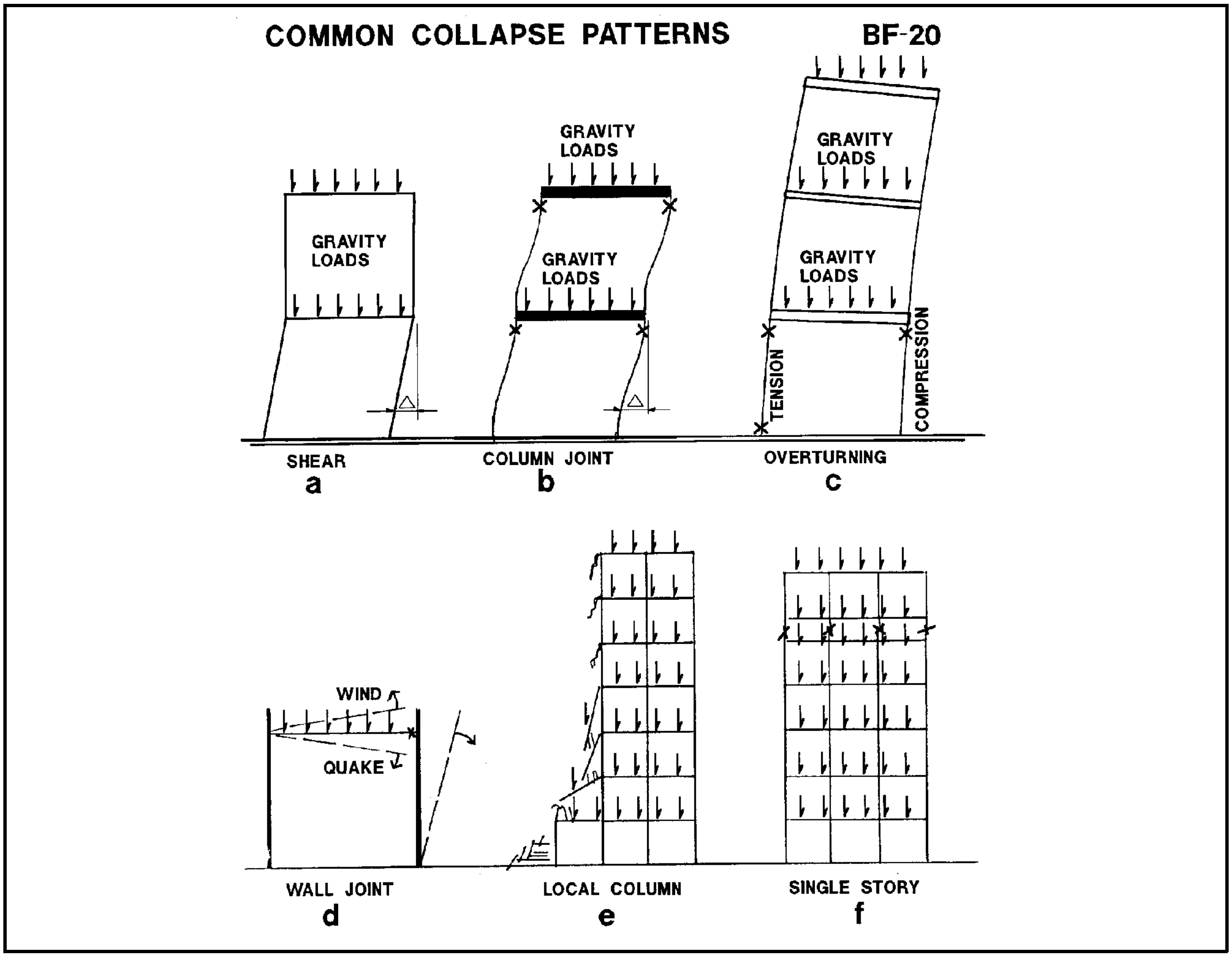


II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

BASIC COLLAPSE PATTERNS

Most building collapses occur due to loss of stability; that is, the basic shape is significantly changed when subjected to a combination of forces. The new, changed shape is much less capable of carrying the forces and, therefore, the structure will rapidly continue to change until it finds a new shape that is stable. A typical example of lost stability is that of the slender column, that "gets out of the way of the load by buckling", as the load comes to rest on the ground/foundation. The most common conditions that lead to building collapse are illustrated by (BF-20).

- ! Inadequate shear strength — failure is normally caused by earthquake shaking, but high velocity winds could produce the same effect. It is most commonly seen in wood structures that have weak wall sheathing or walls of insufficient length, but may also be seen in buildings with unreinforced masonry and/or unreinforced concrete wall, and in diagonally braced steel frames. In rare instances it could also occur when reinforced concrete walls are present.



II. STRUCTURAL ENGINEERING SYSTEMS

B. STRUCTURAL COLLAPSE PATTERNS

BASIC COLLAPSE PATTERNS (continued)

- The basic instability occurs when the gravity load is offset a distance (delta) that is large enough to overcome the shear capacity of walls at a particular level, usually the first story. The horizontal resistance required to maintain stability in the racked condition (parallelogram) illustrated is proportional to the percent of offset (i.e. when a ten-foot-high story is offset one foot, then ten per cent of the total gravity load above that level is required to keep the parallelogram from becoming flatter).

- Inadequate beam/column joint strength — is caused mostly by earthquake shaking of poorly confined concrete. The cycling of the structure when excited by the earthquake causes moment resistant joints to unravel as concrete chunks are stripped away from the reinforcing steel cage. The gravity load can no longer be supported by these columns, and it drives the structure earthward until it stops on the ground or lower floors that have sufficient strength to stop the falling mass. The result of a concrete collapse of this type may be a pancaked group of slabs, a condition where columns are left standing, punched through the slabs, or a group of slabs that are horizontally offset from each other, held apart by broken columns and building contents.

- Tension/compression failure caused mostly by earthquakes and may occur in taller structures with concrete shear walls and/or concrete or structural steel frames. The tension that is concentrated at the edges of a concrete frame or shear wall can produce very rapid loss of stability. In walls, if the reinforcing steel is inadequately proportioned or poorly embedded, it can fail in tension and result in rapid collapse of the wall by overturning. A more common conditions occurs, when the tension causes the joints in a concrete frame to lose bending/shear strength, as previously discussed, a rapid degradation of the structure can result in partial or complete pancaking as in beam/column failure.

- The previously discussed failure of Pino Suarez Tower is an example of how poorly proportioned, steel structures can catastrophically overturn, due to a compression failure of the columns.

- Wall-to-roof interconnection failure — stability is lost in this case since the vertical support of the roof/floor is lost, as well as the horizontal out of plane support of the wall. This condition could be triggered by any of the destructive forces previously mentioned.

II. STRUCTURAL ENGINEERING SYSTEMS
B. STRUCTURAL COLLAPSE PATTERNS

BASIC COLLAPSE PATTERNS (continued)

- ! Local column failure — can lead to loss of stability and/or progressive collapse in a part of a structure, and may, again, be caused by any of the previously mentioned forces. Precast concrete and structures that have wood floors tend to be more susceptible to a progressive type failure (see BF-18), due to the lack of continuity of these construction configurations.

- ! Single floor collapse — has occurred in earthquakes due to pounding or vertical irregularities that focus the damaging effects to a single story.

In summary in most all collapses (except cases when wind causes lifting), the driving force is the gravity load acting on a structure that has become unstable due to horizontal offset or insufficient vertical capacity. In addition, subsequent lateral loads from wind or aftershocks can increase the offset, exaggerating the instability. The structure is often disorderly as it collapses. Some parts may remain supported by un-collapsed adjacent bays as tension structures.

The issue in US&R is not the academic one of how the structure collapsed in order to improve future construction, but what additional collapse is possible and how stable is the existing configuration.

II. STRUCTURAL ENGINEERING SYSTEMS
C. EARTHQUAKE & WIND COLLAPSE PATTERNS

EARTHQUAKE COLLAPSE PATTERNS

The basic principals are:

! Earthquake shaking causes damage to structure.

! Gravity causes collapse.

! Redundancy and ductile behavior can prevent or reduce extent of collapse.

! Brittle behavior enhances possibility and increases extent of collapse.

Based on previous earthquakes the ATC-21 building types can be further divided into four separate groups, with each exhibiting a distinctive collapse pattern. These groups are:

LIGHT FRAME- Mostly wood frame.

HEAVY WALL — URM, Tilt-up, and other low raise buildings with concrete and masonry walls.

HEAVY FLOOR- Concrete frame buildings and highway bridges.

PRECAST CONCRETE BUILDINGS — with fairly heavy floors and some heavy walls.

FEMA US&R RESPONSE SYSTEM
RESCUE SPECIALIST TRAINING 06/97

COLLAPSE PATTERNS

Basic Principles

! Earthquake shaking causes damage to structural load-resisting system.

! Gravity causes structural collapse.

! Redundancy and ductile behavior can prevent structural collapse.

! Brittle behavior enhances possibility of structural collapse.

FEMA US&R RESPONSE SYSTEM
RESCUE SPECIALIST TRAINING 06/97

COLLAPSE PATTERNS

LIGHT FRAME BUILDINGS
! Wood frame, box-type structure, up to 4- story buildings used for living or other occupancy.

! Failure is normally in the thin skin that covers the walls. Walls rack and become parallelograms.

! Heavy and/or poorly connected parts fall away from main bridling.

HEAVY WALL BUILDINGS
! Buildings with thick, bearing walls of URM, tilt-up concrete or other lightly reinforced masonry.

! May be used for living, commercial, or industrial occupancy and rarely exceed 8 stories.

! Failure normally occurs in connection of heavy walls to light, wood floors/roof.

! URM walls can break off above roof, between floors, and/or can peel.

FEMA US&R RESPONSE SYSTEM
RESCUE SPECIALIST TRAINING 06/97

COLLAPSE PATTERNS

HEAVY FLOOR BUILDINGS
! Cast-in-place concrete frame buildings and some highway bridge structures. Buildings may be up to 13 stories and may have some bearing and infill walls.

! Failure most often occurs in columns at joints with floors. Collapse pattern may then be pancake, story offset, weak story, torsion failure of corner buildings, or even over-turning of building.

PRECAST BUILDINGS
! Buildings assembled of factory-built, light weight, concrete parts.

! May be as tall as 13 stories and may be used for living, hospital, school or other occupancies.

! Frame-type with few walls and/or other infill walls have performed very poorly.

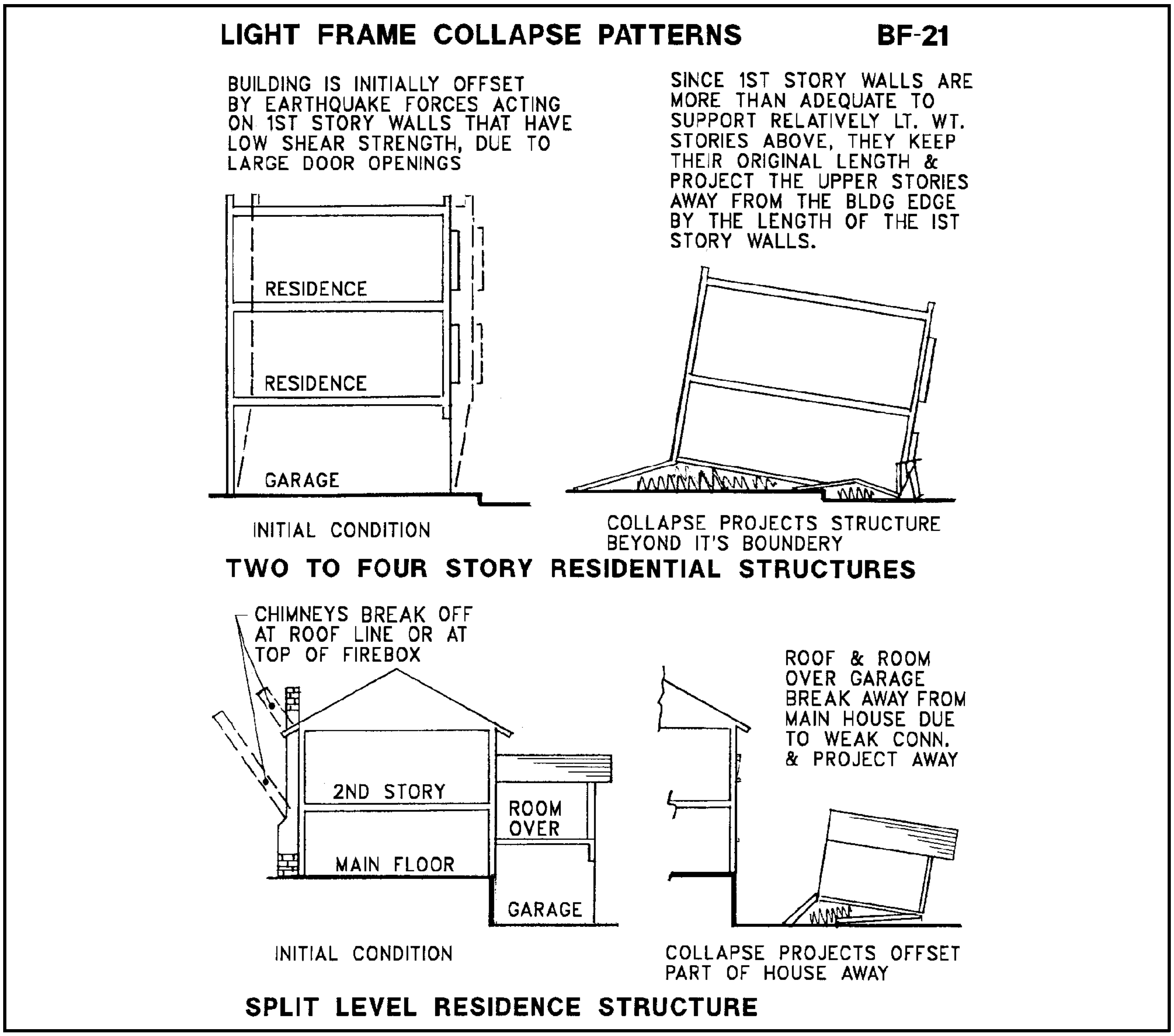
! Failure occurs at interconnection of parts which can result in total or partial collapse.

II. STRUCTURAL ENGINEERING SYSTEMS
C. EARTHQUAKE & WIND COLLAPSE PATTERNS

EARTHQUAKE COLLAPSE PATTERNS (continued)

 # Light Frame Collapse Patterns

- ! Collapse usually occurs when lower walls have insufficient strength to resist the lateral forces and rack (become parallelograms).
- ! If there is a sufficiently heavy load on these walls they can completely collapse as the wall top moves sideways a distance equal to its height as shown in BF-21.
- ! This causes the structural collapse to be in the form of part or all of the building being projected away from its original foundation by the height of the story walls that fail.

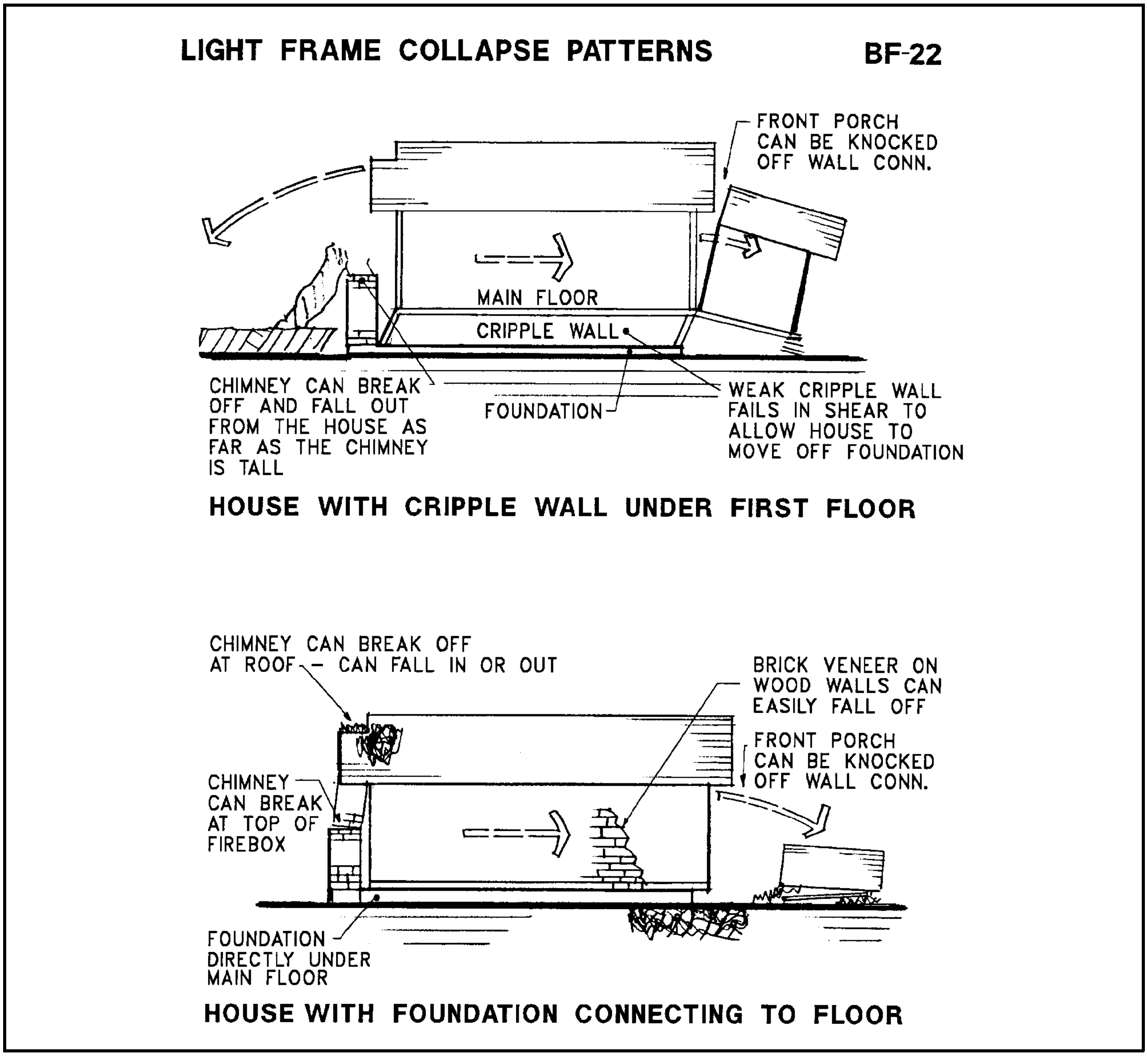


II. STRUCTURAL ENGINEERING SYSTEMS
C. EARTHQUAKE & WIND COLLAPSE PATTERNS

EARTHQUAKE COLLAPSE PATTERNS

Light Frame Collapse Patterns (continued)

- ! When the bottom story of a multi-story light frame structure fails in this way, additional stories can also collapse due to the impact of the first story hitting the ground.
- ! This type of collapse usually leaves many voids that are fairly easily accessible.
- ! There is great danger of fire due to the combination of broken gas (or other fuel) lines and the combustible debris.

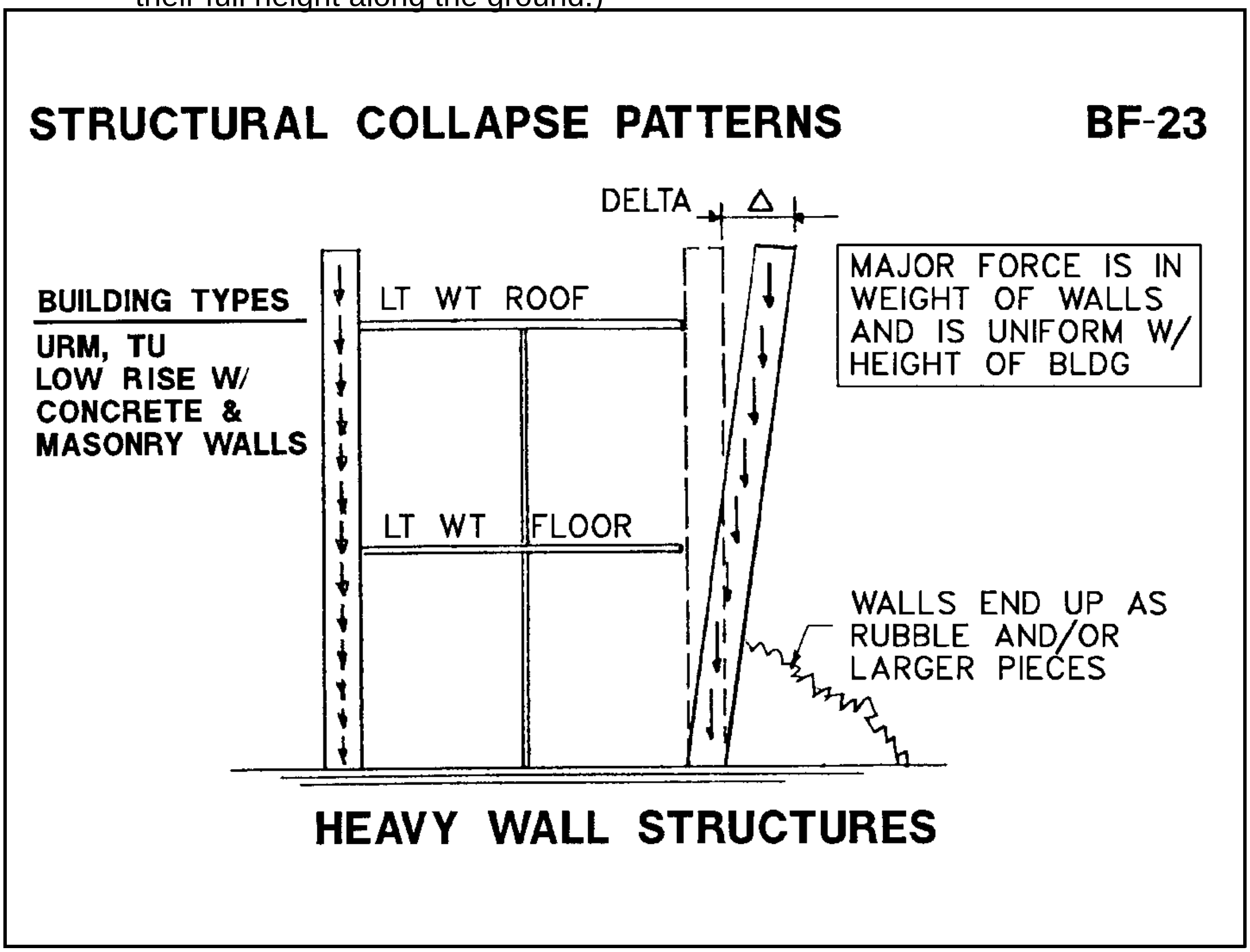


II. STRUCTURAL ENGINEERING SYSTEMS
C. EARTHQUAKE & WIND COLLAPSE PATTERNS

EARTHQUAKE COLLAPSE PATTERNS **(continued)**

Heavy Wall Collapse Patterns

- ! Collapse is usually partial and is strongly related to the heavy, weak bearing walls falling away from the floors.
- ! In URM buildings the walls normally fall away from their original position, but, most often, don't project out as far as their height. The combination of the weak interconnection of the masonry pieces and gravity tend to cause the debris to stay within ten to fifteen feet of the building face. (Note, in collapse due to failure of interior columns or due to fire, it is possible to have the very precarious situation of multi-story heavy walls that are left standing without any laterally supporting floors/roof. For this case it is probable that the wall could fall such that they extend their full height along the ground.)



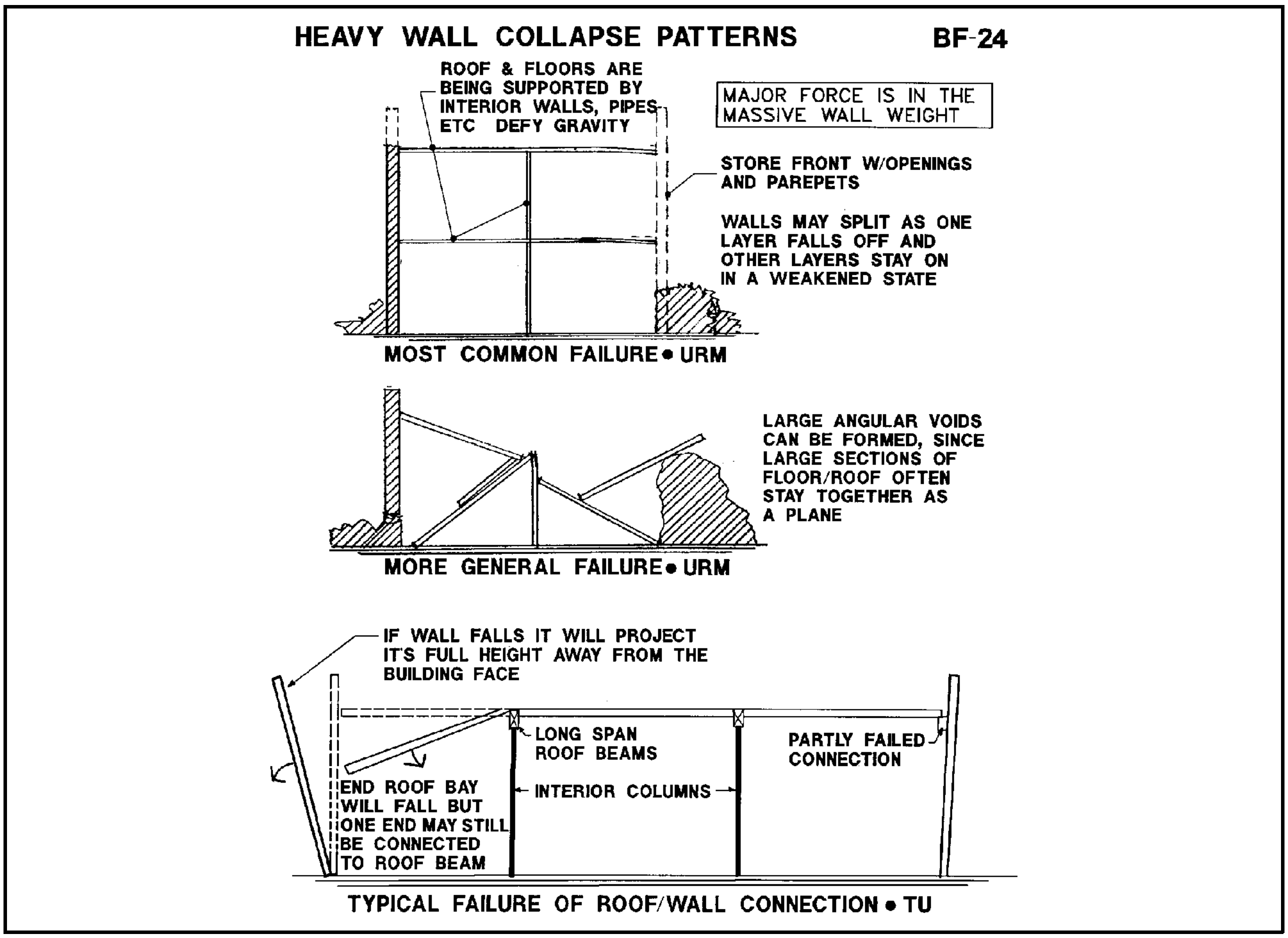
II. STRUCTURAL ENGINEERING SYSTEMS
C. EARTHQUAKE & WIND COLLAPSE PATTERNS

EARTHQUAKE COLLAPSE PATTERNS (continued)

Heavy Wall Collapse Patterns

! Walls in tilt-up buildings also, normally fall away from the roof or floor edge, but since they are very strong panels, the top of the wall will fall as far away from the building as its height. The falling walls can cause the roof and floors that they support to collapse in patterns of Lean-to, Vee, Pancake, and Cantilever.

- Lean-to — can be formed when one exterior wall collapses, leaving the floor supported at one end only.
- V-Shape — occurs when an interior supporting wall or column fails.
- Pancake — can occur when all vertical supporting members fail and most of the floors collapse on top of one another. This is more common in heavy floor buildings.
- Cantilever — is a pancake collapse where some of the floor planes extend out as unsupported members.

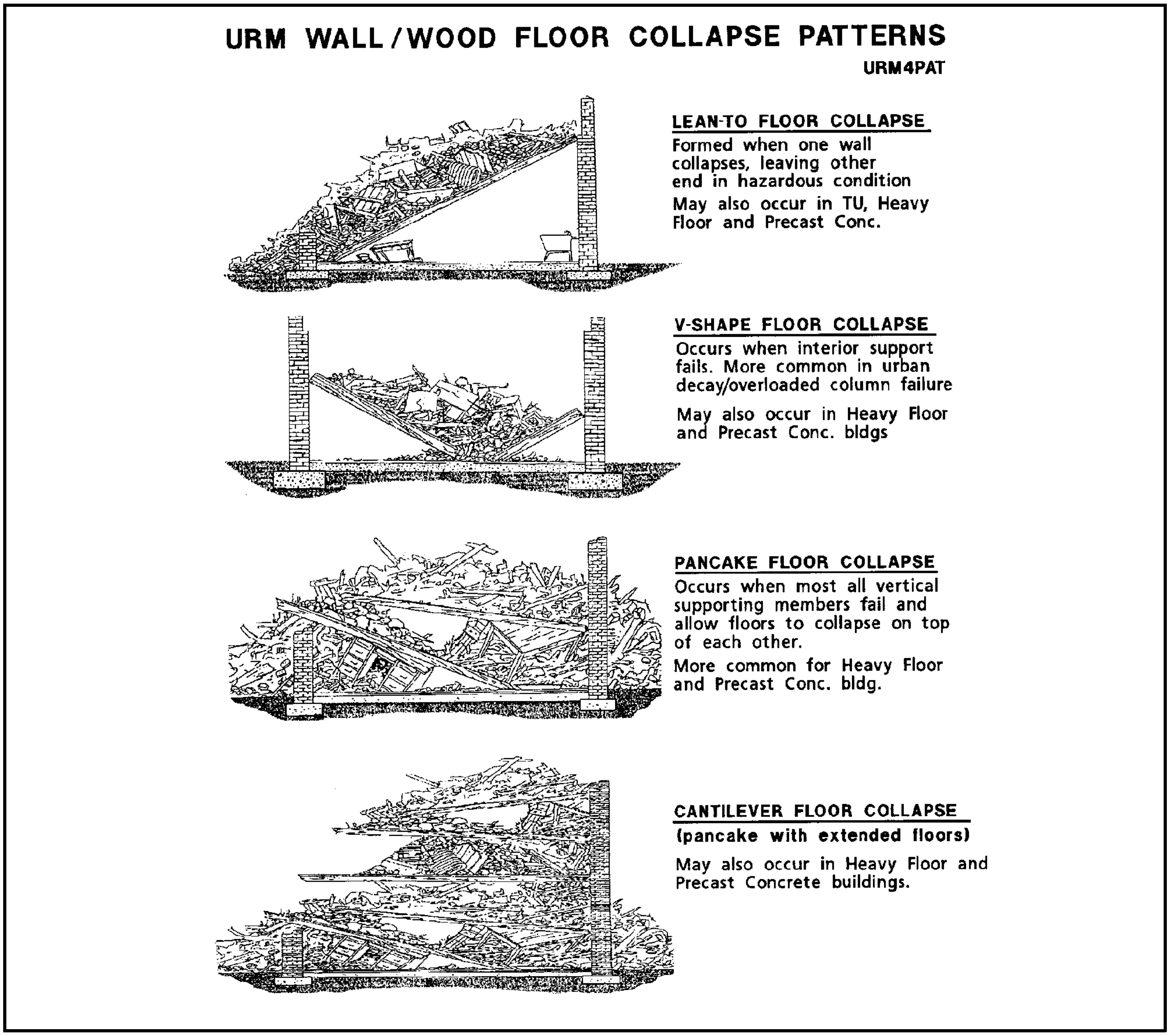


II. STRUCTURAL ENGINEERING SYSTEMS
C. EARTHQUAKE & WIND COLLAPSE PATTERNS

EARTHQUAKE COLLAPSE PATTERNS (continued)

Heavy Wall Collapse Patterns

- ! When property line walls fall on an adjacent, lower buildings, these structures will usually have some sort of roof/floor collapse.
- ! When the wood roof and/or floors collapse, many easily accessible voids can be created.
- ! Areas adjacent to the walls where the heavy debris fall often contain badly injured or dead victims.
- ! The combination of broken gas lines and debris can lead to fire.

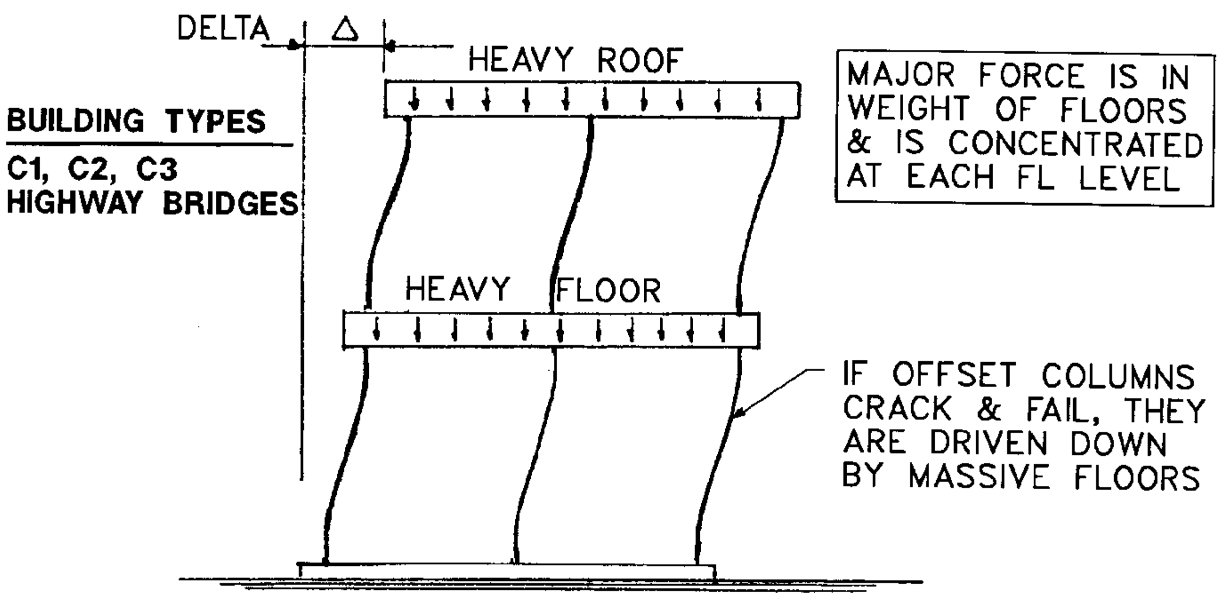


II. STRUCTURAL ENGINEERING SYSTEMS
C. EARTHQUAKE & WIND COLLAPSE PATTERNS

EARTHQUAKE COLLAPSE PATTERNS (continued)

Heavy Floor Collapse Patterns

- ! Collapse can be partial to complete. It is usually caused when columns or walls, weakened by quake motion, are unable to support the heavy floors.
- ! The collapse patterns can be the several shown on BF-25 & 26, but most all share the pattern of thin void spaces forming within the original plan area of the building.
- ! These heavy floor structures usually fall on themselves, but they can project laterally as they fall, if the columns and/or walls are strong enough to not fracture. That is, the columns can fail due to hinging at the top and bottom, and then the collapse looks more like the light frame type.



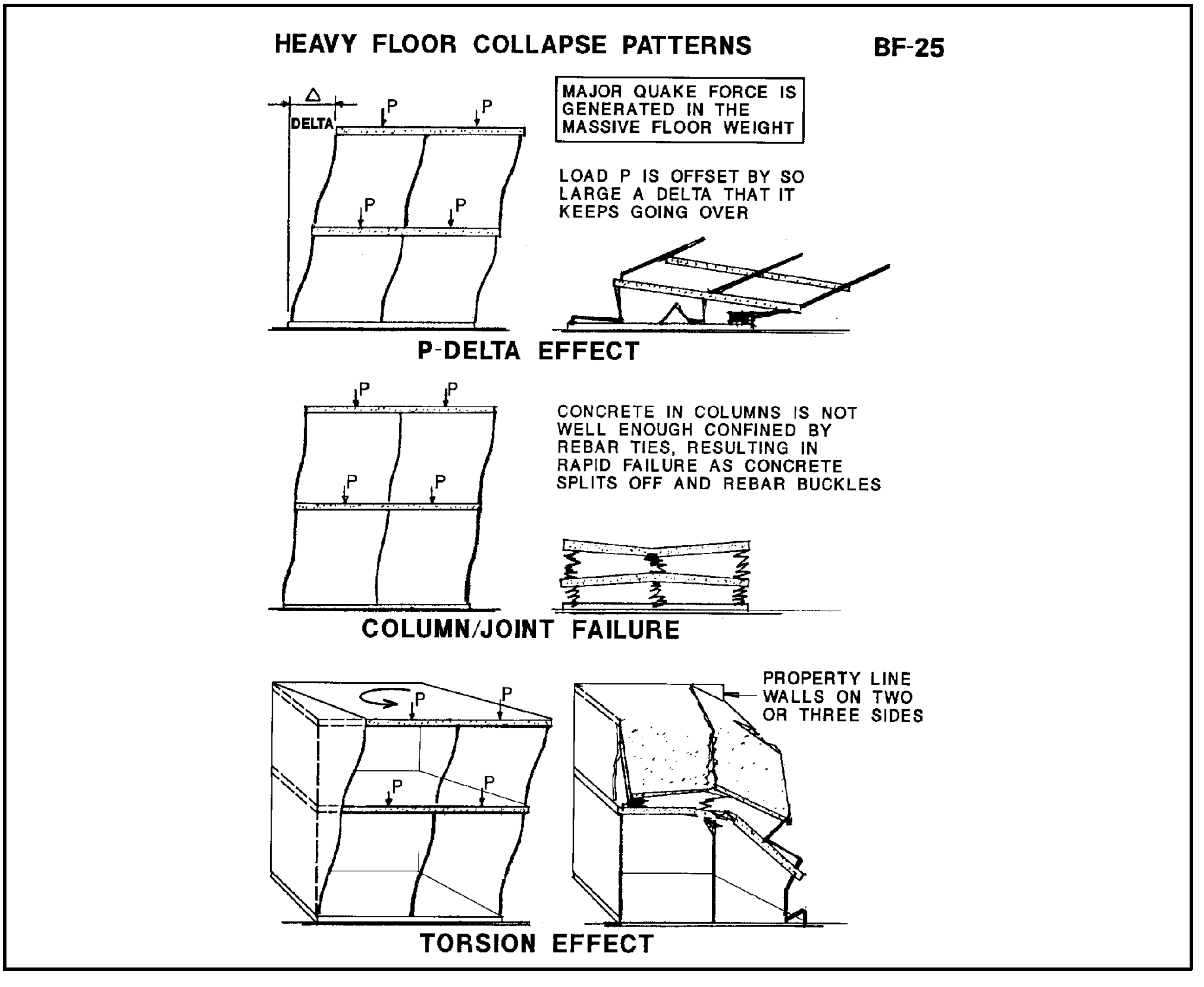
HEAVY FLOOR STRUCTURES

II. STRUCTURAL ENGINEERING SYSTEMS
C. EARTHQUAKE & WIND COLLAPSE PATTERNS

EARTHQUAKE COLLAPSE PATTERNS (continued)

Heavy Floor Collapse Patterns

- ! The voids can be very difficult to access, since even though the heavy floors can have dropped tens of feet they are still usually well interconnected with reinforcing steel.
- ! The height of remaining voids between floors in pancaked buildings will depend on what projections the slabs originally had (beam stems, flat slab drops) and partly crushed contents.
- ! Overturned , normally taller structures with shear walls, will often fail due to tension/ shear failure at the base. In this case the structure can project sideways by its full height.

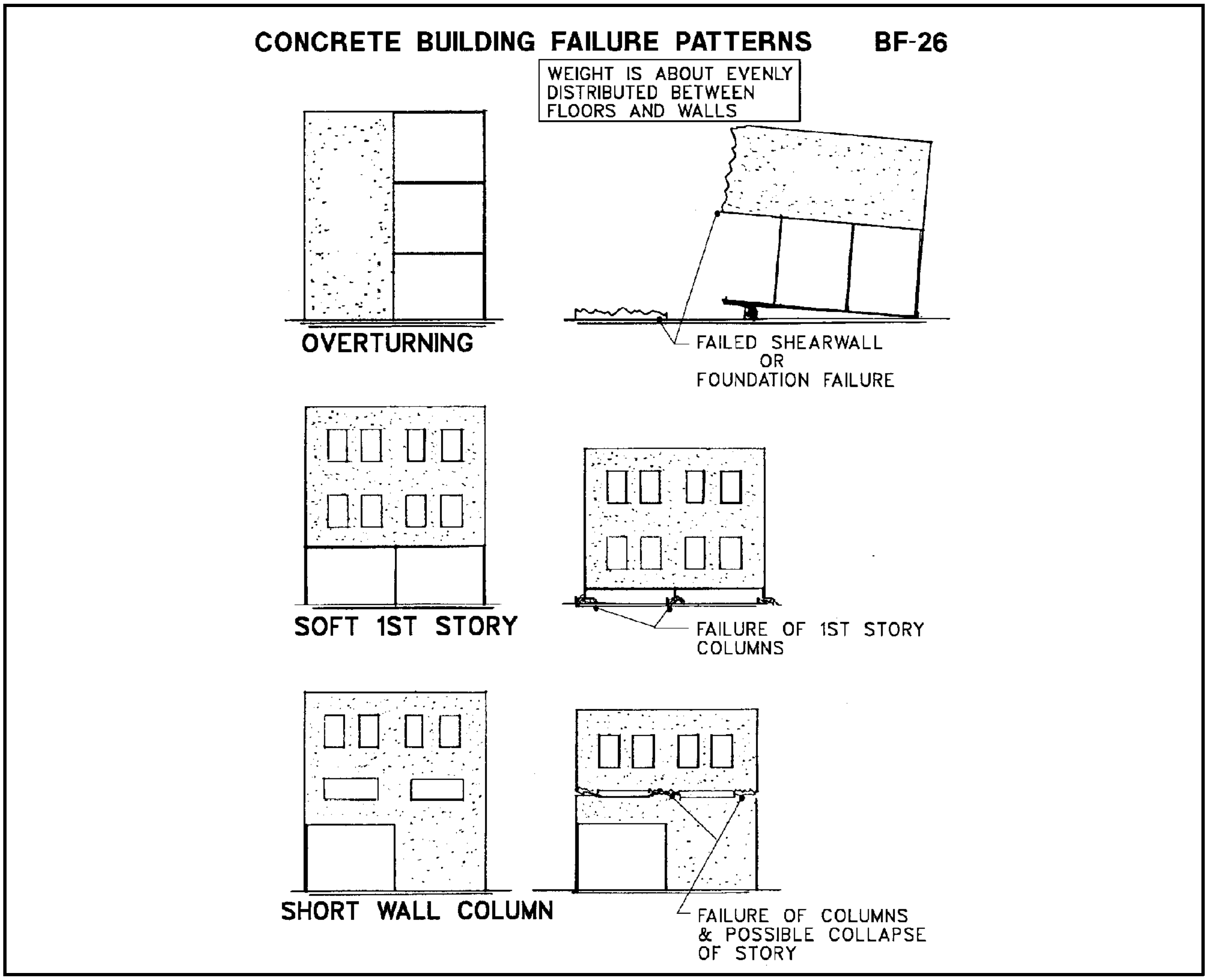


II. STRUCTURAL ENGINEERING SYSTEMS
C. EARTHQUAKE & WIND COLLAPSE PATTERNS

EARTHQUAKE COLLAPSE PATTERNS (continued)

 # Heavy Floor Collapse Patterns

- Tall, moment frame structures, where tension to compression reversal causes an almost explosive failure of exterior columns, may overturn, but more often they will collapse within their plan boundaries due to high gravity forces.
- Many partially collapsed concrete frame structures will contain parts of slabs and/or walls that are hanging off an un-collapsed area. This has been observed in corner buildings when only the street-front bays collapse due to torsion effects, and in long buildings or those with several wings, where some bays do not collapse.
- Pounding can cause one floor to collapse, leaving a difficult problem to assess, due to remaining floors being overloaded etc.
- Fire is usually not a problem in this type of collapse.



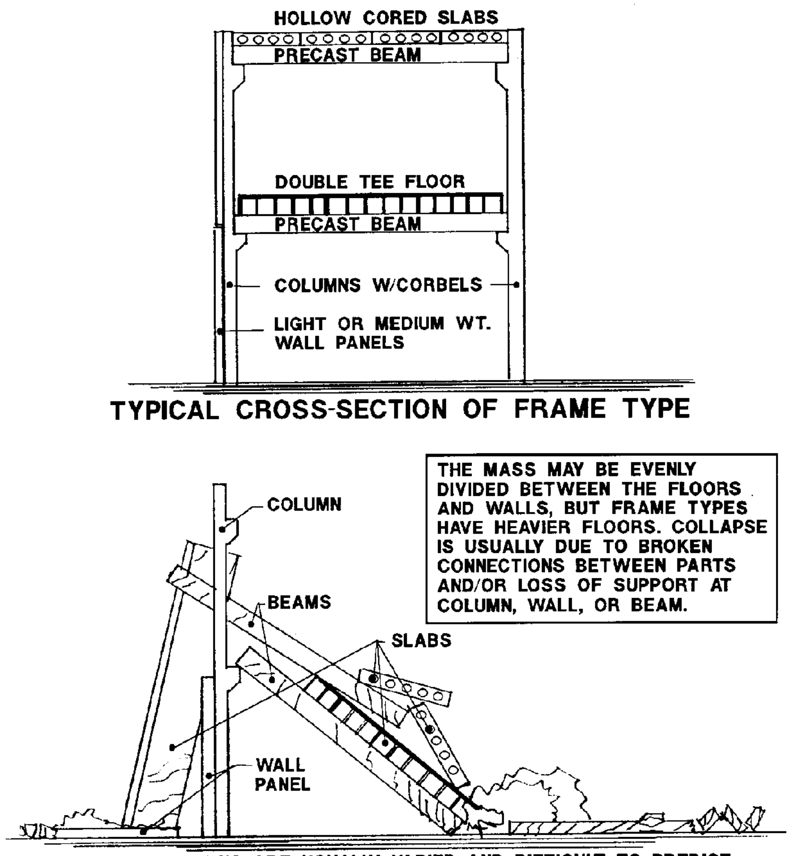
II. STRUCTURAL ENGINEERING SYSTEMS
C. EARTHQUAKE & WIND COLLAPSE PATTERNS

EARTHQUAKE COLLAPSE PATTERNS (continued)

Precast Collapse Patterns

- ! Collapse is usually caused when the precast parts become disconnected from each other, and the structure very rapidly looses stability.
- ! The collapse normally contains numerous layers of broken and unbroken pieces of slabs, walls, beams, and columns.
- ! It is difficult to predict how far the parts can be projected away from the original structure's position, but gravity normally will drive them downward without projecting them, laterally, away from the building.
- ! The voids can be difficult to access, but the slab, etc. can be removed, layer by layer, since interconnections is normally poor to non-existent.

PRECAST CONCRETE COLLAPSE PATTERN BF-27



COLLAPSE PATTERNS ARE USUALLY VARIED AND DIFFICULT TO PREDICT SINCE THE POORLY CONNECTED PARTS SEPARATE AND FALL DUE TO GRAVITY FORCES AND COLLISIONS WITH OTHER PARTS. IN A TOTAL COLLAPSE, A JUMBLE OF HEAVY, UNCONNECTED PARTS IS FORMED. IN A PARTIAL COLLAPSE, MANY HEAVY PARTS MAY BE LEFT IN A CONFIGURATION WHERE THEY ARE LIKELY TO FALL IN AN AFTERSHOCK

II. STRUCTURAL ENGINEERING SYSTEMS
C. EARTHQUAKE & WIND COLLAPSE PATTERNS

WINDSTORM/FLOOD COLLAPSE DAMAGE PATTERNS

Windstorms often produce flooding and the damage to structures by both are similar. They normally affect light, poorly, or non-engineered structures, and generate static and dynamic pressures on the exterior surfaces as well as impact forces from missiles/debris. Well engineered structures are designed to resist wind forces by elastic action (as contrasted to the inelastic response that is assumed in earthquake design) and, therefore, it is unusual to have this class of buildings sustain significant wind damage. Water surge, especially that associated with coastal windstorms, can produce damage and even the collapse of the heaviest of engineered structures, but those that are usually affected are lighter structures.

Building Types Damaged by Wind:

! Wood houses.

! Mobile homes.

! Wood frame, multi-residential, and commercial buildings

! Pre-engineered metal buildings.

! Commercial/industrial buildings with masonry or tilt up walls — especially when wind penetrates openings

! Large aircraft hangers — doors get opened by wind lift on roof — "open structure" damage follows.

! Buildings with high walls and/or long span roofs.

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COLLAPSE PATTERNS

WINDSTORM DAMAGE PATTERNS
! Windstorms often produce flooding.
! Most damage/collapse is to light, poorly or non-engineered structures — but not always.
! Airborne missiles penetrate structure — cause collapse by impact or by creating open structure.

PROBLEMATIC BUILDING TYPES
! Wood houses.
! Mobile homes.
! Wood frame — multi-residential and commercial.
! Light metal buildings.
! Commercial/industrial — walls of URM, RM, TU (when large openings are penetrated).
! Long span structures — high walls, hangers.

II. STRUCTURAL ENGINEERING SYSTEMS
C. EARTHQUAKE & WIND COLLAPSE PATTERNS

<u>WINDSTORM/FLOOD COLLAPSE DAMAGE PATTERNS</u> (cont.)

Most Common Wind Collapse:

! Part or all of light roof is blown off and walls collapse due to lack of lateral support.

! Very tall walls are blown in or out causing the roof to collapse.

! Light metal buildings collapse after loss of cladding, due to buckling or bending failure of long span roof beam/frame or pull out of base connection.

! Missile penetrates glass opening or doors blow in, structure changes from "closed" to "open type", roof and/or leeward wall are blown out. Exterior walls may even be masonry or concrete tilts-up in this scenario, and light interior walls can also be badly damaged.

Common Wind Damage — that could create structural hazards:

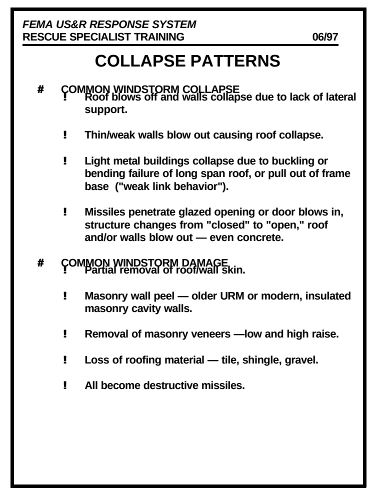
! Partial removal of roof and/or wall skin in light frame building. Partial loss of lateral load resisting system.

! Peeling of outer layer of multi-layer, cavity-type, masonry bearing wall (lightly reinforced, eastern-type construction).

! Removal of masonry veneers on wood and metal frame walls, low and high rise buildings.

! Removal of roofing materials; clay/concrete tile, shingles, gravel, etc.

! All items can be destructive missiles.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COLLAPSE PATTERNS

COMMON WINDSTORM COLLAPSE
! Roof blows off and walls collapse due to lack of lateral support.
! Thin/weak walls blow out causing roof collapse.
! Light metal buildings collapse due to buckling or bending failure of long span roof, or pull out of frame base ("weak link behavior").
! Missiles penetrate glazed opening or door blows in, structure changes from "closed" to "open," roof and/or walls blow out — even concrete.

COMMON WINDSTORM DAMAGE
! Partial removal of roof/wall skin.
! Masonry wall peel — older URM or modern, insulated masonry cavity walls.
! Removal of masonry veneers —low and high raise.
! Loss of roofing material — tile, shingle, gravel.
! All become destructive missiles.

II. STRUCTURAL ENGINEERING SYSTEMS

C. EARTHQUAKE & WIND COLLAPSE PATTERNS

<u>WINDSTORM/FLOOD COLLAPSE DAMAGE PATTERNS</u> (cont.)

Common Flood Damage:

- ! Structures moved partly or completely off foundations. They can slide if moved completely off — or tumble if one side stays attached.
- ! Broken or tilted foundation walls.
- ! Undermined foundations and slabs on grade.
- ! Buildings impacted by objects as large as residential structures, causing part wall and/or roof collapse.

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COLLAPSE PATTERNS

\# FLOOD DAMAGE PATTERN
- ! Windstorms often produce flooding.
- ! Most damage/collapse is to light structures.
- ! Moving water can impact and collapse or flow past and peel off the light walls of structures.
- ! Water-borne debris — up to house-size, can cause collapse by penetrating structures.
- ! Fasting moving river or tidal surge/high waves can cause collapse/damage to engineered structures.

\# COMMON FLOOD DAMAGE
- ! Light frame structure shifted off foundation, slide if free of foundation, tumble if one side stays attached.
- ! Broken and/or tilted foundation walls.
- ! Undermined foundations and slabs on grade.
- ! Buildings impacted by debris (floating houses).
- ! All become destructive missiles.

D. EXPLOSION EFFECTS ON BUILDINGS

The pressures exerted on buildings by explosions may be many orders of magnitude higher (5000 PSI+) than normal design pressures, but their duration is in milliseconds, and they are inversely proportional to the cube of the distance from the center of the source. Damage to structures may be severe, but it is only a fraction of what a proportional static pressure would cause. When large surfaces are engaged by blast pressures they will be moved as the shock wave passes, but the direction of the net force (initial uplift - overpressure) will be determined by the complexities of the wave path and time.

Heavy columns tend to survive, but may have some of the floors that load and laterally brace them removed. Steel frames, beams and columns may also survive, but without all of their intended bracing. The wall and floor planes in frames as well as box buildings, have large surfaces that will receive most of the blast pressure. They likely will be ripped away from their connections, leading to collapse of at least part of the structure.

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BLAST EFFECTS ON BUILDINGS BF-30
W — LIGHT WALL/ROOF SURFACES ARE BLOWN AWAY. REMAINDER COLLAPSES *LEVELED STRUCTURE*

S1 & S2 — BEAMS / COLUMNS ARE RESISTANT TO PRESSURE. LIGHT FLOORS MAY BE BLOWN AWAY, LEAVING POORLY BRACED FRAME STRUCTURE.

S3 — WALL & ROOF PANELS ARE EASILY BLOWN AWAY. FRAMING MAY ALSO BE PUSHED OVER

C1 — LIFT EFFECTS HAVE DEVASTATING EFFECTS ON GRAVITY DESIGNED SLABS. CAN LEAD TO MULTI STORY COLUMNS W/O BRACING BY MISSING FLOORS. *MULTI LEVEL COLLAPSE PROBABLE*

PC2 — PRESSURES CAN DISLODGE WALLS, SLABS, & EVEN BEAMS & COLUMNS. *CONNECTIONS* PROGRESSIVE COLLAPSE POSSIBLE. *BETTER RESPONSE IN MULTI WALL BUILDINGS*

POSTEN — VERY VULNERABLE TO UPLIFT PRESSURES. PROGRESSIVE FAILURE WITHIN ENTIRE SLAB DUE TO LOSS OF TENSION IN UNBONDED CABLE

TU, RM, & URM — LARGE WALL & ROOF SURFACES EFFECTED. LIFTED ROOF AND BLOWN OUT FARSIDE WALLS

II. STRUCTURAL ENGINEERING SYSTEMS
D. EXPLOSION EFFECTS ON BUILDINGS (continued)

The following is a brief description, by type of the most predictable blast damage:

! **Wood Frame - W**- The light wall and roof planes can be blown away and/or shredded. Leveling of all or at least a significant part of the structure, can occur.

! **Steel Frame S1 & S2** - A well designed steel frame may be relatively resistant since beams and columns have resistance to both upward and downward loads as well as tough connections and small dimensions. Light floor framing such as metal deck with concrete fill or bar joist may be separated from beams since they have large areas and small connections that can be "unzipped". The most likely scenario is for at least part of the frame to remain, post blast, but beams may be twisted with large areas of the floor diaphram missing.

! **Light Metal - S3** - The light metal roof and wall panels can be easily blown away leaving a bare, poorly braced frame. Roof, purlins and wall girts normally have relatively light connections and may be removed with the metal panels. The frames may collapse from lack of lateral support and/or push from the blast pressure .

! **Concrete Frames - C1** - The lift pressures have had devastating effects on concrete slabs in gravity type designs. One way slabs hinge up due to the lack of top reinforcing at mid span and continuity splices in bottom bars at supports. A critical location for flat slabs occurs at columns when the uplift pressure fails the slab column joint in upward punching shear, followed by a combination of gravity and positive overpressure that tends to drive the already damaged slab downward. In both the World Trade Center and Murrah Federal Building in Oklahoma City, the result of this was to totally collapse a large area of multi level floors and leave several columns that were supporting hundreds of thousands of pounds without the lateral support of several levels of floor slab.

II. STRUCTURAL ENGINEERING SYSTEMS
D. EXPLOSION EFFECTS ON BUILDINGS (continued)

! **Precast Concrete - PC2** - In precast Frame types structures the lightly (gravity) connected floor slabs and wall planes can be blown away, leaving beams and columns unbraced. If beam/column connections are minimal, entire sections of the structure could collapse. Progressive collapse has occurred when only one column was dislodged by a relatively small gas explosion in a multi-story precast structure (BF-18). In wall type precast (such as the barracks in Saudi Arabia) the wall and floor slabs nearest the blast may be dislodged, and broken loose at their joints. The multi cellular character of these structures made from closely spaced bearing walls, however will tend to limit the collapse damage to those areas where the bearing capacity of wall panels is lost.

! **Post Tensioned Concrete** - If the unbonded cables are damaged and loose tension in only one small area of a floor slab, the entire length of the effected cables can loose tension leading to the collapse of large areas of the effected floors. This type of slab is also very susceptible to upward pressures since the only “reinforcing steel” (draped cables) acts to lift the gravity weight - Very Vulnerable and Dangerous Post Blast Structure.

! **Heavy Wall Building - TU, RM, URM** - Blast pressures will tend to engage the wall and roof surfaces, severing connections and blowing large sections away. For interior blasts, walls will blow out, and roof sections will be lifted. Adjacent parts of the structure can also collapse due to loss of vertical and/or lateral support. For blasts initiated outside the building, the near walls may be shattered or blown in. This can be followed by having roof sections lifted, then dropped as well as having sections of the far side blown out.

In summary the effects of explosions can be compared to a very short term, very high velocity wind. There may be special effects at corners and other discontinuities and shading of one part of a structure by another or one building by another.

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STRUCTURAL HAZARD ID

 # CRACKS IN REINFORCED CONCRETE/MASONRY
- ! Shrinkage cracks.
- ! Temperature cracks.
- ! Tension cracks.
- ! Diagonal tension cracks in beams.
- ! Diagonal tension cracks in walls.

 # IDENTIFICATION OF CRACKS
- ! Shrinkage and temperature occur in slabs, beams, walls and columns.
  - diagonal cracks will originate at re-entrant corners in slabs and walls (mostly at openings).
  - transverse (more or less straight) cracks occur at 5 to 20 ft. apart in long slabs and walls.
  - reinforcing steel (rebar) in these structures is intended to keep these cracks small.
- ! Tension cracks occur in beams, slabs, etc., as a result of normal loading that causes bending.
  - rebar is normally placed where these cracks will occur to make reinforced concrete.
- ! Diagonal tension cracks occur near the ends of floor beams (near supporting columns/walls) and in concrete/masonry shear walls.
- ! Loss of roofing material — tile, shingle, gravel.
- ! All become destructive missiles.

II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

CRACKS IN REINFORCED CONCRETE/MASONRY BUILDINGS

A favorite statement in building design and construction is; "If its not cracked, its not concrete," since cracks must form in concrete for the reinforcing steel to be stressed in tension. Most normal concrete develops cracks that are narrow (hairline) as a result of shrinkage, temperature change, and predictable structural behavior.

Shrinkage Cracks — usually occur in slabs, beams, walls, and even in columns within 60 days of the pour, after the concrete is allowed to dry out. Diagonal cracks will originate from most re-entrant corners in slabs and walls i.e. window, door, and floor openings. Straight cracks (more or less) occur often at five to twenty feet on center in long wall and/or floor surfaces, depending on the amount of reinforcing steel, numbers of pour joints, and curing conditions. The reinforcing steel within the structure is intended to hold the structure together as it shrinks, and keep these cracks small.

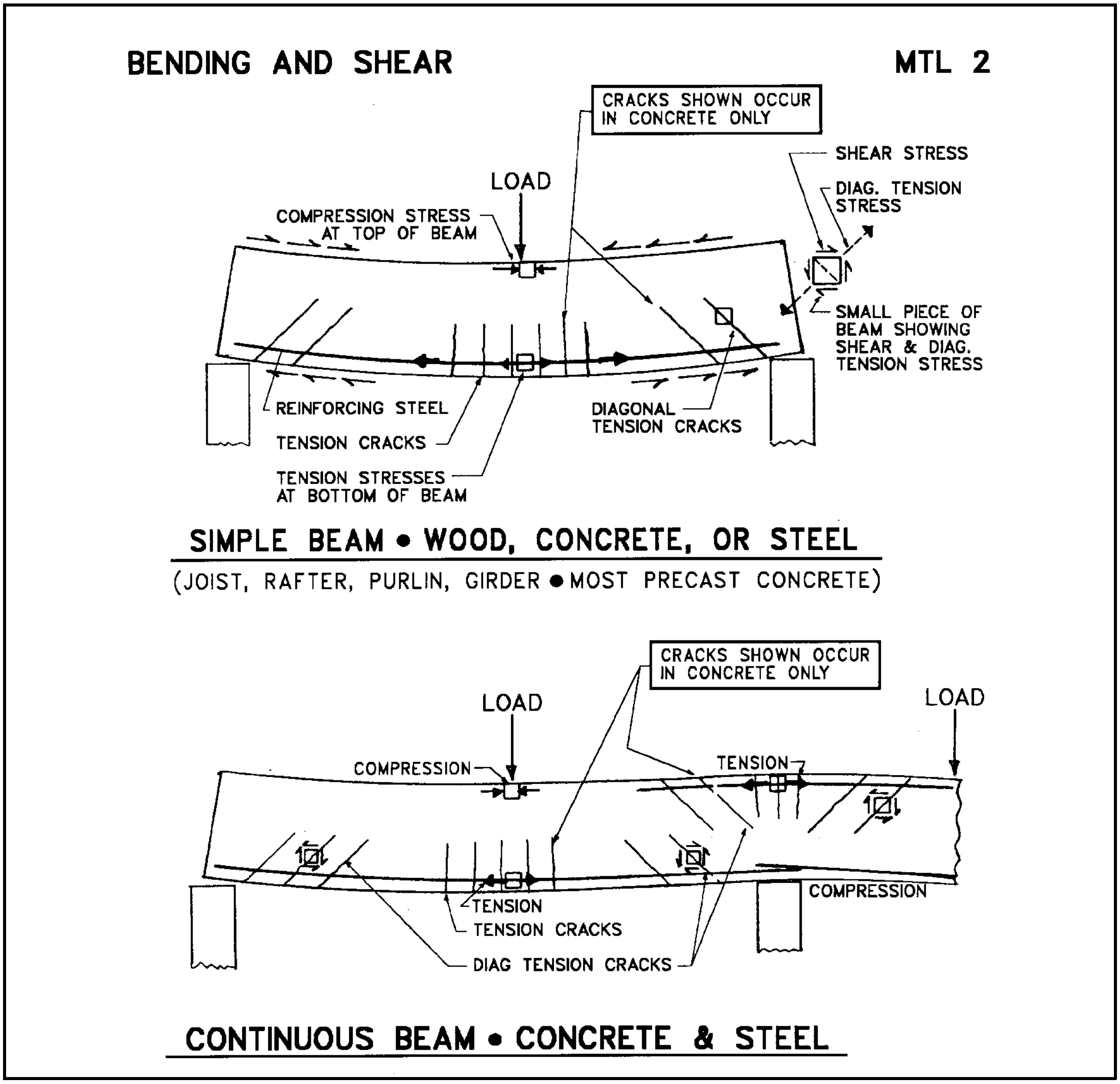
Temperature Cracks — occur in roughly the same pattern as shrinkage cracks, and are difficult to differentiate from them. When the temperature of a concrete structure is decreased, it must shorten (shrink) and, therefore, it cracks, and the reinforcing steel attempts to hold it together. Reinforced concrete structures will, obviously, have more observable temperature/ shrinkage cracking when subjected to the winter cold.

Tension Cracks — occur in concrete slabs, beams, wall, and columns when bending moments cause the tension stresses that stretch the reinforcing steel (sometimes beyond the yield point). Cracks must form in the concrete in order to transfer the stress to the steel, but the cracks normally are usually quite numerous, small and undetectable (except to the trained eye). They form, perpendicular to the long axis of the member, and as long as they remain hairlike, the structure is behaving normally.

II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

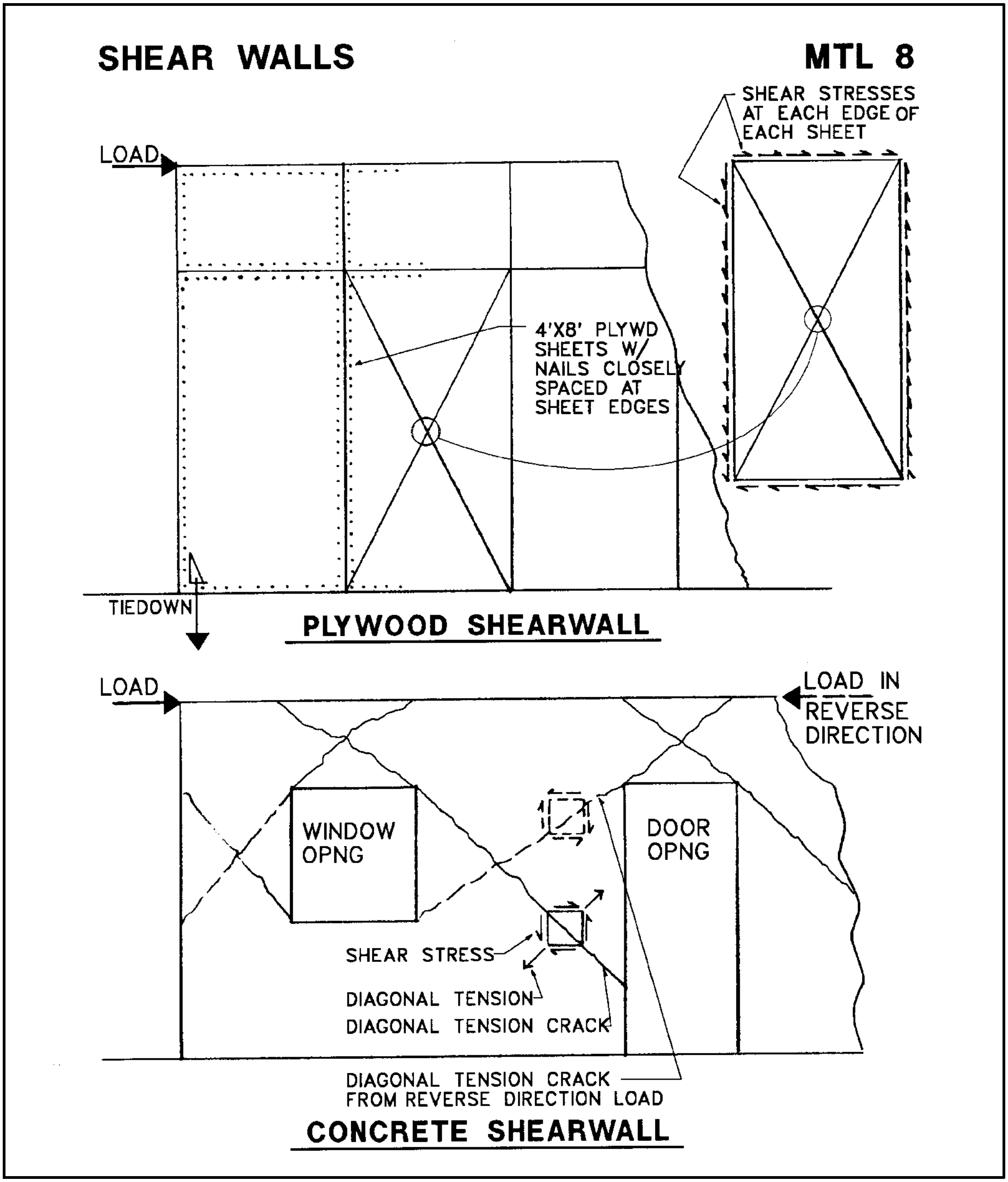
CRACKS IN REINFORCED CONCRETE/MASONRY BUILDINGS (continued)

Diagonal Tension Cracks — occur in high shear stress zones of beams and girders in a typical pattern (MTL-2) under normal vertical load conditions. In shearwalls, large diagonal tension cracks will form when the walls are heavily loaded by severe earthquake shaking (MTL-8). Earthquakes will normally cause a diagonal crack in each direction (Cross Cracking) in the highly stressed areas of shearwalls (i.e., between window openings, over stacked door openings) since the shear reverses causing diagonal tension cracking in each direction.



II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

CRACKS IN REINFORCED CONCRETE/MASONRY BUILDINGS (continued)



II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

CRACKS IN REINFORCED CONCRETE/MASONRY BUILDINGS (continued)

The stability of concrete box-buildings will probably depend on the post cracked strength of the shear walls. Even with unsightly diagonal cracking, a shearwall may still have significant strength (HAZ-CK). The clamping action of the gravity loads, as well as the vertical rebars will tend to hold the irregular surface of the cracks together, preventing the opposing surface from sliding. In addition the rebars that cross the crack can also act as dowels. Both these resistive actions are lessened when there is enough shaking, or continued reshaking due to aftershocks that the crack widens, concrete chunks fall out, and the rebars can be seen in an offset curved condition. In this later degraded condition a shearwall has become unreliable and must be evaluated accordingly.

CRACKS IN UNREINFORCED MASONRY WALLS

- Shrinkage, temperature, and diagonal tension/shearwall cracks also occur in URM and unreinforced concrete walls. In these walls, however, any observable cracking can indicate a significantly degraded structure.

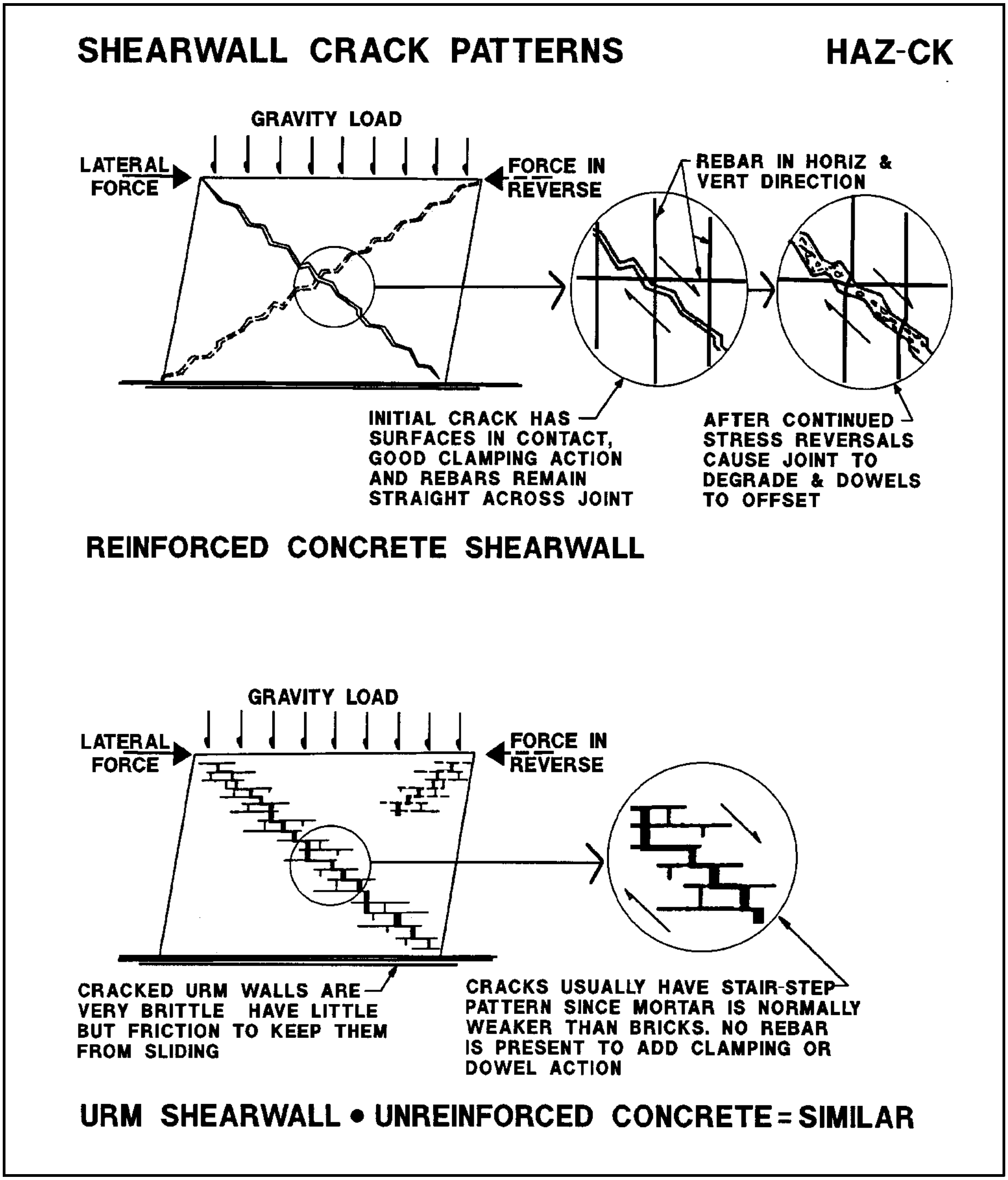
- Diagonal tension cracks form in these walls between openings, as they do in reinforced concrete walls due to earthquake shaking. In addition cracks are often created at wall corners, with the bottom of the crack at the corner and the top extending up to the roof. This is caused by the action of the disconnected roof diaphragm pushing against the corner, attempting to push it out. URM diagonal cracks tend to follow a stair step pattern (HAZ-CK). That is, the crack follows the weaker mortar, rather than going through the bricks. This results in cracked surfaces that are smoother than those in reinforced concrete.

- Masonry walls with significant diagonal tension cracks, must be considered to be capable of a sudden, brittle failure. There is some clamping force on the horizontal steps of the cracks due to the gravity force, but no vertical bars to add clamping or dowel action. The greater smoothness of the joints also reduces the friction that could be developed by the clamping of the vertical force.

- Unreinforced concrete walls also perform poorly during an earthquake. They tend to break apart in pieces, defined by whatever crack pattern existed prior to the quake and/or by the original pour joints.

II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

CRACKS IN UNREINFORCED MASONRY WALLS (continued)



II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

POST EARTHQUAKE HAZARD IDENTIFICATION

In damaged, partly collapsed and collapsed structures we can identify three types of hazards:

- ! **Falling** — where part of the structure or its contents are in danger of falling.
- ! **Collapse** — where the volume of enclosed space made by the structure will be reduced as stability is lost.
- ! **Other** -toxic gas, carbon monoxide, asbestos, other hazardous materials (discussed at length in Haz Mat 1st Responder Course).

Falling and collapse hazards will be discussed here. The degree of hazard in both cases is strongly related to mass and how additional failure may occur. Brittle, sudden failure potential must be recognized as contrasted to structures where material ductility and redundant configuration could provide some warning of an additional collapse.

The problem of identifying, let alone properly evaluating these hazards, is staggering. A well trained engineer may, at best, be able to rate the risk of various hazards on some arbitrary scale like bad, very bad, and deadly. We must consider that:

- ! Judgments can not be precise.
- ! We must try to identify brittle vs ductile behavior.
- ! Partial collapse is very difficult to assess.
- ! The cause of the condition is very important input (i.e., earthquake with expected after-shock, windstorm, etc.).

In evaluating, if a specific structure is at rest, one could state, on the positive side that the structure that was moving had enough resistance to stop moving and achieve, at least temporary stability. However, the damaged structure is difficult to assess, weaker, and more disorganized than the original.

- ! Try to identify the load path, and visualize what could happen during an aftershock or wind gust.

- ! Small, nonstructural elements and debris (loose materials) may be greater hazards than overall structural stability especially in wind gusts and small aftershocks.

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STRUCTURE HAZARD ID

HAZARD IN DAMAGED STRUCTURES
- ! Falling hazards.
- ! Collapse hazards.
- ! Other hazards.

IDENTIFICATION PROBLEMS
- ! Judgement cannot be precise.
- ! Try to identify brittle vs. ductile behavior.
- ! Partially collapsed structures very difficult.
- ! What is expected loading (aftershocks, wind).
- ! Collapsed structure has come to rest, but it is now weaker and more disorganized than original.
- ! Small quake may have caused partial collapse, but remainder may be weak and ready to collapse.
- ! Large quake may have caused significant damage to structure so that aftershocks can cause collapse.

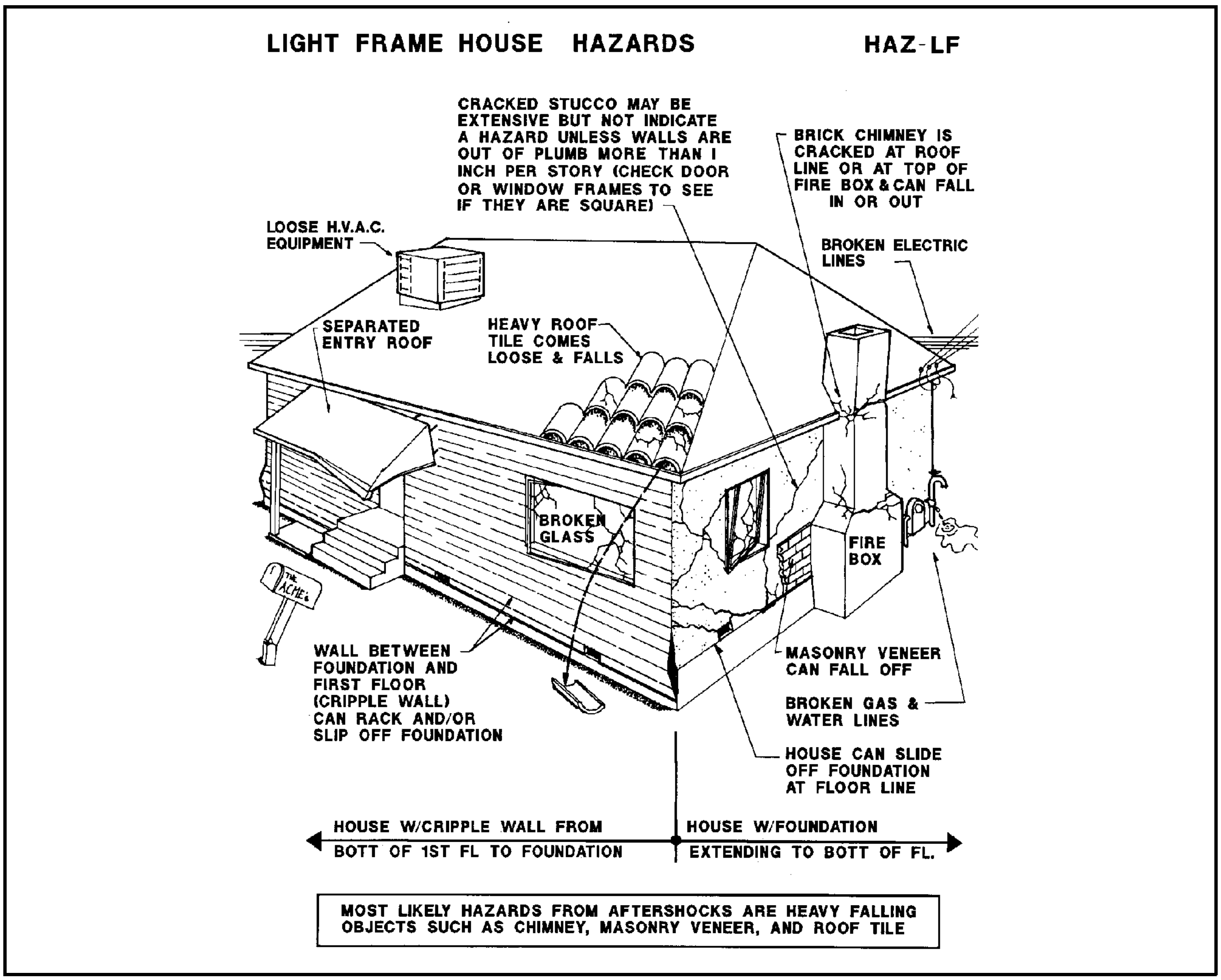
II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

LIGHT FRAME BUILDING HAZARDS

Principal weakness is in lateral strength of walls and connections.

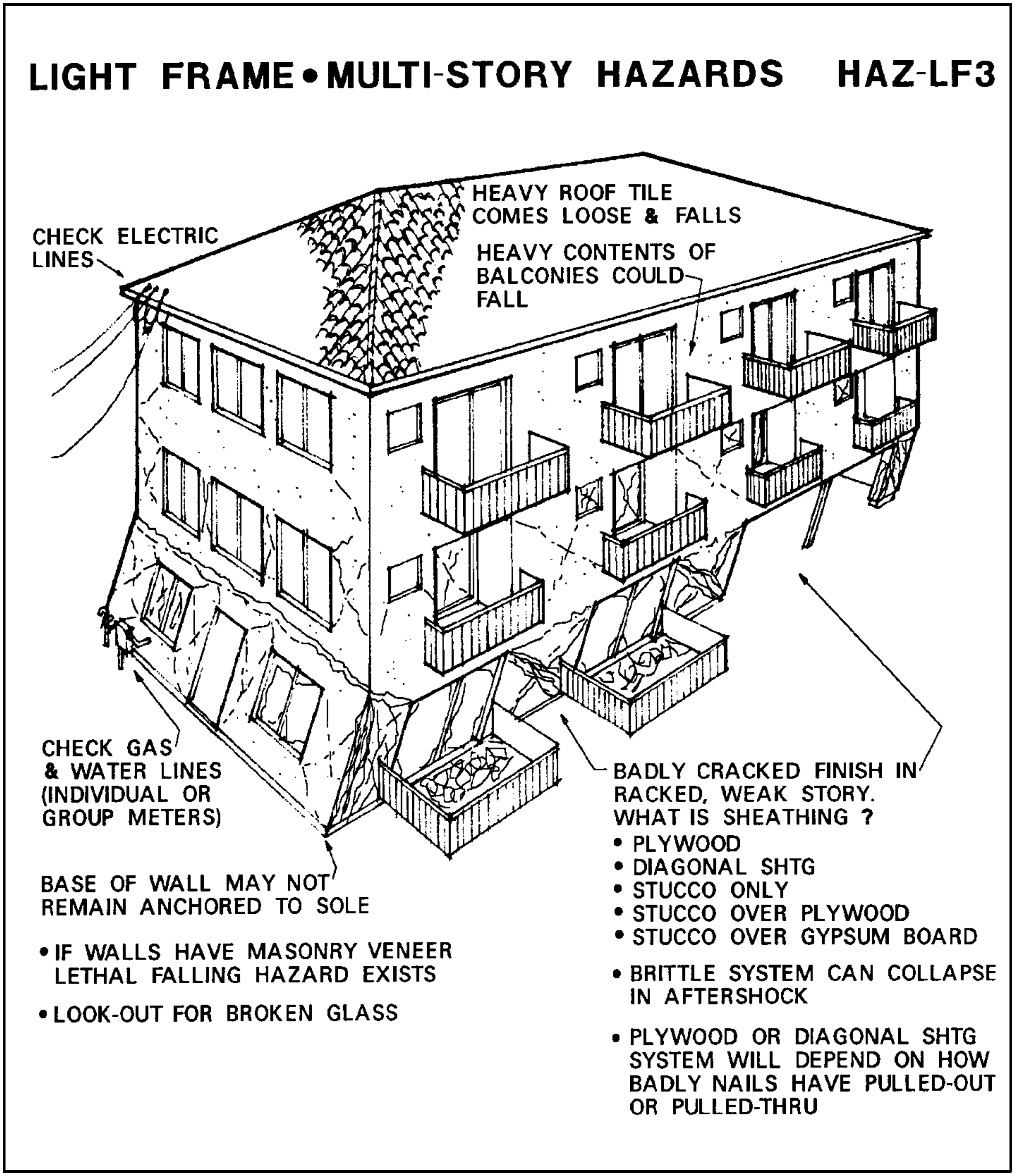
Check Points: (HAZ-LF)
- ! Badly cracked or leaning walls.
- ! Offset residence from foundation Leaning 1st story in multi-story buildings.
- ! Cracked, leaning masonry chimney or veneer.
- ! Separated porches, split level floors/roof.

\# In less than three story structures additional collapse is unlikely due to the light weight of this type of construction. Collapse of this type is often slow and noisy. The hazard of falling masonry chimney and of veneer is the most brittle type of behavior for these structures.



II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

LIGHT FRAME BUILDING HAZARDS



II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

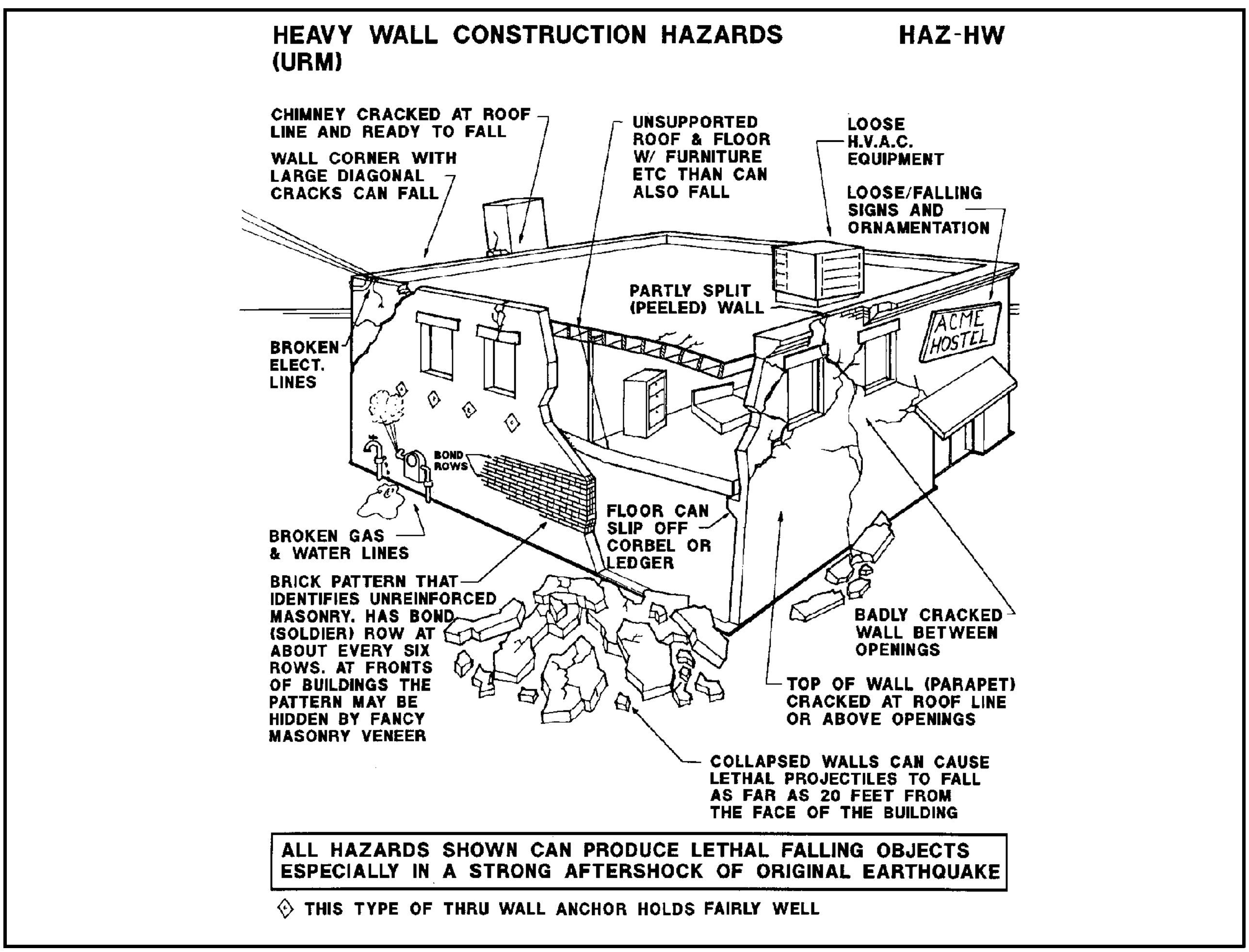
HEAVY WALL BUILDING HAZARDS

Principle weakness is in lateral strength of walls and their connections to floors/roof.

Check points: (HAW-HW)

! Loose, broken parapets and ornamentation.
! Connection between floor and wall.
! Cracked wall corners, openings.
! Peeled walls (split thickness).
! Unsupported and partly collapsed floors.
(* **all failure will probably be brittle** *)

Falling hazards are very common in unreinforced masonry buildings due to the combination of weak and heavy wall elements. Collapse of adjacent buildings can occur due to the falling hazard of party walls.

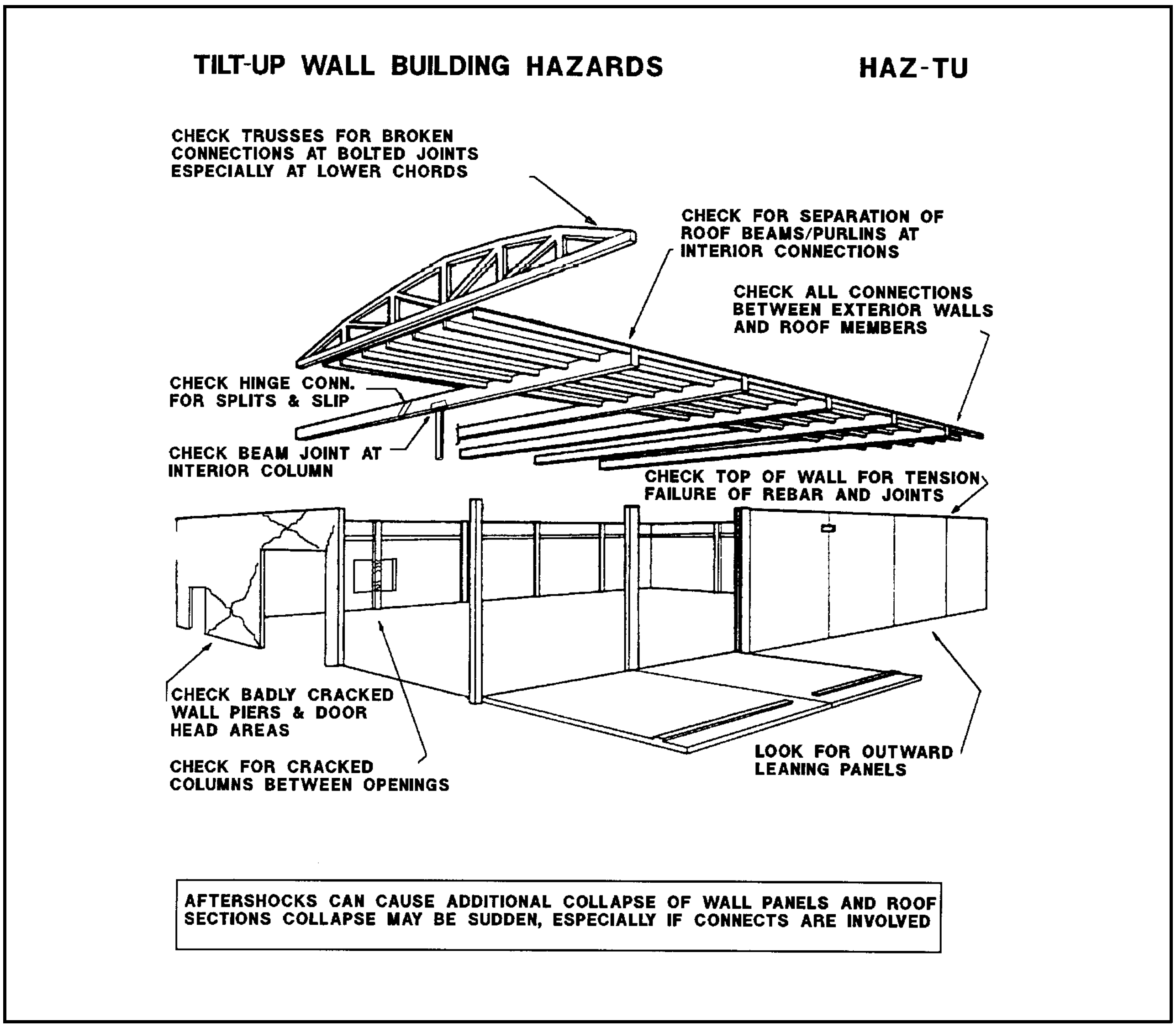


II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

HEAVY WALL BUILDING HAZARDS — TILT-UP
(Low rise reinforced masonry wall buildings w/light roof are similar)
Principle weakness is in connections between wall and floor/roof.

Check Points: (HAZ-TU)
- ! Connection between floor/roof & exterior wall.
- ! Connection between beams and columns, both exterior & interior.
- ! Badly cracked walls and/or columns.

Connection failure will often be brittle. Wall/column failure and shear failure may be more ductile, but single curtain wall reinforcing provides little confinement.



II. STRUCTURAL ENGINEERING SYSTEMS

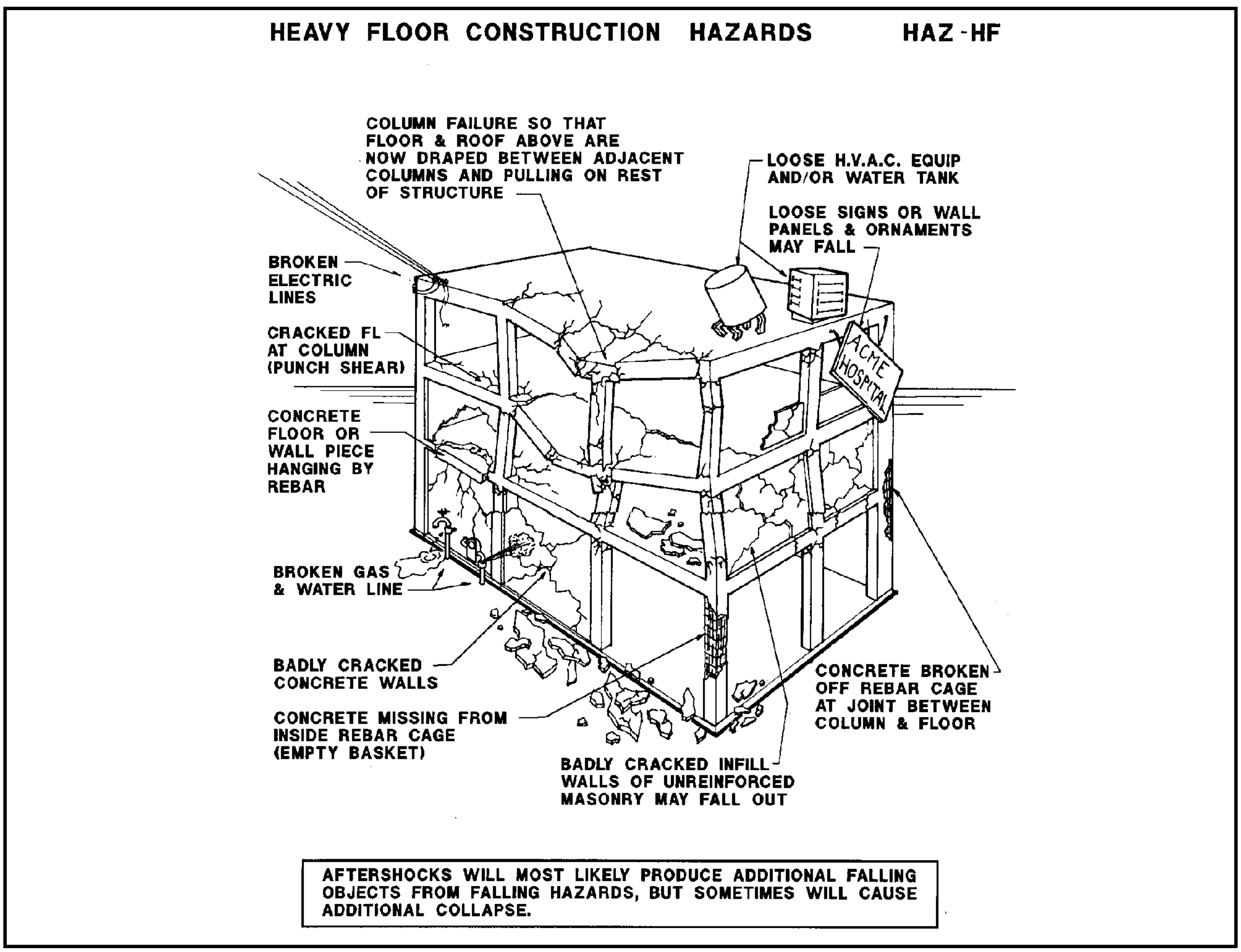
E. HAZARD IDENTIFICATION & BUILDING MONITORING

<u>HEAVY FLOOR BUILDING HAZARDS — CONCRETE FRAMES</u>

Principle weakness is lack of adequate column reinforcing that can properly confine the concrete and inadequate connection between slabs and columns.

Check Points: (HAZ-HF)
- ! Confinement of concrete in columns (empty basket).
- ! Cracking of columns at each floor line (above and below floor).
- ! Diagonal shear cracking in major beams adjacent to supporting columns and walls.
- ! Cracking in flat slabs adjacent to columns.
- ! Attachment of heavy non-structural, unreinforced masonry walls (infill walls).
- ! Cracks in concrete shear walls and/or stairs.

Ductile behavior may still be possible if concrete is confined by reinforcing and the reinforcing is still within lower yielding range.



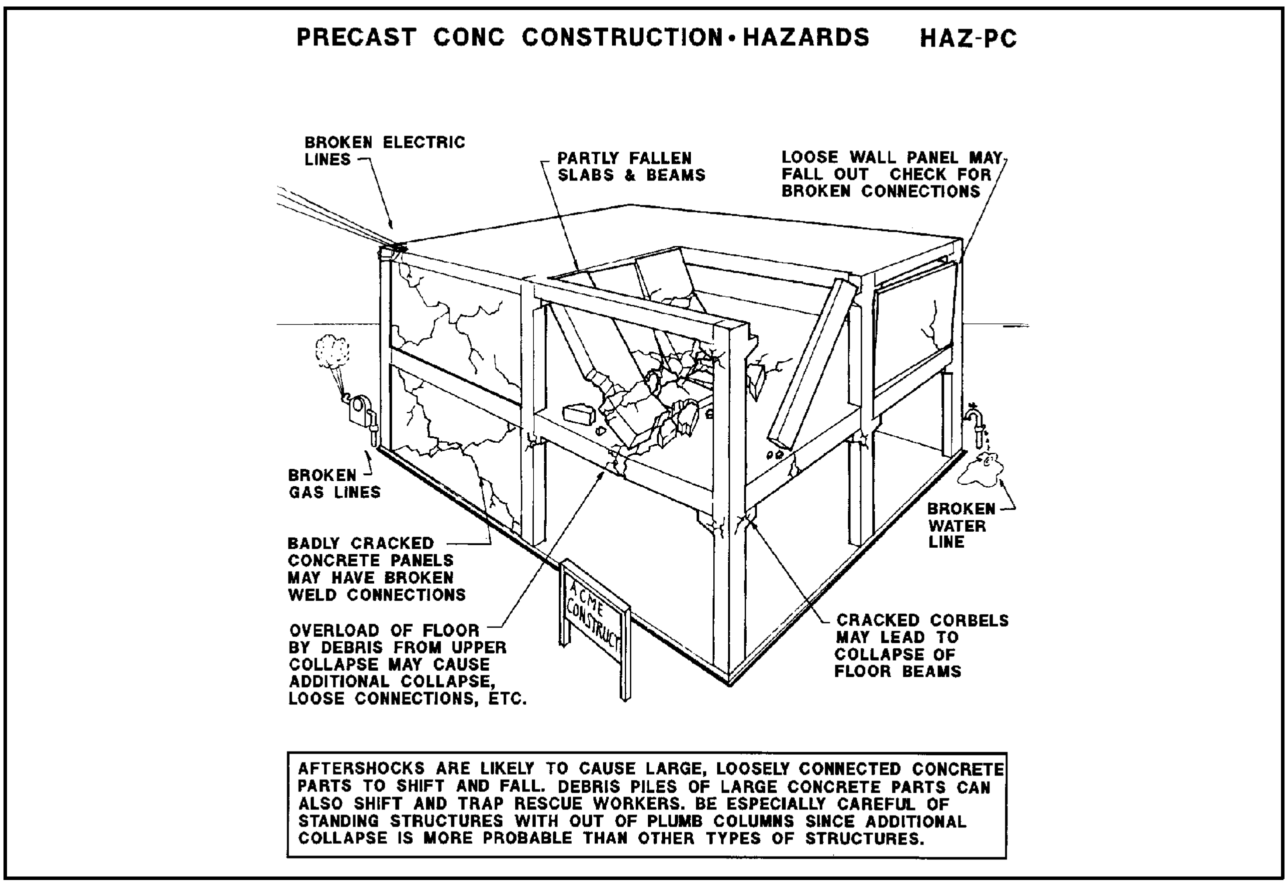
II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

PRECAST BUILDING HAZARDS

Principle weakness is in interconnection of parts: slabs to walls/beams; beams to columns; walls to slabs, etc. It is very difficult to make connections adequate to transfer the strength of parts, which is necessary to survive a maximum earthquake. These buildings can have fairly heavy walls and floors but neither is as heavy as Heavy Wall or Heavy Floor types.

Check points: (HAZ-PC)
- ! Beams to column connections — broken welds, cracked corbels.
- ! Column cracking at top, bottom, wall joints.
- ! Wall panel connections.
- ! Shear wall connections at floors, foundation.
- ! Badly cracked walls.

These structures are often made from lightweight concrete which splits more easily than normal weight concrete. Most failures caused by broken connections will be brittle. Since individual building parts may be quite strong, cracked concrete failures may be ductile if adequate bonded reinforcing is present. Depending on extent of collapse many falling hazards may be present.



II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

SUMMARY OF HAZARD IDENTIFICATION

The problems of identifying hazards after structural collapse are extremely difficult. Buildings are often complicated and there are many different types and configurations. What remains after the triggering event may have come to rest, but the danger of further collapse and/or falling objects is often present. These hazards should be identified by a qualified engineer who understands the basic behavior of structures. Brittle conditions pose the greatest threat due to the probability of sudden failure. As many hazards as possible should be identified, and probable risk factors assigned to them. Measures to avoid or mitigate the danger can then be factored into the overall search and rescue effort.

METHODS TO MONITOR STABILITY

The following indicators have been used to monitor damaged structures in an attempt to warn of change in stability:
- ! Plumb bob.
- ! Engineers transit or theodolite.
- ! Crack measuring device.
- ! Electronic tilt-meters and levels.

A simple plumb bob and string can be used for small to moderate structures to determine changes in position of one story from another, between a story and the ground, or between an upper part of the wall and the ground.

Larger structures and/or taller walls left standing will require the use of a surveyors instrument capable of turning a vertical angle. A transit or theodolite have been used successfully to monitor the movement of multi-story high walls that remained standing after the collapse of the structure's floors. What needs to be continually checked, is the relative position of the wall or building top from the bottom, to see if instability is progressing. Sensitive tilt-meters could also be used to detect building motion.

A digital Tiltmeter is being developed by:
- ! Applied Geomechanics
  1336 Brommer St, Santa Cruz, CA 95062
  (408) 462-9368

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MONITORING STABILITY

DEVICES THAT HAVE BEEN USED
- ! Plumb bobs.
- ! Engineer's transit or theodolite.
- ! Electronic tilt-meter and levels.
- ! Crack measuring devices.

USE OF DEVICES
- ! Plumb bob can be hung from small structure and compared to a point on the ground to observe the change in a leaning structure.
- ! Transit/theodolite can be set up to view a vertical line that will compare a point on the side of a tilted building to a point on the ground in order to detect additional tilt.
- ! Tilt meter with alarms can be placed on structures to signal any movement, but cost thousands of dollars.
- ! Smartlevel (hand level w/ digital readout) can be purchased from Home Depot. Taped to a structure to indicate movement, but must be continually monitored (no alarm).
- ! Cracks can be monitored by:
  - drawing "X" centered on crack.
  - inexpensive plastic strain gauge placed at crack.
  - change in crack thickness can be measured with various thickness gauges.

II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

METHODS TO MONITOR STABILITY (continued)

These can be packaged with an alarm in a portable unit to indicate when pre-determined angular movement has occurred. The complete units will cost several thousand dollars.

A level, sensitive to an angle change of 0.1 degree, with digital read-out, can be purchased at Home Depot for $50. It is self leveling and could be used in any location to determine changes in a structure, but must, obviously be read and interpreted by a task force member.
- ! Made by: Wedge Inc
  2040 Fortune St, San Jose, CA 95131
  (1-800-SMARTLEVEL)

Cracks in concrete or masonry shearwalls or concrete moment frame beams can be monitored in several ways. Obviously, it is important to know if the cracks in a damaged building are of a constant width or enlarging. Methods that have been used include:
- ! Marking an "X" across the crack with the center on the crack. Significant lateral movement changes can be observed.
- ! Placing folded paper in cracks or use automobile thickness gages (.004" to .025") to measure a specific location.
- ! Adhesive or other tape may be placed across the joint to measure change, but dusty conditions may prevent tape from adhering. (Need to be prepared to clean surfaces if this is only option that is available.)
- ! Two parallel sticks (rulers) can be taped across a crack with a perpendicular line being drawn across both of them (or existing lines on two rulers can be aligned). If the crack changes width, then the originally straight line will be offset.

Plastic Strain gages (about $10 ea.) may be placed across cracks to also indicate change.
- ! Made by: Avongard,
  2836 Osage, Waukegan, IL, 60087
  (708) 244-4179

II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

METHODS TO MONITOR STABILITY (continued)

It should be noted that if the structure has significant changes in temperature, the cracks will change width, due to the temperature change. The larger the structure the larger the change.

METHOD TO MONITOR DISASTER SITE

A seismic trigger device can be installed at the site to sense the initial P waves of strong aftershocks. Since the P waves travel at 5 km/sec max. and the damaging S waves follow at approx. 3 km/sec, a warning signal could be triggered at a building site prior to the damaging effects of the S wave.
  ! The device comes in a portable carrying case and would need to be bolted to a solid slab/foundation, etc. somewhere near a damaged building.
  ! For sites within 10 km of the aftershock origin there would not be enough warning to be useful.
  ! For sites over 50 km away there would be would be time to escape to cover etc. (seven seconds +)

A device of this type was used at a site after the Loma Prieta Earthquake. The current cost of the device is approximately $6000.00 and is manufactured by:
  ! Earthquake Safety Systems
  2064 Eastman Ave., Ste 102 Ventura, CA 93003
  (805) 650-5952

The University of California, Livermoore Labs, has made an aftershock warning system available to CAL OES:
  ! The system uses an array of sensors near the fault to detect aftershocks.
  ! A warning signal is relayed by repeaters to individual pagers that will be given to each task force that is involved in rescue operations.
  ! For sites that are about 10 km from the active fault, there will be only 3 seconds warning.
  ! For sites that are 50 km away there will be 12 seconds warning (proportionally greater warning for greater distance from aftershock origin).

II. STRUCTURAL ENGINEERING SYSTEMS
E. HAZARD IDENTIFICATION & BUILDING MONITORING

SUMMARY OF BUILDING MONITORING METHODS

US&R operations will need to be carried out in partially collapsed and badly damaged but uncollapsed structures. These pose the greatest threat for additional collapse and entrapment of rescue workers. Using the suggested indicators it is possible, in most cases, to recognize when further collapse is likely.

The Structures Specialist should become familiar with as many methods as possible through exercising their use in order to be properly prepared for the many variables that he will be faced with at the US&R site. As with most engineering, the simplest method with which he is familiar will probably be the best.

II. STRUCTURAL ENGINEERING SYSTEMS

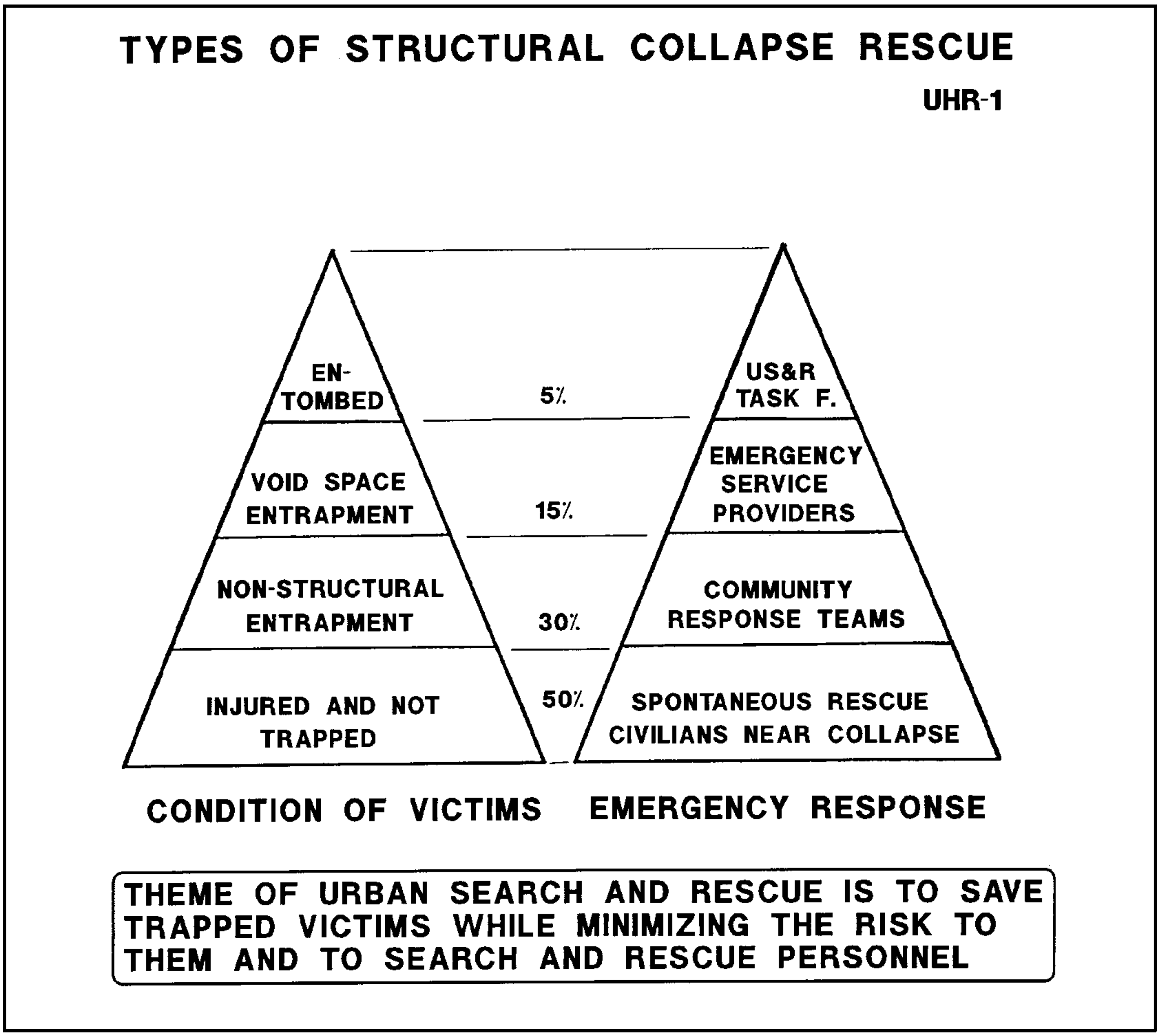
F. US&R STRATEGY & STRUCTURE SIZE UP

INTRODUCTION

Strategies will be presented from a Structures Specialist point of view. Other input such as medical urgency, availability of special equipment and/or trained personnel, other hazardous conditions will also need to be considered.

THE THEME OF US&R MUST BE TO SAVE TRAPPED VICTIMS WHILE MINIMIZING THE RISK TO THE VICTIM AND THE US&R FORCES

It is important for all to understand the typical chronology of an US&R incident, especially one caused by a devastating earthquake. The emergency response normally occurs in the following phases:



II. STRUCTURAL ENGINEERING SYSTEMS

F. US&R STRATEGY & STRUCTURE SIZE UP

- **Initial spontaneous response** — unskilled, neighbors, community response teams, passers-by will heroically help remove lightly trapped and/or injured victims. These rescuers have often acted far beyond their normal skill level and often save three-fourths or more of the total. Survival rates are relatively high, since victims are normally not entrapped. Professional firefighter, law enforcement officers, and emergency medical personnel may participate and better organize the response. This phase will often end during the first night.

- **Planned Community Response** — by local trained community response teams. Call-out and visual search would be used to locate and rescue the non-structurally trapped. Some lifting of objects (furniture, bookcases, etc.) would be done as well as mitigation of hazards (extinguish small fires, turn off gas, observe/refer hazardous materials).

- **Void Space Rescue** — by local emergency services rescue forces. Search elements would help prioritize site to make better risk vs. benefit judgments. Rescue would proceed using existing cavities, duct/plumbing shafts, basements, and/or small cut openings in easily breachable floors and walls. Some shoring might be done to provide safe haven areas and otherwise protect emergency responders and/or victims. This phase may start the first day, but often, not until after some organizing efforts have taken place, requiring at least one hour.

- **Technical, Urban Search & Rescue** — by trained US&R forces, aided by equipment. Site or sites would be re-evaluated, re-searched, and prioritized for the ten-day-long effort. Extensive cutting, shoring, etc., may be done to penetrate the structure. Cranes may be used to remove layers of structural debris or parts of the structure that are hazardous.

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

INITIAL INFORMATION GATHERING

Information gathering techniques will be crucial to the efficient transition of the US&R forces into the incident. It is important for these incoming forces to carefully verify information obtained from the first responders and other individuals at the disaster site. By the time the information exchange takes place, the first responders will probably be subjected to the following:

- ! A many hour period of physically and emotionally draining work. Feelings that it's not possible that other victims have survived within a badly collapsed structure.
- ! A need to experience closure; that the incident is over.
- ! Feelings by relatives/friends of the missing that they have surely survived and are entrapped.

The information gathering must therefore, proceed as swiftly and unemotionally as possible, while testing all current assumptions. Information from others on structural safety issues should be recorded, but the Search Specialist should perform his own assessment, independently, as in any good check.

This section will discuss the following issues that relate to developing the structural approach to a specific disaster site:

- ! Review Initial Phases: Triage, Assessment & Marking
- ! Building Search & Rescue Basic Plans
- ! Hazard Reduction & Victim Access

FEMA US&R RESPONSE SYSTEM
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SUBJECTS TO BE DISCUSSED

FEMA Response System — Appendix D
Phases of Initial Set Up
Structure Triage
Structure I.E. Method
Search & Reconnaissance
- ! Structure/Hazards Evaluation & Marking
- ! Search Assessment Marking

FEMA US&R RESPONSE SYSTEM
RESCUE SPECIALIST TRAINING 06/97

INFORMATION GATHERING

Critical for transition from the initial phase to US&R task force.

First responders will have experienced:
- ! Long periods of emotional and physically draining work.
- ! Need to feel that no one else is trapped.
- ! Need to feel closure , it's over.
- ! Requests by relatives/friends to find their loved ones (they know they are alive).

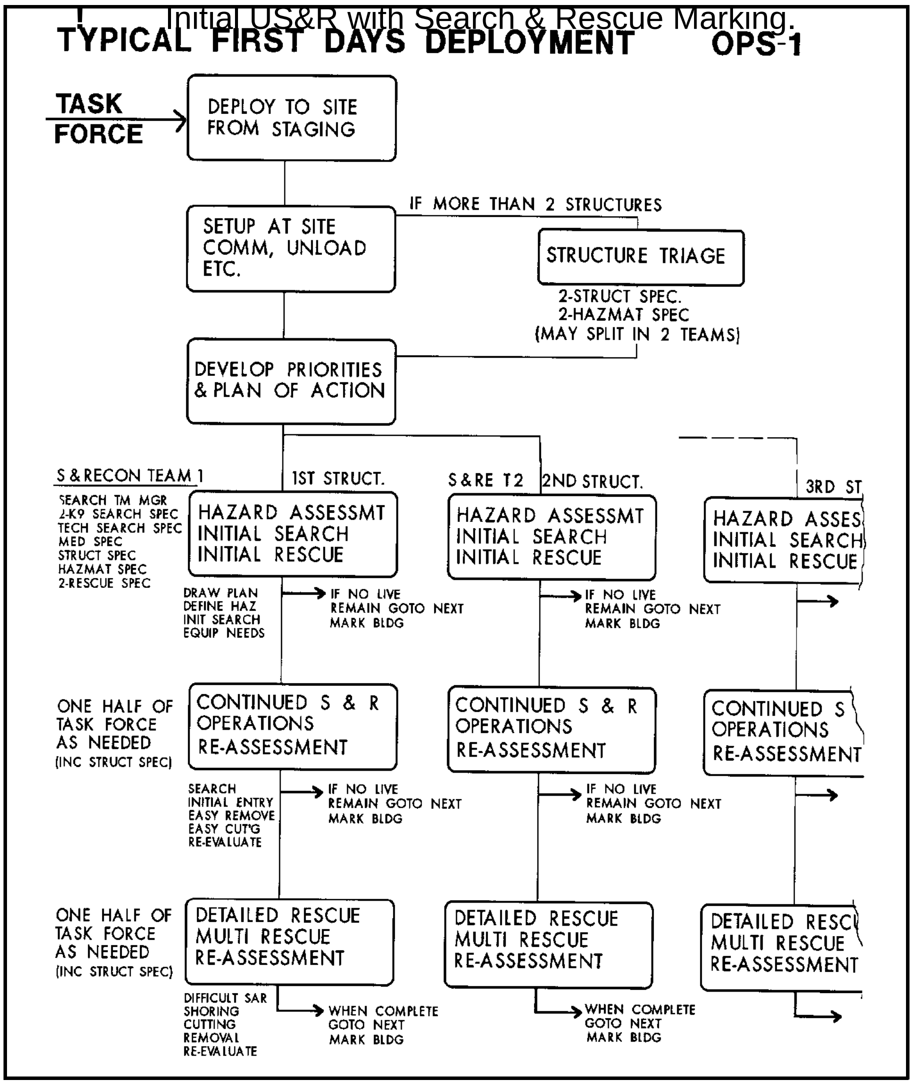
Task force information gathering must:
- ! Proceed swiftly and unemotionally.
- ! Test all previous assumptions.
- ! Perform independent assessments.

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

STRUCTURE TRIAGE, STRUCTURE/HAZARDS EVALUATION & MARKING

Appendix D, FEMA US&R Response System is intended to be the National standard system for evaluating, identifying, and marking buildings. It is expected that immediately after deployment, the following tasks will be performed (in addition to normal Base of Operations setup):

- ! Identification of individual building.
- ! Building triage (only if required).
- ! Structural/Hazard Evaluation & Marking.
- ! Initial US&R with Search & Rescue Marking.

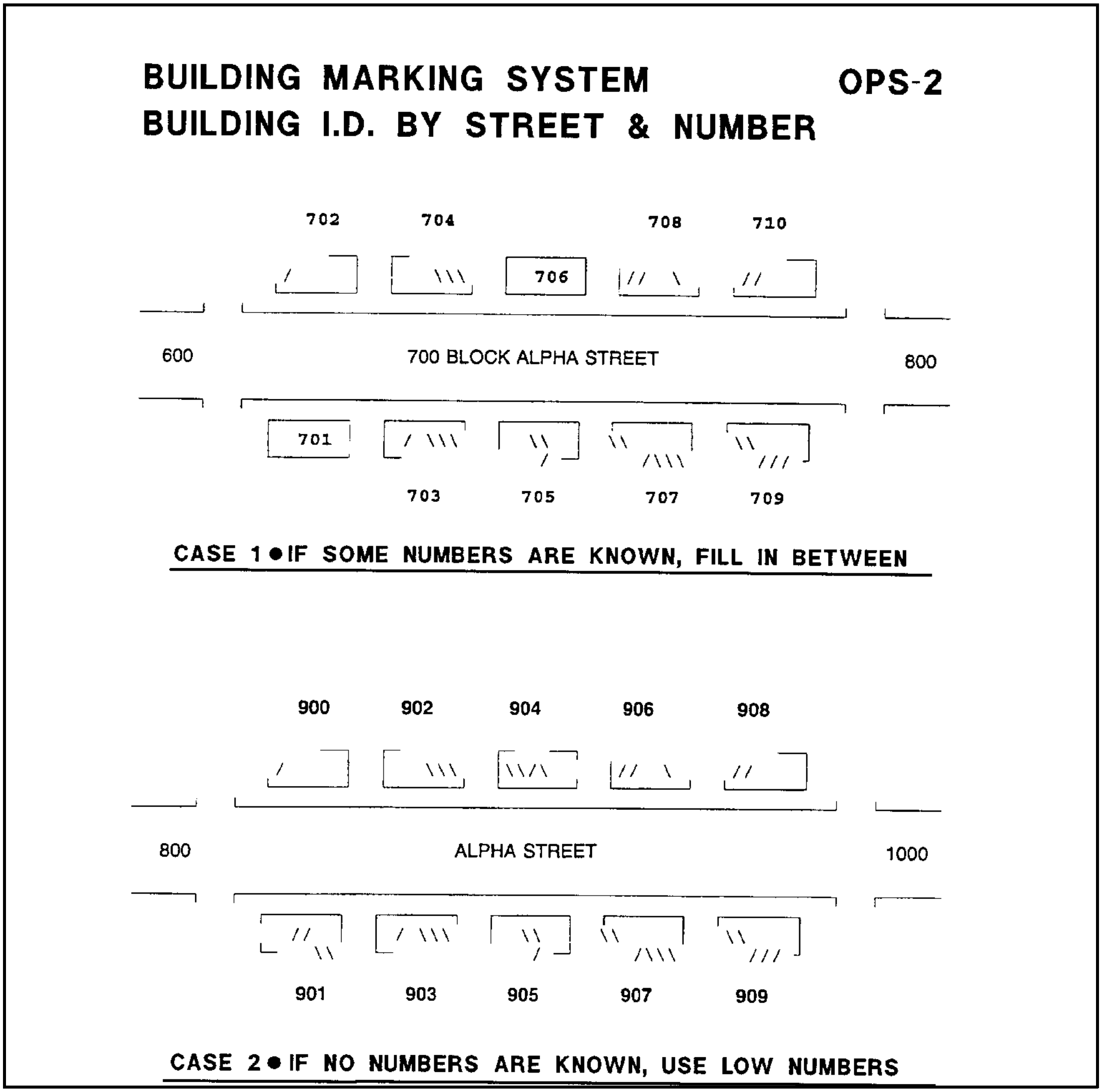


II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

IDENTIFICATION OF INDIVIDUAL BUILDINGS

Standard system to locate building on any block:

- ! Use existing numbers and fill in unknowns.
- ! If all unknowns — keep numbers small — odd and even sides.

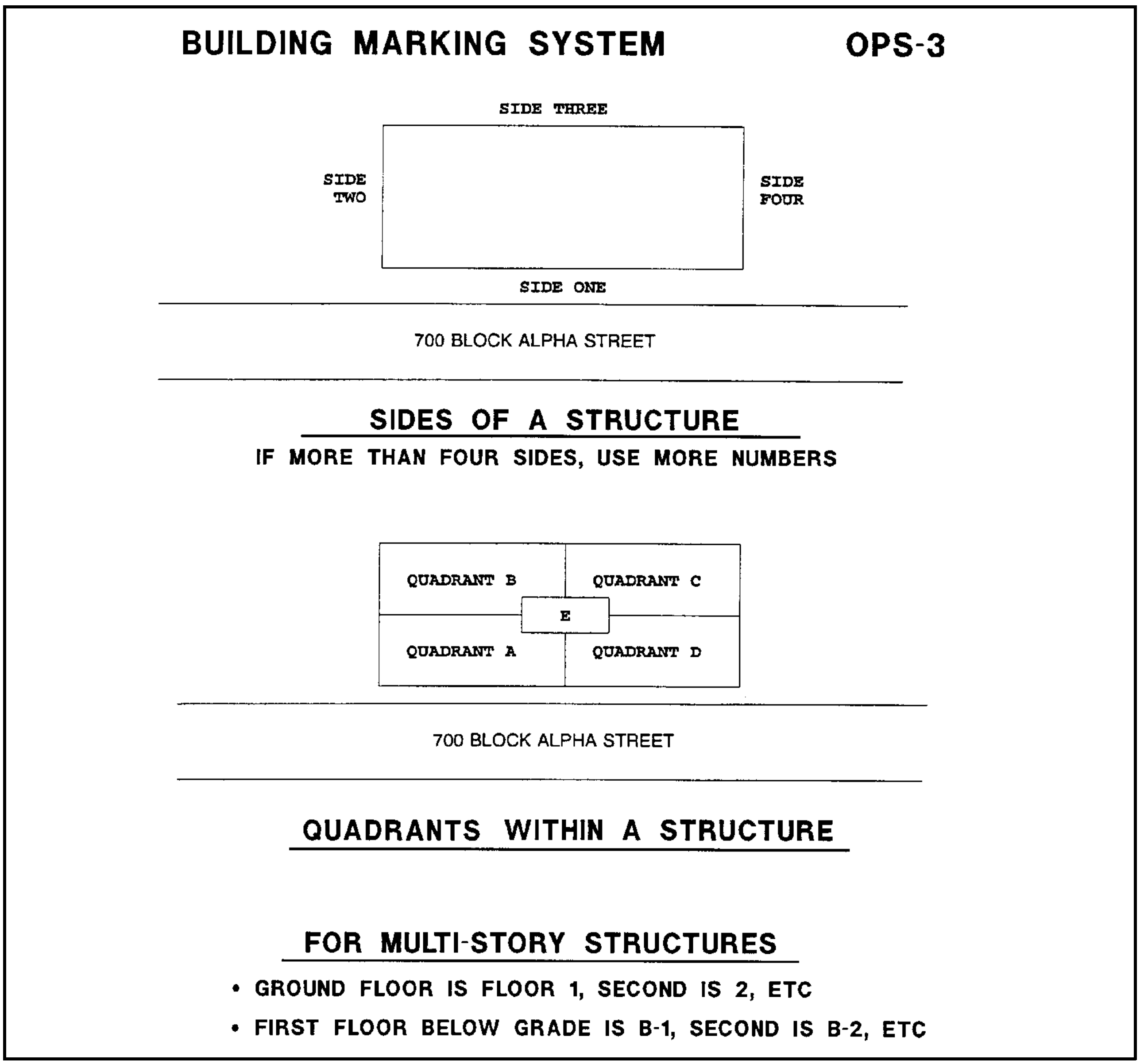


II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

IDENTIFICATION OF INDIVIDUAL BUILDINGS

Standard system for building layout:
- ! Sides 1, 2, 3 and 4 — start at street and go counter clockwise.
- ! Stories are designated : Ground, 2, 3, 4.
- ! Basements are designated: B1, B2, B3.

Quadrants within a building:
- ! Mark A, B, C, D, etc.



II. STRUCTURAL ENGINEERING SYSTEMS

F. US&R STRATEGY & STRUCTURE SIZE UP

BUILDING TRIAGE METHOD

In large disasters where many structures have been seriously damaged and/or collapsed it will be desirable to have some coherent method of prioritizing the effected structures. The method needs to identify and quantify those criteria that will best select those structures that have higher probability of success with respect to finding, accessing, and rescuing live victims. The method needs also to be simple enough to be performed at various response levels, and also consider risk/benefit ratio of very difficult US&R operations.

Multiple building assessment and triage should not be confused with the more detailed Structure/Hazards Evaluation and Building Marking which will occur after an order of priority has been established by the building triage process.

APPLICATION OF TRIAGE METHOD

Immediately after a disaster, a special recon/evaluation team/teams could use triage to prioritize all affected structures in order to help in response planning.

A segment of local emergency response forces could assess and evaluate effected structures within their jurisdiction for their own prioritization, and/or as a part of an overall triage system.

Immediately after deployment, the US&R task force could use triage to help prioritize the group of structures within their a assigned area. They could also use triage to prioritize sections of a very large structure.

FEMA US&R RESPONSE SYSTEM
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BUILDING TRIAGE

WHEN AND PERFORMED BY WHOM
  ! Immediately after disaster by special recon team — all structures in affected area.
  ! Immediately after disaster by local emergency responders — all structures within city/locality.
  ! Immediately after deployment of US&r task force — all structures within assigned area.

HOW RESULTS OF TRIAGE ARE USED
  ! To determine where and in what order to deploy local and imported US&R teams.
  ! To determine priorities for a task force within an assigned area (group of buildings or wing of multi-wing building complex).

TRIAGE BY US&R TASK FORCE
  ! Structures and Haz Mat Specialists perform rapid evaluation to collect triage data for assigned site within first few hours while task force is unloading/setting up.
  ! Hazard I.E. and structure/hazard marking would occur after first triage is completed.
  ! Initial search would occur right after hazard I.D.

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

BASIC ASSUMPTIONS FOR USE OF TRIAGE BY TASK FORCE

Triage will be necessary if there are three or more buildings assigned to a single task force.

Triage would initially be done by a team of Structures Specialist and Haz Mat Specialist as soon as possible upon arriving at the site, and should be accomplished within no more than two hours. The remainder of the task force would be involved in camp set-up, information gathering, etc. during this time period.

No planned search operations would begin until initial triage was completed, in order to establish priority.

The more detailed Structure/Hazards Evaluation and Building Marking would take place (along with the initial search) after structures are initially prioritized. One or more teams of Structures Specialist and Haz Mat Specialist would accomplish Structure/Hazards Evaluation and Building Marking.

Triage criteria would be re-evaluated after initial search in light of locating live victims.

If many buildings were involved, triage would probably be done by two teams, each consisting of one Structures and one Haz Mat Specialist. It would therefore, be imperative that the two teams compare assessment criteria, before and after they do the triage work, in order to assure that uniform evaluations are obtained.

There will be some buildings that will have significant hazards so that search and rescue cannot proceed, until the hazards are mitigated. These buildings will be given "NO GO" assessments (structures on fire, significant haz mat spills).

Some buildings may require rescue operations beyond the capability of the rescue force (i.e., require heavy shoring, require heavy lifting equipment, etc.). These may be assigned "NO GO" status by the Task Force Leader (at least until the required equipment is obtained).

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

BASIC ASSUMPTIONS FOR USE OF TRIAGE BY TASK FORCE

Triage assessments will be based on value judgments that are made on rapidly obtained information, and should always be subject to a common sense review and adjustment by the Task Force Leader and evaluation team.

As in medical triage difficult decisions will need to be made. The goal should always be to rescue the largest number of victims as possible within the first day or so (without creating additional task force victims).

The natural tendency of the Structures Specialist will be to stop at each building and "solve the problem", and not leave a structure where people might be known to be trapped, etc. This tendency must be overcome by maintaining a pre-designated time schedule of 5 to 10 minutes per building, and frequent check-in with task force leadership.

TRIAGE CRITERIA

The following information needs to be considered in determining risk/benefit that will aid in prioritization.

Occupancy — the type of activity done in the building, as well as the potential maximum number of occupants.

Structural Type — what type of materials are involved, in order to help identify difficulty of access, type of collapse, potential hazard mitigation needs, etc.

Collapse Mechanism — how building failed in order to provide an indication of type of voids that might be available for victim survival.

FEMA US&R RESPONSE SYSTEM
RESCUE SPECIALIST TRAINING 06/97

BUILDING TRIAGE

TRIAGE CRITERIA (info considered to determine risk/benefit ratio)
! Occupancy — type of activity and potential maximum number of occupants.
! Structure Type — type of materials involved will help define difficulty of access and hazards.
! Collapse Type — indicates type of voids and potential for victim survival.
! Time of Day — when quake occurred vs. occupancy.
! Resources Available — shoring, cranes, other tools.
! Structural Condition — effort required to stabilize.
! Prior Intelligence — regarding victims.

NUMBER OF OCCUPANTS
Standard building code estimates based on area.

! Schools	varies 1 per	50 to 100 sq. ft.
! Hospitals		50 to 200
! Multi-residential		100 to 300
! Commercial		50 to 200
! Office/gov't. building		100 to 200
! Public assembly		10 to 50
! Public safety		100 to 200
! Industrial		100 to 300
! Warehouse		400 to 900

II. STRUCTURAL ENGINEERING SYSTEMS

F. US&R STRATEGY & STRUCTURE SIZE UP

TRIAGE CRITERIA (continued)

Time of Day — refers to the time of the event which caused the collapse. This is a critical factor when combined with the occupancy type. For example, if an earthquake occurs at 2100 hours and collapses an office building and an apartment building, the apartment building would normally represent the higher potential for a success rescue than would the office building. If the event occurred at 1000 hours, the opposite would be true.

Prior Intelligence — information from the general public, local authorities, first responders, etc. relating to known trapped victims.

Search and Rescue Resources Available — does the particular building require resources beyond what is readily available to the task force (i.e., is heavy equipment required to gain access).

Structural Condition of the Building — generally, can search and rescue operations proceed with a minimum of stabilization effort.

TRIAGE SCORING FACTORS

The following factors will be used to obtain a numerical score for each structure in a group of buildings. The intent is, the higher the numerical score the better the risk/benefit ratio.

ZERO OCCUPANTS PROBABLE A notation of "ZERO" would be written in the score column if the earthquake occurred at a time of day when the type of occupancy contained in the structure was such that the building would have been normally unoccupied (school rooms on Sunday, retail shops at 6 A.M., etc.). The triage team would then proceed to the next building.

FEMA US&R RESPONSE SYSTEM
RESCUE SPECIALIST TRAINING **06/97**

SCORING SYSTEM

System is based on value judgements, made by trained Structures and Haz Mat Specialists:
- ! **Zero victims probable — write zero and go to next.**
- ! **Number of potential trapped victims** **1 to 50**
  (potential number divided by 5)
- ! **Condition of voids —** **1 to 20**
  (compact/separated layers/partial collapse)
- ! **Time required to access victims —** **1 to 20**
  (one day to two hours)
- ! **Danger of additional collapse —** **-1 to -20**
  (low to high chance)
- ! **Special occupancy — children** **+25**
  each known live victim **+5**
- ! **No-Go condition (fire/haz mat) —**
  (add info on when to re-evaluate/revisit)

This triage method is intended to be a logical documentation of common sense. A quick way of recording the value judgements required to make the difficult choices.

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

TRIAGE SCORING FACTORS (continued)

TOTAL NUMBER OF POTENTIALLY TRAPPED VICTIMS. This will be assessed knowing the type of occupancy, the floor area of collapsed entrapping structure, the time of day the incident occurred, and the type of collapse. The following are suggested as average total number occupants for various occupancies:

! **Based on units other than area:**

Schools	25 to 35 students per classroom
Hospitals	1.5 occupants per bed
Residential	2.0 occupants per bedroom
Others	1.5 occupants per parking space

! **Based on area:**

			Variation
Schools, Library	1 per	70 SQ. FT.	50-100
Hospitals	1	100	80-150
Multi Residential	1	200	100-300
Commercial	1	100	50-200
Office, Inc Govt.	1	150	100-200
Public Assembly	1	25	10-050
EOC, PD, FD	1	125	100-150
Industrial	1	200	100-300
Warehouse	1	600	400-900

! As discussed, the time of day that the incident occurred may indicate that there was very little possibility of a structure being occupied. The type of collapse (auto garage only, partial collapse) may also indicate that few occupants would remain entrapped even if many occupied the structure during the incident. The numerical value of this criteria will vary from 1 to 50 as the number of potentially trapped victims varies from 1 to more than 200. Between 5 and 250 the value is the total number of possible trapped victims divided by 5.

II. STRUCTURAL ENGINEERING SYSTEMS

F. US&R STRATEGY & STRUCTURE SIZE UP

TRIAGE SCORING FACTORS (continued)

CONDITION OF VOIDS. This criterion will attempt to assess the degree of survivability of the potentially trapped victims. Victims don't survive well in tightly compacted collapsed areas consisting of rubble masonry, badly broken cast in place concrete and precast concrete. Hollow, survivable voids are often found under wooden floor panels, that are collapsed into angular interlocking planes and in reinforced concrete structures, where floors have projecting beam elements, parts of columns/walls and furnishings that hold the slabs apart. Partly collapsed structures may have large triangular voids or entrapped victims in large voids due to blocked exits etc. These large voids have the best chance of having surviving entrapped victims. The numerical value of this criteria will vary from 1 to 20.

TIME REQUIRED TO ACCESS VICTIMS. This will be an estimate of the time required to get to the first victim. It should include the time required to cut through floors/roofs etc., and the time required to shore/brace the access route and appropriate adjacent structures. The numerical value will vary from 1, for more than one day, to 20 for taking only two hours.

DANGER OF ADDITIONAL COLLAPSE DUE TO AFTERSHOCK. This criteria will be represented by a minus number between -1 for low probability to -20 for high probability of additional collapse, assuming the proposed shoring/bracing is installed from criteria 3.

SPECIAL OCCUPANCY INFORMATION. For this criteria one will add 25 points if the occupancy is a school, day care center, hospital, or other occupancy that could involve children. In addition 5 points should be added for each potential live victim that is confirmed by previous intelligence, search, etc.

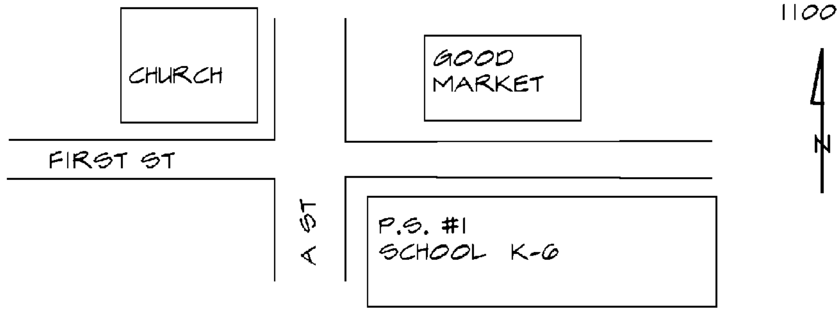
"NO GO" CONDITIONS. These would include structures that are on fire, have significant haz mat spills or otherwise have conditions that would make search and rescue operations too risky. Buildings with "NO GO" conditions would be expected to be re- evaluated when those conditions were mitigated, and some comment would be made regarding this should be recorded on the form.

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

UHR-2A SUN

STRUCTURE TRIAGE ● DATE/TIME 24FEB92/1600 **PG** 1 **of** 1

MAP (PAGE 1 ONLY) **TEAM & S. SP.** D. HAMMOND/CAL #13 **DATE/TIME OF QUAKE** SUN 23FEB92 1100 HRS



BLDG I.D. CORNER 1ST & A	1. ZERO VICTIMS PROBABLE, WRITE ZERO, GOTO NEXT BLDG	
FLOOR AREA 10,000 SF	2. POTENTIAL NO. OF TRAPPED ÷ 5 (MIN = 1 MAX = 50)	40
STORIES ONE	3. CONDITION OF VOIDS 1 VERY COMPACT — SEPARATE LAYERS — PART COLLAPSE → 20	10
OCCUPANCY CHURCH	4. TIME GET TO VICTIM 1 ONE DAY — 2 HRS → 20	1
MATERIAL (CIRCLE ALL THAT APPLY) W (C) S URM PC	5. CHANCE OF COLLAPSE -1 LOW CHANCE — HI CHANCE → -20	-1
CALCULATE AREA & NO. TRAPPED 10,000SF/50 = 200	6. SPECIAL INFO: SCHOOL / HOSPITAL = +25 KNOWN LIVE VICTIM = + 5 EA	0
	NO GO (CIRCLE, WRITE NO-GO & WHEN/IF TO REVISIT) FIRE HM	50 BLDG TOTAL

BLDG I.D. P.S.1 @ 1ST & A ST	1. ZERO VICTIMS PROBABLE, WRITE ZERO, GOTO NEXT BLDG	0
FLOOR AREA 70'X120'X3=25KSF	2. POTENTIAL NO. OF TRAPPED ÷ 5 (MIN = 1 MAX = 50)	
STORIES 3	3. CONDITION OF VOIDS 1 VERY COMPACT — SEPARATE LAYERS — PART COLLAPSE → 20	
OCCUPANCY SCHOOL	4. TIME GET TO VICTIM 1 ONE DAY — 2 HRS → 20	
MATERIAL (CIRCLE ALL THAT APPLY) W C S (URM) PC	5. CHANCE OF COLLAPSE -1 LOW CHANCE — HI CHANCE → -20	
CALCULATE AREA & NO. TRAPPED 25KSF/70 = 360 IF OCCUPIED BUT REPORT NOT OCCUPIED	6. SPECIAL INFO: SCHOOL / HOSPITAL = +25 KNOWN LIVE VICTIM = + 5 EA	
	NO GO (CIRCLE, WRITE NO-GO & WHEN/IF TO REVISIT) FIRE HM	0 BLDG TOTAL

BLDG I.D. MARKET @ 1ST & A	1. ZERO VICTIMS PROBABLE, WRITE ZERO, GOTO NEXT BLDG	
FLOOR AREA 100'X120'=12KSF	2. POTENTIAL NO. OF TRAPPED ÷ 5 (MIN = 1 MAX = 50)	12
STORIES ONE	3. CONDITION OF VOIDS 1 VERY COMPACT — SEPARATE LAYERS — PART COLLAPSE → 20	5
OCCUPANCY GROCERY	4. TIME GET TO VICTIM 1 ONE DAY — 2 HRS → 20	10
MATERIAL (CIRCLE ALL THAT APPLY) W C S URM (PC)	5. CHANCE OF COLLAPSE -1 LOW CHANCE — HI CHANCE → -20	-10
CALCULATE AREA & NO. TRAPPED 12KSF/200 = 60	6. SPECIAL INFO: SCHOOL / HOSPITAL = +25 KNOWN LIVE VICTIM = + 5 EA	0
	NO GO (CIRCLE, WRITE NO-GO & WHEN/IF TO REVISIT) FIRE HM	17 BLDG TOTAL

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

UHR-2A MON

STRUCTURE TRIAGE • DATE/TIME 25FEB92/1600 **PG** 1 **of** 1

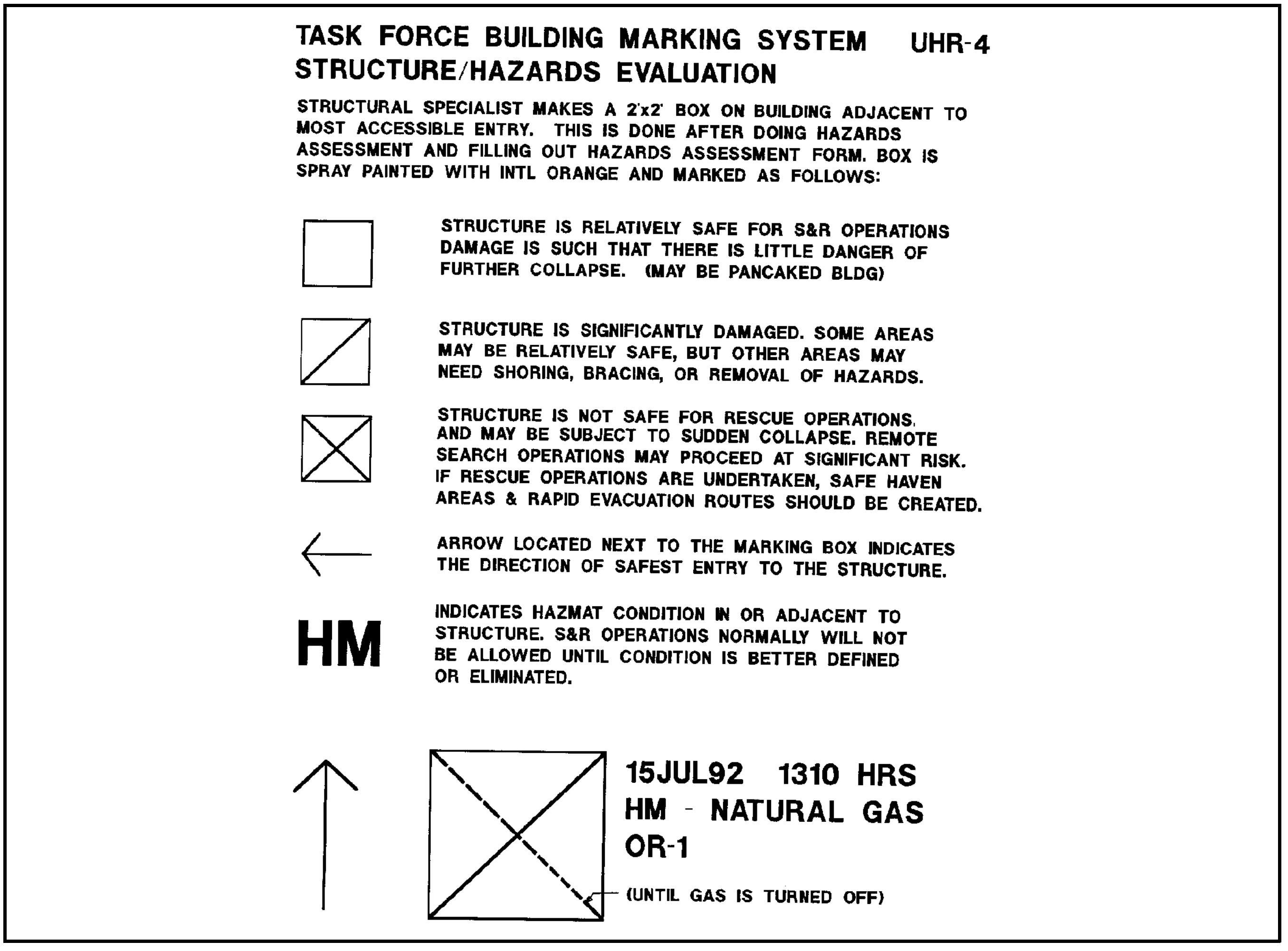
MAP (PAGE 1 ONLY) **TEAM & S. SP.** D. HAMMOND/CAL #13 **DATE/TIME OF QUAKE** MON 24FEB92 1100 HRS

BLDG I.D. CORNER 1ST & A **FLOOR AREA** 10,000 SF **STORIES** ONE **OCCUPANCY** CHURCH **MATERIAL (CIRCLE ALL THAT APPLY)** W (C) S URM PC	1. ZERO VICTIMS PROBABLE, WRITE ZERO, GOTO NEXT BLDG	
	2. POTENTIAL NO. OF TRAPPED ÷ 5 (MIN = 1 MAX = 50)	1
	3. CONDITION OF VOIDS 1 VERY COMPACT — SEPARATE LAYERS — PART COLLAPSE → 20	10
	4. TIME GET TO VICTIM 1 ONE DAY — 2 HRS → 20	1
	5. CHANCE OF COLLAPSE -1 LOW CHANCE — HI CHANCE → -20	-1
CALCULATE AREA & NO. TRAPPED 10,000SF BUT NOT TOO MANY OCCUPY ON MON	6. SPECIAL INFO: SCHOOL / HOSPITAL = +25; KNOWN LIVE VICTIM = +5 EA	0
	NO GO (CIRCLE, WRITE NO-GO & WHEN/IF TO REVISIT) FIRE HM	11 BLDG TOTAL
BLDG I.D. P.S.1 @ 1ST & A ST **FLOOR AREA** 70'X120'X3=25KSF **STORIES** 3 **OCCUPANCY** SCHOOL **MATERIAL (CIRCLE ALL THAT APPLY)** W C S (URM) PC	1. ZERO VICTIMS PROBABLE, WRITE ZERO, GOTO NEXT BLDG	
	2. POTENTIAL NO. OF TRAPPED ÷ 5 (MIN = 1 MAX = 50)	36
	3. CONDITION OF VOIDS 1 VERY COMPACT — SEPARATE LAYERS — PART COLLAPSE → 20	1
	4. TIME GET TO VICTIM 1 ONE DAY — 2 HRS → 20	20
	5. CHANCE OF COLLAPSE -1 LOW CHANCE — HI CHANCE → -20	-10
CALCULATE AREA & NO. TRAPPED 25KSF/70 = 360 HAVE INFO THAT ABOUT 1/2 GOT OUT	6. SPECIAL INFO: SCHOOL / HOSPITAL = +25; KNOWN LIVE VICTIM = +5 EA	25
	NO GO (CIRCLE, WRITE NO-GO & WHEN/IF TO REVISIT) FIRE HM	72 BLDG TOTAL
BLDG I.D. MARKET @ 1ST & A **FLOOR AREA** 100'X120'=12KSF **STORIES** ONE **OCCUPANCY** GROCERY **MATERIAL (CIRCLE ALL THAT APPLY)** W C S URM (PC)	1. ZERO VICTIMS PROBABLE, WRITE ZERO, GOTO NEXT BLDG	
	2. POTENTIAL NO. OF TRAPPED ÷ 5 (MIN = 1 MAX = 50)	12
	3. CONDITION OF VOIDS 1 VERY COMPACT — SEPARATE LAYERS — PART COLLAPSE → 20	5
	4. TIME GET TO VICTIM 1 ONE DAY — 2 HRS → 20	10
	5. CHANCE OF COLLAPSE -1 LOW CHANCE — HI CHANCE → -20	-10
CALCULATE AREA & NO. TRAPPED 12KSF/200 = 60	6. SPECIAL INFO: SCHOOL / HOSPITAL = +25; KNOWN LIVE VICTIM = +5 EA	0
	NO GO (CIRCLE, WRITE NO-GO & WHEN/IF TO REVISIT) FIRE HM	17 BLDG TOTAL

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

STRUCTURE/HAZARD EVALUATION & MARKING

Structural/Hazard Evaluation should take place AFTER a priority list of structures has been established by the leadership, using Triage or just common sense, if only a few structures are involved. The Structure/Hazards Evaluation form has, deliberately, been made different from the ATC-20 "Safety Assessment" placards and forms. It should be assumed the US&R task force will be dealing with buildings that have or would have received a red tag (Using ATC-20). The greatest area of concern is not with the fully collapsed structures, but with those that have partly collapsed. The Search Specialist and Haz Mat Specialist should be prepared to fill out the US&R Structure/Hazard Evaluation Form, identifying structure type, occupancy, hazards, etc. In addition the Search Specialist will generate notes and diagrams regarding search operations (locations of voids, shafts, shoring, etc.). It is anticipated, however, that in some cases the assessment will only indicate that the building is too dangerous to conduct US&R operations.



TASK FORCE BUILDING MARKING SYSTEM UHR-4
STRUCTURE/HAZARDS EVALUATION

STRUCTURAL SPECIALIST MAKES A 2'x2' BOX ON BUILDING ADJACENT TO MOST ACCESSIBLE ENTRY. THIS IS DONE AFTER DOING HAZARDS ASSESSMENT AND FILLING OUT HAZARDS ASSESSMENT FORM. BOX IS SPRAY PAINTED WITH INTL ORANGE AND MARKED AS FOLLOWS:

STRUCTURE IS RELATIVELY SAFE FOR S&R OPERATIONS DAMAGE IS SUCH THAT THERE IS LITTLE DANGER OF FURTHER COLLAPSE. (MAY BE PANCAKED BLDG)

STRUCTURE IS SIGNIFICANTLY DAMAGED. SOME AREAS MAY BE RELATIVELY SAFE, BUT OTHER AREAS MAY NEED SHORING, BRACING, OR REMOVAL OF HAZARDS.

STRUCTURE IS NOT SAFE FOR RESCUE OPERATIONS, AND MAY BE SUBJECT TO SUDDEN COLLAPSE. REMOTE SEARCH OPERATIONS MAY PROCEED AT SIGNIFICANT RISK. IF RESCUE OPERATIONS ARE UNDERTAKEN, SAFE HAVEN AREAS & RAPID EVACUATION ROUTES SHOULD BE CREATED.

ARROW LOCATED NEXT TO THE MARKING BOX INDICATES THE DIRECTION OF SAFEST ENTRY TO THE STRUCTURE.

HM INDICATES HAZMAT CONDITION IN OR ADJACENT TO STRUCTURE. S&R OPERATIONS NORMALLY WILL NOT BE ALLOWED UNTIL CONDITION IS BETTER DEFINED OR ELIMINATED.

15JUL92 1310 HRS
HM - NATURAL GAS
OR-1
(UNTIL GAS IS TURNED OFF)

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

STRUCTURE/HAZARD EVALUATION & MARKING (continued)

The term safe should be understood by the Structures Specialist in a context very different from that of " safe for occupancy". All the structures will be damaged, and the value judgment of "safe enough for the risks of US&R" will need to be measured. It is strongly suggested that Structures Specialist works with another person during this phase (just as engineers do in ATC-20 type assessment) for safety reasons as well as being able to have immediate access to second opinions on all critical decisions. The second person would ideally be the other Search Specialist, however, in larger incidents this may be impractical. Each Structures Specialist would, more probably, be paired with a Haz Mat Specialist in order to evaluate all hazards during this evaluation (just as during triage).

The Structure/Hazard Evaluation Marking is then placed on the building near each entry etc.

U.S.&R. STRUCTURE/HAZARDS EVALUATION • BY ____________
Where required, circle all the information items that apply — NOTE: AFTERSHOCKS MAY CAUSE ADDITIONAL DAMAGE THAN NOTED

STRUCTURE DESCRIPTION BLDG I.D. ________ No. Stories ____ No. Basements ____	MARK ☐ ◱ ☒ DATE/TIME EVALUATE
MATERIALS W C S URM PC Other ________	TYPE OF COLLAPSE PANCAKE SOFT 1ST STORY WALL FAILURE TORSION MIDDLE STORY OVERTURN Other
FRAMING SYSTEMS SHEARWALL MOMENT FRAME BRACED FRAME Other	LOCATION OF VOIDS BETWN FLOORS BASEMENT SHAFTS Other
OCCUPANCY Hospital Police Sta Fire Sta Emer Op Center Office Bldg School Public Assembly Industrial Hotel Apartment Retail Store Other ____	DESCRIBE UNSAFE AREAS ________
VICTIM & OTHER INFO ________	
LOCATION OF BEST ACCESS & SAR STRATEGY ________	DESCRIBE HAZARDS ________

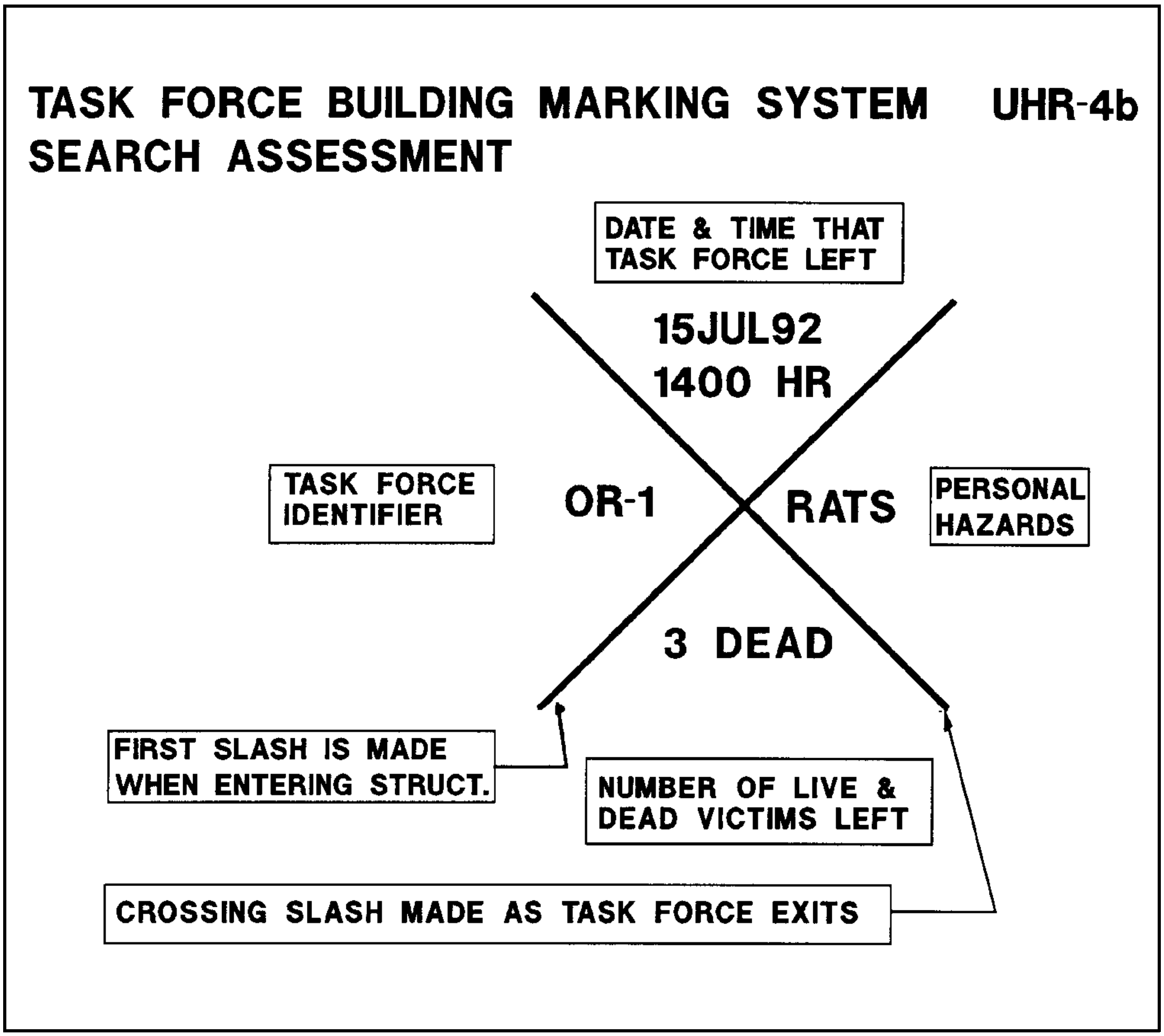
SKETCH

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

SEARCH & RESCUE ASSESSMENT MARKING

Standard SAR assessment marking is designed to perform two functions:

- ! First, when SAR personnel enter the building or parts of the building, the initial diagonal line is drawn so that others will be informed of “on going operations”.
- ! When operations are completed in the building (or parts of the building) the crossing diagonal line will be drawn and information added to indicate by whom and what was accomplished.
- ! The finished mark can then indicate to other SAR forces the outcome of previous operations.



II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

HAZARD ASSESSMENT & MITIGATION

Hazard Assessment for US&R — based on principles previously discussed in Hazard Identification Section. Need to add some additional considerations for US&R, since staying out of the structure is probably not an option.

! Assessment applies to building structural system and individual void systems.

! First question should be: Do we need to be in this area at all ?.

! Hazard avoidance is the preferred option

! What are global vs local hazards

! Look up first! Small, nonstructural elements may be greatest hazards.

! Debris and other loose materials can fall in wind gusts and aftershocks - these are hazards during hazard assessment

! What if there is an aftershock ? What is the plan - what are the escape routes and/or safe haven ?

HAZARD REDUCTION

The basic alternatives to deal with structural collapse or falling hazards are to:

! **AVOID** — Plan direction of SAR activities away from hazard and its effects. Access of badly collapsed structure should start from the top, rather than from the edge (between layers), or than by tunneling. The use of mining techniques of tunneling and shoring with individual vertical posts has lead to aftershock caused shore failures. Consider alternatives, consult with others, be as resourceful as possible.

II. STRUCTURAL ENGINEERING SYSTEMS

F. US&R STRATEGY & STRUCTURE SIZE UP

HAZARD REDUCTION (continued)

- **EXPOSURE REDUCTION** - One of the most efficient method of hazard reduction is to limit the time of exposure , and to limit the number rescuers that are being exposed to a potentially dangerous situation. Because of the natural tendency of rescuers to be helpful and “Part of the Action”, one will often find more than the minimum required number in a confined space especially when a live rescue in nearing completion. Risk is a function of both severity and exposure.

- **REMOVE** — May be more efficient than shoring. Parts of URM walls may be removed by hand, using aerial ladders for upper portions, or in larger pieces using crane and clamshell. Precast concrete sections are more easily removed by small cranes or other concrete removal machines, due to their moderate size and lack of interconnections compared to cast in place concrete. If at all possible - Lift Off, Push Over, or Pull Down (safely ofcourse) as a first choice

- **SHORE** — Provide both vertical and lateral support, build safe haven areas. This will be discussed in detail in its own section, with special emphasis on slow/forgiving failure modes . Lateral bracing of damaged columns, beams, and entire leaning buildings may be required. Tension tieback bracing can also be effective for holding walls, and cranes have been used to temporily suspend parts of damaged buildings.

- **MONITOR** - as discussed previously, methods including the use of crack measuring devices, Theodolites and other tilt measuring devices (Change in Tilt) are used to monitor damaged structures. To be effective these devices must be continually read and accompanied by an effective alarm system that activates an efficient evacuation plan.

- **RECOGNIZE** and refer hazardous materials to Haz Mat Specialist. Shut off all fire hazards possible.

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

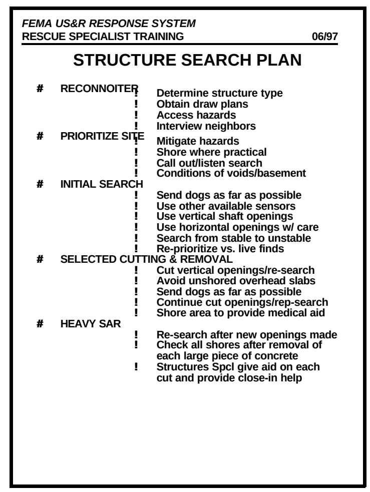
BASIC BUILDING SEARCH & RESCUE PLANS

Basic Plan (for individual building):
(See Appendix B — Rescue Operation Strategy & Tactics)

- ! **Reconnoiter Site** — collecting as much information as possible
  - Determine structure type — to better assess type of failure, type of hazards, ease of entry and cutting etc.
  - Interview neighbors, survivors, interested people (how many potential victims; where last seen, location of stairs, elevators, basement, etc.).
  - Obtain building plan an/or draw crude plan with special emphasis on probable location of voids, existing shafts, basement.
  - Search Specialists re-assess building in detail to re-identify hazards.

- ! **Prioritize site** — use collected data to obtain best risk/benefit ratio.
  - Conduct callout/listen search.
  - Plan shoring at access, and/or use most efficient access.
  - Determine condition of basement.
  - Avoid falling hazards unless they can be removed and/or shored.

- ! **Initial search** — Appendix C, FEMA US&R Response System, on Search Strategy and Tactics, addresses this subject. Properly trained search dogs and electronic locators have been used successfully in US&R to locate deeply buried victims. Both have significant limitations, i.e., the dogs must be repeatedly trained in the rubble environment in order to effectively find human scent, not be concerned about their own safety, and to ignore animal, food, and/or sewer gases. Even properly trained dogs may only be able to indicate direction of scent, which is not necessarily the direction of the victim.


FEMA US&R RESPONSE SYSTEM
RESCUE SPECIALIST TRAINING 06/97

STRUCTURE SEARCH PLAN

RECONNOITER
! Determine structure type
! Obtain draw plans
! Access hazards
! Interview neighbors
PRIORITIZE SITE
! Mitigate hazards
! Shore where practical
! Call out/listen search
! Conditions of voids/basement
INITIAL SEARCH
! Send dogs as far as possible
! Use other available sensors
! Use vertical shaft openings
! Use horizontal openings w/ care
! Search from stable to unstable
! Re-prioritize vs. live finds
SELECTED CUTTING & REMOVAL
! Cut vertical openings/re-search
! Avoid unshored overhead slabs
! Send dogs as far as possible
! Continue cut openings/rep-search
! Shore area to provide medical aid
HEAVY SAR
! Re-search after new openings made
! Check all shores after removal of each large piece of concrete
! Structures Spcl give aid on each cut and provide close-in help

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

BASIC BUILDING SEARCH & RESCUE PLANS (continued)

Electronic devices, even when operated by trained personnel, may be only able to detect victims that are very actively sending tapping signals.

- Use search dogs with "send out" as far as possible into structure. Check alerts with second dog/observer/handler.
- Use listening/seismic finders if available.
- Explore existing vertical shaft openings if available.
- Explore horizontal openings with great care (send dog in and keep people out if practical).
- In general search from safe — stable areas into unstable.
- Re-prioritize site vs. location of potential live victims.

! **Selected Cutting & Removal** — based on priorities of initial search vs. probable hazards. (Appendix B, Phase Four)

- Cut vertical openings and re-search, re-check with dogs and/or listening/viewing devices.
- Initial shoring for access.
- Avoid un-shored overhead structures.
- Recheck all shoring after cutting and removal, loading can change.
- Continue process of cutting layers, re-searching, and re-prioritizing.
- Stabilize area at victim to give medical aid.

! **Heavy Search & Rescue**

- Continue search after prolonged cutting and/or removal.
- Give victim aid and gain information regarding additional victims.
- Re-check all shoring after cutting and removal, since loading can change.

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

SAR PLAN - LIGHT FRAME BUILDINGS

Search Items

! Callout/listen search may be effective due to lower density of wood floors.

! Acoustic listening devices will probably be more effective than seismic type sensors in these buildings that have wood floors and walls. Broken wood is relatively poor transmitters of vibrations.

! Dogs may be able to sent through cracks in wood floors if they are not heavily covered.

Hazard Reduction Items

! Shut off gas (and electricity) and reduce other fire hazards. (**This applies for all types of buildings)**

! Assess / refer chemical hazards. **(What's in the typical kitchen?)**

! Remove / avoid or topple leaning chimney

! Place vertical and / or lateral shores. Leaning multi-story buildings may be shored using diagonal timbers.

Victim Access Items

! Use horizontal entry thru cavities or thru walls.

! Make vertical access thru holes cut in roof / floor

! Remove / shore hazards as required.

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

SAR PLAN - HEAVY WALL BUILDINGS - URM & TU

Search Items

! Callout/listen search may be effective due to lower density of wood floors.

! Acoustic listening devices will probably be more effective than seismic type sensors. Most of these structures will have wood floors that have collapsed in large planes and badly broken masonry, both of which are relatively poor transmitters of vibrations.

! K9 may be able to sent through cracks in wood floors if they are not heavily covered.

Hazard Reduction Items - URM

! Shore hazardous floors with vertical shores.

! Remaining uncollapsed URM walls are brittle, aftershock/wind falling hazards. Either avoid, remove, tieback, or raker shore them. May need to shore in both IN and OUT direction.

! Beware of all falling hazards - peeled, cracked, & split URM walls are very brittle. High potential for falling & collapse hazards.

Hazard Reduction Items - TU & Low Rise

! Use diagonal or raker shores for hazardous walls.

! Shore hazardous roof / floor beams, etc.

Victim Access Items - URM

! Use horizontal entry thru existing openings with great care.
! Vertical access through wood floors should be easy and least dangerous.
- avoid cutting large beams and more than two joists in a row.

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

 # Victim Access Items - URM (continued)

- ! Avoid cutting walls. Holes can greatly reduce strength of poorly cemented walls - most are important bearing walls
- ! Beware of roof/floor joist/beams that are not sitting on their original flat bearings or ledges, they can slide down walls and produce outward forces as they move to find next stable position.
- ! Basement may provide good access, but should shore for safety. Failure of wood column or beams can be sudden.
- ! Hand removal of bricks may be required.
- ! Large pieces of wall may be removed by clamshell or other bucket with thumb. (need to prevent parts from falling)

 # Victim Access Items - TU & Low Rise

- ! Use horizontal entry thru existing openings with great care.
- ! Vertical access through wood roof/floors should be easy and least dangerous.
- ! Holes in wall panels should best be made 2 ft min away from joints. If wall has concrete pilaster/column, one may cut opening next to column on side away from joint.
- ! Wall panels and large pieces of roof may be lifted by crane or other equipment.

<u>SAR PLAN - CONCRETE FRAME BUILDINGS</u>

 # Search Items - Heavy Floor

- ! Not likely to hear callout of victims through floors due to high density of concrete.
- ! Seismic listening devices can be most effective in these, heavy structures, especially when floor slabs remain intact and form thin void spaces as in pancake type collapse.

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

Search Items - Heavy Floor (continued)

! K9 will indicate direction of scent which may be flowing around large slabs, back and forth across the building. (**Location of victim must be interpreted from conditions**) Area should be re-checked by dogs after layers have been removed. Best time to use dogs — in early morning and at dusk — scent is rising.

Hazard Reduction Items - Heavy Floor

! In partly collapsed building (upper floors, etc.) is very important to check floors that support debris load.
- read cracks to determine if more and progressive collapse is probable.
- multi-story shoring may be only safe procedure.
- it normally takes at least two un-damaged floors to support shores from one damaged floor that contains little debris (if heavy concrete debris from upper floors is present, shores need to extend down to additional, undamaged floors - two more floors per 12" of debris)

! Shore/avoid badly cracked beams.

! Shore/avoid hanging slabs/beams.

! Shore heavily loaded flat slabs (beamless slabs) - punching shear.

! Beware of all falling hazards - parts of slabs, walls, etc. May be hanging from exposed rebar - how well is rebar embeded?

Victim Access Items - Heavy Floor

! Use any existing vertical shaft.

! Basement may be good access, but need to evaluate floor slab above and possibly shore. How many bsmt levels?

! Preferred access in usually made by cutting thru slabs from above collapse.

! Best to cut slabs mid-way between beams & columns.

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

Victim Access Items - Heavy Floor (continued)

! Check for thinnest slab area. Pan joist and waffle slabs have ribs spaced 3ft or so with 3 or 4" slab between.

! Do not cut columns - usually do not need to.

! Avoid cutting concrete/masonry walls. They may be bearing walls. If have masonry infill wall in concrete frame cutting is possible - check first to see if frame is loading wall due to collapse.

Note: Inexpensive ($100) metal detectors can be used to locate rebar or prestress cables prior to cutting slabs and walls.

<u>**SAR PLAN - PRECAST CONCRETE BUILDINGS**</u>

Search Items - Precast Concrete

! Callout/listen search may be effective. It depends on size of voids between larger pieces of concrete.

! Effectiveness of listening devices will depend on the interconnection of the collapsed, structural parts. Acoustic sensors may not be effective in compact rubble, and seismic sensors may not be effective due to poor transfer through badly broken concrete parts.

! K9 search may be effective - again depending on compactness of concrete rubble.

Hazard Reduction Items - Precast Concrete

! Remove/avoid hanging pieces of structure. There may be many loose or poorly connected pieces of precast concrete. Use cranes and other equipment.

! Shore beams adjacent to badly cracked columns.

! Remove/shore tilted wall panels or pieces.

! Partly collapsed buildings may have adjacent slabs and/or wall panels that have damaged connections that may break loose in aftershocks or if loading shifts.

II. STRUCTURAL ENGINEERING SYSTEMS
F. US&R STRATEGY & STRUCTURE SIZE UP

Victim Access Items - Precast Concrete

! Cutting of cored slabs & tee slabs should be done at edges (Thru thinnest part of section and away from ribs).

- cut ½ of hole in each of two adjacent precast pieces.

! Don't cut ribs in Tees or walls & don’t cut columns.

! Walls may be cut with care.
- cut holes at least 2ft away from joints.
- consider problems of shoring vs. removal (removal may be more efficient).
- check wall welded joints for signs of movement.
- some walls may be infill URM and may be cut if not loaded by collapsed concrete pieces.

! Basements may not be good access unless basement walls and first floor slab are cast in place concrete. Shoreing may be required in any case.

! Use horizontal access thru existing cavities - used great care

! Lift off loose concrete pieces with cranes or other equipment

! Great care must be taken when lifting and/or shoring large concrete pieces, since adjacent pieces may shift..

! Precast concrete will often weigh about 70% of normal (150 PCF) concrete. It also splits more easily.

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

OVERVIEW OF DESTRUCTIVE FORCES

Earthquakes cause shaking that has its greatest effect on weak, heavy, and structures that are dynamically coupled with their sites.

Wind — hurricanes and tornados cause damage due to wind velocity, airborne missiles, tidal surge, and difference in atmospheric pressure. Wind affects mostly light, un-engineered buildings and structures that are penetrated, thereby causing high uplift/blowout forces.

Floods — are normally classified as riverine flooding, and costal flooding. Riverine flooding may be flash type, which has a rapid water rise, high velocity, and may produce a wall of water effect. Other river flooding may be the relatively slow unconfined flow over a low lying broad area. Costal flooding is caused by severe storms that may be combined with high tides. The step up surges of hurricanes combined with their high winds produce combined forces from wind and flooding. The damage from flooding is caused by hydrostatic lateral pressure/lifting, hydrodynamic forces due to velocity and wave height, and debris impact from waterborne objects.

Snow and Heavy Rain- cause roof collapse due to overload. Most often occurs in long span construction with relatively flat roof, where roof beam or truss fails, leading to partial collapse. Snow build up can cause more complete collapse due to failure of vertical supporting elements.

Construction Problems — most often caused by lack of temporary lateral bracing or inadequate vertical shoring. Failures have occurred during concrete pours, while placing large roof beams and trusses, and during lifting of large concrete slabs. In addition collapse has been caused by overloads due to stockpiling of materials and non-engineered alterations.

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

OVERVIEW OF DESTRUCTIVE FORCES (continued)

Explosions — have been caused by natural gas build up as well as deliberately set bombs. Light weight wood and steel structures often have weakest part blown out to reduce pressure (i.e., roof or wall skins, windows) entire roof or wall may be blown out. Reinforced concrete structures contain blast better, often causing greater loss of life, and if columns or walls are badly damaged, collapse of floors can result. Precast structures are especially vulnerable, since large concrete parts can become disconnected or blown out, leading to progressive collapse.

Structural Decay- has lead to collapse of older buildings and bridges. Collapse can be most devastating when vertical support members fail, leading to multi-floor collapse. In older buildings the exterior unreinforced masonry walls can be left standing full height without any bracing by pancaked floors. Walls could later fall in on floor debris pile, or out into the street, or adjacent buildings — very significant hazard.

Fire — wood or metal roof/floors often collapse due to burn-through and can pull exterior masonry or concrete walls in or leave them standing in an unbraced condition. A steel structure left standing after a fire can have significantly reduced strength due to loss of original heat treatment. A remaining concrete structure can be damaged due to spalling and shearwalls can be cracked due to expansion of floors.

Transportation Accidents — have caused structures to collapse due to impacts and spillage of large quantities of materials.

EFFECTS CAUSED BY EARTHQUAKES

Faulting of Ground — can occur directly over trace of fault where ground has offset as much as 20 feet horizontally and 10 feet vertically. Few structures can survive this effect.

Landslides, Rockslides, and Ice/Mudslides — have caused great loss of life when entire towns have been buried (Andes Mts). Automobile-size boulders have caused great damage and great landslides have moved structures hundreds of feet.

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

EFFECTS CAUSED BY EARTHQUAKES (continued)

Liquefaction — occurs in loose deposits of saturated, fine uniform sands. If such a deposit is subjected to a sudden disturbance or shock, as in an earthquake, the material tends to decrease rapidly in volume under the suddenly developed shearing stresses. The soil gets temporarily transformed into a fluid mass with negligible shear strength. In the large earthquake at Niigata, Japan in 1963, the liquefaction of a sand deposit caused a group of concrete apartment buildings to drop suddenly, some as much at one story and to tilt more than 30 degrees. Sand boils and other disruption of the ground surface also have occurred.

Tsunami — can be caused by significant shaking of land beneath and adjacent to the ocean. When the wave sweeps ashore it can devastate all but the heaviest structures. Islands and low lying costal areas are most vulnerable, and inlet configuration can cause an amplification of the wave.

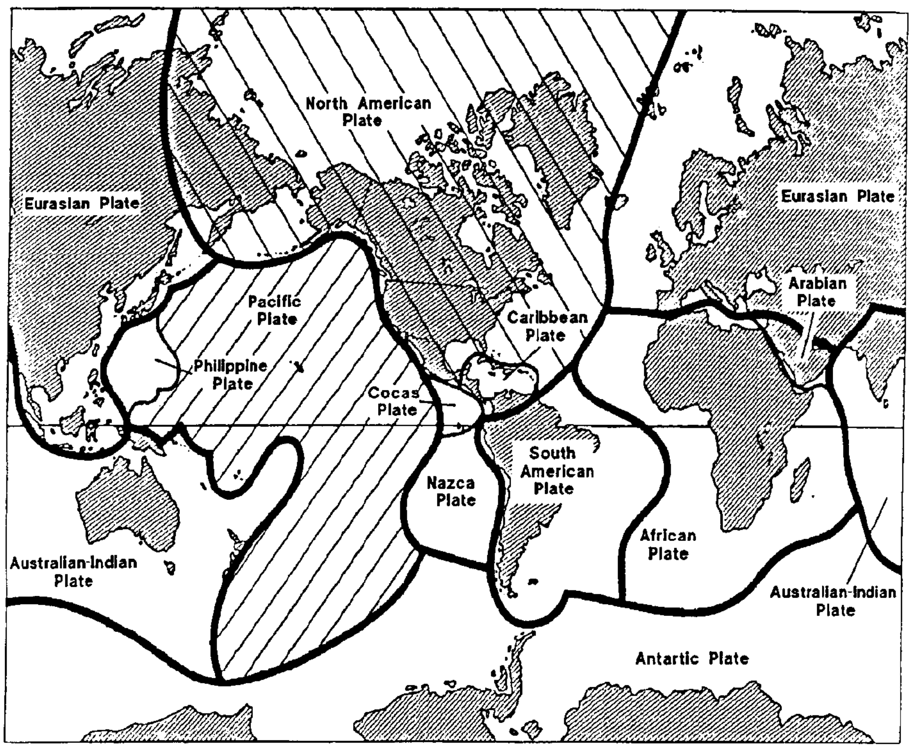
Shaking — is the effect that is most commonly experienced by structures and can be felt as far as hundreds of kilometers from the earthquake origin. Near field shaking is what occurs within tens of kilometers from the fault, and the far field effects occur at distances beyond that.

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

EARTHQUAKE FAULTS

Most, but not all active faults are located at the boundaries of the giant plates of rock mass that float on the molten core of the earth, called Plate Tectonics. The action as the boundaries of these plates attempt to move with respect to each other is what causes earthquakes. In some cases one plate is moving under another. Some plates are moving apart, and in many cases they are also moving laterally with respect to each other. Some faults occur within plates that are forming or changing.

EARTH PLATES **EQ-1**



EFFECTS CAUSED BY EARTHQUAKES

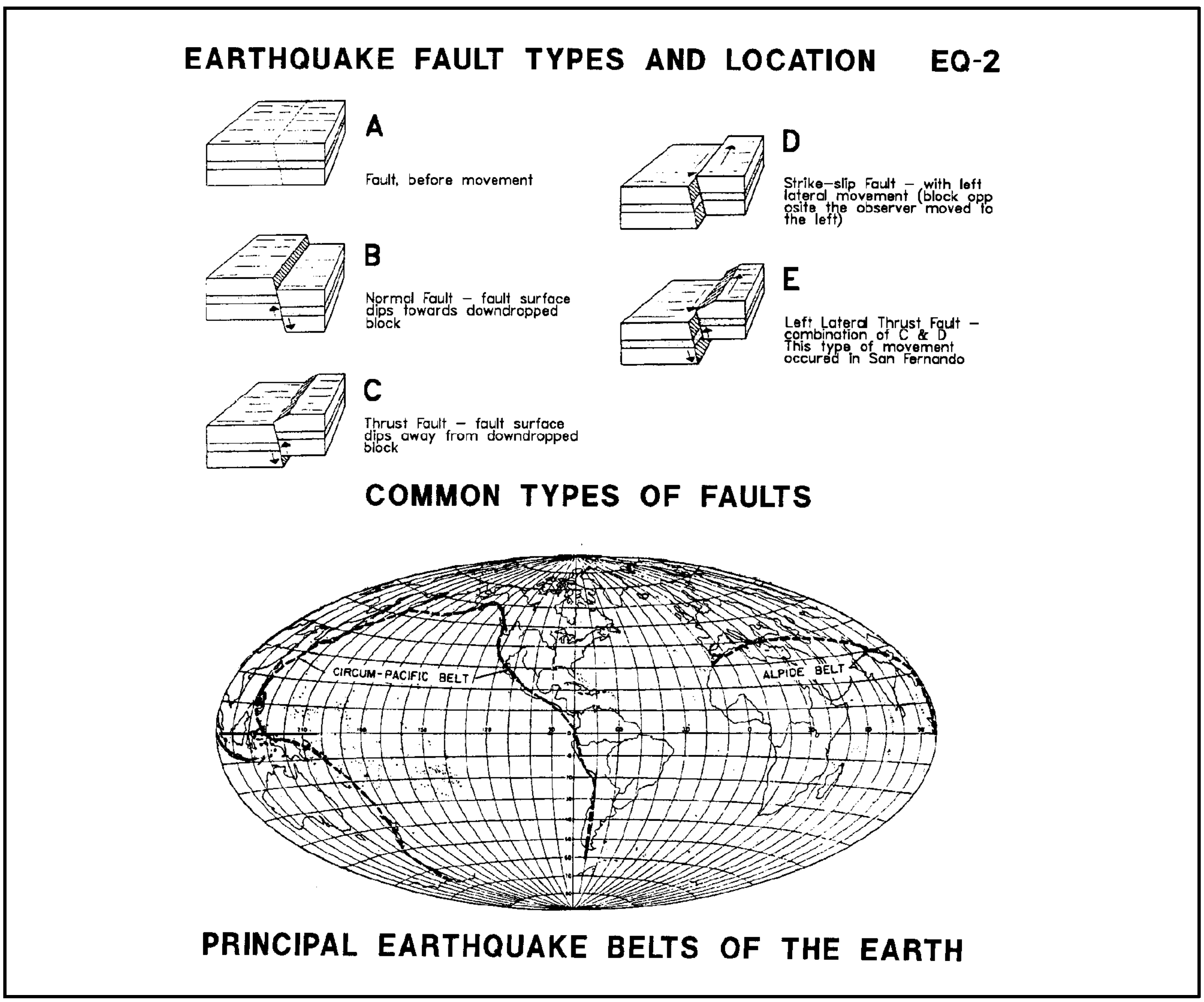
- **FAULTING OF GROUND**
- **LANDSLIDES, ROCKSLIDES, ICESLIDES**
- **LIQUEFACTION**
- **TSUNAMI**
- **SHAKING**

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

EARTHQUAKE FAULTS (continued)

There are two extremely active earthquake belts on earth; The Circum-Pacific Belt and the Alpide Belt. The counterclockwise rotation of the Pacific Plate is the principal action that causes earthquakes along the Circum Pacific Belt. This action is attempting to move the Pacific Ocean about 2 cm per year North relative to the Pacific Coast of California, and causes the Aleutian Islands of Alaska to be the most active seismic region in the world.

Some potentially active seismic zones occur within plates, such as the New Madrid Zone in the North American Plate. It is thought that this faulting was the result of a failed plate boundary separation (similar to the active Mid-Atlantic Boundary) with faulting being similar to that at the Red Sea.

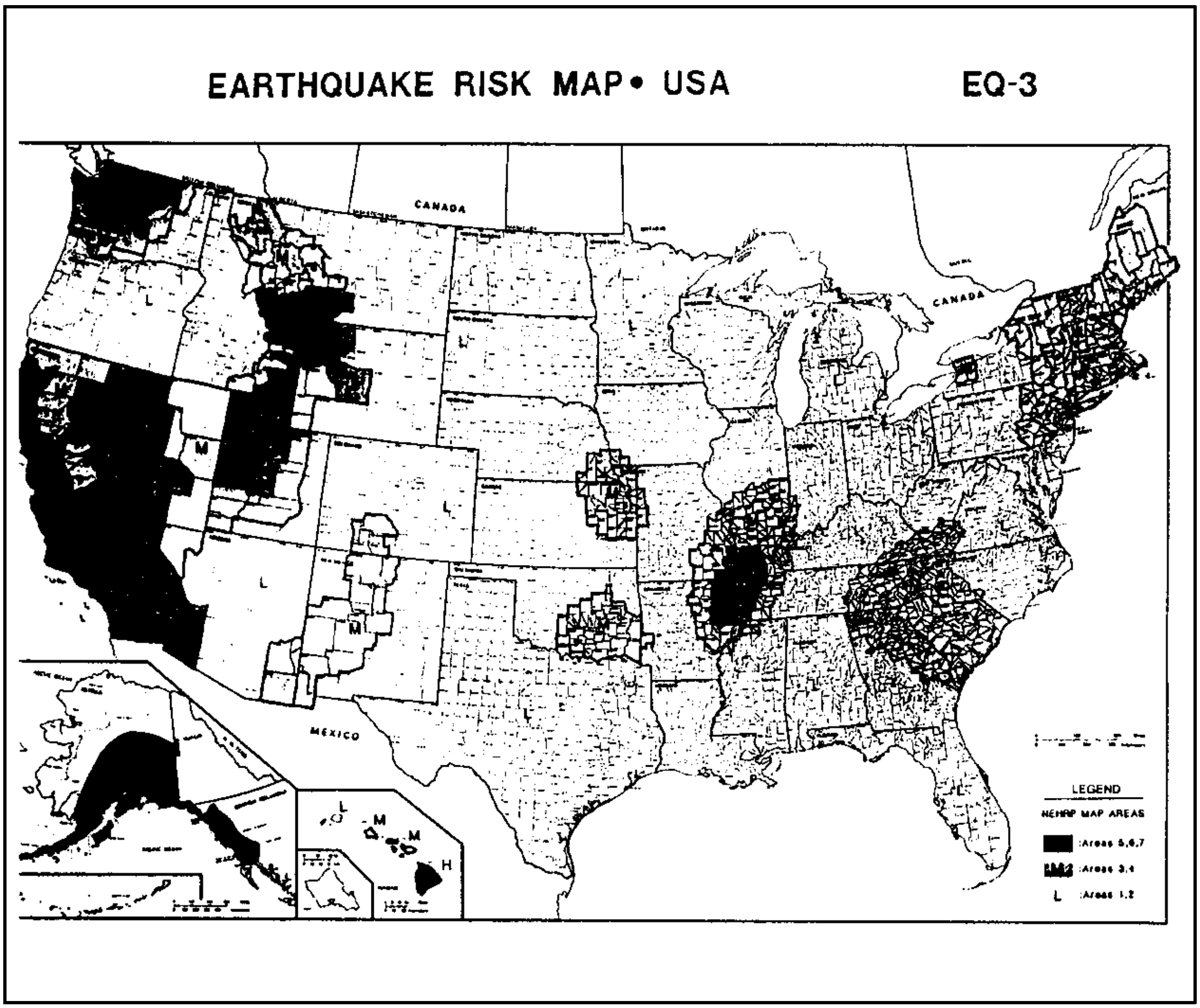


II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

<u>EARTHQUAKE FAULTS</u> (continued)

The large plates on either side of the fault are attempting to continually move with respect to each other, but the rock surfaces are locked together at the plate boundary. An earthquake occurs as this interconnected surface ruptures, locally, and the plate boundaries shift (Elastic Rebound Theory). This adjustment may occur over the length of a few kilometers or a few hundred kilometers.

In any local area, faults may be of any one of several types (i.e. ,normal, thrust, or strike slip). In many cases the movement of the fault surfaces is both horizontal and vertical. An example is the 1971 San Fernando Earthquake, which was caused by left lateral plus vertical movement of the fault. Quakes on thrust faults (San Fernando 1971, Armenia 1989) have been observed to have been very destructive to structures.

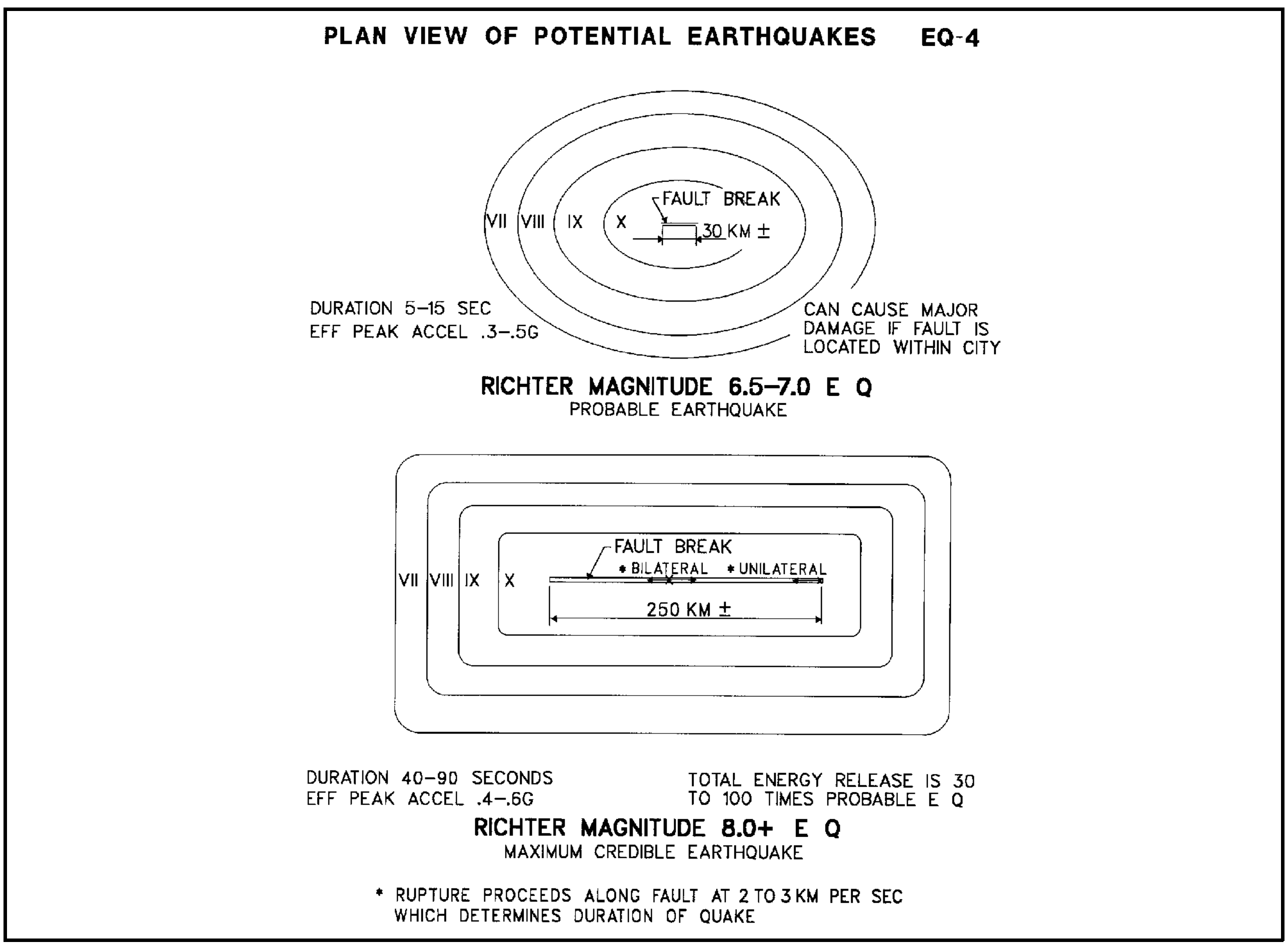


II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

EARTHQUAKE ORIGIN AND DURATION

Strong shaking at the fault lasts as long as it takes the rupturing to move from the point where it starts to the end of the effected fault length. This action moves at 2 to 3 km/sec, and usually occurs as a unilateral fault break (i.e., rupture starts at one end and progress to opposite end). In this type of break the greater amount of energy is released in the direction of the fault rupture. In other earthquakes a bilateral fault break occurs (i.e., the rupture starts in the middle of effective fault and progresses in both directions). One would expect less damage in a bilateral break, since the strong shaking would last only half as long, and the energy would be dispersed in both directions.

The initial point of rupture, called the focus, often occurs at a depth of 5 km or more beneath the earth's surface, and the epicenter is a point on the surface directly above the focus. This location is of scientific interest, but since the destructive energy essentially radiates out from the fault break, it is one's distance from that long line (say 30 to 300 kilometers) that will determine potential damage.



II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

EARTHQUAKE WAVES

Body waves have been identified as those that travel within the body of the earth. There are primary (P waves) that are like sound waves, that compress and expand material as they travel. They travel at about 3 to 5 km/sec and go through solids and liquids. They travel to a point on the surface direct from some depth and therefore, have both vertical and horizontal components. Secondary (S waves) are also body waves. These travel at 2/3 speed of P waves, travel only through solids, have vertical and horizontal components, but are lateral waves that move from side to side and up and down as they move from their source. S waves are damped out rapidly as the rigidity of the material that they pass through drops, but are thought to cause most of the structural damage in the near field.

EARTHQUAKE WAVES **EQ-5**

TYPICAL EARTHQUAKE ACCELEROGRAM

BODY WAVES

PRIMARY WAVES - P ARE COMPRESSION WAVES
- TRAVEL AT ABOUT 5KM/SEC
- TRAVEL THRU SOLIDS & LIQUIDS

SECONDARY WAVES - S LATERAL, SHEAR WAVES
- TRAVEL AT 2/3 SPEED OF P WAVE
- TRAVEL THRU SOLIDS, NOT LIQUIDS
- PRODUCE HORIZONTAL & VERTICAL MOTION
- DAMP OUT RAPIDLY AS THE RIGIDITY OF MATERIAL THAT THEY FLOW THRU FALLS
- PRODUCE MOST DAMAGE IN NEAR FIELD

SURFACE WAVES - LONG WAVES - L

RAYLEIGH WAVES
- ARE LONG SLOW WAVES

SIDE VIEW

LOVE WAVES
- ARE SLOW SHEAR WAVES WITH NO VERTICAL MOTION

PLAN VIEW

WAVE COMPLEXITIES
- S WAVES OFTEN HIT BEFORE TAIL OF P WAVES PASS
- SURFACE WAVES ARE REFRACTED AND REFLECTED
- WAVES MAY COMBINE TO FORM LARGE AMPLITUDE OBSERVABLE TRAVELING SURFACE WAVE
- RICHNESS OF HARMONICS DEPENDS ON EARTHQUAKE, REGIONAL GEOLOGY, AND SITE CONDITIONS

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

EARTHQUAKE WAVES (continued)

Surface waves are longer period waves that travel at the surface, out from a fault more slowly than body waves. The two principal types of surface waves that have been identified are Rayleigh Waves and Love Waves. These waves are thought to cause the greatest damage in the far field (more than 50 km from the fault). Rayleigh Waves are long rolling waves that have greatest effect on taller structures. Love Waves are lateral shear waves, but have only horizontal (no vertical) component. Surface waves damp out much more slowly than body waves.

Earthquake waves form complex patterns at any particular location as the train of S Waves hits before the P waves pass. Reflections of P and S waves occur at the earth's surface which may create PP, PS, SP, and SS waves. Surface waves are often refracted and reflected. Waves may combine to form large amplitude traveling surface waves, that have been observed in many earthquakes. The richness of the harmonics contained by waves reaching any one point will depend on the particular earthquake, the regional geology, and local site conditions.

The far field effects and measurements are usually explainable, elastically. Near field effects are not well defined, often inelastic, and local damage may be difficult to explain and not be related to overall effects.

The difference in speed and wave action of P waves and S waves is being used to manufacture seismic warning devices. Since the damaging S waves are slower by about 2km/sec in arriving from the source fault to a specific site, there can be a few to several seconds between the sensing of P to arrival of S. A triaxial seismic trigger can be installed at any site and configured to sense the initial P waves of strong earthquakes and aftershocks. These devices are currently being installed to shut down nuclear plants, gas lines, elevators etc. and warn schools, high rise buildings, hospitals, institutional facilities, industrial and military installations. The lead time available can be as little as 1 second for a site 10 km from the shaking source to over 10 seconds for a site that is 100 km away.

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

EARTHQUAKE WAVES (continued)

Another warning system is available that uses an array of seismic sensors , placed near the fault, that are coupled with pagers that can be carried by US&R forces. When an aftershock occurs, a warning signal will be sent to the pagers that can give a 3 second warning for sites that are 10 km from the aftershock origin to 25 second warning for a site 100 km away.

EARTHQUAKE MAGNITUDE AND INTENSITY

Modified Mercalli Intensity — is a subjective scale of classifying areas of damage patterns that are observed after the earthquake. It is subject to human interpretation, and may be skewed if the effected structures are of unusually good vs. unusually poor construction. It is, however, the best method of assessing the amount of damage caused to structures by any particular earthquake.

MODIFIED MERCALLI EARTHQUAKE INTENSITY **EQ-6**

I. Not felt. Marginal and long-period effects of large earthquakes.

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

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

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

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

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

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

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B.; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved of foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in the flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

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

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

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

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

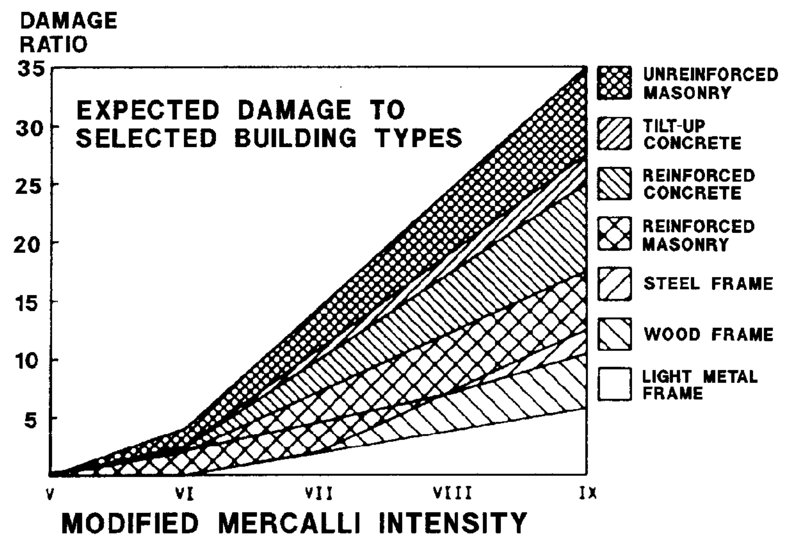
Masonry A — good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.
Masonry B — good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.
Masonry C — ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.
Masonry D — weak materials, such a adobe; poor mortar; low standards of workmanship; weak horizontally.

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

EARTHQUAKE MAGNITUDE AND INTENSITY

Richter Magnitude — is a quantitative measurement using a specific type of measuring device. Either P or R (Rayleigh) waves are measured with adjustment for 100 km. distance from the source, and different measuring stations may produce different magnitudes. Magnitude may be based on greatest P wave or greatest R wave of 20 second period swing of Woods/Anderson Seismometer. If an earthquake has a very deep focus, one cannot find the R wave record. Richter Magnitude usually gives a good method for quantifying length of fault rupture, duration of shaking, and total energy release. There is often little correlation between local peak accelerations and damage patterns.

MAGNITUDE AND INTENSITY **EQ-7**



RICHTER MAGNITUDE

- QUANTITATIVE MEASURE OF MAXIMUM INTENSITY (EFFECTIVE PEAK ACCELERATION) & TOTAL ENERGY RELEASE - APPROXIMATE
- MEASURES MAXIMUM AMPLITUDE RECORDED ON STANDARD WOOD-ANDERSON TORSION SEISMOMETER
- LOGARITHM OF THIS AMPLITUDE IS USED AND IS CORRECTED FOR THE STANDARD DISTANCE OF 100 KM FROM EPICENTER
- A CHANGE IN RICHTER MAG. OF ONE REPRESENTS A CHANGE OF TEN TIMES IN THE AMPLITUDE BEING MEASURED
- RICHTER MAG. CAN VARY FROM ZERO TO MORE THAN 9
- A CHANGE IN RICHTER MAG. OF ONE REPRESENTS A CHANGE OF THIRTY TIMES IN THE TOTAL ENERGY RELEASED BY AN EARTHQUAKE
- ENERGY RELEASED BY RICHTER MAG. 8 WOULD BE ABOUT 1000 TIMES AS MUCH AS A RICHTER MAG. 6

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

ATTENUATION

- As waves spread out geometrically from a source the effected area is greatly increased and energy concentration diminished.

- Attenuation is caused by the viscous properties of rocks and soils, scattering of energy, irregularities, and discontinuities in surface materials. As mentioned, S waves diminish rapidly as the rigidity of the material that they pass through falls.

- Dispersion by geologic structure occurs particularly at distances over 50 km which can also cause a lengthening of duration of shaking.

- Shorter period body waves (especially S waves) attenuate much faster than longer period surface waves. Therefore, there are often special effects in the far field (50 km+ from fault) that cause damage to longer period (taller) structures, while adjacent shorter structures may be undamaged.

- It should be noted that, due to its more uniform geology, the area east of the Rocky Mountains is expected to exhibit much less attenuation of earthquake waves than areas of the western U.S. This would mean that if a strong earthquake does occur within the New Madrid Seismic Zone, the area of significant damage could be very large.

AMPLIFICATION

- Amplification can be described as the focusing of high intensity shaking in small, limited areas. This occur near the fault (near field), but the more devastating examples have occurred in the far field. In mountainous regions, areas of higher intensity shaking have occurred at hill tops, but the more common examples of amplification have occurred in adjacent valleys where bedrock is overlain with soft, often wet, alluvial soils.

- Amplification in alluvial soils can occur when the predominate frequency of the shaking is similar to the natural frequency of the alluvium (determined by depth/density, etc.). The shaking that originates in bedrock below the alluvium can be intensified as much as tenfold, with devastating results to buildings and other structures that have similar harmonic properties.

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

AFTERSHOCKS

They can cause the very significant re-shaking of damaged structures which makes earthquake induced disasters more hazardous to US&R than most others.

It is very important to understand this potential for additional disaster.

Occur after most earthquakes as the ruptured surface makes smaller adjustments than the one causing the original quake.

Arrays of strong motion instruments can be set out after an earthquake and data from aftershocks will allow the mapping of the fault surface.

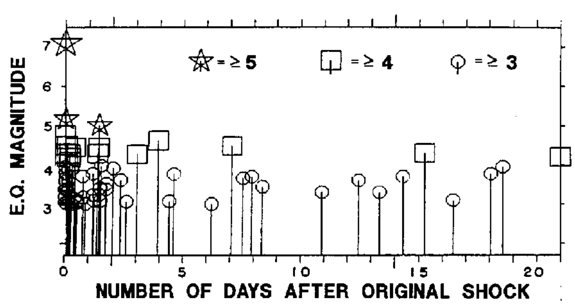
Aftershocks diminish in intensity and number with time. They generally follow a pattern of there being at least one large (within one Richter Magnitude) aftershock, at least ten lesser (within two Richter Magnitude) aftershocks, one hundred within three, and so on.

AFTERSHOCKS **EQ-8**

- ARE SMALLER EARTHQUAKES THAT OCCUR ON THE SAME FAULT AFTER THE ORIGINAL QUAKE. THEY ARE MORE MINOR ADJUSTMENTS ALONG THE SAME AREA OF THE FAULT
- THEY WILL OCCUR AFTER MOST ALL EARTHQUAKES REGARDLESS OF SIZE OF ORIGINAL SHOCK
- AFTERSHOCKS HAVE BEEN ALMOST AS LARGE AS ORIGINAL SHOCK WHEN ORIGINAL WAS IN RANGE OF RICHTER MAG. 6
- U.S.G.S. RULE OF THUMB (MINUS ONE TIMES TEN)

IF ORIGINAL QUAKE IS MAG. 7
THEN EXPECT
1 AFTERSHOCK IN RANGE OF MAG. 6
10 " " " " 5
100 " " " " 4
1000 " " " " 3

AFTERSHOCKS CAN BE OF GREAT DANGER TO U.S.&R. WORKERS. THEY HAVE CAUSED PREVIOUSLY DAMAGED BUILDINGS TO COLLAPSE AND RESCUE TUNNELS/BRACING TO CAVE IN. THEY ARE WHAT MAKE EARTHQUAKE DISASTERS THE MOST DANGEROUS TO DEAL WITH.



DISTRIBUTION OF AFTERSHOCKS AFTER LOMA PRIETA E.Q.

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

AFTERSHOCKS (continued)

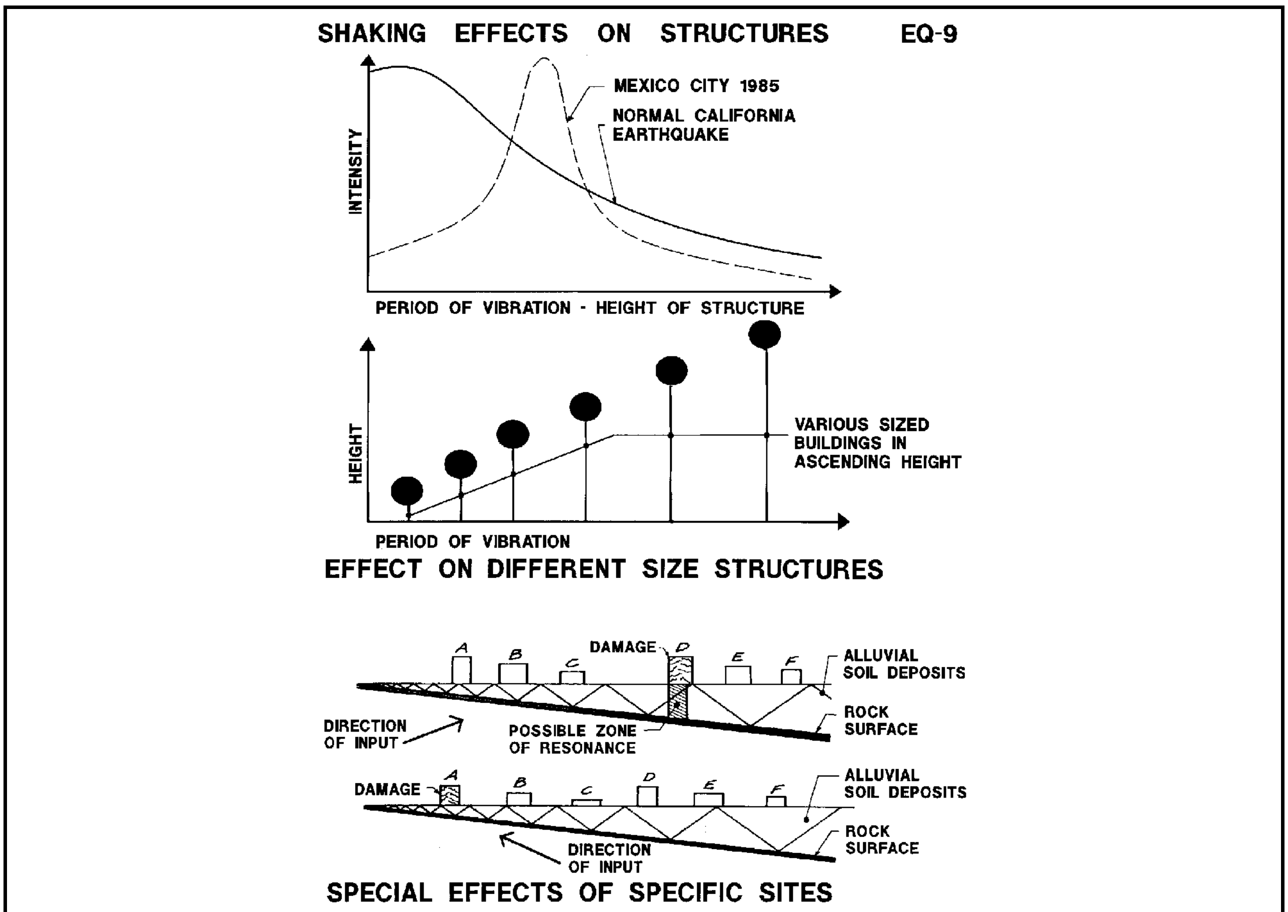
A number of moderate quakes (6+ magnitude) have had aftershocks that were very similar in size to the original quake.

The Loma Prieta earthquake had many aftershocks, but the largest was only magnitude 5.0 with the original quake being magnitude 7.1 or so.

Wood, masonry, and concrete structures have collapsed during aftershocks, (even during a Loma Prieta relative moderate 5.0 aftershock).

EARTHQUAKE EFFECTS ON STRUCTURES

Every structure has a fundamental period of vibration. The period for a one-story structure may be 0.1 second or less (10 Hz) and that for a ten-story building will be in the range of 1 second (1 Hz). A structures fundamental period will normally decay (become longer) as the structure suffers damage. This usually, but not always, helps a structure survive a quake.



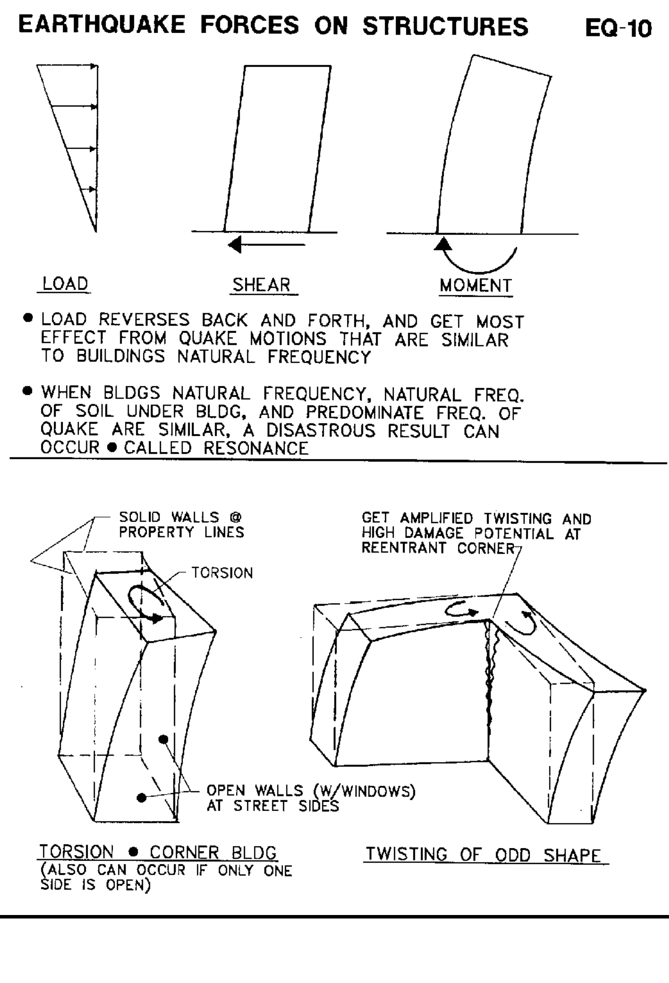
II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

EARTHQUAKE EFFECTS ON STRUCTURES (continued)

Earthquake motion is usually initially rich in frequencies that are similar to those of structures (.5 to 10 Hz) and, therefore, it can excite and damage structures. The interaction of effects is expressed as a spectrum. In the near field, where most frequencies are present in the shaking, the most intense effects are felt by shorter, stiffer structures.

In near field, the strong shaking that is felt by structures will have significant vertical as well as horizontal effects. Since a building's vertical load systems are designed for more than gravity loading the additional quake vertical load is normally not critical. The horizontal shaking subjects structures to shear and overturning forces that may require construction with a tough, consistent, lateral load-resisting system.

Duration, frequency content, and effective peak acceleration can determine overall effect on the entire family of structures near the fault, but often local damage pattern is not related to magnitude and peak acceleration.



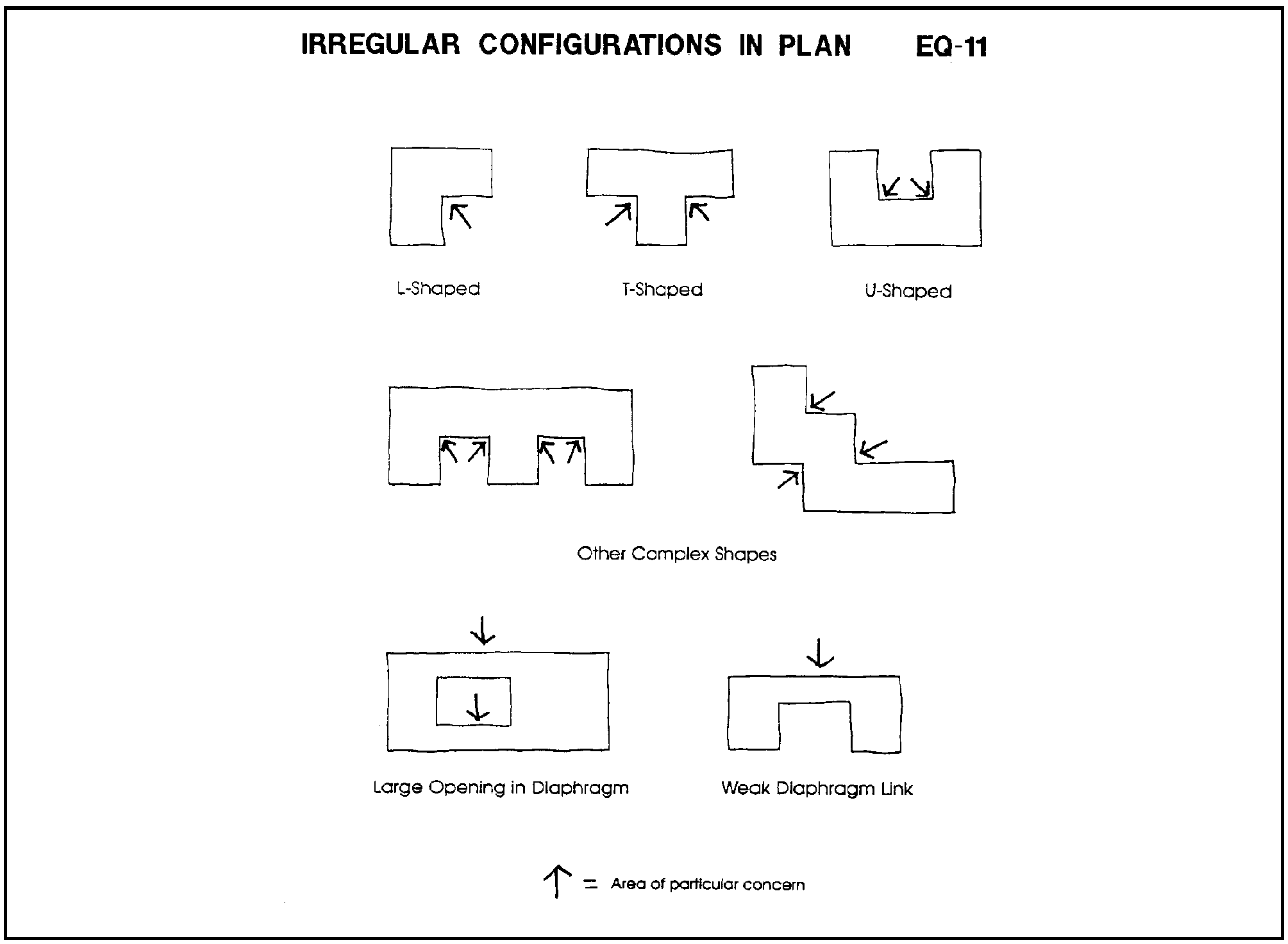
II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

EARTHQUAKE EFFECTS ON STRUCTURES (continued)

In the far field, special effects can occur that will cause severe damage to taller (longer period) structures, since these frequencies are not attenuated as greatly as the shorter ones. When the harmonics of a site couple with the structure founded on it and the quake shaking, a very devastating resonance can occur, which greatly amplifies the response. The collapse of 10- and 20-story buildings in Caracas in 1967, and 8- to 12-story buildings in Mexico City in 1985 are unfortunate examples of this effect. Softer, alluvial soils normally cause special problems for structures built on them.

There can be amplification or de-amplification effects as the depth of the alluvial material changes. Moderate quakes often exhibit greater amplification effects, since the lower intensity motion allows the soils to behave in a more linear fashion than the more non-linear behavior caused by great earthquakes.

Structures that have discontinuities in plan or in elevation will normally perform more poorly, since the damage will tend to be focused at the discontinuity.



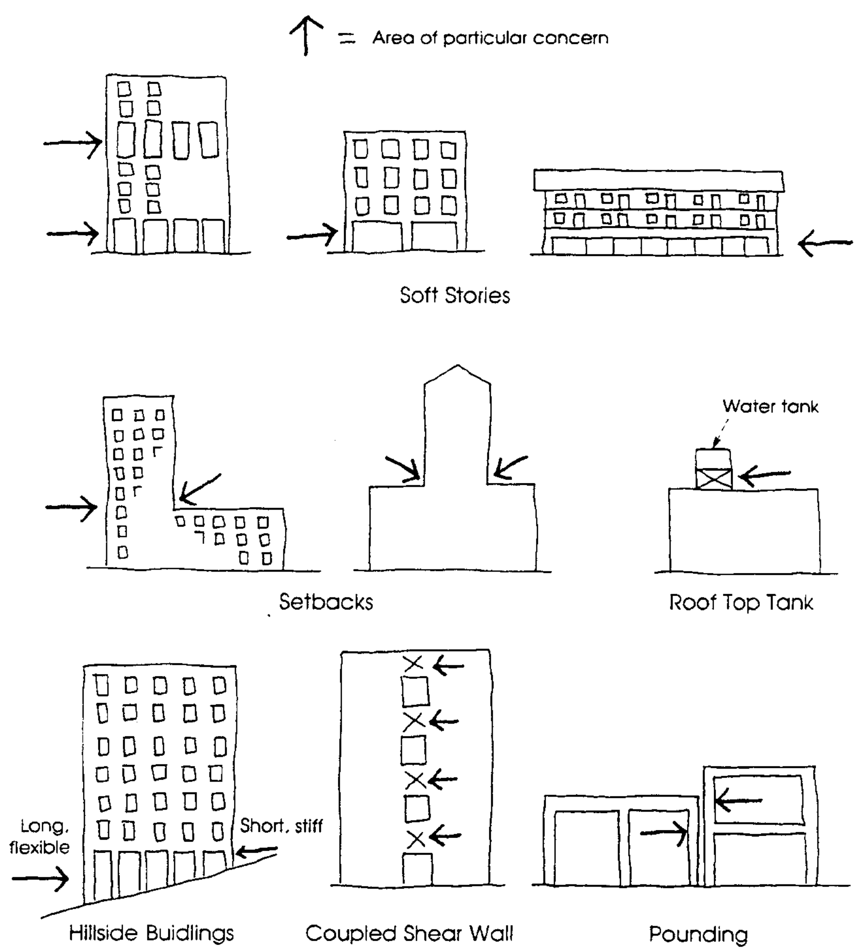
II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

<u>EARTHQUAKE EFFECTS ON STRUCTURES</u> (continued)

When rows of buildings are placed close together they can pound together near the top. If the floors of adjacent buildings align, the effect of the pounding may be only crushing, but if the hard edge of the floor of one building strikes the middle of a supporting column in another building, the column may collapse and cause significant damage. In some cases, pounding has been credited with stopping the destructive resonance type shaking of a structure. In other cases, pounding has been blamed for increasing damage to corner buildings.

When softer, frame type buildings that have full basements suffer damage or collapse the basements are often undamaged, and therefore, provide a good access for search and rescue.

VERTICAL DISCONTINUITIES & IRREGULARITIES EQ-11a

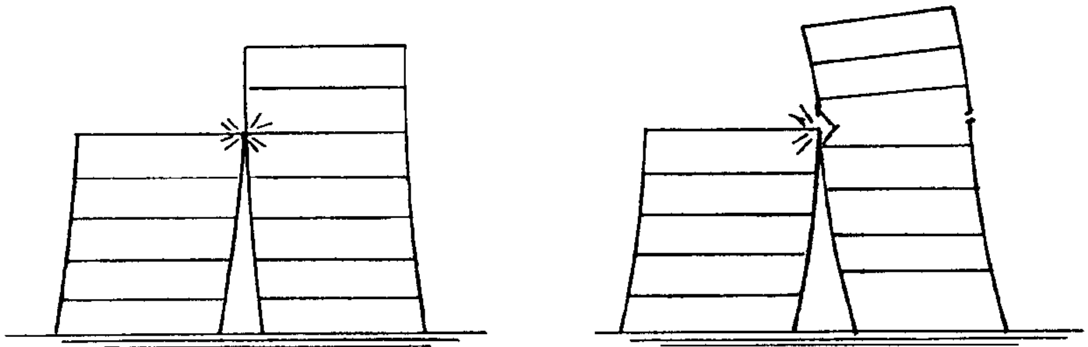


II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

EARTHQUAKE EFFECTS ON STRUCTURES (continued)

QUAKE EFFECTS ON BUILDINGS EQ-12

- **POUNDING OF ADJACENT BUILDINGS**



BUILDINGS W/ FLOORS ALIGNED

CAN HAVE SIGNIFICANT DAMAGE BUT MOSTLY LOCAL CRUSHING AT FLOOR LINE

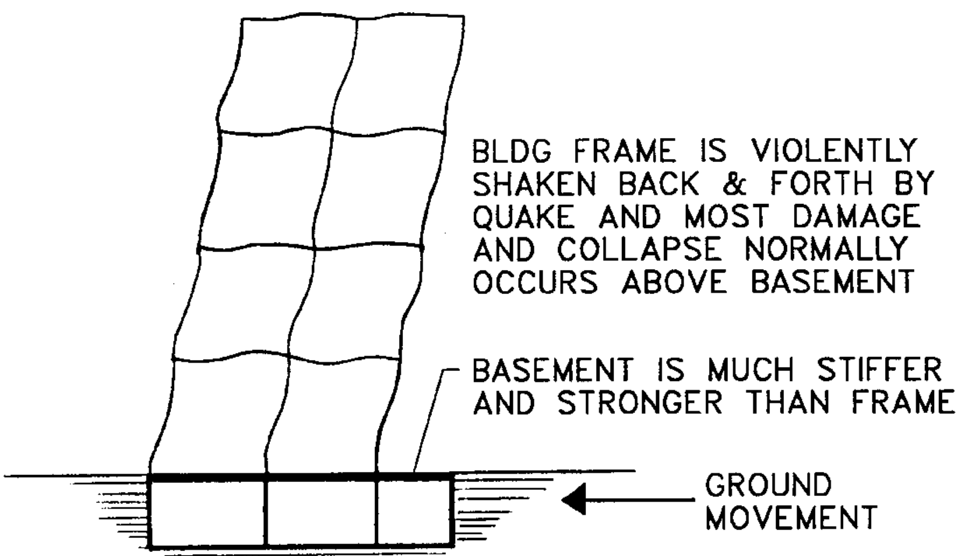
CAN ACTUALLY BE BENEFICIAL IN DAMPING OUT LARGE OSCILLATIONS THAT COULD CAUSE GREATER DAMAGE

W/ FLOORS NOT ALIGNED

FLOOR OF ONE BUILDING CAN HIT AND SEVERLY DAMAGE COLUMN OF OTHER

UPPER PART OF DAMAGED BLDG CAN COLLAPSE AND EVEN FALL ON TOP OF BLDG THAT HIT IT

- **FRAME BUILDINGS WITH BASEMENTS**



BUILDING WITH BASEMENT

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

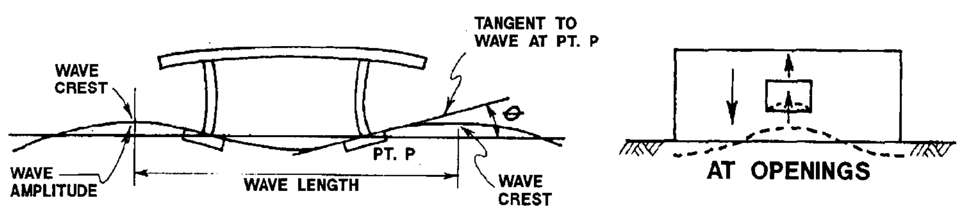
<u>EARTHQUAKE EFFECTS ON STRUCTURES</u> (continued)

Traveling surface waves have been observed during many earthquakes. This phenomenon can cause especially devastating effects to large stiff structures such as highway bridges and brittle walls of buildings. A wave of this type probably resulted in the unusual movement of the slab on ground joints during the Loma Prieta quake.

Severe structural damage can be caused by moderate (magnitude 6.5 +/-) earthquakes when the rupturing fault is located near or within an urban area, or by great earthquakes (magnitude 8+) since its potential damage pattern is spread over a very large area.

The most consistent observation is that individual earthquakes are different, contain complex shaking that is modified by geologic effects, and often produce some surprises.

TRAVELING SURFACE WAVES **EQ-13**



ROTATION OF FOUNDATION **VERTICAL SHEAR FORCE**

1. Chimbote, Peru, earthquake, 1970: A Marionist Brother said he saw wave lengths with crests 12 ft. apart and a depth of about 12 in.
2. El Centro, California, earthquake, 1979: A Hertz automobile employee said waves could be seen going down the street.
3. Coalinga, California, earthquake, 1983: In a softball game, the centerfielder said home plate disappeared behind the pitcher's mound.
4. Long Beach, California, earthquake, 1933: Mr. Gordon Oakeshott, a geologist, stated, "We had proof that wave lengths were on the order of 30 feet."
5. Anchorage, Alaska, earthquake, 1964: An airport guard commented that waves must have been at least 2 feet deep.
6. Central Greece earthquakes, Feb. and Mar. 1981: Technical observers stated, "Individual rows of soil that had been plowed parallel to the fracture were seen to heave and roll, so that the entire plowed surface appeared to be in disharmonic motion. Also, small cracks were observed opening parallel to the plowed furrows. The ground shaking lasted 4 to 5 seconds. . . . (This occurred in an aftershock.)
7. In a report by Professor A. J. Schiff on the Morgan Hill, California, earthquake, he quotes an observer at the Los Banos Transmission Substation: "An operator inside the building who had not felt the first motion looked up and out of the front door, which faces north, to see what appeared to be approaching waves. The station floor followed the wave motion which was estimated to be between 3 inches to 6 inches crest to trough. There was no estimate for the wave length."
8. Surface waves were reported seen in the Mexico City 1985.

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

DESTRUCTIVE WINDSTORMS

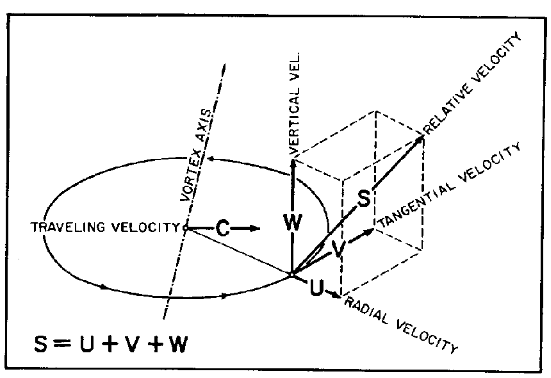
Hurricanes are large circular systems that are created by low pressure centers over the ocean near the equator. They may be hundreds of miles in diameter, and have winds in excess of 150 mph. Typhoons and cyclones are the same type of storms, but occur in the Orient and Indian Ocean respectively. The storm center rarely moves faster than 50 mph, and most destruction is caused to coastal areas.

Tornado Cyclones, Tornadoes, and Suction Vortices are all related rotating, violent windstorms that originate over land, usually created by the colliding air masses of severe thunderstorms. Tornadoes are found in all parts of the world, and the U.S. is the country most frequently plagued by them. Larger tornadoes may be 1 mile in diameter, containing several suction vortices, and have maximum wind speeds of 300 mph.

WIND RELATIVE VELOCITY **W-1**

STORM TYPE	• TANGENTIAL WIND	• STORM CENTER SPEED
HURRICANE	100MPH +	50MPH -
TORNADO CY	50MPH -	60MPH ±
TORNADO	100MPH +	50MPH ±
S VORTEX	100MPH +	100MPH + (WITH STRONG VERT COMPONENT)

- STORM OR VORTEX CENTER MAY MOVE MORE OR LESS IN STRAIGHT LINE
- MAXIMUM RELATIVE WIND SPEED COULD BE AS HIGH AS 300MPH
- OBJECTS AS LARGE AS LOCOMOTIVES, HOPPER CARS, ETC HAVE MOVED



Breakdown of S, the relative velocity into its three components: U, the radial velocity; V, the tangential velocity; and W, the vertical velocity. If the tilt angle of the vortex axis changes with time, the traveling velocity of the vortex center varies with height.

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

<u>HURRICANES</u>

Most hurricanes occur within a three-month period each year.

In the Northern Hemisphere they rotate counter-clockwise (clockwise in the Southern Hemisphere).

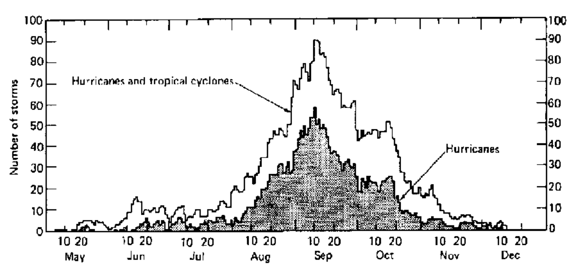
In addition to producing destructive winds, there is also an elevating of the ocean surface that can produce great damage when it sweeps into the land at the coast. Along the eastern coast this tidal surge always occurs to the north of the storm center, caused by the counter-clockwise winds.

The Saffir/Simpson Scale is used to classify hurricanes. Maximum wind speeds rarely exceed 150 mph. Damage potential is related to wind speed, since higher winds produce greater direct pressures as well as higher tidal surge. Hurricanes may travel over a thousand miles and last as long as 10 days.

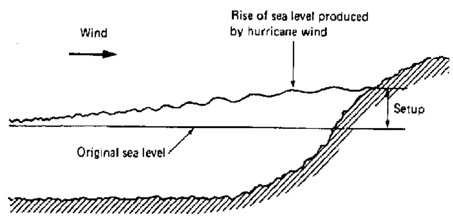
HURRICANES **W-2**

HURRICANES - TYPHOON - CYCLONE

N. HEMISPHERE - COUNTERCLOCKWISE
S. HEMISPHERE - CLOCKWISE



Monthly variation of hurricanes and tropical cyclones of the north Atlantic Ocean. (From Neumann et al. 1981).



Waves and tides generated by hurricane wind.

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

HURRICANES (continued)

Hurricanes produce a great number of missiles from the size of splinters to larger pieces of wood. The missiles normally do not cause significant structural damage, but blown down trees, utility poles etc., can cause great disruption to roadways and communications.

The heavy rains can lead to flooding of low lying areas which causes significant damage.

Loss of life is normally limited, since there is normally plenty of warning and large storms are usually easy to track.

HURRICANE INTENSITY SCALE W-3

Classification of Hurricanes by Saffir/Simpson Scale

Saffir/Simpson Number	Wind Speed (mph)	Possible Tidal Surge (feet above sea level)	Damage Potential
1	74–95	4–5	Minimal
2	96–110	6–8	Moderate
3	111–130	9–12	Extensive
4	131–155	13–18	Extreme
5	156 and above	19 and above	Catastrophic

Note:
1. The wind speed referred to in the Saffir-Simpson scale is the "sustained speed" at 10-m height. The U.S. National Weather Service uses 1-minute average to determine the "sustained wind speed."
2. The damage to houses are for those in hurricane regions which normally follow more stringent construction practices than in the nonhurricane regions.

Scale no. 1. Damage primarily to shrubbery, trees, foliage, unanchored mobile homes, and so on.

Scale no. 2. Major damage to exposed mobile homes. Extensive damage to poorly constructed signs. Some damage to roofing materials, windows, and doors.

Scale no. 3. Large trees blown down, some structural damage to small homes, and so on.

Scale no. 4. All signs blown down, extensive damage to roofing materials, windows and doors, complete failure of roofs on many houses, complete destruction of mobile homes, and so on.

Scale no. 5. Complete failure of roofs on many industrial buildings, small buildings overturned or blown away, and so on.

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

HURRICANES (continued)

Just as for earthquakes, individual hurricanes of the same category, based on maximum wind speed, may have far different effects (W-4). Hurricane Hugo has a larger area of destructive winds, much higher tidal surge and greater rainfall than Andrew. Hugo however, produced much less damage to structures since it did not pass over a heavily populated area like South Miami.

W-4

SAME CATEGORY HURRICANES CAN BE VERY DIFFERENT

	HUGO	ANDREW
Category	4	4
Sustained Winds	135 mph	143 mph
Gusts	160 mph	175 mph
Hurricane Winds (extended from eye)	140 miles	45 miles
Tidal Surge	10 to 20 feet	5 to 8 feet
Rainfall	5 to 10 inches	2 to 5 inches

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

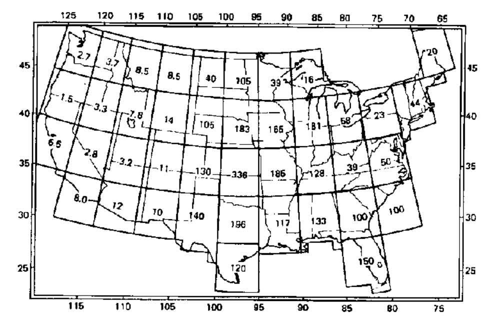
TORNADOES

The probability of a tornado reoccurring at a specific site each year is as high as one-third of a percent in Oklahoma and adjacent states. This is the area of greatest probability in the U.S. Most tornadoes occur in March through June in the U.S.

Most but not all tornadoes rotate counter-clockwise in the U.S., and the larger tornadoes can have several suction vortices that rotate and twist around within it. The tornado-cyclone is normally a circulation that is embedded within a severe thunderstorm that can lead to the formation of a large tornado.

The Fujita Scale is used to classify tornadoes. Total wind speed seldom exceeds 300 mph and 88 percent of tornadoes are classified as F-2 or less.

TORNADO PROBABILITY & INTENSITY W-5



TORNADO STRIKE PROBABLY x 10^{-6} PER YR

Classification of Tornadoes by Fujita Scale

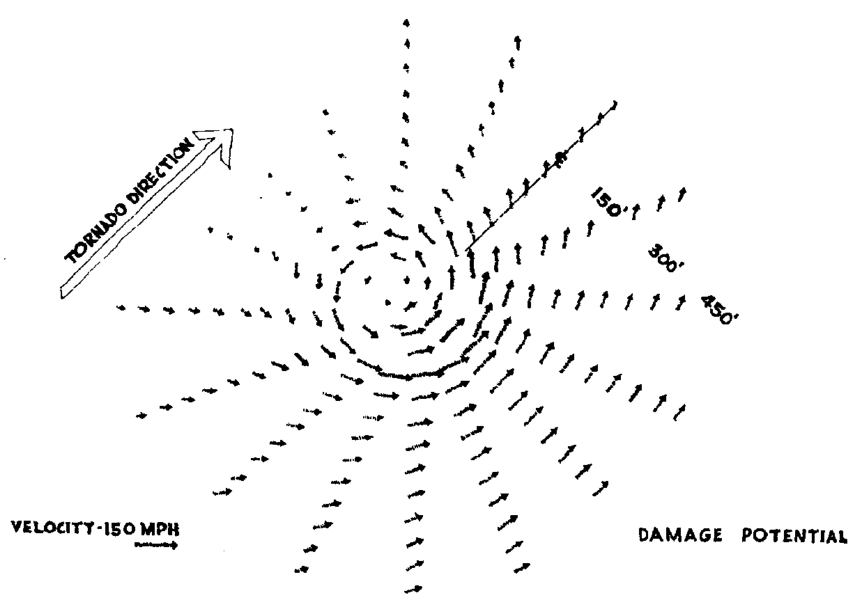
Wind Speed	Damage Potential	Effect Observed
F-0 (40–72 mph)	Light	Some damage to chimneys; branches broken off trees; shallow-rooted trees pushed over; sign boards damaged.
F-1 (73–112 mph)	Moderate	Peel surface off roofs; mobile homes pushed off foundations or overturned; moving autos pushed off roads.
F-2 (113–157 mph)	Considerable	Roof torn off from houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted, light-object missiles.
F-3 (158–206 mph)	Severe	Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forests uprooted; heavy cars lifted off ground and thrown.
F-4 (207–260 mph)	Devastating	Well constructed houses leveled; structures with weak foundations blown off some distance, cars thrown and large missiles generated.
F-5 (261–318 mph)	Incredible	Strong frame houses lifted off foundations and carried considerable distance to disintegrate; automobile-sized missiles fly through air in excess of 100 m; trees debarked; incredible phenomena will occur.
F-6 to F-12 (319 mph–sonic velocity)	Currently believed nonexistent.	

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

TORNADOES (continued)

Most tornadoes in the U.S. approach from the southwest at about 50 mph and do not last longer than 30 minutes. The largest known tornadoes had a path of over 300 miles and a life span of over three hours. South walls of buildings are most susceptible to damage, followed by west and east walls.

TORNADO DAMAGE POTENTIAL **W-6**



150MPH REL V V - 110MPH + C - 40MPH
(85% OF U.S. TORNADOES HAVE LOWER REL V)

DAMAGE POTENTIAL FOR U.S. IS MOST ON SOUTH FACE WALLS, SECOND MOST ON WEST WALLS, THIRD ON EAST FACING WALLS AND NOT MUCH ON NORTH WALLS. THIS IS BECAUSE MOST (NOT ALL) TORNADOES APPROACH FROM THE SOUTH-WEST.

FUJITA CLASSIFICATION & TORNADO OCCURRENCE

FUJITA CLASSIFICATION	MAXIMUM WIND SPEED (MPH)	PERCENT OF OBSERVED TORNADOES IN CLASSIFICATION	MEAN ANNUAL FREQUENCY OCCURENCE IN SUBJECT AREA
F0	40 - 72	19.9	0.995
F1	73 - 112	44.0	2.200
F2	113 - 157	26.6	1.330
F3	158 - 206	7.2	0.360
F4	207 - 260	2.1	0.105
F5	261 - 318	0.2	0.010

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

TORNADOES (continued)

Tornadoes, due to their very swift winds with significant vertical components are associated with lifting very large objects and creating large missiles. Significant damage can be done by the winds as well as the missiles.

Tornado warnings can only be given for the general areas where they can occur, but since they normally effect only a relatively small area the loss of life is usually kept to a low number for any individual storm.

W-7

WINDSTORM MISSILES

MAXIMUM WEIGHT MOVED:

92K switching locomotive pushed 150 feet along track with brakes on.

50K Wabash locomotive lifted and thrown on back at foot of a 15 foot-high embankment without damage to track or embankment.

26K fertilizer tank moved 3600 feet.

62K hopper cars carried 170 feet and overturned.

16"-diameter oak tree with roots carried 200 feet.

MOST COMMON MISSILES PENETRATE STRUCTURE

Wood pieces varying in size from splinters to large glued, laminated timbers — also entire roof sections.

Roofing materials — tile, shingles, gravel, metal panels, etc.

Barrel, trash containers, outdoor furniture.

Rooftop equipment.

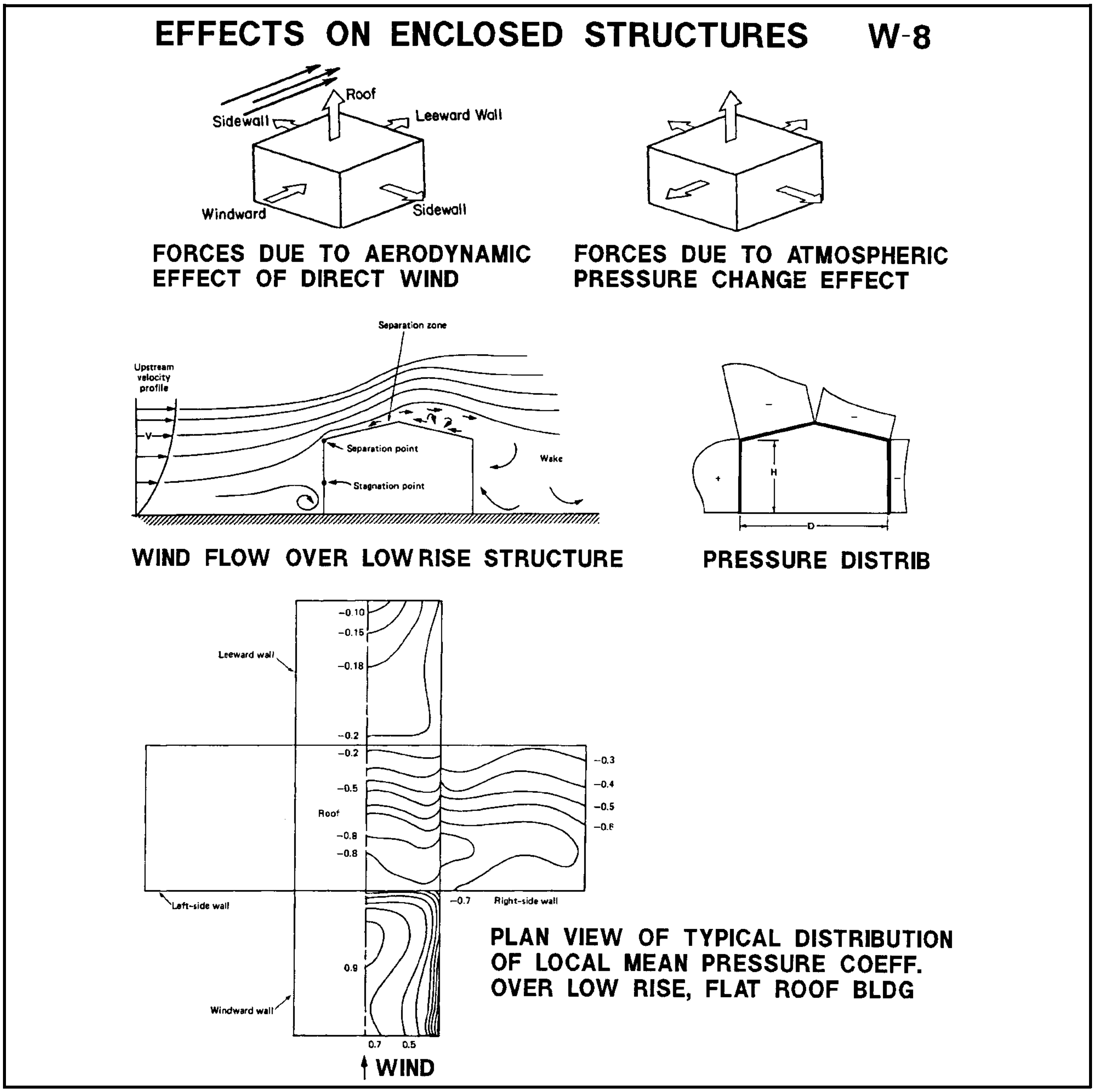
Round objects such as pipes, wood poles, etc. usually do not be airborne.

Vehicles tend to roll and tumble, move only a short distance.

II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

WIND STORM EFFECTS ON STRUCTURES

Forces on structures are due to the direct aerodynamic effect of winds as well as the effects of changes in atmospheric pressures. The direct wind pressure is related to the velocity squared, and the reduction in atmospheric pressure can cause additional suction forces on building surfaces. The effects of atmospheric pressure drop are rarely as significant as those of wind velocity and missile penetration.



II. STRUCTURAL ENGINEERING SYSTEMS
G. CAUSES OF COLLAPSE

WIND STORM EFFECTS ON STRUCTURES (continued)

Wind velocity varies with height. It is near zero at the ground surface and reaches maximum within about 100 feet of the ground depending on surface roughness. Velocity causes inward pressures on windward walls and outward pressures on roof, side walls, and leeward walls. Pressures tend to peak at roof edges and wall corners, and if the roof has overhanging eaves or rake, large uplift pressures can be generated.

Windows and doors can be left open to reduce atmospheric pressure change effects, but if the opening turns out to be on the windward side of the structure, the wind can enter and cause a more devastating ballooning effect.

The most common structural problems caused by severe winds include:
! Lifted roofs of light weight materials
! Fallen chimneys.
! Ballooned roofs and walls.
! Peeled wall veneers and finishes.
! Blown in walls, and door frames.

Common missiles include:
! Roofing gravel,other roofing material, and glass.
! Light weight roof and wall panels.
! Wood pieces from splinters to large roof timbers and sections of roofs.
! Barrels, trash containers, out door furniture roof top equipment.

The largest building damaged by a tornado was the 20-story Great Plains Life Building, in Lubbock, TX, in 1970. This steel frame building 56' x 120 'x 226' high had its top story permanently offset by 12 inches, many windows broken, and many racked door frames. Also 30,000- to 100,00-gallon water storage structures have been collapsed by tornadoes.

Severe winds have caused special dynamic problems to special structures such as bridges and tall stacks due to vortex shedding and fatigue. Fatigue has also caused failure in the connections of light weight roof panels. (This can be easily overcome by using neoprene washers.)