Earthquake-Resistant Systems

3-1 Structural Systems Defined:

The *Uniform Building Code* (UBC) earthquake provisions recognize these building structural systems:

1- Bearing Wall Systems
2- Building Frame Systems
3- Moment Resisting Frame Systems
4- Dual Systems

1- Bearing wall systems consist of vertical load carrying walls located along exterior wall lines and at interior locations as necessary. Many of these bearing walls are also used to resist lateral forces and are then called shear walls. Bearing wall systems do not contain complete vertical load carrying space frames but may use some columns to support floor and roof vertical loads.

2- Building frame systems use a complete three dimensional space frame to support vertical loads, but use either shear walls or braced frames to resist lateral forces. A building frame system with shear walls is shown in Figure (3.1).
3- Moment-resisting frame systems, shown in Figure (3.2), provide a complete space frame throughout the building to carry vertical loads, and they use some of those same frame elements to resist lateral forces.
4. A dual system is a structural system in which an essentially complete frame provides support for gravity loads, and resistance to lateral loads is provided by a specially detailed moment-resisting frame and shear walls or braced frames. The moment-resisting frame must be capable of resisting at least 25 percent of the base shear, and the two systems must be designed to resist the total lateral load in proportion to their relative rigidities.

This system, which provides good redundancy, is suitable for medium-to-high rise buildings where perimeter frames are used in conjunction with central shear wall core. Concrete intermediate frames cannot be used in seismic zones 3 or 4.
3-2 Lateral-Force-Resisting Elements

Lateral-force-resisting elements must be provided in every structure to brace it against wind and seismic forces. The three principal types of resisting elements are shear walls, braced frames, and moment-resisting frames.

3-2-1 Shear Walls:

A shear wall is a vertical structural element that resists lateral forces in the plane of the wall through shear and bending. Such a wall acts as a beam cantilevered out of the foundation, and, just as with a beam, part of its strength derives from its depth. Fig. (3.3) shows two examples of a shear wall, one in a simple one-story building and another in a multistory building.

Fig. (3.3) Shear Walls
In Fig. (3.3.a), the shear walls are oriented in one direction, so only lateral forces in this direction can be resisted. The roof serves as the horizontal diaphragm and must also be designed to resist the lateral loads and transfer them to the shear walls.

Fig. (3.3.a) also shows an important aspect of shear walls in particular and vertical elements in general. This is the aspect of symmetry that has a bearing on whether torsional effects will be produced. The shear walls in Fig. (3.3.a) show the shear walls symmetrical in the plane of loading.

Fig. (3.3.b) illustrates a common use of shear walls at the interior of a multistory building. Because walls enclosing stairways, elevator shafts, and mechanical shafts are mostly solid and run the entire height of the building, they are often used for shear walls. Although not as efficient from a strictly structural point of view, interior shear walls do leave the exterior of the building open for windows.

Notice that in Fig. (3.3.b) there are shear walls in both directions, which is a more realistic situation because both wind and earthquake forces need to be resisted in both directions. In this diagram, the two shear walls are symmetrical in one direction, but the single shear wall produces a nonsymmetrical condition in the other since it is off center. Shear walls do not need to be symmetrical in a building, but symmetry is preferred to avoid torsional effects.

Shear walls, when used a lone, are suitable for medium rise buildings up to 20 stories high.
Shear walls may have openings in them, but the calculations are more difficult and their ability to resist lateral loads is reduced depending on the percentage of open area.

**What is a Shear Wall Building?**

Reinforced concrete buildings often have *vertical plate-like* RC walls called *Shear Walls* (Fig. 3.4) in addition to slabs, beams and columns. These walls generally start at foundation level and are continuous throughout the building height. Their thickness can be as low as 150mm, or as high as 400mm in high rise buildings. Shear walls are usually provided along *both* length and width of buildings (Fig. 3.4). Shear walls are like *vertically-oriented* wide *beams* that carry earthquake loads downwards to the foundation.

![Fig. (3.4) Reinforced Concrete Shear Wall](image-url)
Advantages and Disadvantages of Shear Walls in Reinforced Concrete Buildings:

Properly designed and detailed buildings with shear walls have shown very good performance in past earthquakes.

Shear walls in high seismic regions require special detailing. However, in past earthquakes, even buildings with sufficient amount of walls that were not specially detailed for seismic performance (but had enough well-distributed reinforcement) were saved from collapse. Shear wall buildings are a popular choice in many earthquake prone countries, like Chile, New Zealand and USA. Shear walls are easy to construct, because reinforcement detailing of walls is relatively straightforward and therefore easily implemented at site. Shear walls are efficient, both in terms of construction cost and effectiveness in minimizing earthquake damage in structural and nonstructural elements (like glass windows and building contents).

On the other hand, shear walls present barriers, which may interfere with architectural and services requirement. Added to this, lateral load resistance in shear wall buildings is usually concentrated on a few walls rather than on large number of columns.

Architectural Aspects of Shear Walls:

Most RC buildings with shear walls also have columns; these columns primarily carry gravity loads (i.e., those due to self-weight and contents of building). Shear walls provide large strength and stiffness to buildings in the direction of their orientation, which significantly reduces
lateral sway of the building and thereby reduces damage to structure and its contents. Since shear walls carry large horizontal earthquake forces, the overturning effects on them are large. Thus, design of their foundations requires special attention. Shear walls should be provided along preferably both length and width. However, if they are provided along only one direction, a proper grid of beams and columns in the vertical plane (called a moment-resistant frame) must be provided along the other direction to resist strong earthquake effects. Door or window openings can be provided in shear walls, but their size must be small to ensure least interruption to force flow through walls. Moreover, openings should be symmetrically located. Special design checks are required to ensure that the net cross-sectional area of a wall at an opening is sufficient to carry the horizontal earthquake force.

Shear walls in buildings must be symmetrically located in plan to reduce ill effects of twist in buildings (Fig. 3.5). They could be placed symmetrically along one or both directions in plan. Shear walls are more effective when located along exterior perimeter of the building – such a layout increases resistance of the building to twisting.
Ductile Design of Shear Walls:

Just like reinforced concrete beams and columns, reinforced concrete shear walls also perform much better if designed to be ductile. Overall geometric proportions of the wall, types and amount of reinforcement, and connection with remaining elements in the building help in improving the ductility of walls.

Overall Geometry of Walls:

Shear walls are rectangular in cross-section, i.e., one dimension of the cross-section is much larger than the other. While rectangular cross-section is common, L- and U-shaped sections are also used (Fig. 3.6). Thin-walled hollow reinforced concrete shafts around the elevator core
of buildings also act as shear walls, and should be taken advantage of to resist earthquake forces.

![Shear Wall Geometry](image)

**Fig. (3.6) Shear Wall Geometry**

**Braced Frames:**

A braced frame is a truss system of the concentric or eccentric type in which the lateral forces are resisted through axial stresses in the members. Just as with a truss, the braced frame depends on diagonal members to provide a load path for lateral forces from each building element to the foundation. Fig. (3.7.a) shows a simple one-story braced frame. At one end of the building two bays are braced, and at the other end only one bay is braced. As with Fig. (3.7.a), this building is only braced in one direction and uses compression braces because the diagonal member may be either in tension or compression, depending on which way the force is applied.
Fig. (3.7.b) shows two methods of bracing a multistory building. A single diagonal compression member in one bay can be used to brace against lateral loads coming from either direction. Alternately, tension diagonals can be used to accomplish the same result, but they must be run both ways to account for the load coming from either direction. Braced framing can be placed on the exterior or interior of a building, and may be placed in one structural bay or several. Obviously, a braced frame can present design problems for windows and doorways, but it is a very efficient and rigid lateral force resisting system.
3-2-3 Moment-Resisting Frames:

Moment-resisting frames carry lateral loads primarily by flexure in the members and joints. Joints are designed and constructed so they are theoretically completely rigid, and therefore any lateral deflection of the frame occurs from the bending of columns and beams. They are used in low-to-medium rise buildings.

The UBC differentiates between three types of moment resisting frames.

The first type is the special moment-resisting frame that must be specifically detailed to provide ductile behavior and comply with the provisions of the UBC.

The second type is the intermediate moment-resisting frame, which is a concrete frame with less restrictive requirements than special moment-resisting frames. However, intermediate frames cannot be used in seismic zones 3 or 4.

The third type is the ordinary moment-resisting frame. This concrete moment-resisting frame does not meet the special detailing requirements for ductile behavior. Ordinary concrete frames cannot be used in zones 3 or 4.

Moment-resisting frames are more flexible than shear wall structures or braced frames; the horizontal deflection, or drift, is greater, and thus non-structural elements become more problematic. Adjacent buildings cannot be located too close to each other, and special attention must be paid to
the eccentricity developed in columns, which increases the column bending stresses. Two types of moment-resisting frames are shown in Fig. (3.8)

![Figure (3.8) Moment Resisting Frames](image)

**Advantages:**

- Provide a potentially high-ductile system with a good degree of redundancy, which can allow freedom in architectural planning of internal spaces and external cladding.
- Their flexibility and associated long period may serve to detune the structure from the forcing motions on stiff soil or rock sites.

**Disadvantages:**

- Poorly designed, moment resisting frames have been observed to fail catastrophically in earthquakes, mainly by formation of weak stories and failures around beam-column joints.

- Beam column joints represent an area of high stress concentration, which needs considerable skill to design successfully.

- Requires good fixing skills and concreting.
3-2-4 Horizontal Elements (Diaphragms):

In all lateral force-resisting systems, there must be a way to transmit lateral forces to the vertical resisting elements. This is done with several types of structures, but the most common way used is the diaphragm. A diaphragm acts as a horizontal beam resisting forces with shear and bending action.

There are two types of diaphragms: flexible and rigid. Although no horizontal element is completely flexible or rigid, distinction is made between the two types because the type affects the way in which lateral forces are distributed.

A flexible diaphragm is one that has a maximum lateral deformation more than two times the average story drift of that story. This deformation can be determined by comparing the midpoint in-plane deflection of the diaphragm with the story drift of the adjoining vertical resisting elements under equivalent tributary load. The lateral load is distributed according to tributary areas as shown in Fig. (3.9.a).

With a rigid diaphragm, the shear forces transmitted from the diaphragm to the vertical elements will be in proportion to the relative stiffness of the vertical elements (assuming there is no torsion), as shown in Fig. (3.9.b). If the end walls in the diagram are twice as stiff as the interior walls, then one-third of the load is distributed to each end wall and one-third to the two interior walls, which is equally divided between these two.
The illustration shows symmetrically placed shear walls, so the distribution is equal. However, if the vertical resisting elements are asymmetric, the shearing forces are unequal.

Concrete floors are considered rigid diaphragms, as are steel and concrete composite deck construction. Steel decks may be either flexible or rigid, depending on the details of their construction. Wood decks are considered flexible diaphragms.

Fig. (3.9) Diaphragm Load Distribution
**Load Path:**
The structure shall contain one complete load path for Life Safety for seismic force effects from any horizontal direction that serves to transfer the inertial forces from the mass to the foundation.

There must be a complete lateral-force-resisting system that forms a continuous load path between the foundation, all diaphragm levels, and all portions of the building for proper seismic performance.

The general load path is as follows: seismic forces originating throughout the building are delivered through structural connections to horizontal diaphragms; the diaphragms distribute these forces to vertical lateral-force-resisting elements such as shear walls and frames; the vertical elements transfer the forces into the foundation; and the foundation transfers the forces into the supporting soil.

If there is a discontinuity in the load path, the building is unable to resist seismic forces regardless of the strength of the existing elements. Mitigation with elements or connections needed to complete the load path is necessary to achieve the selected performance level. The design professional should be watchful for gaps in the load path. Examples would include a shear wall that does not extend to the foundation, a missing shear transfer connection between a diaphragm and vertical element, a discontinuous chord at a diaphragm notch, or a missing collector.

In cases where there is a structural discontinuity, a load path may exist but it may be a very undesirable one. At a
discontinuous shear walls, for example, the diaphragm may transfer the forces to frames not intended to be part of the lateral-force-resisting system. While not ideal, it may be possible to show that the load path is acceptable.

**Primary Load-Path Elements:**

Within every building, there are multiple elements that are used to transmit and resist lateral forces. These transmitting and resisting elements define the building’s lateral-load path. This path extends from the uppermost roof or parapet, through each element and connection, to the foundation. An appreciation of the critical importance of a complete load path is essential for everyone involved in the design, construction, and inspection of buildings that must resist earthquakes.

There are two orientations of primary elements in the load path: those that are vertical, such as shear walls, braced frames, and moment frames, and those that are essentially horizontal, such as the roof, floors, and foundation.

The roof and floor elements are known as diaphragms. Diaphragms serve primarily as force-transmitting or force-distributing elements that take horizontal forces from the stories at and above their level and deliver them to walls or frames in the story immediately below. Diaphragms are classified as either flexible or rigid, and the method of distributing earthquake forces from the diaphragm to the resisting elements depends on that classification. Concrete diaphragms are considered rigid.
Shear walls and frames are primarily lateral force-resisting elements but can also perform force-transmitting functions. For example and while not necessarily desirable, an upper-story interior shear wall may not continue to the base of the building and therefore must transmit its forces to a floor diaphragm. Also, at the base of a frame or a shear wall, forces are transmitted into a foundation element. The primary structural elements that participate in the earthquake load path are shown in Fig. (3.10).

![Fig. (3.10) Primary Structural Load Path Elements](image)

Foundations form the final link in the load path by collecting the base shear and transmitting it to the ground. Foundations resist lateral forces through a combination of frictional resistance along their lower surface and lateral
bearing against the depth of soil in which they are embedded.
Foundations must also support additional vertical loads caused by the overturning forces from shear walls and frame columns.

**Secondary Load-Path Elements:**

Within the primary load-path elements, there are individual secondary elements needed to resist specific forces or to provide specific pathways along which lateral forces are transmitted.

Particular attention must be given to transmitting forces between horizontal seismic elements (diaphragms) and vertical seismic elements.

Two important secondary elements are chords and collectors. A chord is a structural member along the boundary of a diaphragm that resists tension and compression forces. A collector is a structural member that transmits diaphragm forces into shear walls or frames. Fig. (3.11) depicts the overall function of chords and collectors.
In the case of floors and roofs, the perimeter edges or boundaries are critical locations because they form the interface between the diaphragms and the perimeter walls. The perimeter is typically the location for vertical seismic elements, although many buildings also have shear walls or frames at interior locations. An interior line of resistance also creates a diaphragm boundary.

Boundary elements in diaphragms usually serve as both chords and collectors, depending on the axis along which lateral loads are considered to be applied.

As shown in Fig. (3.11), the forces acting perpendicular to the boundary elements tend to bend the diaphragm, and the chord member must resist the associated tension and compression. Similar to a uniformly loaded beam, a diaphragm experiences the greatest bending stress and largest deflection at or near the center of its span between vertical resisting seismic elements. The chord on the side of the diaphragm along which the forces are being applied is
in compression, and the chord on the opposite side is in tension. These tension and compression forces reverse when the earthquake forces reverse. Therefore, each chord must be designed for both tension and compression.

In concrete walls, reinforcing steel is placed at the diaphragm level to resist the out-of-plane bending in the wall. Collectors are needed when an individual shear wall or frame in the story immediately below the diaphragm is not continuous along the diaphragm boundary (See Figure 3.12). This is a very common situation because shear walls are often interrupted by openings for windows and doors, and because resisting frames are normally located in only a few of the frame bays along a diaphragm boundary. A path must be provided to collect the lateral forces from portions of a diaphragm located between vertical resisting seismic elements and to deliver those forces to each individual

![Fig. (3.12) Use of Collector Element at Interior Shear Wall](image)
shear wall or frame. The collector member provides that path. Collectors are commonly called drag struts or ties. Collectors are also needed when an interior shear wall or frame is provided (see Fig. 3.12). In this case, the collector is placed in the diaphragm, aligned with the wall or frame, and extends to the diaphragm edges beyond each end of the wall or frame. Collectors can occur in spandrel beams, of concrete, that link sections of shear walls together.

The following statements contained in the 1997 UBC clearly require that a complete load path be provided throughout a building to resist lateral forces. “All parts of a structure shall be interconnected and connections shall be capable of transmitting the seismic force induced by the parts being connected.”

“Any system or method of construction shall be based on a rational analysis... Such analysis shall result in a system that provides a complete load path capable of transferring all loads and forces from their point of origin to the load-resisting elements.”

To fulfill these requirements, connections must be provided between every element in the load path. When a building is shaken by an earthquake, every connection in the lateral-force load path is tested. If one or more connections fail because they were not properly designed or constructed, those remaining in parallel paths receive additional force, which may cause them to become overstressed and to fail. If this progression of individual connection failures continues, it can result in the failure of a complete resisting seismic element and, potentially, the entire lateral-force-resisting system. Consequently, connections are essential
for providing adequate resistance to earthquakes and must be given special attention by both designers and inspectors.

Connections are details of construction that perform the work of force transfer between the individual primary and secondary structural elements discussed above. They include a vast array of materials, products, and methods of Construction.

In concrete construction, diaphragm-reinforcing steel resists forces in the diaphragm and chord tension stresses, and reinforcing dowels are generally used to transfer forces from the diaphragm boundaries to concrete walls or frames.