MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 1. BUILDING MATERIALS & STRUCTURAL SYSTEMS

In this introductory section our **Objectives** are as listed in the adjacent slides. We will quickly review the basics of how various building materials resist forces, the importance of Ductile vs. Brittle behavior, the concepts of Vertical and Lateral Load Resisting Systems, and Structural Redundancy.

TERMINAL OBJECTIVES

- The Student shall understand the essential materials and components of structures, and how they behave when subjected to normal and extreme loading

ENABLING OBJECTIVES

- Understand the Tension, Compression, Bending, and Shear Forces that are exerted on building materials, and how they behave.
- Understand the concepts of Ductile and Brittle behavior.
- Introduce the concept of Vertical Load Path and Vertical Load Resisting Systems

ENABLING OBJECTIVES

- Discuss Lateral Load Resisting Systems, including Box, Moment Frame, and Diagonally Braced Frame Systems
- Define and discuss Structural Redundancy

FORCE TYPES

Individual LOADS, usually referred to as FORCES can be divided into four types: **Tension. Compression, Bending, and Shear.**

- When a FORCE is applied to an individual member, it produces STRESSES, which are defined as the FORCE divided by the cross-sectional area on which it acts.
- **Example:** If a 1000lb FORCE acting in Tension on a 2 inch x 2 inch steel bar, will produces a 250 lbs per square inch (psi) Tension STRESS.
- For simplicity we will we will discuss the effects of FORCES, and assume that the student understands the relationship between FORCES and STRESSES

TENSION FORCES stretch members of steel or wood. Concrete and masonry have no reliable tension strength.

- When a moderate tension force is applied a steel bar will lengthen, and when the force is removed, the bar will return to its original length. This is called ELASTIC Behavior and can be repeated many times in competent steel or wood members.
- If a much larger force is applied to the steel bar it will start to lengthen more rapidly. When this rapid lengthening begins, one can observe that the cross-section of the bar will start to get smaller (neck down). When the force is removed, the bar will not return to it's original length, since it has experienced permanent yielding (DUCTILE Behavior)
- The DUCTILE behavior of steel in tension provides the special property of forgiveness (warning of failure) and response which makes it especially desirable in resisting dynamic loading.

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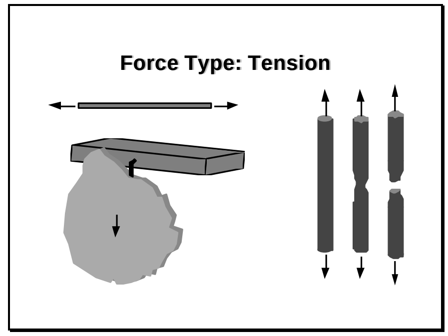
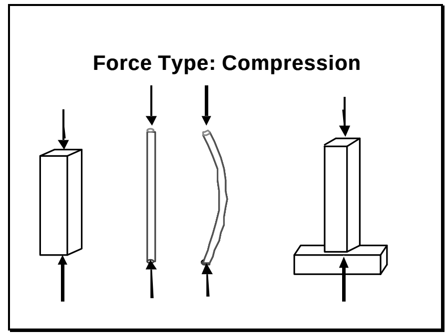
TENSION FORCES (continued)



- **Ductile** behavior is the ability of a material to stretch and/or bend without suddenly breaking, and after the load is removed it can remain stretched/bent and then be re-loaded.
- **EXAMPLE**: one can bend a hook on a rebar, and even unbend it without breaking

- **Brittle** behavior means that the material will break without warning (Catastrophic Failure)

COMPRESSION FORCES



- These forces push on members and can lead to crushing of materials when the members are short and relatively fat. (small length to width ratios, L/D)

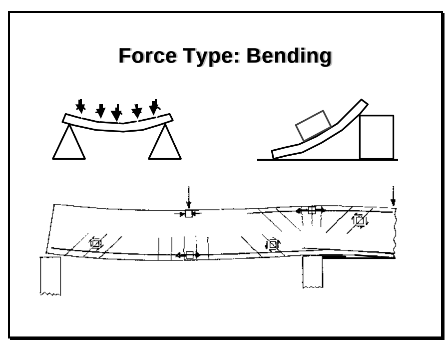
- At bearing surfaces between wood or concrete beams and columns, crushing can also occur.

  - The crushing failures tend to give warning, such as local splitting of concrete and noisy, slow, compression of wood fibers

- When long, slender members are loaded in compression, they can fail suddenly by BUCKLING (bowing)

  - This type of sudden failure wants to be avoided

BENDING FORCES



- These occur mostly as a result of Vertical Loads from gravity are applied to floor slabs and beams. They also occur in sloped roof rafters and sloped slabs in rubble piles.

- Bending causes the bottoms of simple beams to become stretched in TENSION and the tops of beams to be pushed together in COMPRESSION.

- Continuous beams and cantilever beams have tension forces at the top + compression at the bottom near their supports. In mid span the forces are in the same locations as for simple beams and slabs.

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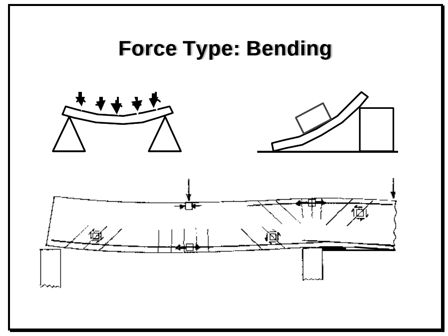
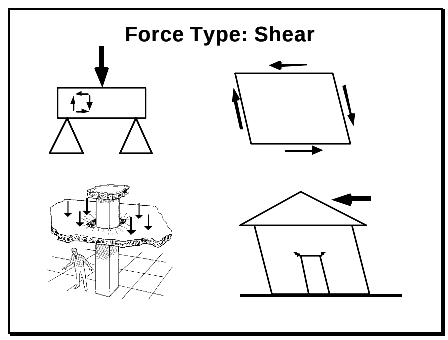
BENDING FORCES (continued)



- Vertical cracks develop near the midspan of concrete, since the Tension Force causes the concrete to crack in order for the Reinforcing Steel (Rebar) to resist the Tension Force.
  - This cracking can be observed in damaged structures to monitor and determine the potential for collapse.
  - Stable, hairline cracks are normal, but widening cracks indicate impending failure
- 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.
- Shear Forces are also produce in beams and slabs, and they will be discussed next.

SHEAR FORCES occur in all beams, and are greatest adjacent to supports



- Shear stress can be described as the tendency to tear the beams surfaces apart.

Example: Consider a beam that is made from a group of individual books as they sit on a bookcase, with a long threaded rod extending all the way through them, tightened with nuts at each end. If this beam is placed so that it spans between 2 tables and one attempts to push one of the books down to the floor below, a SHEAR FORCE will be exerted on the surface of the books immediately adjacent to the one that is being pushed out

- In concrete beams these shear stresses develop diagonal tension cracks, since concrete is very weak in tension.
  - This cracking can also be monitored in a damaged structure
- Wood beams are strong in tension and compression, but are particularly weak in shear along the horizontal plane of the softer spring wood.

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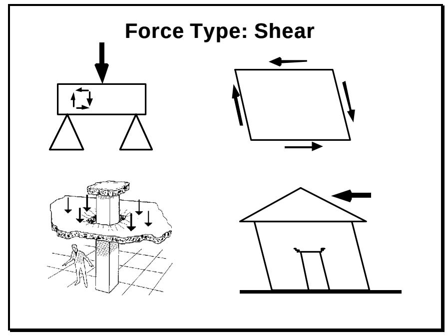

PUNCHING SHEAR occurs where a two-way concrete flat slab is connected to a column and it is the tendency of the slab to drop as a unit around the column.

- 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.

BOLT SHEAR is the tendency of steel pin-like connector (bolt, nail, and screw) to break across its cross section.

Example: A roll of coins is Sheared off as each coin slips past the other

- This type of failure can be sudden.
- Nail failures in wood structures, which involve some degree of pullout, can occur with enough deformation to give warning.

BUILDING WALL SHEAR AND OVERTURN FORCES

- Lateral forces (forces applied horizontally to a structure) derived from winds or earthquakes cause shear and bending forces in walls.
- The Shear Forces tend to tear the wall surface, just as if you had a piece of paper attached to a frame and changed the frame's shape from a Rectangle to a Parallelogram.
  - The changing of shape from a Rectangle to a Parallelogram is called RACKING.
  - When Shear Walls are pushed out of plumb in their plane they are said to have been RACKED
- At the ends of Shear Walls there is a tendency for the wall to be Lifted Up at the end where the Lateral Force is applied, and a tendency for the Wall to be Pushed Down at the end away from the force.
  - This action is called OVERTURNING

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Material Properties
Brittle vs Ductile

- **Wood**
- **Steel**
- **Reinforced Concrete**
  - **C.I.P or P.C.**
  - **Rebar or Prestress Cable**
- **Unreinforced Masonry**

MATERIAL PROPERTIES

WOOD

- Is tough, light fibrous, fire supporting, cut from living trees and graded by humans.
- Has defects like knots, splits and non-straight grain that cause stress concentration.
- The growth pattern of fast growing spring wood vs. slower growing summer wood leads to structural problems. These problems include:
  - Weakness in cross grain tension and compression.
  - Weakness in parallel to grain, shear strength
  - Shrinkage and Splitting
- Live wood may be as much as one half water, while older, seasoned wood (as found in a structure) may contain as little as 10% water
  - Its volume can change as much as 10% over this range.
- Shrinkage (usually 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 are best made by bearing one member on it's supporting member, however, metal connection devices can be successfully used
  - Nailed connections perform well as long as splitting is avoided, and bolting may be successful if adequate spacing and edge distances are provided.
- Properly proportioned wood structures can exhibit Ductility
  - When wood posts are kept short and bear on the cross grain surfaces of beams or sole plates, slow crushing of the cross grain can be observed to warn of failure
  - Box Cribbing will exhibit this same failure mode since all the load is transferred in cross grain bearing
- Plywood sheathing of wood structures makes them very tough and earthquake resistant as long as it is nailed properly.

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MATERIAL PROPERTIES (continued)

STEEL

- Is tough, light, strong, ductile, and 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 stressed beyond it's Elastic Limit and severely bent, but still have enough strength to resist failure.
  - This makes it the ideal structural material, in that it gives warning of collapse (has forgiveness).
- Steel is strong in **Tension, Compression, and Shear**
- 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.
  - As will be discussed later, diagonal bracing members can overload columns during earthquakes if the columns are not proportioned such that their strength exceeds the total force that can be delivered to them by the diagonals.
- Steel can be very efficiently connected by bolting or welding (older structures used rivets instead of bolts).
  - Welded joints must be properly designed and constructed or they can lead to a brittle failure.

CONCRETE

- Is essentially cast rock, that is strong in compression but weak in tension and shear.
- Steel bars are cast into concrete to provide for the longitudinal tension force 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.

Material Properties
Brittle vs Ductile

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<u>MATERIAL PROPERTIES</u> (continued)

CONCRETE (continued)

- Concrete can also be reinforced by adding high strength cable or 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 stretched in a form, then bonded to the concrete when it is cast.

- Another method is to place cables that are enclosed in plastic sleeves in the forms at a job site, pour the concrete, and then stretch and Anchor the cables after the concrete has cured and achieved sufficient strength. (**Post-Tensioned**)

  - In this case the cables are not bonded to the concrete, but only anchored at the edges of the structure.

  - These **unbonded** cables can cause difficulties when dealing with a damaged **Post-Tensioned** structure.

- Concrete shrinks, cracks, and creeps under normal circumstances, and this **normal** behavior needs to be differentiated from the cracking and spalling that indicates 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 seismically 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.

Material Properties
Brittle vs Ductile

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MATERIAL PROPERTIES (continued)

UNREINFORCED CONCRETE

- 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. **Very Brittle Material**

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 seismically resistant construction.
- Since masonry properties are similar to concrete, reinforcing steel bars are normally added to provide tension and shear resistance.
  - In reinforced brick masonry, two single brick thick outer layers (wythes) are laid up, then rebar and grout are placed between the layers.
    - The wythes are connected together with large wire to prevent blow-out when the grout is poured.
    - Small heavy wire ladder type reinforcing is used at the joints in some cases.
  - In Concrete Hollow Unit Masonry (CMU), each block comes with preformed cavities.
    - As the units are laid up, horizontal reinforcing (small rebar or large wire) is placed in the joints.
    - After the wall reaches a predetermined height, vertical rebar is placed in specified cells and grout is poured to bond the reinforcing steel to the concrete units.
- Masonry wall construction is highly dependent on workmanship to provide adequate mortar and grout strength.
  - These products are often job mixed in small quantities.
- Adequately reinforced masonry walls can be used in seismically resistant construction if carefully detailed and constructed.
  - They can exhibit very good **ductility** when properly designed and constructed.

Material Properties
Brittle vs Ductile

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MATERIAL PROPERTIES (continued)

UNREINFORCED MASONRY - URM

- Not currently built in seismic risk areas, but many structures with URM walls still exist throughout the world.
  - This is a very **Brittle** material
- 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.
- URM 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.
  - Masonry veneers are also found on the outside surfaces of wood walls.
    - There veneers are subject to the same anchorage problems, as well as being dynamically incompatible with the flexibility of the wood walls.
- URM walls are made from native stone in many places in the world, and have performed very poorly in earthquakes

Material Properties
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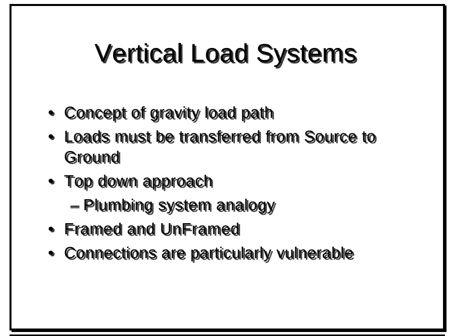
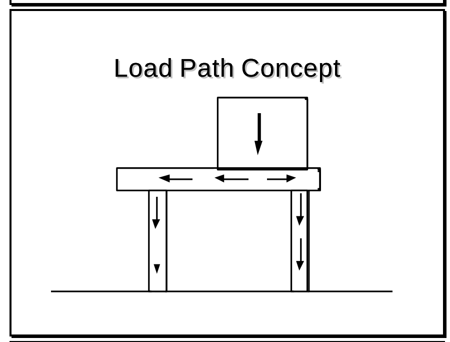
VERTICAL LOAD SYSTEMS

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.

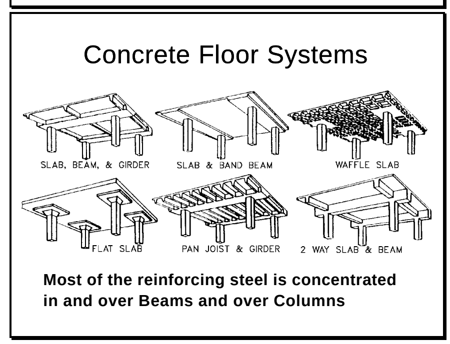


HORIZONTAL MEMBERS support floor and roof planes and are normally loaded in bending such as:

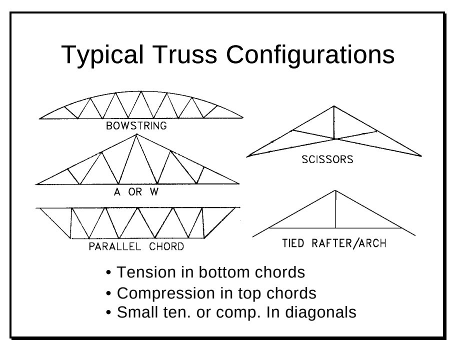
- Wood; rafters, joist, purlins, beams, girders.
- Steel; corrugated sheets (filled with concrete), joist, purlins, beams, girders.



- Reinforced concrete floor systems may be of many types. 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.

- 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, and rain/snow).
- Compression members are normally governed by buckling and tension members are normally governed by their connections.

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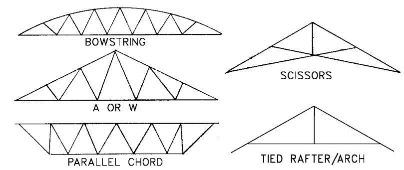
TRUSSES (continued)

- 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.

- 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

- 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.)

Typical Truss Configurations

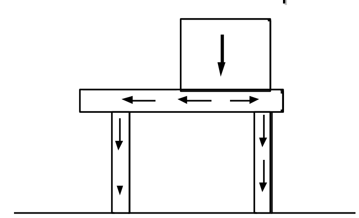


- Tension in bottom chords
- Compression in top chords
- Small ten. or comp. In diagonals

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.
- All vertical load systems need some system to provide for lateral stability (i.e., the proper alignment of vertical load path). These Lateral Load Systems need to be capable of resisting lateral forces that are at least two percent of the structure's weight. (much more in Seismic Zones)

Load Path Concept



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LATERAL LOAD RESISTANT SYSTEMS

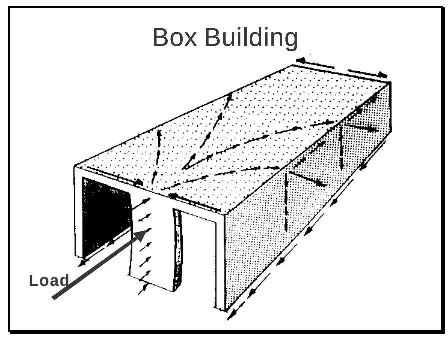
Most structures can be grouped into two basic types of lateral load systems: shear wall/box system and frame system. Buildings may contain sections of each type. Some buildings have been designed with a dual system containing both types of lateral bracing in order to provide a more redundant system,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

Lateral Load Resisting Systems

- Concept of load paths
- Pushover analogy
- Connections are particularly vulnerable
- Systems
  - Box Buildings
  - Moment Frames - (Ductile ?)
  - Diagonally Braced Frames

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 the adjacent slide. Floor/roof planes act like giant beams as stresses in tension and compression are generated at 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.

- 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.

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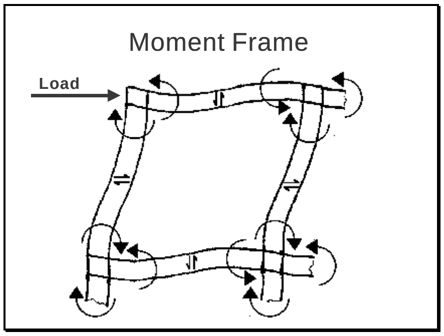
LATERAL LOAD RESISTANT SYSTEMS (continued)

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.
- 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.
- 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.

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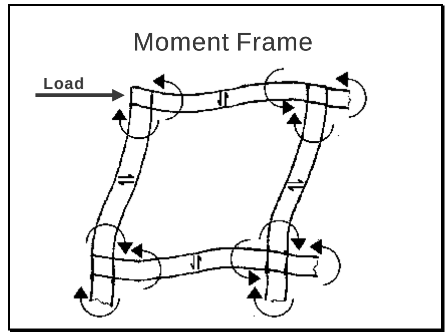
<u>LATERAL LOAD RESISTANT SYSTEMS</u> (continued)

FRAME BUILDINGS MOMENT RESISTANT (continued)

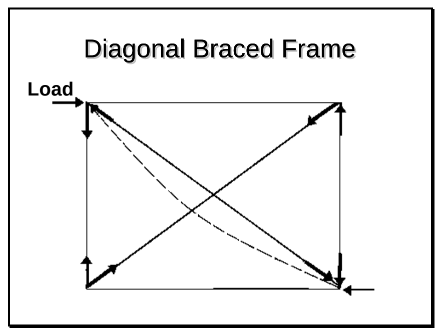
- Modern building codes require that the columns be stronger than the sum of the connecting beams at any story, in order that when inelastic action occurs it will form plastic hinges in the beams, not the columns. Since modern steel moment frames are connected by welding, good workmanship is critical. 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.

- Older, pre-1960, steel moment frames may be covered with cast-in-place concrete fireproofing. (Important identification info.)

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.

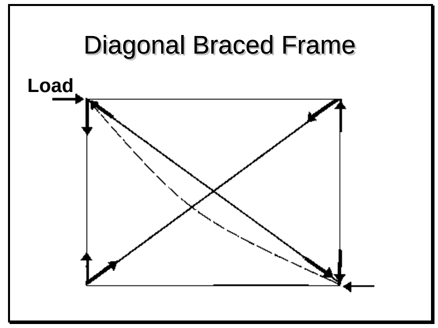
- The columns in diagonally braced frames need to be proportioned so that they are stronger than the tension capacity of the braces that are connected to them. This is in order to assure that failure will not occur in the columns, and has only been required in recent building codes.

- 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.

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 1. BUILDING MATERIALS & STRUCTURAL SYSTEMS

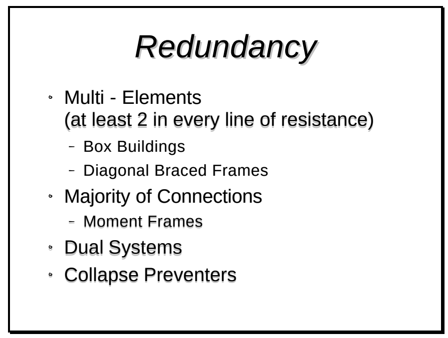
<u>LATERAL LOAD RESISTANT SYSTEMS</u> (continued)

FRAME BUILDINGS DIAGONALLY BRACED (continued)



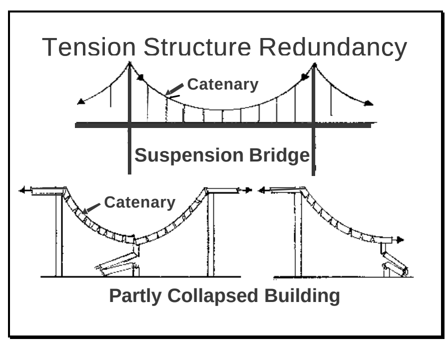
- Diagonal braced frames have been used in combination with moment resistant frames to provide a highly desirable, dual system. They also are configured as eccentric braces within a moment frame bay to provide a bracing system that combines the toughness of moment frame with the rigidity of braced frame.

REDUNDANCY



- Especially in Seismic Zones, it is important for the Lateral Load System to possess some degree of Redundancy.
- Redundancy in a structure means that there is more than one path of resistance for Lateral Forces.
- This can be achieved by having more than one Shearwall Panel or more than one Diagonal Brace in every line of resistance, or
- This can be achieved by having a Moment Resistant Frame with many columns and beams, all with ductile connections, or
- This can be achieved by having a Dual System, like Shearwalls plus a Moment Resistant Frame

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. (as shown in adjacent slide) 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.

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

The Objectives for this section are listed in adjacent slides, and we will discuss the folowing:

- The types of forces that load structures
- The method that is used to classify structures, and the types of problems that buildings have experienced in the past.
- The Collapse Patterns that have occurred that will give us some insight as to how structures will behave in the future.

EARTHQUAKE BASICS
Earthquakes are catastrophic events that occur mostly at the boundaries of portions of the Earth's crust called Tectonic Plates. When movement occurs in these regions, along Faults, waves are generated at the Earth's surface that can produce very destructive effects. The things that US&R forces **NEED** to know about these events are summarized in the following.

EARTHQUAKE MAGNITUDE
Is a way of measuring the total energy released by a quake, which could also relate to the total damage done (all else being equal). If we compare the two quakes illustrated (Large Quake and Great Quake) at the right, we can demonstrate what this means to US&R. For a bigger Magnitude the following can be said:

- The maximum intensity of the shaking may be similar
- The duration of the shaking (at the fault) is longer.
- The length of the fault break is longer (directly related to duration)
- The area of the Earth that will be effected by intense shaking is MUCH larger, and, therefore, the potential for greater US&R involvement is MUCH larger

AFTERSHOCKS
These smaller quakes occur after ALL large Earthquakes. They are usually most intense in size and number within the first week Of the original quake.

- They can cause the very significant re-shaking of damaged structures which makes earthquake induced disasters more hazardous to US&R than most others.
- A number of moderate quakes (6+ magnitude) have had aftershocks that were very similar in size to the original quake.

TERMINAL OBJECTIVES

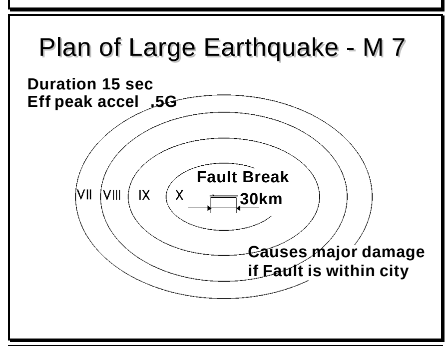
- The Student shall understand the how building structures can be separated into specific types that exhibit unique collapse patterns when subjected to extreme forces due to Earthquake Wind , and Explosions
- The Student shall be able to recognize their unique Collapse Patterns

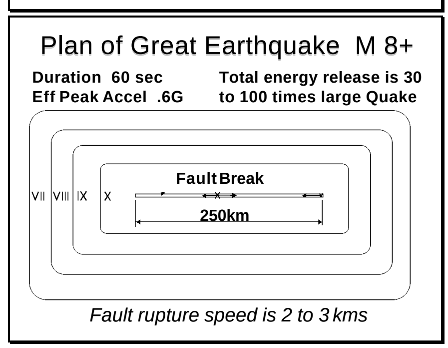
ENABLING OBJECTIVES

- Understand the extreme environmental and man caused forces that effect structures.
- Define and Understand how buildings are classified by engineers based on their Construction Materials and Lateral Load Resisting Systems.
- Discuss the most common Collapse Patterns that have been observed as a result of Earthquakes, Windstorms, and Explosions

Earthquake Basics

- Extent of damage is determined by
  - type of shaking that occurs at site
  - coupled with the structures response
- Magnitude (energy release)
  - determines POTENTIAL number of effected structures
- Aftershocks
  - Earthquakes are unique type of Disaster
  - just keeps on giving





MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

EARTHQUAKE BASICS (continued)

AFTERSHOCKS (continued)

- Arrays of strong motion instruments can be set out after an earthquake and data from aftershocks will allow the mapping of the fault surface. These instruments can also be coupled with a warning system to notify US&R TF prior the effect being felt at a building site – discussed in Monitoring.
- 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
- 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 one of the Loma Prieta relative moderate 5.0 aftershocks).

BASIC STRUCTURAL LOADING

EARTHQUAKES

- 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.
- 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. Seismically 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.

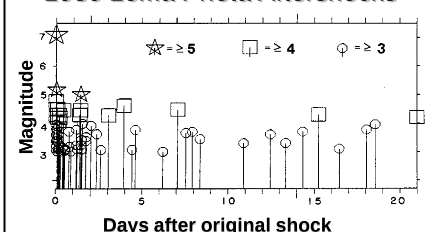
Aftershocks

- Smaller quakes that occur on same fault as original quake. Minor fault adjustments
- Occur after most quakes regardless of size of original shock
- Some have been almost as large as original. (in range of M 6)
- Will occur during US&R Ops since are most prevalent in first week.

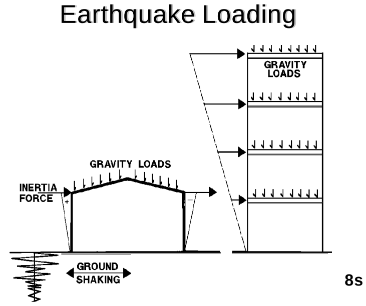
How Many Aftershocks ?

- USGS - Rule of Thumb
  - For every single decrease in magnitude, get 10 fold increase in number
- If original quake is M 7
  - 1 or so aftershock in range of M 6
  - 10 " " " " 5
  - 100 " " " " 4
  - 1000 " " " " 3

1989 Loma Prieta Aftershocks



Earthquake Loading



8s

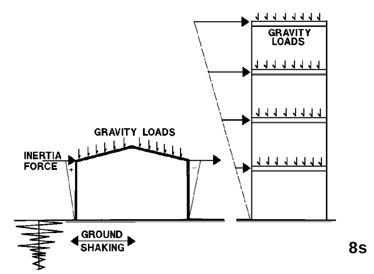
MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BASIC STRUCTURAL LOADING (continued)

EARTHQUAKES (continued)

- There are also vertical loads generated in a structure by earthquake shaking, but as mentioned previously, 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.)

Earthquake Loading



WIND STORMS

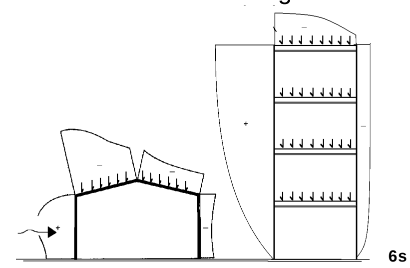
- Forces are generated on the exterior of the building based on its height, local ground surface roughness (hills, trees, other buildings) and the square of the wind velocity. The weight of the building, unlike the earthquake condition, has little effect on wind forces, but is helpful in resisting uplift.

- 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.

- 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.

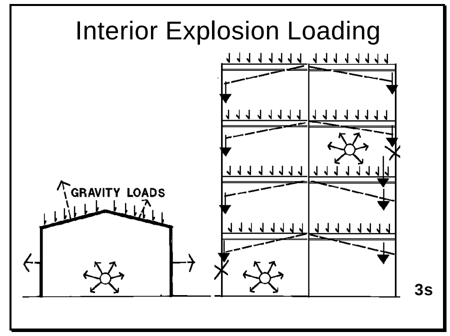
- The overall structure must be designed for the sum of all lateral and uplift pressures and individual parts must be designed to resist the outward and inward pressure concentrations, and must be connected to supporting members (beams, columns, walls, foundation) to form a continuous resistance path. Forces are also generated on structures by airborne missiles that vary in size from roofing gravel to entire sections of roofs.

Wind Loading



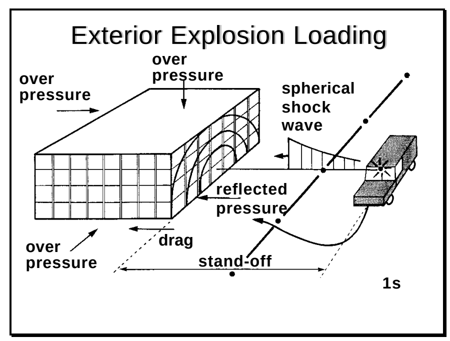
MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BASIC STRUCTURAL LOADING (continued)

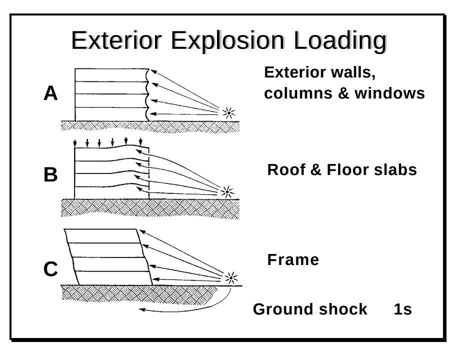


EXPLOSION

- They occur 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 (fireball) and a shock wave that propagates, radially outward from the source at subsonic speeds for most Low Explosives and 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.
- 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 in the slide at the top of the page. In 1960 a progressive collapse started when a natural gas explosion caused the collapse of an exterior wall on the 18th floor of a 22-story building. The force of falling debris from floors 19 to the roof then caused the remaining floors to collapse in that section of the building.



- 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.



- A secondary effect of an air-blast is a very high velocity wind that propels the debris (becoming deadly missiles), and in addition a high intensity, short duration ground shaking (earthquake) may be induced.

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

<u>BASIC STRUCTURAL LOADING</u> (continued)

EXPLOSION (continued)

- 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.

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.

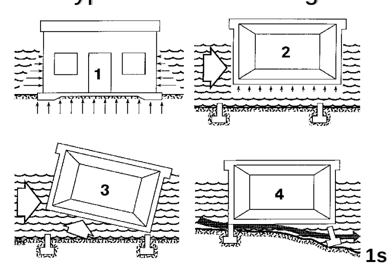
Loading Caused by Fire

- Burnout of Wood Roof can lead to dangerous unbraced walls 1s
- Fire in Steel Building can lead to damage due to expansion 1s
- Heat from Burned Wood Apartment caused Expansion Damage to RM shearwalls in Basement Garage 2s

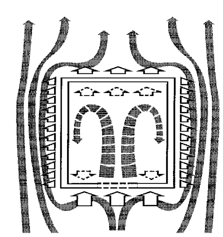
FLOOD

- 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.

Typical Flood Loading



Flood Loading in Plan



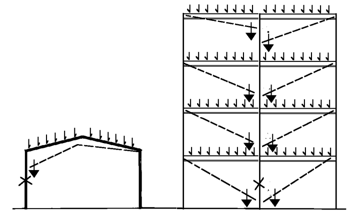
MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BASIC STRUCTURAL LOADING (continued)

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).

Construction Bracing, Overload



4s

VEHICLE IMPACT LOADING

- Structures have been severely damaged and set on fire by vehicle impacts.
- 1989 train derailment in California lead to a well organized, integrated response that was successful in saving a victim in what was originally perceived as an un-survivable condition.

Vehicle Impact Loading

- Planes, Trains, Boats, & Highway Vehicles have impacted Structures
- Collapse and often Fires have resulted
- 1989 Train Derailment in So Cal buried several homes.
  - CAL OES organized and directed a successful deployment of K9 Search to aid local Fire/Rescue forces
  - Demonstrated Value of Integrated US&R

2s

ATC-21 NOMENCLATURE

ATC-21, Rapid Visual Screening of Buildings For Potential Seismic Hazards was funded by FEMA and written by Applied Technology Council (ATC) in 1988. ATC was created by the Structural Engineers Assn. Of California to develop and manage research and other projects that add to the body of knowledge regarding Structures.

- ATC-21 defined twelve specific building types, based on how they respond to Earthquakes.
  - They are listed in the slides at right, and are defined by the type of material used in construction as well as the type of Lateral Load Resistant System employed.
  - As an example for Concrete Construction, we have a C1 Type that has a Moment Resistant Frame, a C2 Type that is a Box Building with Shear Walls for lateral resistance, and C3 Type to cover the many buildings that have a Moment Resistant Frame with some sort of masonry infill walls for fireproof exterior enclosure

Building types - ATC-21-1

- W Wood buildings of all types
- S1 Steel moment resisting frames
- S2 Braced steel frames
- S3 Light metal buildings
- S4 Steel frames w/C I P conc walls

Building types - ATC-21-1

- C1 Concrete moment resisting frames
- C2 Concrete shear wall buildings
- C3/S5 Conc/steel frame w/urm infill walls
- TU Tilt-up concrete wall building
- PC2 Precast concrete frame buildings
- RM Reinforced masonry buildings
- URM Unreinforced masonry building

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

ATC-21 NOMENCLATURE (continued)

- The FEMA US&R Response System has adopted the ATC-21 nomenclature for use in identifying damaged structures.
  - It has be used in this Training Manual and for the Structure Triage and Structure/Hazard Evaluation Forms.
- Other systems, such as given in the Building Code and in Francis Brannigan's Building Construction for the Fire Service are based on resistance and response to Fire.
  - They are not as specific enough to differentiate to be usefull in describing structural response to Earthquake and the other destructive forces encountered in US&R.
  - The slide at the right gives a comparison between the Building Types listed by Brannigan and ATC-21

Compare Brannigan to ATC

- ATC has more categories and relates to how structures respond to Earthquakes.
- Brannigan relates to how structures are effected by Fire
  - Wood Construction = W
  - Ordinary Construction = URM, RM, TU
  - Steel Construction = S1, S2, S3, S4, S5
  - Concrete Construction = C1, C2, C3
  - High Raise Constr. = S1, S2, C1, C2, C3
  - Garden Apartments = W

PROBLEM BUILDINGS

The adjacent slide lists some of the building types that have been susceptible to Quake and/or Wind damage in the past. As one can see the list includes most all structural types.

- S2, C1, C3/S5, TU, PC2 and URM are expected to be most susceptible to earthquake damage thruout the U.S.
- Wood residential structures have also experienced a large number of failures in California, since they are, by far, the most prevalent building type. There is potential for entrapment of victims in multi-story wood structures.
  - Poorly tied wood structures are also very vulnerable to Wind Damage
- Type S3 is listed since it is very susceptible to damage by wind.
- Many S1 structures experienced cracks in their welded connections during the Northridge (L.A.) quake, which is of great concern to design profession.
  - None of these buildings were damaged to an extent that would cause collapse, but they may become a problem in future quakes.

Problem Buildings

W	1 to 3 story houses & 2 to 4 story apartments (especially pre 1970)
S1	Frames w/brittle welded conns
S2	Frames where column capacity is less than capacity of diag braces
S3	Light structure vulnerable to Wind
C1/C3	Pre 1971 bldgs (espec pre 1941)
PC2/TU	Factory built precast & tilt-up wall
URM	1 to 8 story (most 3 story & less) + steel & conc frames w/URM infill
Others	Irregular - soft story, open front

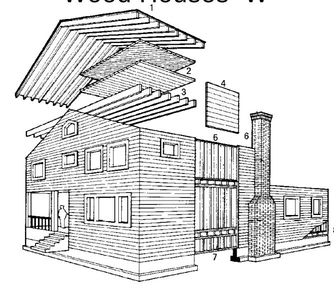
MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BUILDING DESCRIPTIONS & PROBLEMS

WOOD FRAME BUILDINGS W

These structures can vary from 1 to 4 stories and contain from one to over 100 living units.

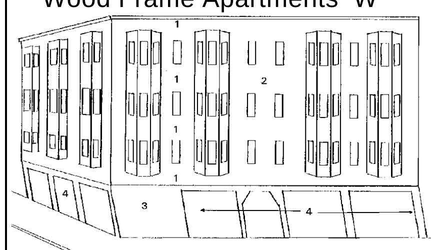
Wood Houses W



2s

- 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.
    - These structures are especially vulnerable to Quake damage when light weight concrete fill has been added to provide better sound control. (greater mass means greater Quake force is generated)

Wood Frame Apartments W



3s

  - 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.

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS

PART 2. COLLAPSE PATTERNS

WOOD FRAME BUILDINGS W (continued)

WOOD HOUSES - W BF-3

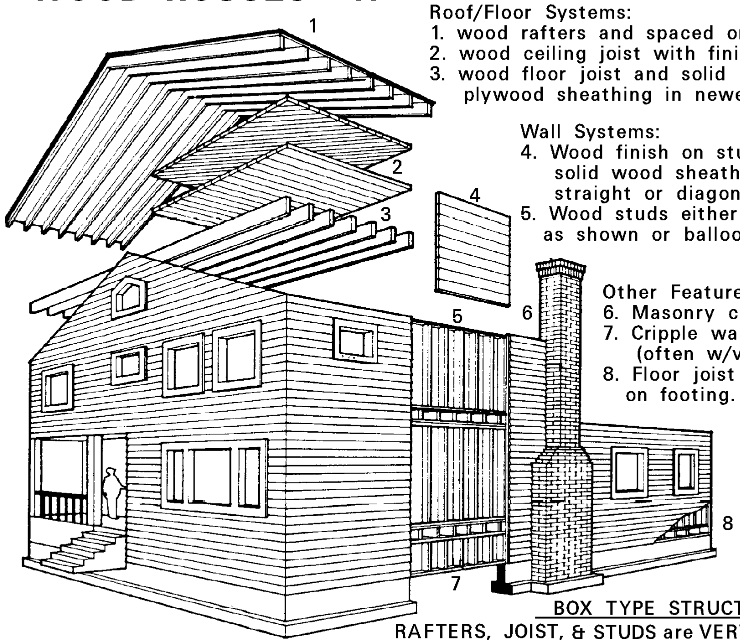
Roof/Floor Systems:
1. wood rafters and spaced or solid sheathing
2. wood ceiling joist with finish
3. wood floor joist and solid 1x sheathing or plywood sheathing in newer houses

Wall Systems:

4. Wood finish on studs or Stucco on solid wood sheathing: plywood, 1x straight or diagonal boards.
5. Wood studs either platform framed as shown or balloon framed

Other Features:

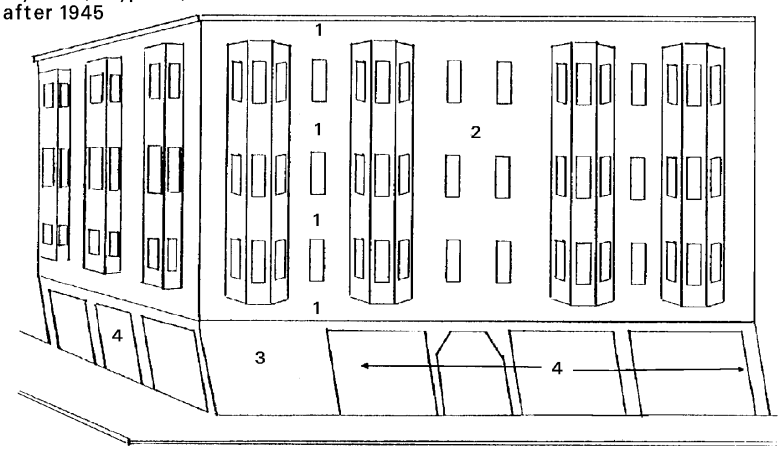
6. Masonry chimney
7. Cripple wall below 1st floor (often w/vent holes)
8. Floor joist may bear directly on footing.



BOX TYPE STRUCTURE
RAFTERS, JOIST, & STUDS are VERTICAL LOAD SYS.
SHEATHING is LATERAL LOAD SYSTEM

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.

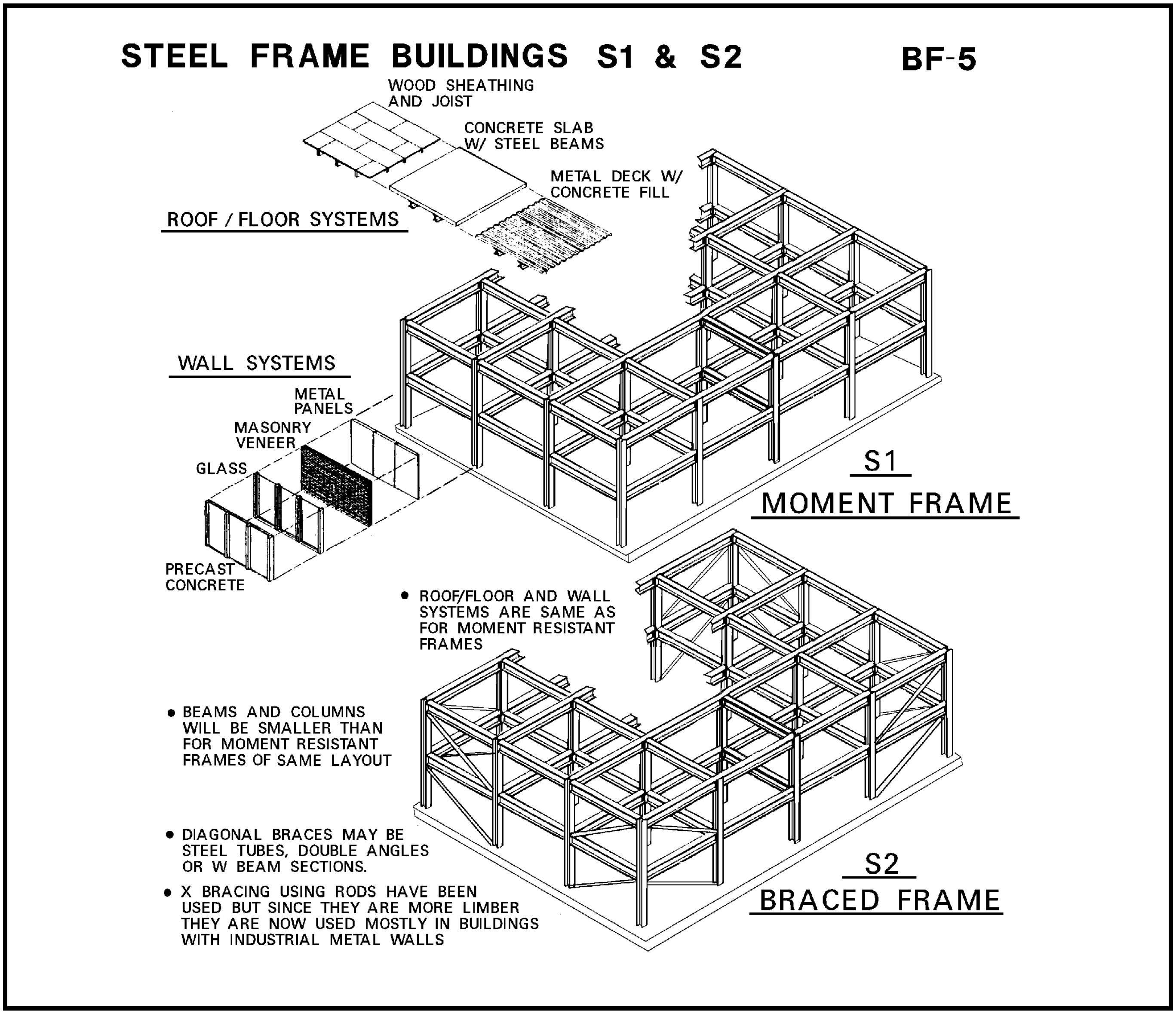


MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BUILDING DESCRIPTIONS & PROBLEMS (continued)

STEEL MOMENT– RESISTING FRAME BUILDINGS S1
These may be from one- to over one hundred-story office buildings with glass or other non-structural exterior covering. Steel buildings in general have performed well, but in recent earthquakes **MOMENT- RESISTANT FRAMES** have exhibited the following problems:

- In both Northridge and Kobe Earthquakes, the violent shaking has caused some welded connections to crack.
- No buildings of this type collapsed during these quakes, but a few were racked out of plumb, and new, better performing, joints have been designed to repair/replace questionable ones.



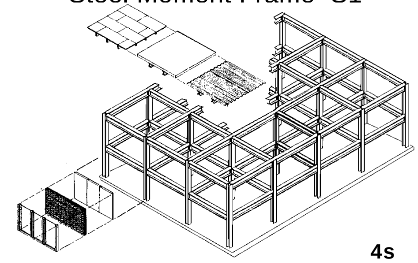
MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BUILDING DESCRIPTIONS & PROBLEMS (continued)

STEEL MOMENT– RESISTING FRAME BUILDINGS – S1 (continued)

- Since these connections are what gives Moment Resisting Frames their lateral resistance, it is possible that a future Great Earthquake (M 7.5 to 8.5) could cause a catastrophic collapse., especially if the following occurred:
  - Shaking lasts for more than 30 seconds
  - A structure has little redundancy (only a few columns with welded joints), and the joints are the types that can crack and fail.

Steel Moment Frame S1



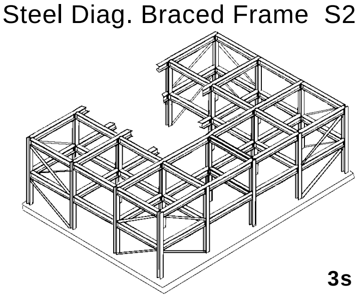
4s

DIAGONALLY BRACED STEEL FRAMES - S2

These 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.
- 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.

Steel Diag. Braced Frame S2



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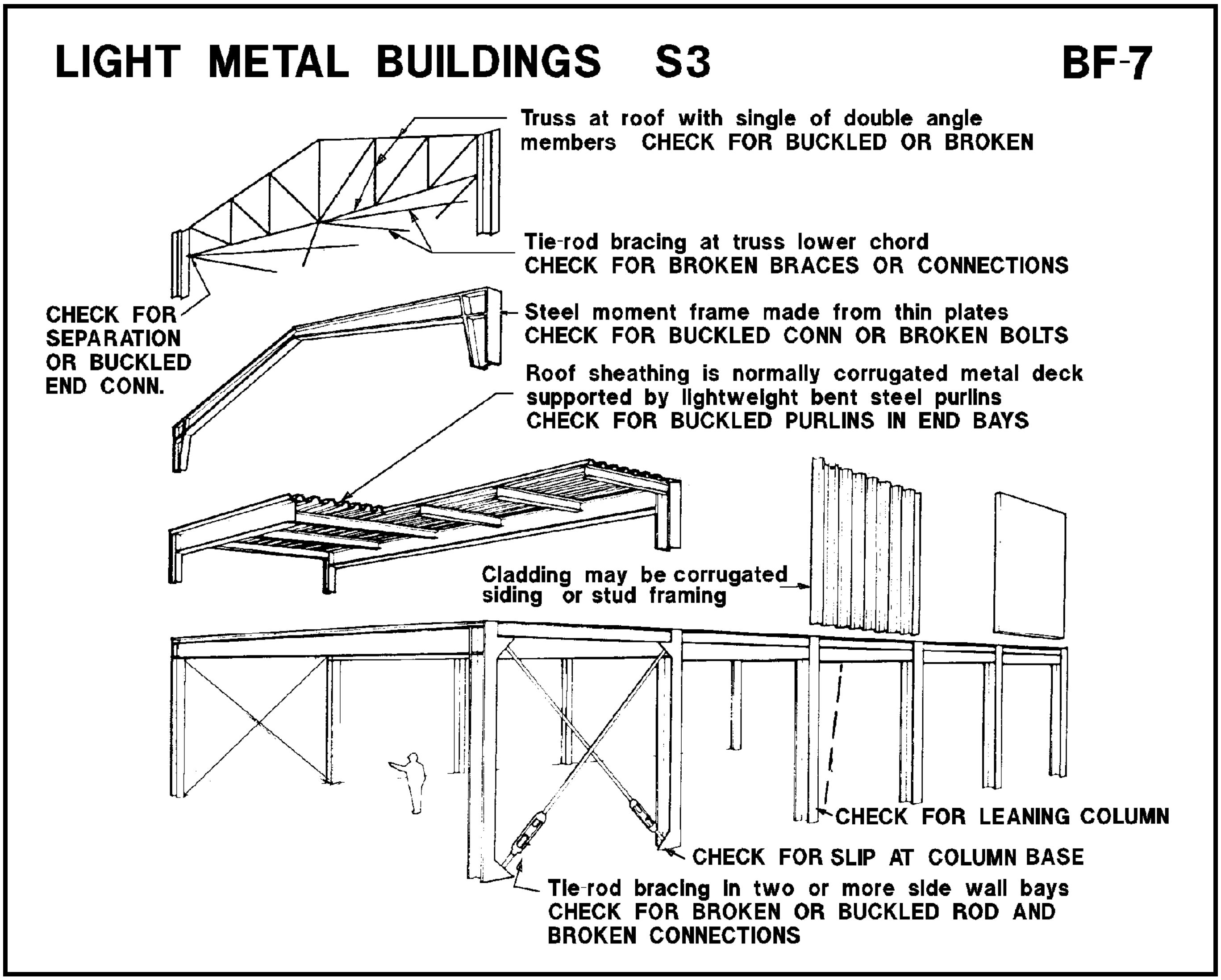
MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BUILDING DESCRIPTIONS & PROBLEMS (continued)

LIGHT METAL BUILDINGS - S3

These 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:

- 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.

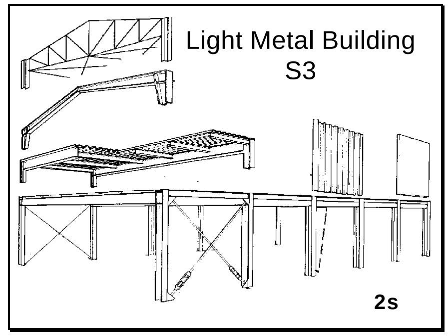


MODULE 1c STRUCTURAL ENGINEERING SYSTEMS

PART 2. COLLAPSE PATTERNS

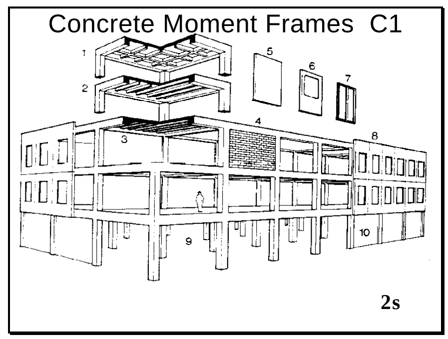
BUILDING DESCRIPTIONS & PROBLEMS (continued)

LIGHT METAL BUILDINGS - S3 (continued)



- 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



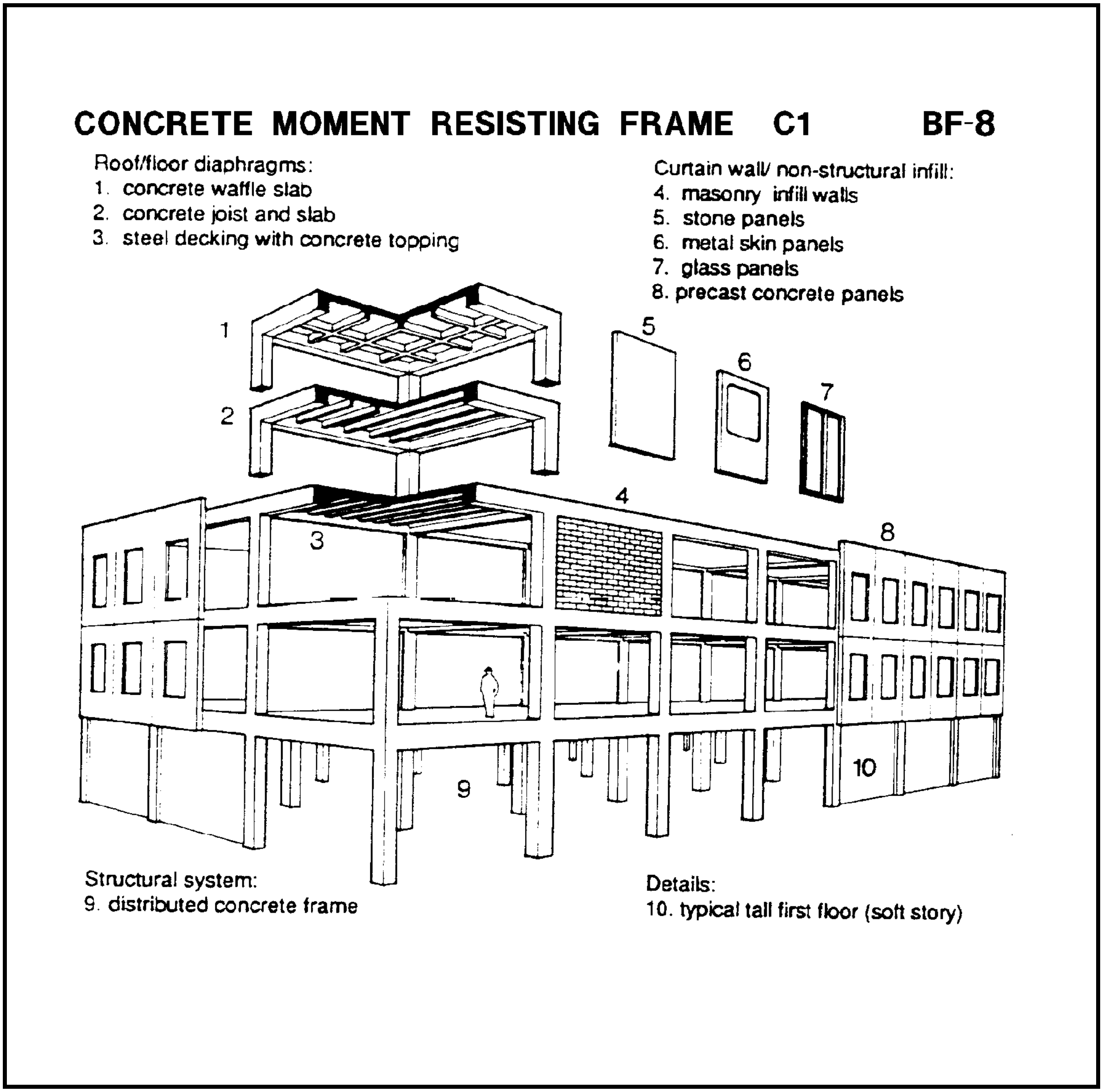
Older frames are from one to thirteen stories high, and may have URM infill walls. Older frames in California had thin concrete infill walls on property lines in some cases. The most hazardous configurations include soft (high, open) first stories, open front buildings (typical of retail one and two 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.
- 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.

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

<u>BUILDING DESCRIPTIONS & PROBLEMS</u> (continued)

CONCRETE FRAME BUILDINGS C1, C3 (continued)

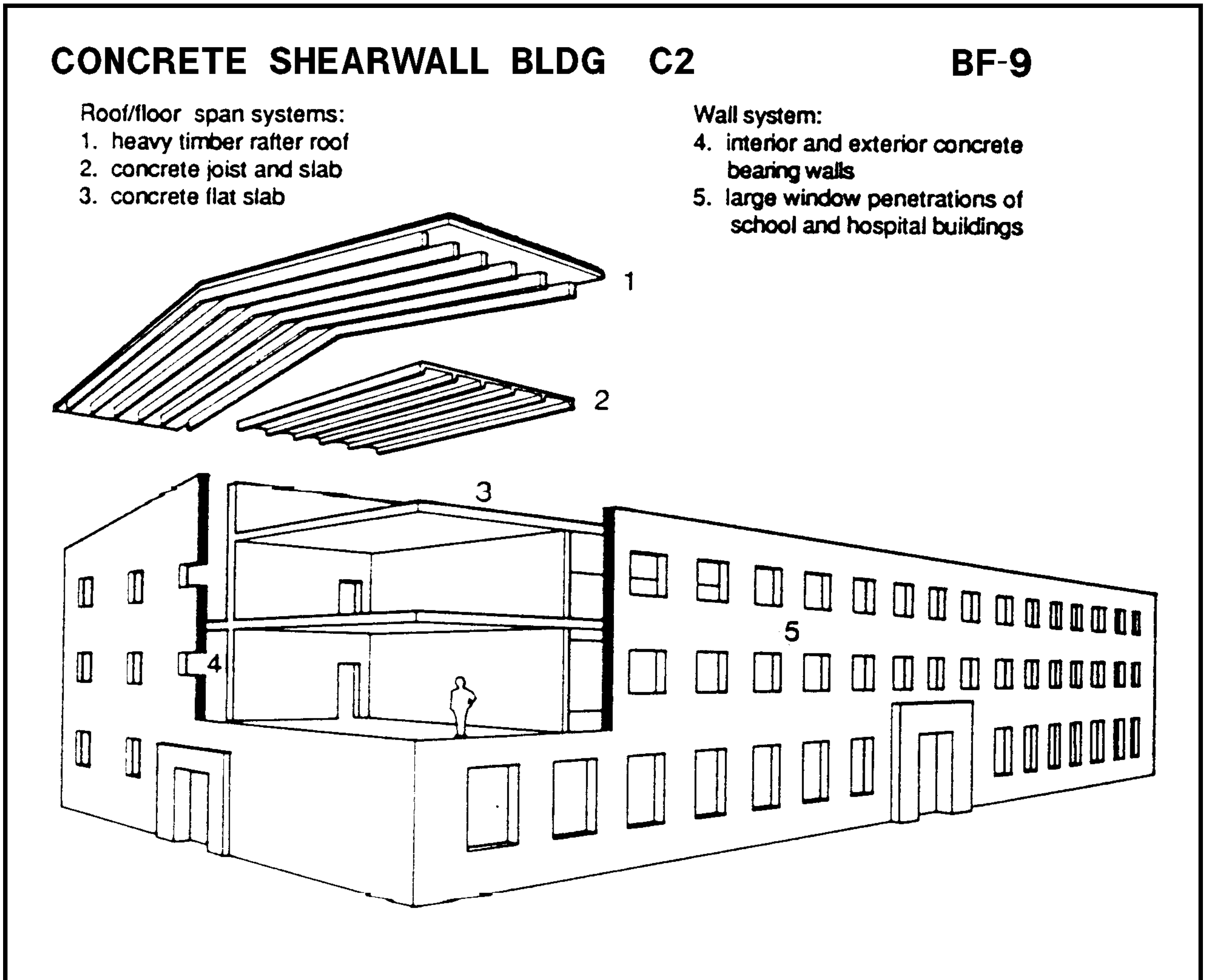


MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BUILDING DESCRIPTIONS & PROBLEMS (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.).

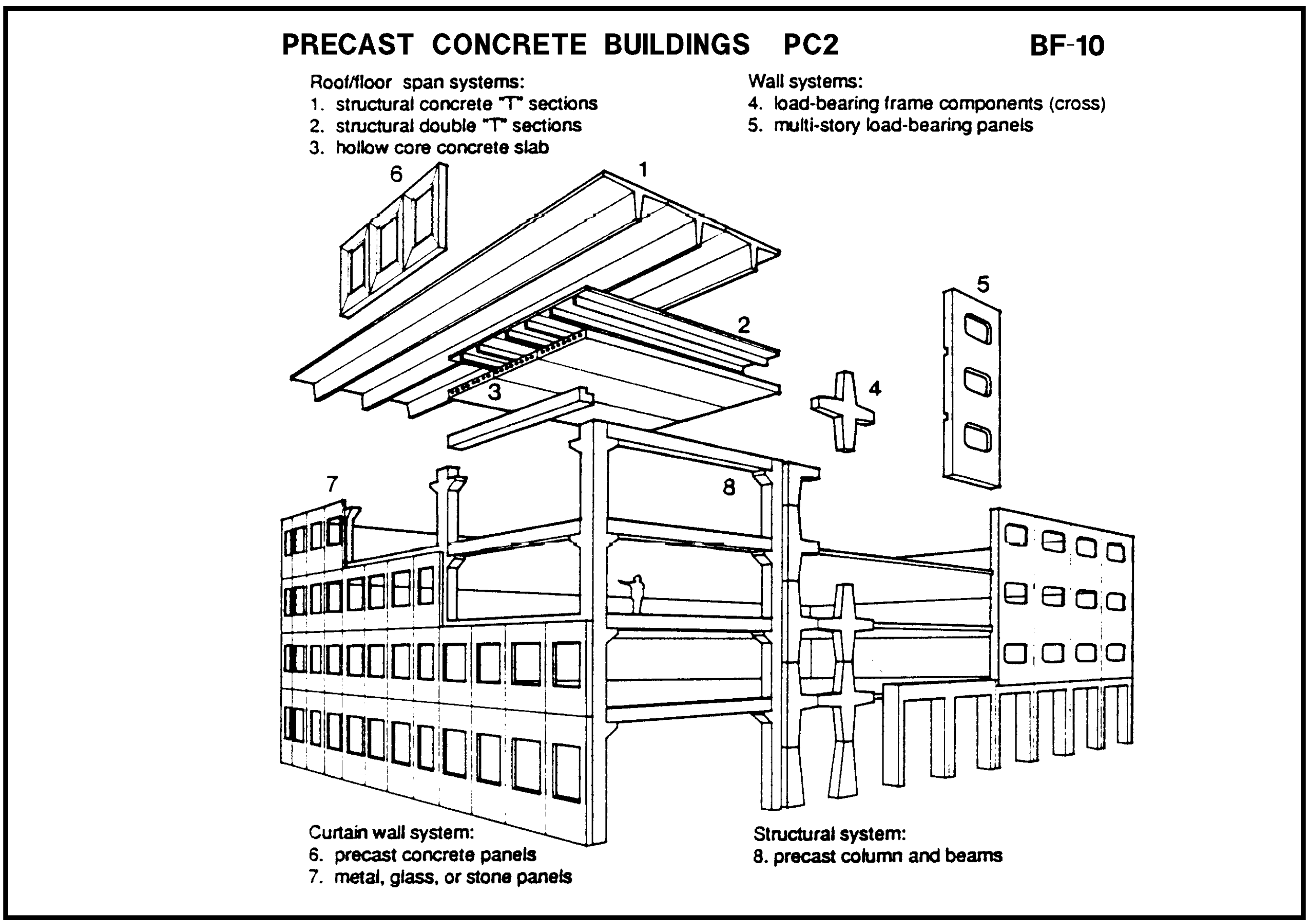


MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BUILDING DESCRIPTIONS & PROBLEMS (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 at 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.

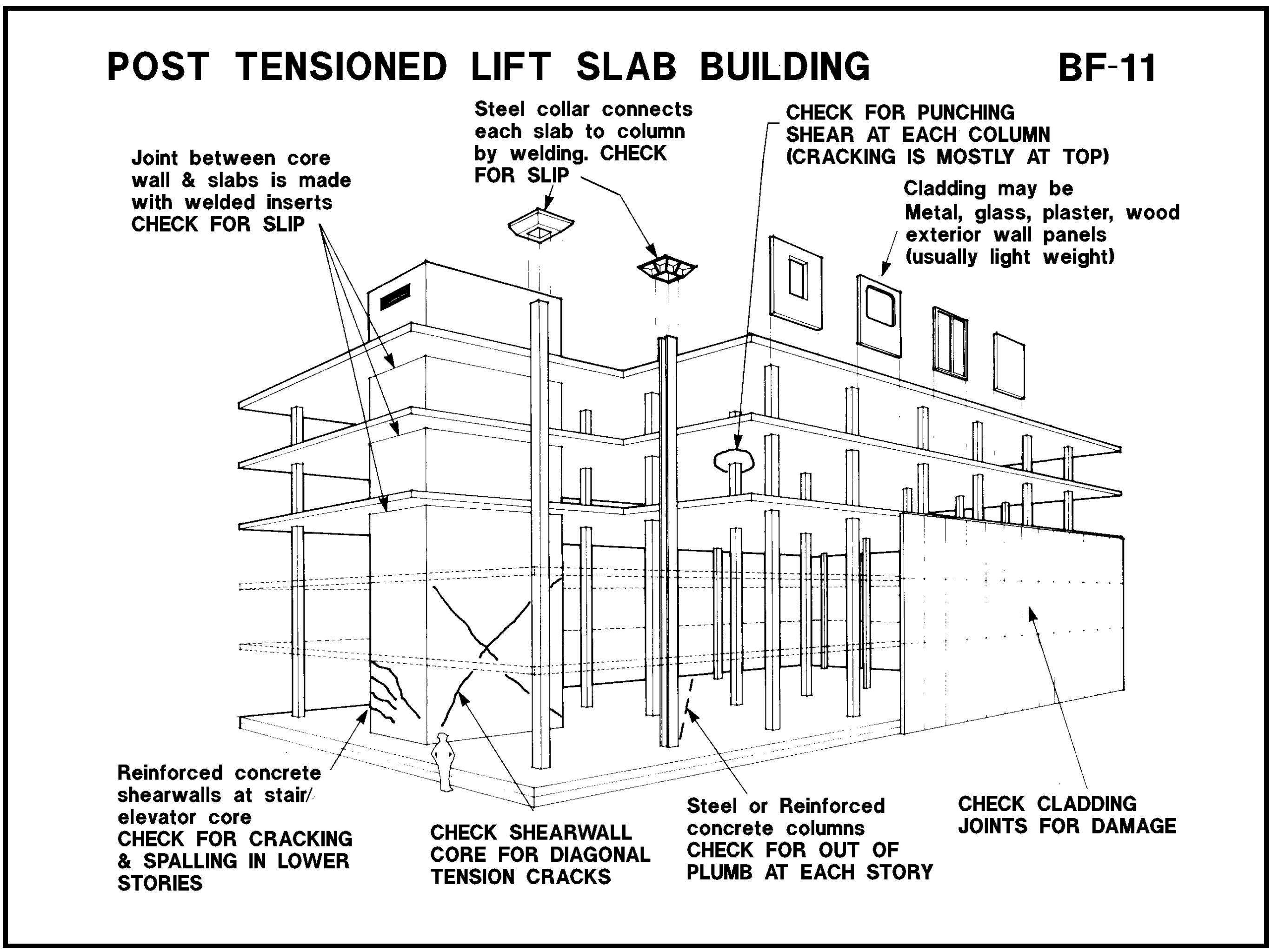


MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BUILDING DESCRIPTIONS & PROBLEMS (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 stairwells 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.

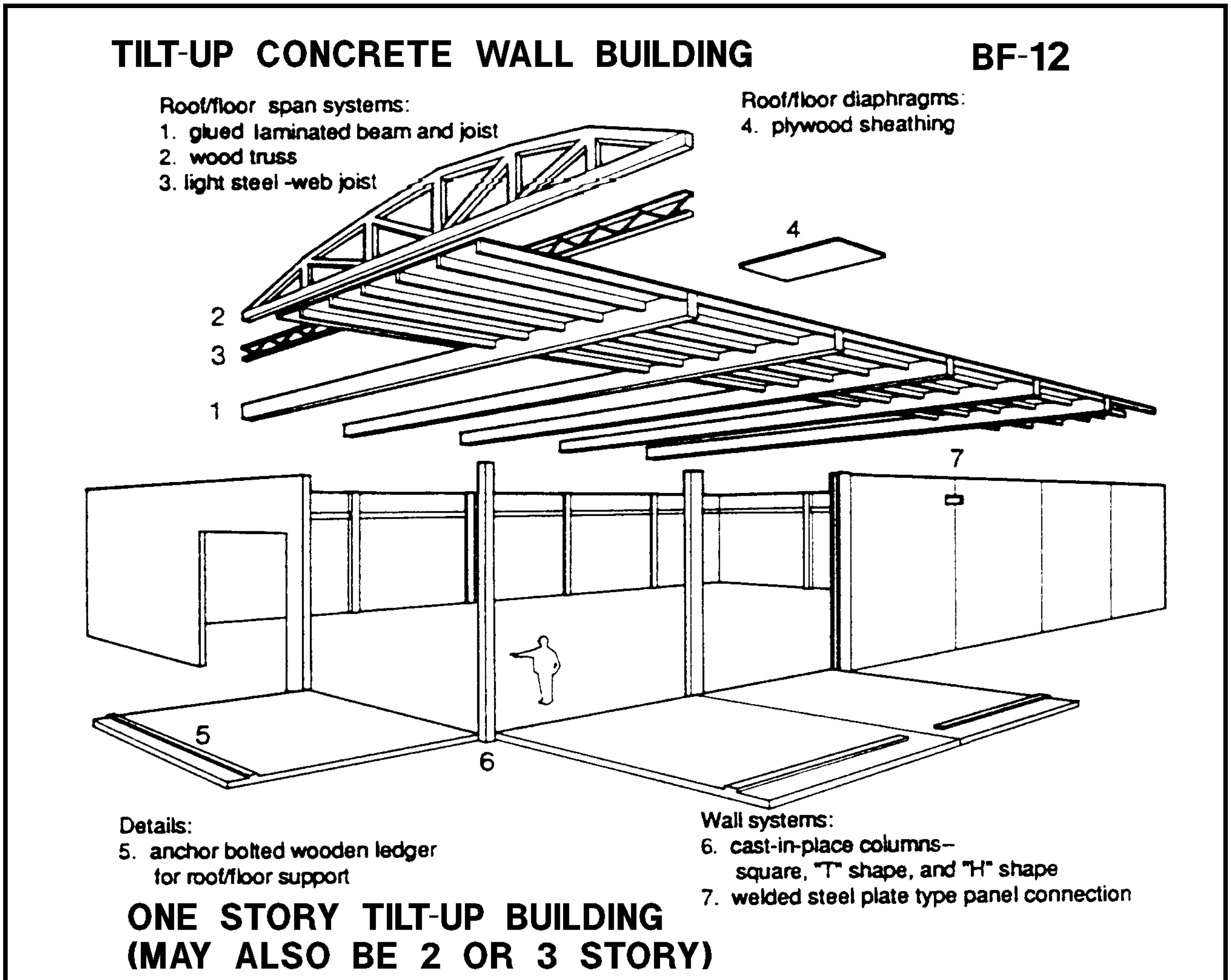


MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BUILDING DESCRIPTIONS & PROBLEMS (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 1 ½ " concrete fill on wood floor. The common earthquake problems are:

- Walls can separate from wood floors/roof causing at least local collapse of floor/roof, possible general collapse of walls and floor/roof.
- 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 horizontal forces as high as 200% times to weight of the structure can be generated at the mid-span of wood roof diaphragms.



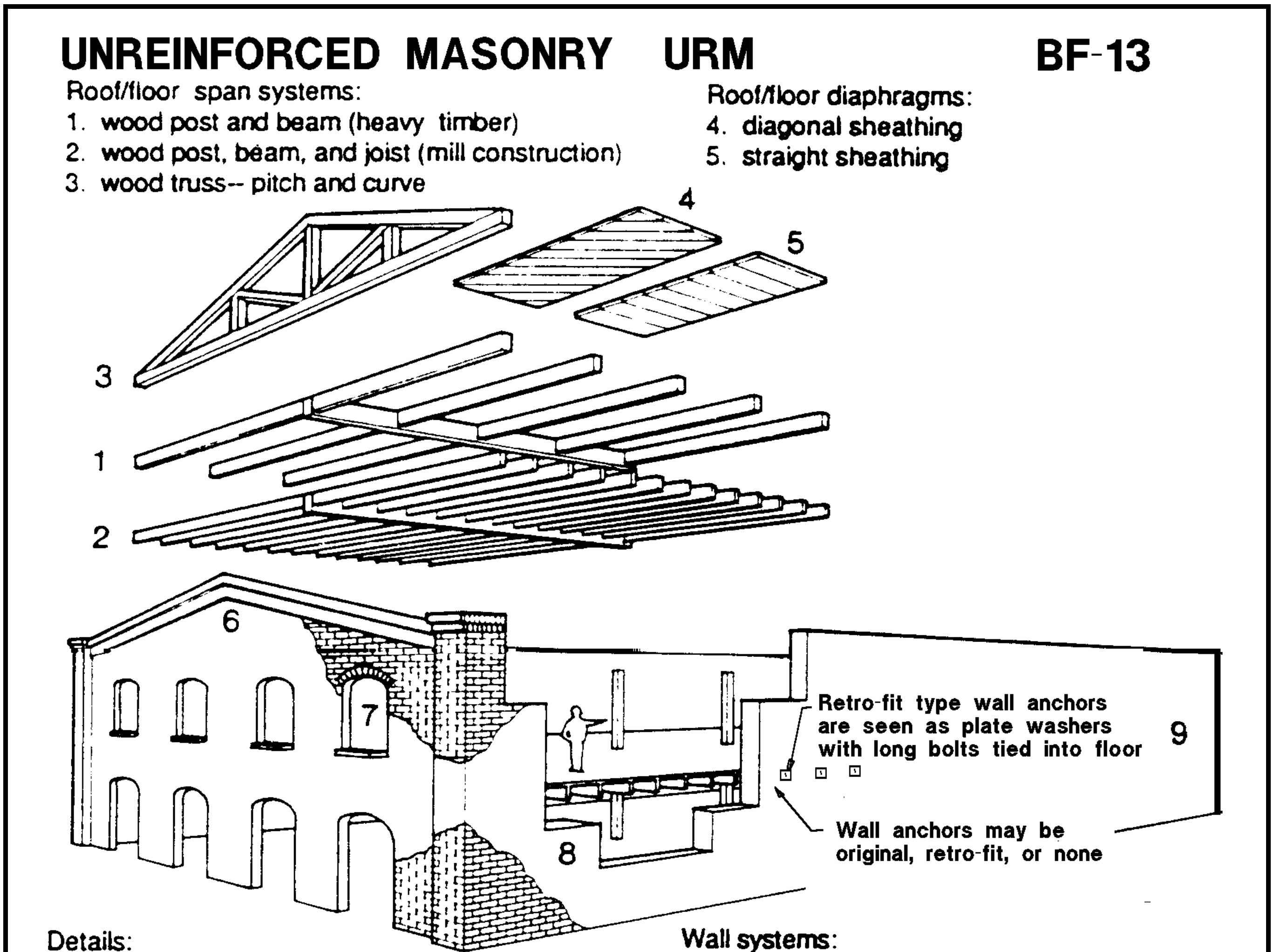
MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BUILDING DESCRIPTIONS & PROBLEMS (continued)

TILT UP CONCRETE WALL BUILDINGS - TU (continued)

- Suspended, precast concrete wall panels can fall off buildings. (Note: suspended cancrete wall 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



MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BUILDING DESCRIPTIONS & PROBLEMS (continued)

UNREINFORCED MASONRY BUILDINGS - URM

Are usually from one to six-story buildings with URM bearing walls and wood floors. There are estimated to be as many as 50,000 in California, however, most have been strengthened. This would include steel and concrete frames with URM infill.

In addition to bearing wall URM, there are structures with 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:

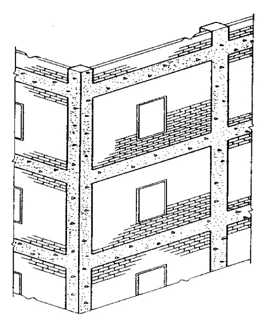
- Parapets and full walls fall off buildings due to inadequate anchors.
- Multi thickness walls split and collapse or break at openings.
- Mortar is often weak and made with too high a lime content.
- Walls that are more heavily loaded by roof and floors tend to perform better than walls that are parallel 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.
- Older steel frame buildings with unreinforced or lightly reinforced masonry infill, often shed this weak, brittle covering as they flex to resist the quake.
- Broken bricks often line the streets where these buildings are located and people can be trapped on the sidewalk, auto, etc.
- Cavities are usually formed by wood floors in familiar patterns of Vee, Lean-to, and complicated Pancake. This will be discussed later under Earthquake Collapse Patterns.

Types of URM Buildings

- Brick bearing wall buildings -
  - URM exterior walls
  - Wood floors & interior walls.
- URM infill - in concrete or steel frames.
  - infill is brick, hollow clay tile, hollow CMU
- UR, hollow conc block bearing wall .
  - may have bond beams at floor & roof
  - may have vertical bar at edges of opngs

Types of URM Buildings

- UR or under-reinforced cavity walls.
  - insulation layer between masonry layers
  - relatively modern construction
  - may be used as infill or bearing walls with bond beams.
- Masonry veneer on wood or steel studs
  - anchorage is all important due to interaction of brittle wall covering on flexible structure.
- Native stone, adobe, mud, etc. bearing wall buildings.



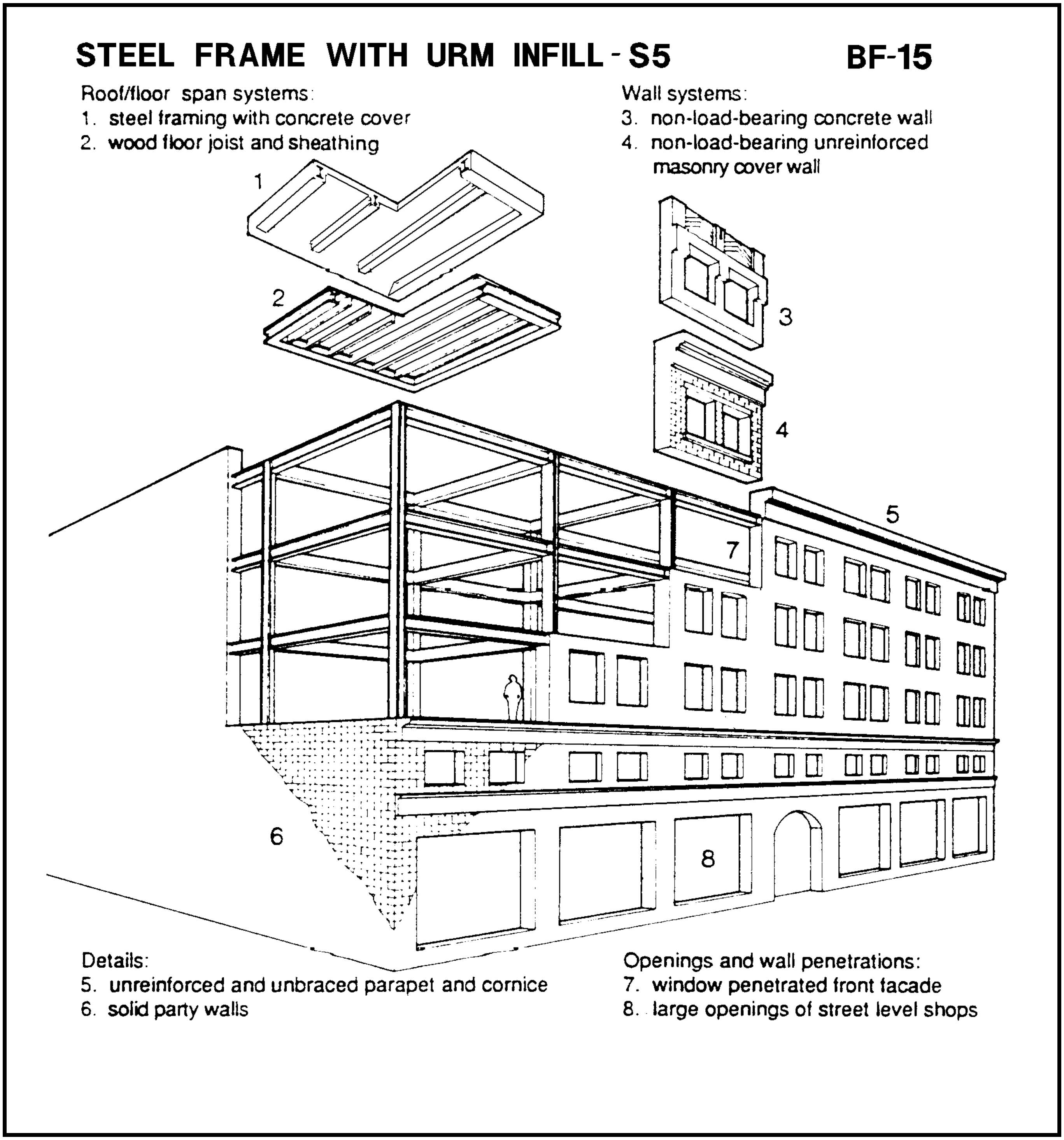
URM Concrete Frame

1s

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

<u>BUILDING DESCRIPTIONS & PROBLEMS</u> (continued)

UNREINFORCED MASONRY INFILL IN STEEL FRAME - S3

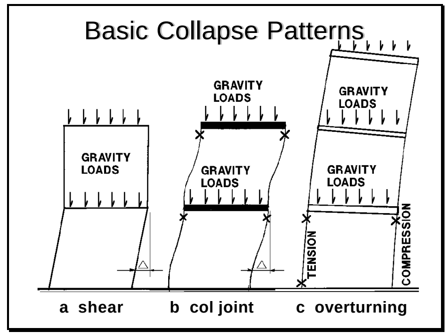


MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

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. Basic Collapse Patterns can be summarized as follows:

a. Inadequate shear strength where 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.



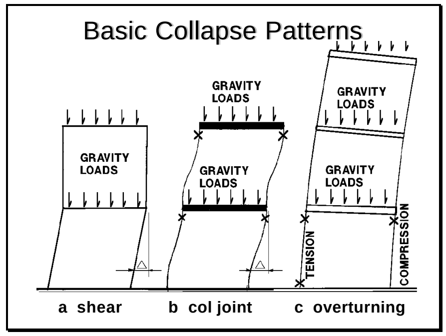
The basic instability occurs when the gravity load is offset a distance (delta) that is large enough to overcome the shear capacity of walls at a particular level, usually the first story. The horizontal resistance required to maintain stability in the racked condition (parallelogram) illustrated is 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).

b. Inadequate beam/column joint strength. Failures are caused mostly by earthquake shaking of buildings that have joints with 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 this type of collapse may be a pancaked group of slabs held apart by broken columns and building contents, or a condition where columns are left standing, punched through the slabs. The slabs may or may not be horizontally offset from each other.

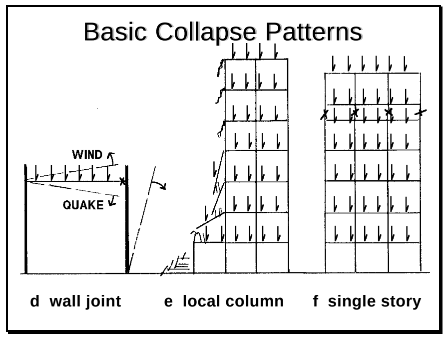
MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BASIC COLLAPSE PATTERNS (continued)



c. Tension/compression failure caused mostly by earthquakes and usually occurs in taller structures with concrete shear walls and/or concrete or structural steel moment resistant 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 moment 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.



d. 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.

e. 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, due to the lack of continuity of these construction configurations.

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

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

BASIC COLLAPSE PATTERNS (continued)

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.

EARTHQUAKE COLLAPSE PATTERNS

THE BASIC PRINCIPALS

- 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.

BASIC PRINCIPLES
Earthquake Caused Collapse
- 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

BASIC BUILDING TYPES
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 rise 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.

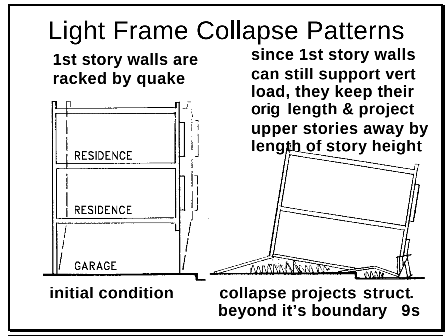
Earthquake Collapse Patterns
- Light Frame - wood frame buildings 1 to 4 stories, residential & other
- Heavy Wall - URM, TU, & other low rise w/concrete or masonry walls
- Heavy Floor - Concrete frame bldgs
- Precast Concrete - fairly heavy floors & some w/heavy walls

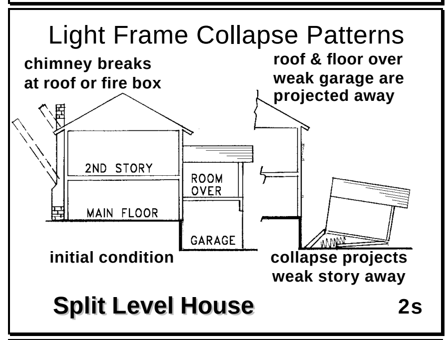
MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

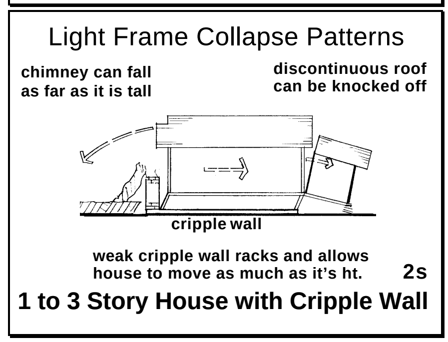
<u>EARTHQUAKE COLLAPSE PATTERNS</u> (continued)

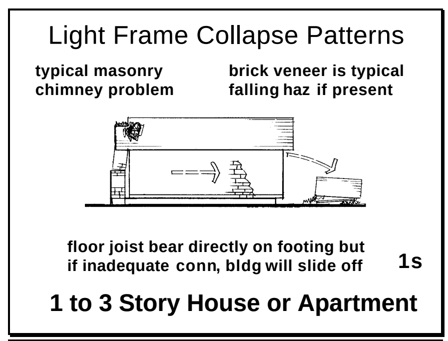
LIGHT FRAME COLLAPSE PATTERNS

- 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 adjacent slides.
- 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.
- 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.



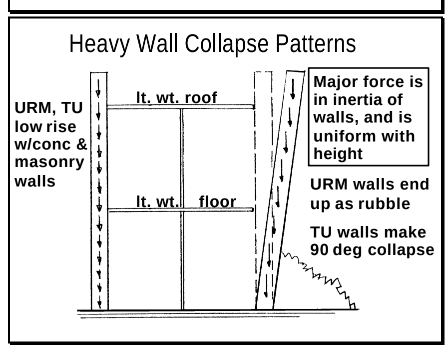






HEAVY WALL COLLAPSE PATTERNS

- 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.
- When property line walls fall on an adjacent, lower buildings, these structures will usually have some sort of roof/floor collapse.



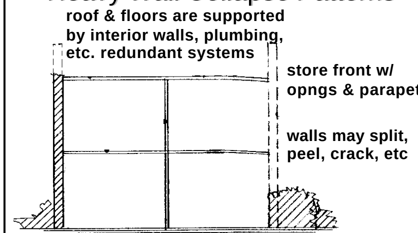
MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

<u>EARTHQUAKE COLLAPSE PATTERNS</u> (continued)

HEAVY WALL COLLAPSE PATTERNS (continued)

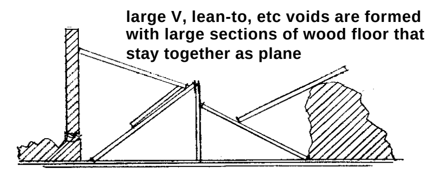
- However, in collapse due to failure of interior columns or due to fire, it is possible to have the very precarious situation of multi-story heavy walls that are left standing without any laterally supporting floors/roof. For this case it is probable that the wall could fall such that they extend their full height along the ground.
- 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.
- The falling walls can cause the roof and floors that they support to collapse in patterns of Lean-to, Vee, Pancake, and Cantilever. See following page.
    - **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.
- 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 adjacent section of roof will then collapse, although it may still be supported at it's far end.
    - There will be tension forces imposed on the roof system, therefore, all beam to beam and beam to column connections may be damaged and/or pulled-out

Heavy Wall Collapse Patterns



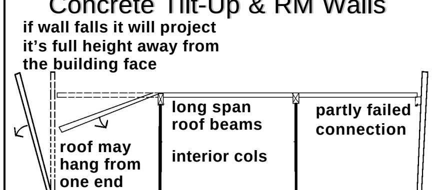
Most Common URM Failure 5s

Heavy Wall Collapse Patterns



More General URM Failure 5s

Heavy Wall Collapse Patterns
Concrete Tilt-Up & RM Walls



Typical Failure of Roof to Wall Conn. 6s

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS

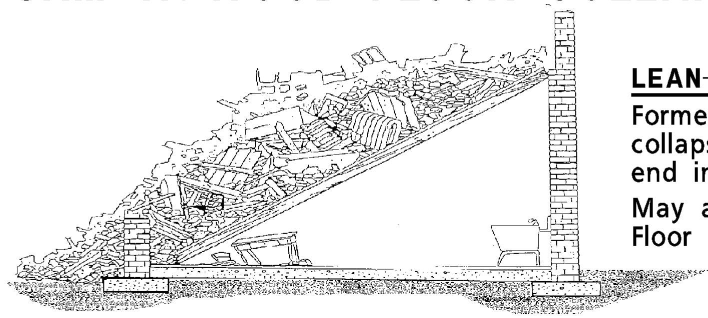
PART 2. COLLAPSE PATTERNS

<u>EARTHQUAKE COLLAPSE PATTERNS</u> (continued)

HEAVY WALL COLLAPSE PATTERNS (continued)

URM W/WOOD FLOOR COLLAPSE PATTERNS

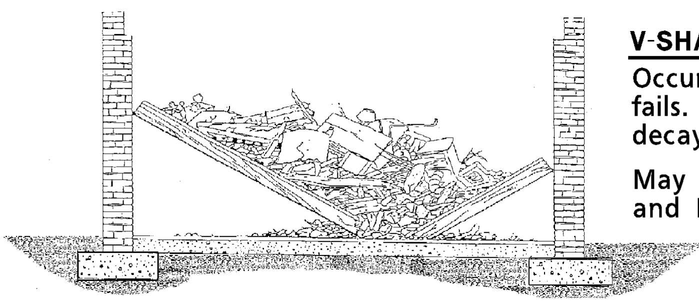
URM4PAT



LEAN-TO FLOOR COLLAPSE

Formed when one wall collapses, leaving other end in hazardous condition

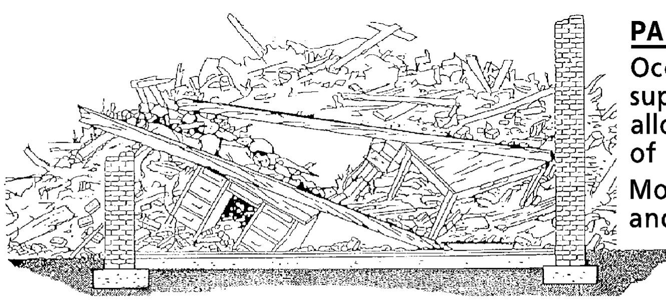
May also occur in TU, Heavy Floor and Precast Conc.



V-SHAPE FLOOR COLLAPSE

Occurs when interior support fails. More common in urban decay/overloaded column failure

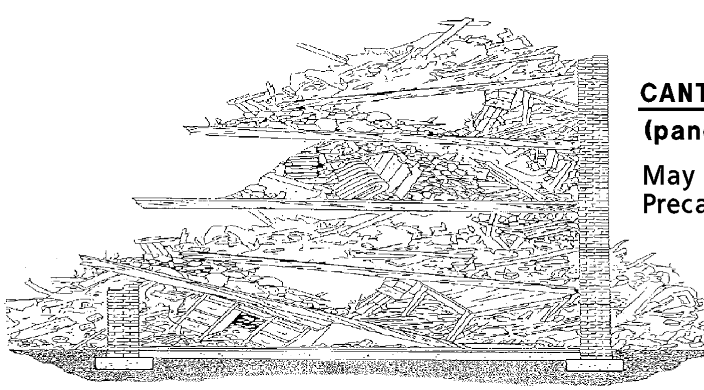
May also occur in Heavy Floor and Precast Conc. bldgs



PANCAKE FLOOR COLLAPSE

Occurs when most all vertical supporting members fail and allow floors to collapse on top of each other.

More common for Heavy Floor and Precast Conc. bldg.



CANTILEVER FLOOR COLLAPSE

(pancake with extended floors)

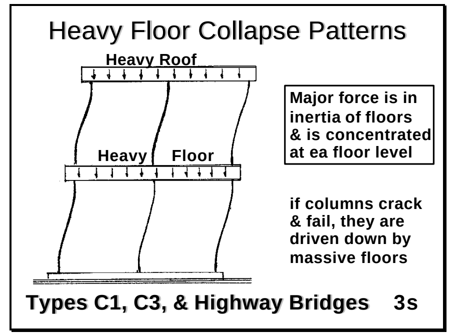
May also occur in Heavy Floor Precast Concrete buildings.

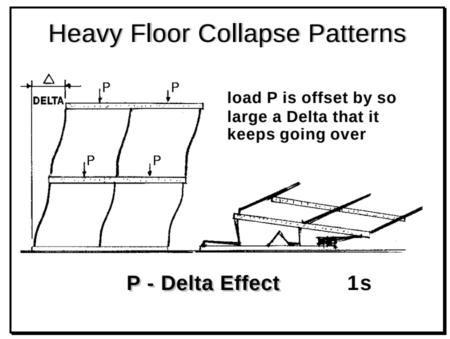
MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

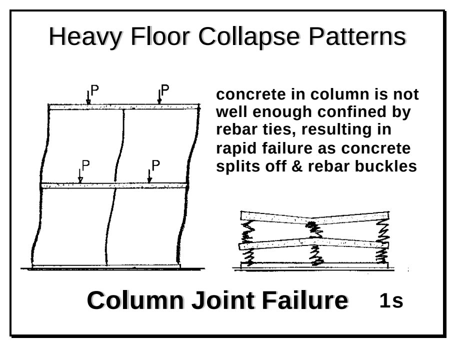
<u>EARTHQUAKE COLLAPSE PATTERNS</u> (continued)

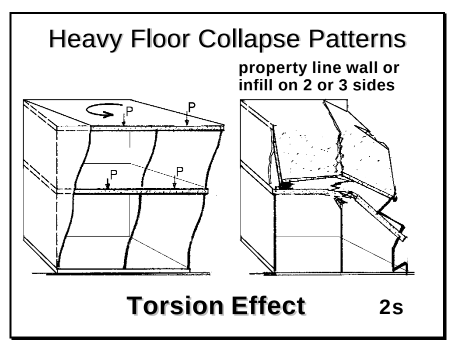
HEAVY FLOOR COLLAPSE PATTERNS

- 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 the adjacent slides, 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.
- 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.
- 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.
- **Torsion Effects** – occur in Concrete Frame Structures when URM infill is placed in exterior, property line walls for fire resistance. These walls become stiffer than all other parts of the building, and cause a temporary, eccentric condition, which can lead to a collapse of the columns on the opposite side of the building.







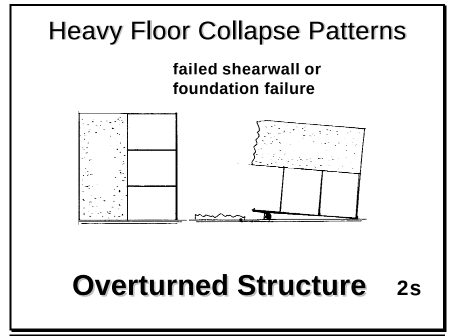


MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

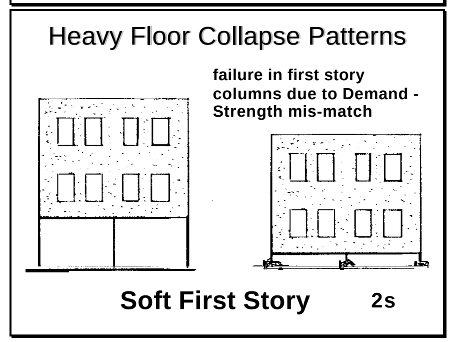
<u>EARTHQUAKE COLLAPSE PATTERNS</u> (continued)

HEAVY FLOOR COLLAPSE PATTERNS (continued)

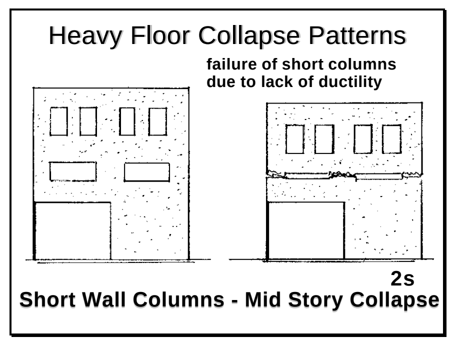
- **Overturned**, normally taller structures with shear walls, will often fail due to tension/ shear failure at the base. In this case the structure can project sideways by it's full height.



- **Soft First Story Collapse** – occurs in buildings that are configured such that they have significantly less stiffness (much fewer walls or no walls) in the first story than in the stories above.
  - This configuration may occur in wood as well as concrete structures.
  - The collapse is often limited to the one story only, as the building becomes one story shorter.



- **Mid Story Collapse** – can occur when a mid story is configured with much different stiffness than the stories above and below.
  - Can occur when a story has no walls, and the ones above and below have significant walls.
  - Can occur when a story has stiff, short columns, and the ones above and below have longer, more limber columns.



- **Pounding** - can cause a mid-story collapse, leaving a difficult problem to assess, due to remaining floors being overloaded etc.
  - Pounding collapse normally occurs when two adjacent buildings have floors that are at different elevations.
  - The very stiff /strong edge of a floor in one will cause the collapse of the adjacent building's column when they collide.
- Fire is usually not a problem for Heavy Floor Buildings, unless the contents are particularly combustible.

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

<u>EARTHQUAKE COLLAPSE PATTERNS</u> (continued)

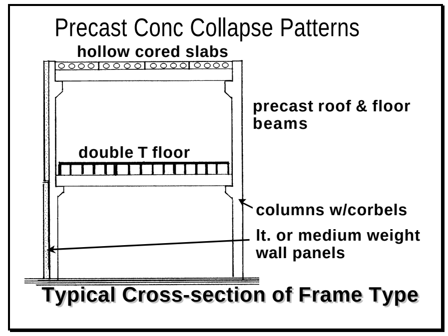
PRECAST COLLAPSE PATTERNS

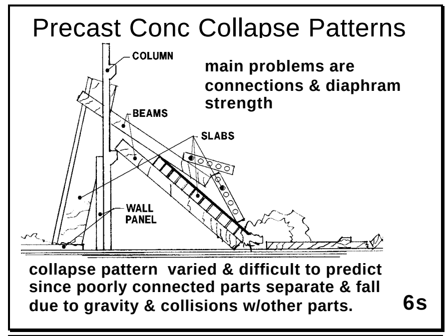
- Collapse is usually caused when the precast parts become disconnected from each other, and the structure very rapidly looses stability.

- 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.





<u>WINDSTORM/FLOOD COLLAPSE DAMAGE PATTERNS</u>

WINDSTORM BASICS

- They often produce flooding and the damage to structures by both is 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.

Windstorm Basics

- windstorms often produce flooding
- most damage/collapse is to light, poorly or non-engineered structures
- high winds load & peel off light walls/ roof of structures - especially open structures
- airborne missiles penetrate structure - cause collapse by impact or by creating open structure
- tidal surge/high waves can cause collapse/damage to engineered structures

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

WINDSTORM/FLOOD COLLAPSE DAMAGE PATTERNS

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.
- Problematical Structure Types are listed in adjacent slide.

COMMON WIND DAMAGE that 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.

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.

Common Windstorm Collapse
- roof blows off & walls collapse due to lack of lateral support
- weak walls blow out causing roof collapse
- light metal bldgs collapse due to buckling or bending failure of long span roof, pull out of frame base " weak link behavior "
- missile penetrates glazed opening or door blows in, structure changes from "closed" to "open", roof and/or walls blow out (even tilt-up concrete, etc.)

Problematic Building Types
- Wood houses
- Mobile homes
- Wood frame - multi-residence & other
- Light metal buildings
- Commercial/industrial - walls of URM, RM, TU (if large opngs are penetrated)
- Long span structures - high walls
- Aircraft Hangers

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 & high rise 1s
- loss of roofing material - tile, shingle, gravel
- all become destructive missiles

Flood Damage Patterns
- windstorms often produce flooding
- most damage is to light structures
- moving water can impact & collapse or flow past & peel off the lt. walls of bldgs s
- waterborne debris - up to house size - can cause collapse by penetrating structures
- fast moving river or tidal surge/high waves can cause collapse/damage to engineered structures

Common Flood Damage
- light frame structure shifted off foundation
- can slide if free of foundation or will tumble if one side stays attached
- broken and/or tilted foundation walls
- undermined foundations & slabs on grade
- buildings impacted by debris (floating houses)

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

EXPLOSION EFFECTS ON BUILDINGS

BASIC EXPLOSION EFFECTS

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.

Basic Explosion Effects

- Large Pressures exerted by explosions
  - can be 5000 psi +
  - duration only milliseconds
  - inversely proportional to cube of distance from source
- Severe damage to structures
  - but not proportional to static pressure effects
- Effects of fast moving shock wave
  - may be very complex

EXPLOSION EFFECTS ON SPECIFIC BUILDINGS

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.

Blast Effects on W & S Buildings

- W - Wood Structures
  - light wall/roof surfaces are blown away. remainder collapses
  - end up with leveled structure 1s
- S1 & S2 - Steel Frame Structures
  - beams / columns have small dimensions and are very resistant to sudden forces.
  - light floors may be blown away, leaving poorly braced beams & columns. 4s

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

EXPLOSION EFFECTS ON SPECIFIC BUILDINGS (continued)

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.
- The result can be a completely collapsed pile of bent and twisted steel members (structural steel spaghetti)

CONCRETE FRAMES - C1, C2, & C3 - 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.
- The remaining structure may contain columns that are standing, exposed for several stories without the lateral bracing that the collapsed floors used to provide
  - In both the World Trade Center and Murrah Federal Building in Oklahoma City, large areas of several floors collapsed leaving columns that extended a far as six stories without lateral support
  - These columns were still loaded with hundreds of thousands of pounds of load from the uncollapsed floors above, but were standing without the lateral support previously provided by the collapsed floors.
  - Lateral bracing was then provided using steel tubes.
- In C3 type concrete frames the URM infill is also particularly vulnerable to blast pressure
  - Large areas, very little resistance to the lateral pressure.

Blast Effects on S3 Buildings

- Wall & roof panels are easily blown away. and steel framing may be pushed over
- Blast at Explosives Manufacturing Plant near Reno NV ,1998.
  - First explosion was in primer mixing room
  - Set off 2nd blast and completely disintegrated structures.
  - Miraculously 12 of 16 workers escaped 4s

Blast Effects on C1, C2, & C3 Concrete Framed Structures

- Lift forces have especially devastating effects on gravity designed slabs
  - when gravity force is overcome, slabs and beams can hinge where rebar is not continuous
    - at mid-span and at span ends
- This can result in multi story columns left standing w/o enough lateral bracing
  - multi level collapse is then probable 6s
- C3 type, URM infill is also blown in/out 2s

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
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EXPLOSION EFFECTS ON SPECIFIC BUILDINGS (continued)

PRECAST CONCRETE - PC2 In precast Frame types structures the lightly (gravity) connected floor slabs and wall planes can be blown away, leaving unbraced beams and columns.

- 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.
- In Box type PC2 (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.

Blast Effects on PC2 Buildings

- PC2 - Frame type structures
  - pressures can dislodge walls, slabs
    - beams & columns then effected by lack of bracing.
  - break/damage many connections
  - progressive collapse possible.
    - Due to missing supports and dis-continuous members.
- PC2 - Box type structures
  - pressures can dislodge walls & slabs
    - break/damage many connections
  - better response in multi wall buildings 1s

POST TENSIONED CONCRETE - If the unbonded cables are damaged, becoming un-tensioned in only one small area of a floor slab, the entire length of the these cables can be effected, which can lead to the collapse of the full length of the floor.

- This type of slab is also very susceptible to upward pressures since the cables are normally draped to lift the gravity weight of the structure
- The floor slabs or beams may also have some rebar, but these bars are placed at the bottoms of slabs near mid-span and at the top near supports (as in a normal gravity design) and will not be effect in resisting the upward pressures from blasts.
- This is a **Very Vulnerable and Dangerous Post Blast Structure.**

Blast Effects on Buildings

- Postensioned Concrete - 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 3s

Blast compared to very short term - high velocity wind w/special effects

MODULE 1c STRUCTURAL ENGINEERING SYSTEMS
PART 2. COLLAPSE PATTERNS

EXPLOSION EFFECTS ON BUILDINGS (continued)

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.

Blast Effects on 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 3s

Blast compared to very short term - high velocity wind w/special effects

REVIEW OF TOPICS

In this section we have discussed:
- The types of forces that load structures
- The method that is used to classify structures
- The types of problems that various building types have experienced in the past.
- The various Collapse Patterns that have occurred that will give us some insight as to how structures will behave in future disasters.

In **Structural Engineering Systems – Parts 3 & 4** we will focus more specifically on the US&R issues of how to deal with damaged and collapsed structures.

Review of Topics

- Basic Structural Loading
- ATC -21 building classification
- Problematical building types
- Basic collapse patterns
- Earthquake collapse patterns
- Windstorm / flood collapse patterns
- Blast effects on buildings