PART 3

THE TECTONICS OF FLEXURAL STRUCTURES

Flexural structures are the structures which respond to external loading by developing mainly bending stress in their elements. The elements of these structures are usually straight. Reinforced concrete or steel frame systems and shear wall systems, which take place within this group, are studied in Chapter 9. This chapter covers elements of flexural structures, their structural behaviour, reasons of selecting flexural structures, earthquake resistant design of them, case-studies of reinforced concrete and steel frame systems and shear wall systems, and finally a discussion about the tectonics of flexural structures.

Most of the buildings which have flexural structures are modern. These buildings are frequently subjected to functional changes and they are usually re-designed by interior architects at a later stage. During this design process of the existing building the structural elements of the building are also re-considered: they can be subtracted, changed or new elements can be added to the existing structure. The structural guidelines about the ways of handling flexural structures during the interior design process are collected in Chapter 10.

Flexural structures are also used in the design of high-rise buildings. Frame and shear wall systems can be used up to a limit. Various types of tubular structures, which are also flexural structures, are used for the highest buildings. Strategies of increasing the height of building structures and structural guidelines for high-rise building structures are studied in Chapter 11. Similar to Part 2, Part 3 also ends with a discussion about the never ending contradiction between the structural guidelines and architectural examples.

CHAPTER 9

THE TECTONICS OF FRAME AND SHEAR WALL SYSTEMS

Main characteristics of frame systems can be better understood by comparing frame systems with post and lintel systems. Figure 9.1 shows these two systems together.

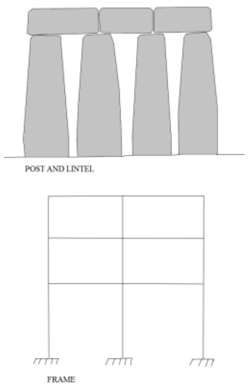


Figure 9.1. Frame system and post and lintel system

The horizontal elements in post and lintel systems work with bending stress and vertical elements work with compression. However, both the horizontal and vertical elements in a frame system bend as seen in Figure 9.2. The main reason for this is continuity between the elements. If a beam bends, the column adjacent to that beam will also bend because of the continuity. Since the angle between the beam and the column is assumed to remain the same, the column also bends together with the beam.

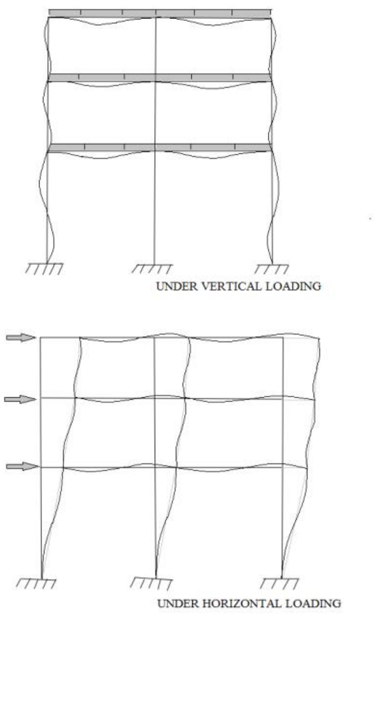


Figure 9.2. Deformation of frames under vertical and horizontal loads

The compression in the columns of a frame effects the beams as shear force as seen in Figure 9.3. Every joint should be in equilibrium in Figure 9.3. Similarly, the shear in the columns of a frame affects the beams as tension or compression. Axial force (tension or compression) and bending exist simultaneously in all frame elements.

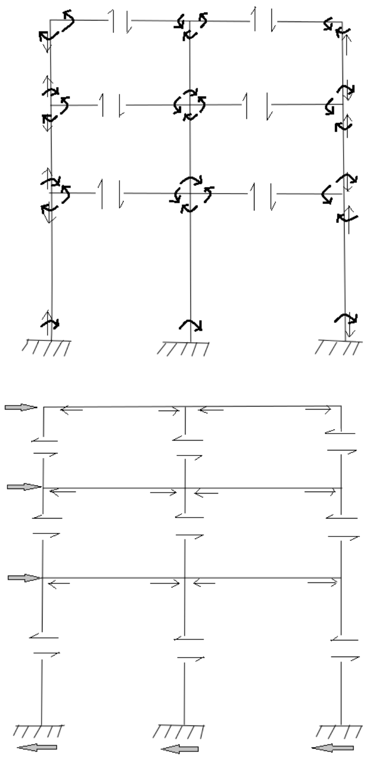


Figure 9.3. Axial force and shear force in the elements of frames

Continuity makes frame systems stronger than post and lintel systems, because all frame elements help each other.

Elements of Frame Systems

As seen in Figure 9.4, three dimensional frame systems can be analyzed as two dimensional frames in both orthogonal directions with beams connecting them to create the whole. There are two dimensional frames on axes A, B, C, 1 and 2.

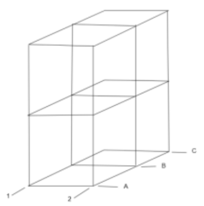


Figure 9.4. Two dimensional frames within a 3D frame

Common elements which make up frame systems are as follows:

- Beams,
- Columns,
- Slabs,
- Partition walls,
- Stairs,
- Foundations,

- Expansion joints.

Beams

Beams in frames are usually horizontal elements, which have bending, shear and axial stress simultaneously. They can be slightly curved in plan, but it is beneficial for them not to contain any corners in them. Corners and strong curves cause twisting and stress concentration in the beams.

Approximate dimensions of beams can be determined by considering the type of material used. The approximate depth of reinforced concrete beams is calculated as follows:

d = length / 10

where;

d: depth,

length: span (distance between two supports - columns)

According to the Turkish building code the minimum depth of a beam can be 30 cm (Ministry of Public Works and Settlement Government of the Republic of Turkey, 2007).

The approximate depth of steel beams is calculated as follows:

d = length / 20

The depth of beams is more critical than their width because of the direction of bending stress in them. Chapter 4 studies the subject of bending stress in detail. The minimum width of reinforced concrete beams is 20 cm, because this is the minimum required in order to physically place reinforcement into the formwork and work on it.

High strength reinforced concrete beams can span up to approximately15 meters (Engel, 1997). The moment created by the dead-weight of the beam might exceed the moment resisting capacity of it, depending on the further increase in span. However, the optimum span for reinforced concrete beams is approximately 4,5 or 5 meters and this reduces the cost of the structure.

Prefabricated pre-stressed reinforced concrete box girders can span up to 18 meters (Mieczyslaw, Zbigniew, 2014) However, the current research about UHPFRC (Ultra-high Performance Fiber Reinforced Concrete) and its applications show that the span of UHPFRC single span beams can go up to 70 meters. The depth to span ratio of these beams can be 1/38. This means that a beam spanning 70 meters can be 1,8 meters deep as it is the case in Passerelle des Anges Footbridge in Herault Gorges, France (Abrams, 2013; Resplendino, Toulemonde, 2010).

The optimum span of steel beams is around 7 meters. Specially designed steel beams can span up to 20 meters. Box girder bridges can be shown as examples for longer span steel structures, which can span up to 100 – 200 meters (Steel Construction Info, n.d.).

Columns

Columns in frames are usually vertical elements, which have bending, shear and axial stress simultaneously. They can be inclined too. If the structure will take place in a low risk earthquake region, the approximate dimensions of columns can be determined by examining other existing structures which are similar in size and structural material.

The minimum practical plan dimensions of reinforced concrete columns is 20 cm by 20 cm. Otherwise it will not be possible to replace reinforcement into the formwork. The minimum for reinforced concrete columns is defined as 25 cm to 30 cm by the Turkish building code (Ministry of Public Works and Settlement Government of the Republic of Turkey, 2007).

The thickness of steel plates is around 4 to 5 cm for steel columns. Proportions of these plates, in terms of the ratio between width and thickness, is important (Ministry of Public Works and Settlement Government of the Republic of Turkey, 2007).

Columns usually resist bending and compression. There might also be buckling problem if the column is slender. The subject of buckling is studied in Chapter 4 under the heading of “compressive stress.”

It is better if all columns reach the foundations. The direction of the columns on a plan should be well distributed. It is better to use the outer columns perpendicular to the facade of the building as seen in Figure 9.5. These columns will resist against horizontal loads acting on the structure.

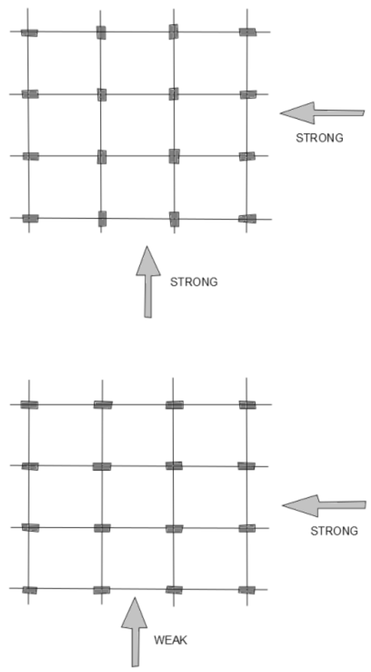


Figure 9.5. Directions of the columns in plan

Slabs

Slabs can be classified according to their structural material. This book covers only reinforced concrete and steel slabs.

Reinforced concrete slabs

As seen in Figure 9.6, the most common reinforced concrete slab types are as follows:

- One way slab,
- Two way slab,
- Flat slab,
- Ribbed slab,
- Waffled slab.

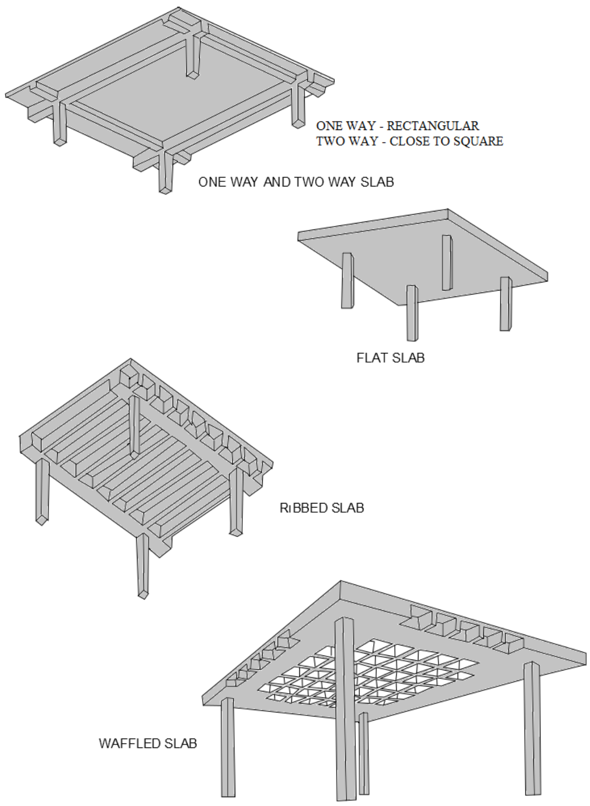


Figure 9.6. Reinforced concrete slab types

One Way and Two Way Slabs **-** If the slab is supported by beams in all directions and if the shorter dimension of the slab is under 7 m, a one or two way slab is used. A one way slab is preferred if the longer dimension of the slab is equal to or over two times its shorter dimension. The structural plan and section of one way and two way slabs are as seen in Figure 9.7.

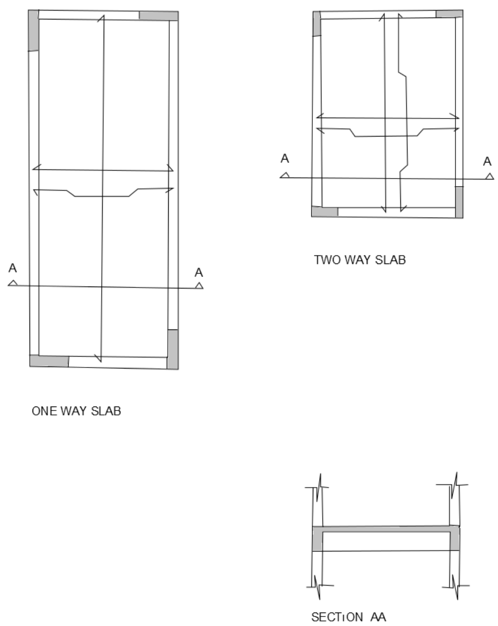


Figure 9.7. Structural plan (with reinforcement) and section of one way and two way slabs

A two way slab is preferred if the shape of the slab is closer to a square. The main reinforcement direction in one way slabs is in the shorter direction. Two way slabs contain reinforcement in both orthogonal directions (See Figure 9.7).

The depth of one way slabs can be between length/20 and length/30, while depth of two way slabs can be between length/30 and length/40, having length as the shorter span (ACI318-95, 1995). The thickness of these slabs is usually around 15 cm. If the thickness exceeds 20 cm, it is better to use either ribbed or waffled slabs to avoid extra dead load.

Flat Slab **-** If a slab is not supported by beams, it can be called a flat slab. There are no beams, but the reinforcement between the columns is more than the other parts of the slab. Figure 9.8 shows different applications of flat slabs. Since this type of slab is weaker than one way and two way slabs, their span is usually kept around 4 m in earthquake regions. However, according to the Cement and Concrete Association of Australia (2003) it is economic to span 6 to 8 meters with flat slabs. If they are pre-stressed this becomes 8 to 12 meters.

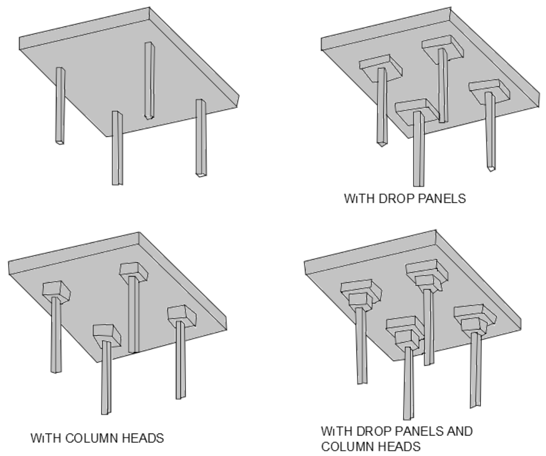


Figure 9.8. Different applications of flat slab

Ribbed and Waffled Slabs **-** Ribbed and waffled slabs are used if the shorter span of the slab is longer than 7 m. A ribbed slab is preferred if the slab shape is rectangular and a waffled slab is preferred if the slab shape is close to square.

Concrete is weak against tension. Since the bottom parts of slabs are in tension under the effect of dead loads, it is better to reduce the concrete and increase the steel at these locations. The concrete should be concentrated at the top part of slabs, where compression exists. Figure 9.9 shows structural plan and section of a ribbed slab.

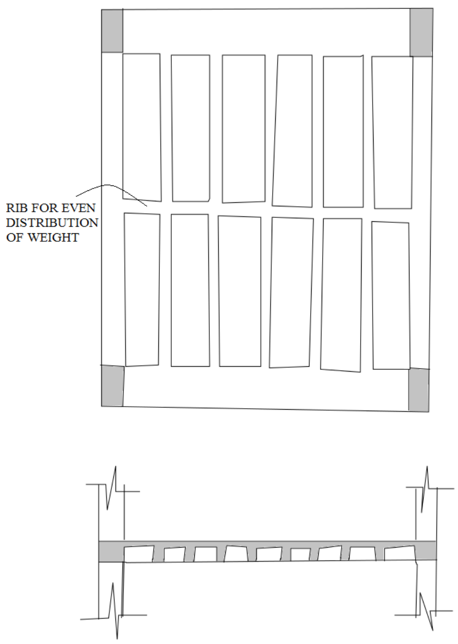


Figure 9.9. Structural plan and sections of a ribbed slab

Ribs are not as thick as beams. They can be 15 cm thick. The distance between the two ribs is maximum 1 m (See Figure 9.10). Since ribs are closely placed, ribbed slabs behave all together. A force on one rib affects all ribs. If the slab size is large, another rib in the opposite direction is added to distribute the load to all ribs evenly.

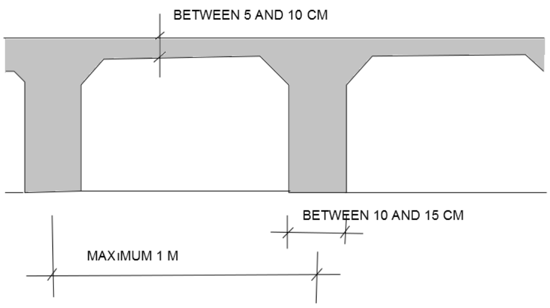


Figure 9.10. Dimensions of ribs

Ribs can be used in the longer direction in order to avoid heavy load on the longer beam. If an additional column supports the beam in the longer direction, then ribs can be used in the shorter direction.

Ribs are used in two directions in waffled slabs as seen in Figure 9.11. Waffled slabs can be used up to 15 m of span (Cement and Concrete Association of Australia, 2003). They can be longer if they are post-tensioned. It is also possible to have triangular waffled slabs, which can span longer distances.

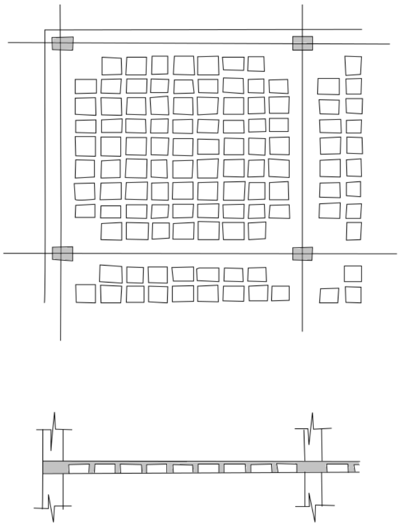


Figure 9.11. Structural plan and section of a waffled slab

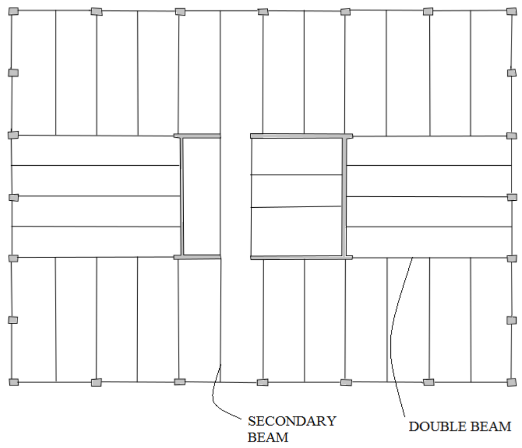
Waffled slabs can also be used for irregularly formed slabs. To avoid complication in the arrangement of formwork, the form of the beam can be designed as seen in Figure 9.12.

Figure 9.12. An example of arrangement of ribs and beams in irregularly formed slabs

The span to depth ratio of waffled slabs changes between 15 and 20 (Cement and Concrete Association of Australia, 2003). However, they are usually designed at the same depth as the beams surrounding them for aesthetic reasons. If the seismic risk is high, this can be done by increasing the width of the beam and reducing its depth. However, it is not good to reduce the depth of the beam too much. For example, the Turkish building code (Ministry of Public Works and Settlement Government of the Republic of Turkey, 2007) limits the depth to width ratio of reinforced concrete beams. According to New Zealand building code, ratio of length of the beam to its width should be equal to or under 25 (NZS3101.1, 2006).

Steel Slabs

Steel slabs can be formed by using secondary steel beams or trusses. The secondary beams, which can be 7 to 20 meters long, can be placed in the shorter direction in every 2 to 5 meters depending on the cover on top of them as seen in Figure 9.13. Similarly, secondary trusses might be spaced 1 to 3 meters. F.D.K. Ching`s (1991) book shows various applications of such steel slabs.



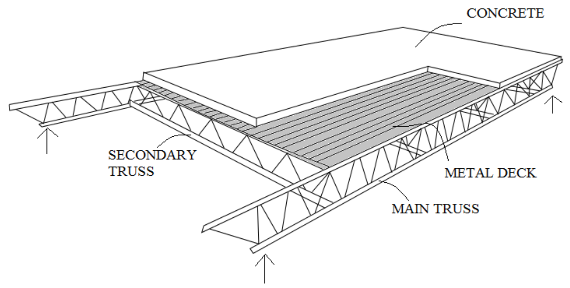


Figure 9.13. Use of secondary steel beams and trusses

Partition Walls

One of the most important tectonic characteristics of frame systems is their lightness in comparison to masonry structures. Frames are lighter because the walls in the structure are non-load bearing walls and they can be replaced by large openings. Such walls are called partition walls and they are different to load bearing walls.

Non-load bearing walls can be classified into two groups from a structural point of view. There can be lightweight partition walls, such as timber, gypsum and metal panels. There can also be rigid partition walls, which can be built with the help of various types of non-load bearing bricks.

Unlike light weight panels, rigid partition walls affect the structural behaviour of frame systems by not allowing deflection of adjacent beams and columns. Badly placed rigid partition walls can cause damage to structures during earthquakes. Similarly, correctly placed rigid partition walls can increase the earthquake resistance of structures. Thus, the arrangement of rigid partition walls should be considered consciously during architectural design. This subject will be studied further within this chapter under the heading of "Earthquake Resistant Design of Frame Systems".

It is better to place rigid partition walls over the beams (or very close to the beams) of a frame in order to be able to transfer their weight directly to these beams.

Stairs

Stairs are special elements in frame structures. There can be various arrangements of stair-case structures. These are:

- Supporting flights and landings in a staircase with stringer beams,
- Design of landings and steps in a flight as cantilevers,
- Design of the whole staircase as a cantilever.

Supporting flights and landings in a stair-case with stringer beams

The structure of these types of stairs can be understood by imagining flights (or steps) in a stair-case as slabs, which can be carried by stringer beams in two different ways. As seen in Figure 9.14 there can be a stringer beam at the middle of the flight or there can be two stringer beams on two sides of the flight.

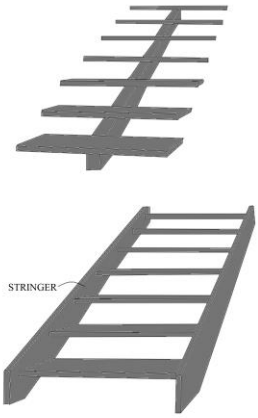


Figure 9.14. Structure of a flight

These stringers can sit directly on beams, which take place on two sides of the stair, or they can be designed as bent stringers and sit on beams, which are 1 or 1,5 meters away from the flight, as seen in Figure 9.15. These beams can be the beams of the frame system, which sit on columns on two sides.

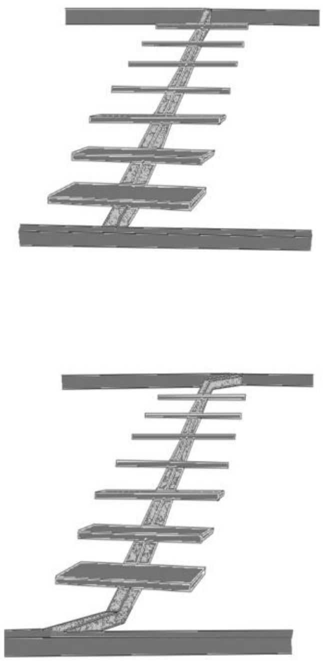


Figure 9.15. Transfer of the weight of the flight to the frame through beams

However, if there are landings in a stair-case, these landings should also be supported. Figure 9.16 shows some arrangements of beams to carry the flights and landings in different types of arrangements.

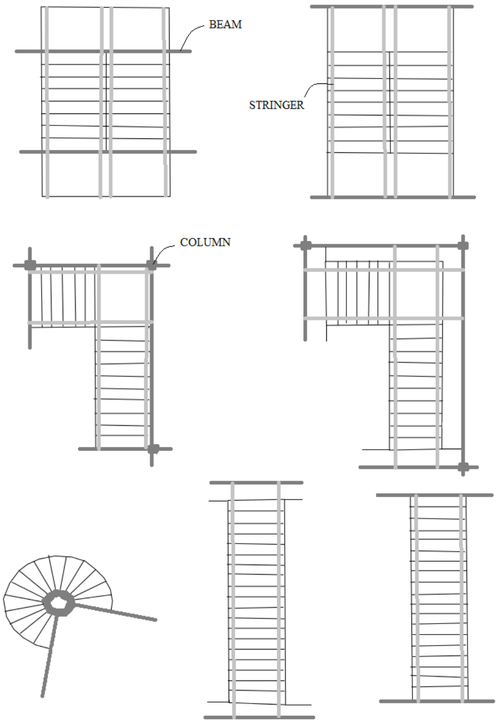


Figure 9.16. Use of beams to carry flights and landings in different arrangements

As seen in Figure 9.16 there is a hierarchy between the elements in stair-cases. The main beam of the frame is the first in the hierarchy. Then there can be beams around the landing which are the second in the hierarchy and the beams carrying the flights (stringers) can be the third in the hierarchy. These beams rest on each other, which is not seen as a good solution for the beams of a frame. With the exception of the stair-case beams, it is better not to let beams sit on each other. Because, if beams sit on each other, this means that one of them applies concentrated load to the other and this increases the moment in the second one.

The stairs, which take place within this group, can be achieved by using different types of structural materials, such as steel, timber and reinforced concrete.

Design of landings and steps in a flight as cantilevers

Each step can be designed as a cantilever from a wall, a beam or a column. Figure 9.17 shows a stair-case, in which steps are cantilevering from a beam.

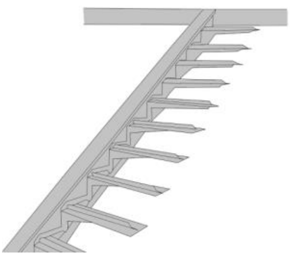


Figure 9.17. Cantilevering steps

This type of stairs can also be achieved by using various structural materials, such as steel, timber and reinforced concrete. Many stone stair-cases are arranged with the help of stone steps cantilevering from stone walls.

Design of whole stair-case as a cantilever

If the structural material is monolithic, such as reinforced concrete, it also becomes possible to design the whole stair-case as a cantilever as seen in Figure 9.18.

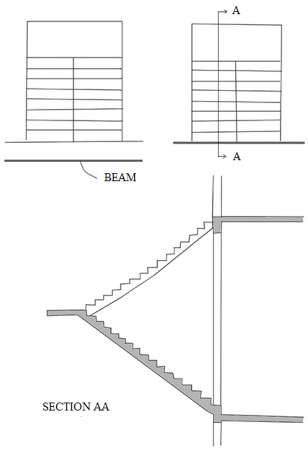


Figure 9.18. Whole stair-case as a cantilever

Structure of slabs which are adjacent to stairs

Stairs are one of the first things to control in a student project in order to evaluate the structural proposal. However, the problem usually arises not because of the structure of stairs, but because of the structure of the adjacent slabs. It is better to have all of the slabs around a stair-case surrounded by beams which directly sit on columns. Figure 9.19 shows a problematic and a correct solution of slab structures which are adjacent to stair-cases.

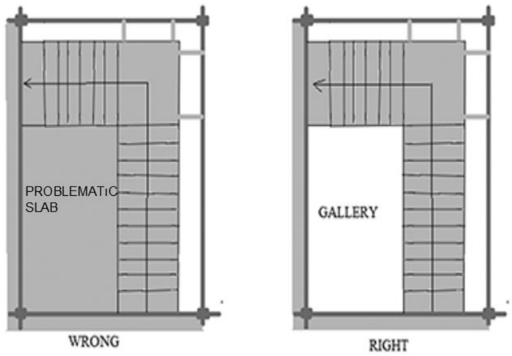


Figure 9.19. A problematic and correct solution of slab structures adjacent to stair-cases

Foundation Systems which are used with Frame Systems

The role of foundations are:

- To transfer loads acting on the building structure to earth,
- To avoid overturning instability,
- To avoid lateral sliding,
- To avoid uneven settlement.

Types of foundation systems which can be used together with frame systems can be categorized into four groups. These are:

- Individual footings,

- Slab-on-ground foundations,
- Raft (mat) foundations,
- Pier and pile foundations.

The type of foundation is chosen according to soil quality and the loads affecting the building structure. If the soil is sufficiently strong to carry the weight of the building, individual footings might be preferred. Slab-on-ground foundations are used on expansive soil and for small buildings, which are not higher than two floors. Raft foundations distribute heavy loads to weak and expansive soil. Pier and pile foundations can be used if the firm soil is deep and difficult to reach.

Individual footings are used under each column and they are connected to each other at footing level and earth level as seen in Figure 9.20.

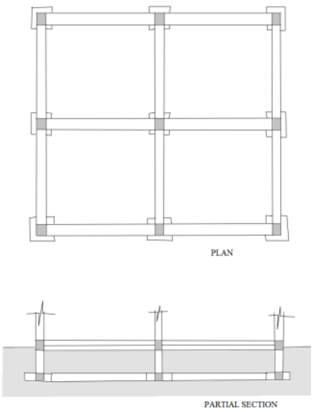


Figure 9.20. Plan and section of a structure with individual footings

The depth of these foundations is determined according the depth of firm soil and frost level. However, they are often around 80 cm deep. The area of the footings is determined according to the bearing capacity of the soil and the weight of the building. If individual footings get too close to each other they are connected as shown in Figure 9.21.

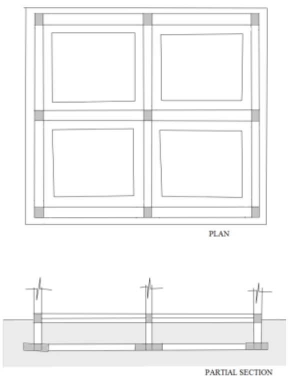


Figure 9.21. Connecting individual footings to each other

Slab-on-ground foundations have to be a minimum of 50 cm deep in the ground and 10 cm outside the ground; a total of 60 cm deep as seen in Figure 9.22. They are used for buildings under two floors in order to avoid overturning due to earthquake forces.

Figure 9.22. Section of slab-on-ground foundation

If the building is on rock, then the reinforced concrete foundation surface over the rock should be connected with the help of borings.

Raft or mat foundations can be imagined as inverted slabs, which can be in various forms as seen in Figure 9.23. The simplest type of raft foundation has similarities to a boat in the sea. If the weight of the removed soil from the building site is equal to the weight of the building, this means that the soil at that level can easily carry the weight of the building. This structure is similar to an inverted flat slab. By adding inverted beams, ribs and waffles to it the resistance of the inverted slab can be increased.

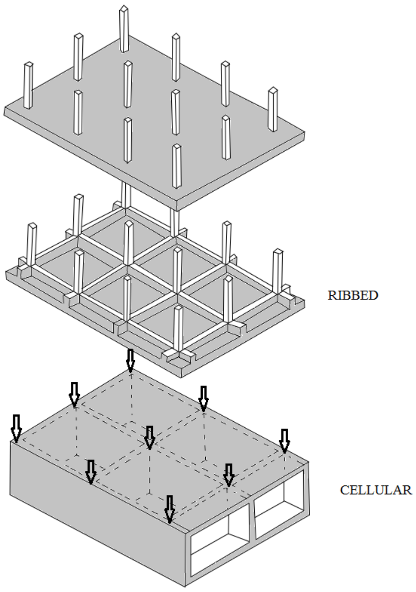


Figure 9.23. Various applications of raft foundation

Pile foundations are more slender than pier foundations and they can reach deeper levels. End bearing pile foundations can reach the firm soil at deep levels. If the firm soil is unreachable, then friction piles are used (See Figure 9.24). The surface of friction piles are designed in such a way that the pile can carry the weight of the building with the friction on its surfaces. There can be concrete, wood and steel piles. Concrete encased with a circular steel shell can also form a pile.

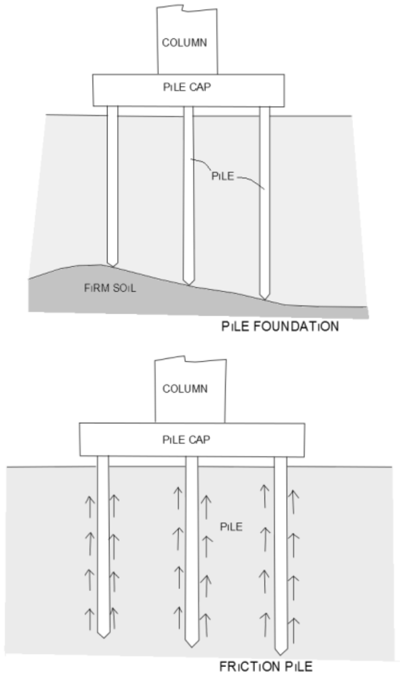


Figure 9.24. Pile foundations

Expansion Joints

Expansion joints separate building structures into parts for various reasons. Expansion joints might be needed in the following conditions, which are shown in Figure 9.25:

a. If one part of the building is much higher than the other parts, expansion joint is used to separate the structures of these parts with different heights,

b. If one part of the building has another structural material / structural system, then the parts with different structural materials / systems are separated with expansion joints,

c. If the plan of the building contains deep recesses, this might cause problems in case of earthquakes. Thus, the recesses are separated from the main body by using expansion joints,

d. If the plan of the building is larger than 30 m by 30 m, then the structure of the building is separated into smaller pieces with the help of expansion joints in order to decrease temperature load (See Chapter 4, types of loads),

e. If the building sits partially on strong soil and partially on weak soil, then the part of the building on strong soil is separated from the part on weak soil with the help of expansion joints.

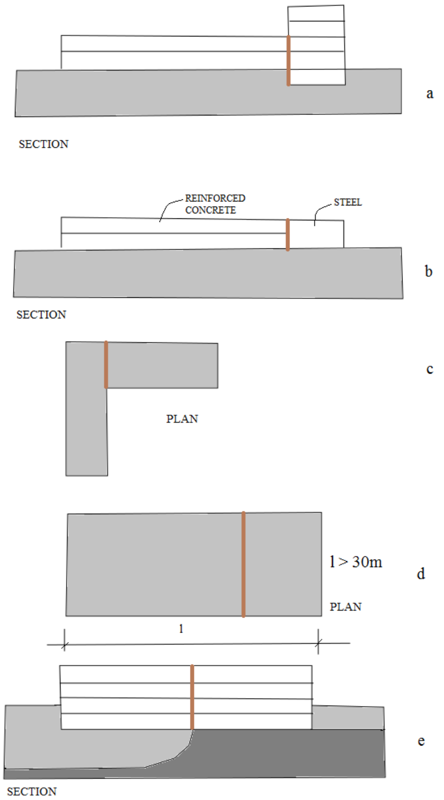


Figure 9.25. Places to use expansion joints

If the expansion joint is needed to avoid temperature load, then it is not necessary to continue the expansion joint at foundation level. However, if the expansion joint is needed for any of the other reasons, then it is better to continue the expansion joint at the foundation level. If the expansion joint continues at the foundation level, it simplifies the structural design process, because the different parts of the structure become totally independent from each other.

The minimum thickness of an expansion joint is approximately 3 cm. According to the Turkish building code, if the building is higher than 6 meters, then 1 cm is added to the thickness of expansion joints for every additional 3 meters (Ministry of Public Works and Settlement Government of the Republic of Turkey, 2007). For example, for a 5 floors high building the expansion joint will be approximately 6 cm.

Expansion joints can be arranged in framed structures in three different ways, which are shown in Figure 9.26. Similar applications can be carried out by separating the foundations. Whether the foundations are separated or not, the expansion joint can be between the columns or cantilevers.

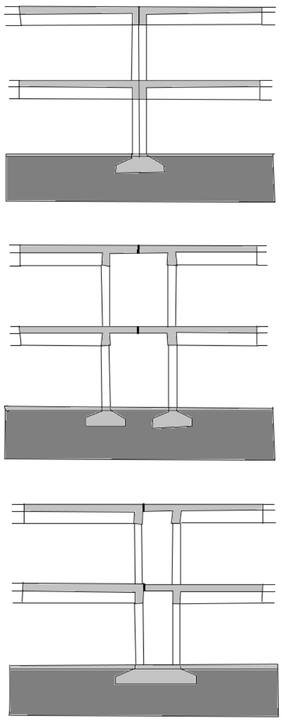


Figure 9.26. Different applications of expansion joints

Shear Wall Systems and use of Shear Walls Together with Frame Systems

The Turkish building code defines the minimum dimensions of reinforced concrete shear walls as 20 cm in thickness and seven times the thickness in length as seen in Figure 9.27.a (Ministry of Public Works and Settlement Government of the Republic of Turkey, 2007). The American Concrete Institute defines the thickness of shear walls as length/25, having 'length' as either height or length, whichever is shorter (ACI318-95, 1995).

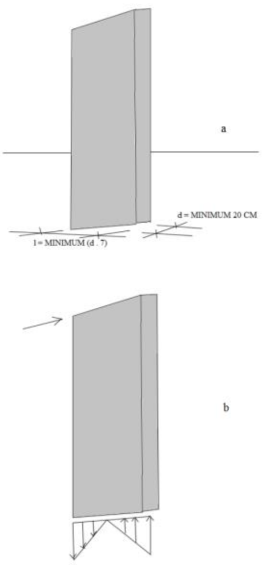


Figure 9.27. a. Minimum dimensions of reinforced concrete shear walls
b. Transfer of horizontal load by reinforced concrete shear walls

A shear wall is very useful in resisting horizontal (lateral) loads such as earthquake and wind loads. It can transfer horizontal loads to foundations as seen in Figure 9.27.b. Thus, all shear walls should reach the foundations.

The ratio of wall area to floor area can be between 5% and 10% according to the NIST (National Institute of Standards and Technology, 2012)

There can also be steel shear walls with various applications of bracing as seen in Figure 9.28.

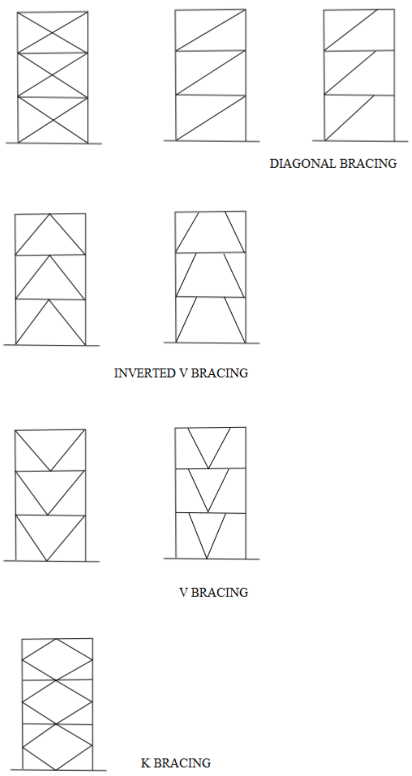


Figure 9.28. Steel shear walls

Shear force in a steel shear wall is taken by the diagonal elements as seen in Figure 9.29. One diagonal is in tension and the other is in compression. Similarly, one column is in tension, while the other is in compression.

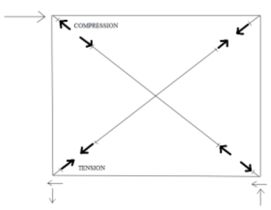


Figure 9.29. Internal forces in a steel shear wall

Buildings can be formed by using shear walls as the only structural system. However, the most common application of shear walls is with frame systems. Shear wall structures are very frequently used together with frames to increase the resistance of frames against horizontal loads. The Japanese building code suggests the use of frames together with shear walls as one of the main strategies against earthquakes (Paz, 1994). These shear walls should be evenly distributed in both of the orthogonal directions, as seen in Figure 9.30, in order to avoid twisting instability problem, which is described under 9.5.

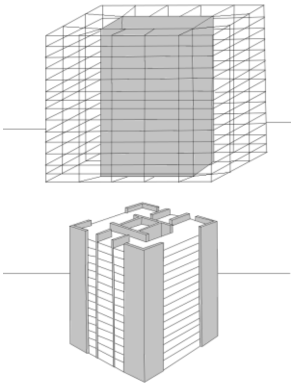


Figure 9.30. Distribution of shear walls within the structure

Finding Internal Forces in Frames

Finding internal forces in frames is not one of the common practices in an architect`s professional life. However, it is still taught in schools of architecture for the following reasons:

- To be able to communicate at the level of the scientific knowledge about building structures,
- Solving problems teaches a lot about the structural issues, which are difficult to teach in other ways,
- To be able to communicate with structural engineers,
- To be able to make some simple calculations during architectural design.

Still, the author of this book thinks that the way architects are educated in addressing internal forces must be different than the way structural engineers are educated. It is better to teach structures to students of architecture by using graphical and approximate methods. It is also better to base the knowledge of structures on deformed or deflected shape of the structure in order to let architects imagine what might happen to the structures of their projects in the future. For this reason, this part of the book teaches the following methods:

- Drawing N (axial force), V (shear force), M (moment) diagrams and deflected shape of determinate systems (small systems with maximum 3 unknown support reactions),

- Drawing N, V, M diagrams and deflected shape of indeterminate frames (larger systems with more than 3 unknown support reactions) by using the Portal Method.

Drawing N, V, M Diagrams and the Deflected Shape of Determinate Systems

The first step in drawing internal force diagrams N (axial), V (shear), M (moment) and deflected shape is to find the unknown reactions. Reactions of determinate systems, which have only 3 unknown reactions, can be found by using 3 equations of equilibrium as described in Chapter 4. Then, the diagrams can be drawn. N diagram is not related to V and M diagrams and deflected shape, but M diagrams can be drawn with the help of V diagrams and deflected shape can be drawn with the help of M diagrams.

N diagrams shows axial forces at every point of the structural member. It is drawn by considering the effects of forces which are parallel to the axis of the structural member. The four steps of drawing N diagrams are shown in Figure 9.31. The first step is to draw the system without any forces and reactions. The second step is to show the forces, which are parallel to the axis of the member, on the system. The third step is to sign the application points of these forces. There is an axial force between these points. If the forces are towards each other, then there is compression. If the forces are going away from each other, then there is tension. Compression is shown as minus and tension is shown as plus in the axial force diagram. The fourth and the last step is to draw the diagram.

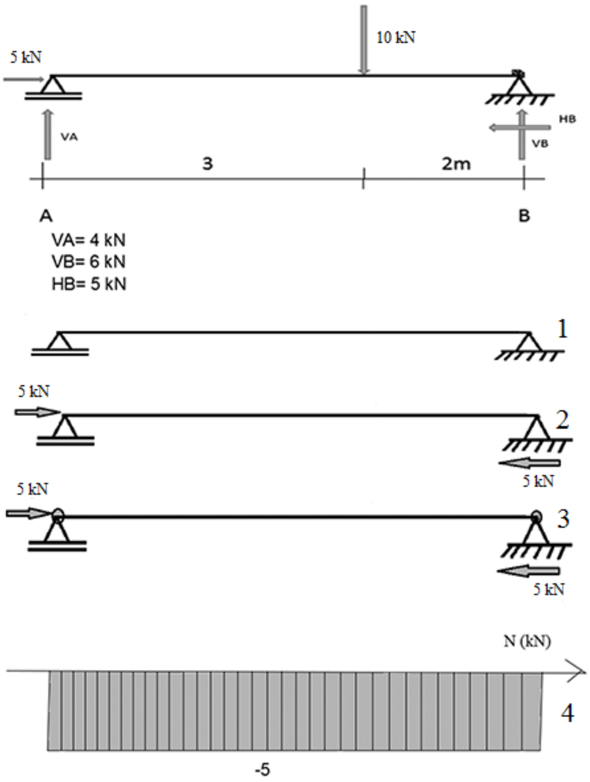


Figure 9.31. The four steps of drawing an N diagram

The V diagram shows shear forces at every point of the structural member. V diagrams are drawn by considering the effects of forces which are perpendicular to the axis of the structural member. To be able to draw the diagram one can start from the left side of the diagram and move his/her pencil together with the forces which are perpendicular to the axis of the member. Figure 9.32 shows steps of drawing shear diagram of the same system. If the V diagram is not closed, this means that there is something wrong in $\sum F_y$ equation.

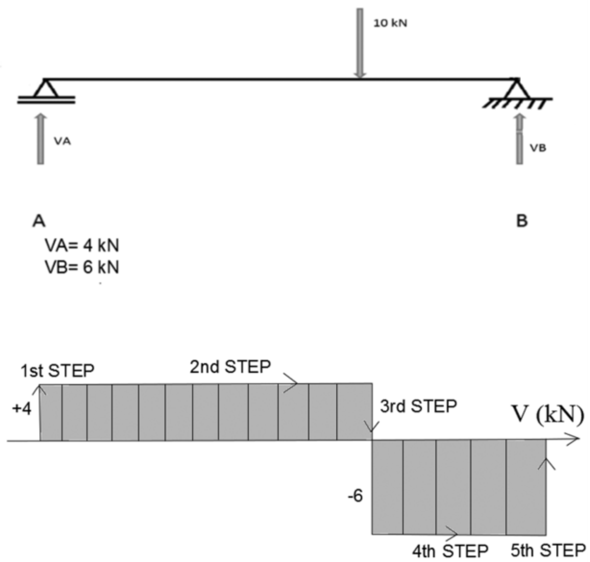


Figure 9.32. Steps of drawing a V diagram

The M diagram shows the moment at every point of the structural member. It is drawn by considering the effects of all forces including vertical and horizontal forces and all moments. Figure 9.33 shows the steps of drawing the M diagram. The first step is to find the moment values at the end points of the system. The moment arrows, which press the top of the member, can be accepted as positive and the moment arrows, which press the bottom of the member, can be accepted as negative. However, the opposite of these signs can also be used.

The rest of the diagram is drawn by considering that *"change in the moment diagram is equal to the corresponding area in the shear diagram.*" For this purpose areas in the shear diagram are calculated as the second step. Then, starting from the left of the M diagram one can move his/her pencil diagonally upwards with the positive shear areas and diagonally downwards with the negative shear areas. This forms the third and last step of drawing a moment diagram. The diagram should be closed. If not, this means that there is something wrong in the application of three equations of equilibrium.

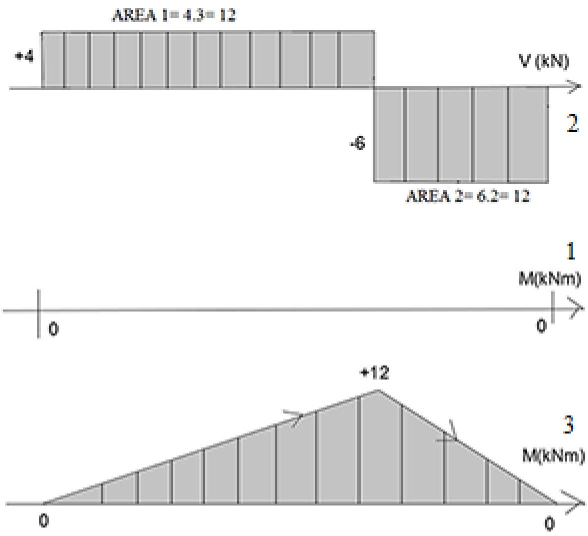


Figure 9.33. Steps of drawing an M diagram

Deflected shape can be drawn with the help of the M diagram. If there is a positive moment in the member, this means that the deflected shape will be negatively curved. If there is negative moment, this means that the deflected shape will be positively curved as seen in Figure 9.34. Determining the shape of the curvature forms the first step of drawing the deflected shape. Then one should consider there cannot be any deflection at the supports of the system. This means that the deflected shape should pass from the support points as the second step of drawing the deflected shape.

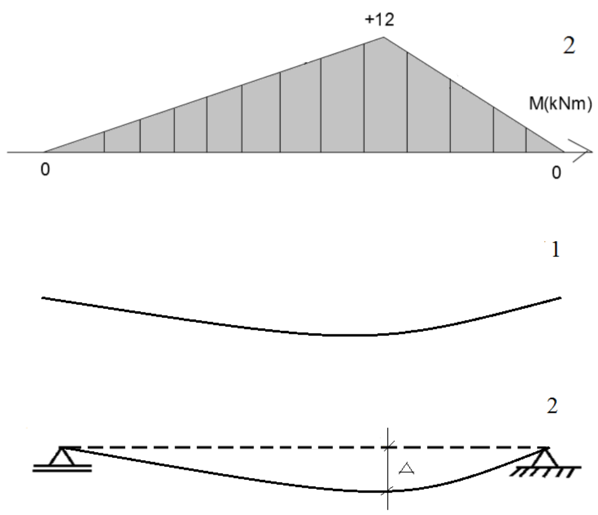


Figure 9.34. Steps of drawing deflected shape

Concentrated forces cause rectangular areas in the V diagram and triangular areas in the M diagram. Distributed forces cause triangular areas in the V diagram and parabolic areas in the M diagram. To be able to draw the parabolic curves in the M diagram, one should divide the corresponding triangular area in V diagram into small pieces and consider that the smaller areas will create less change, whilst the larger areas create more change as seen in Figure 9.35.

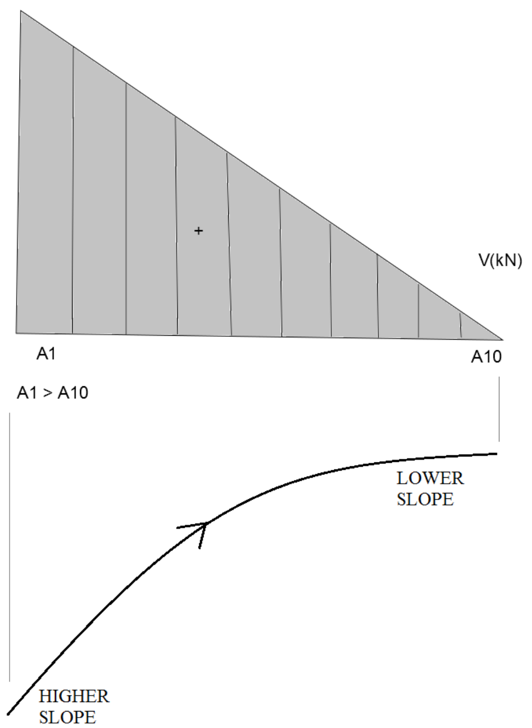


Figure 9.35. Drawing parabolic curves in the M diagram

Example 9.1. Draw the N,V,M diagrams and the deflected shape of the system shown in Figure 9.36.

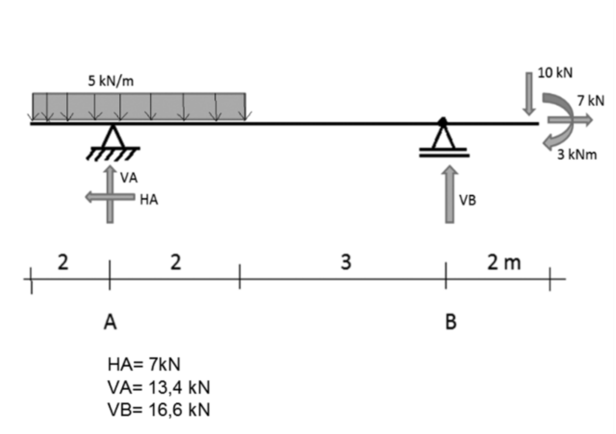


Figure 9.36. A system to draw N,V,M diagrams and deflected shape

Figure 9.37 shows the N,V,M diagrams and deflected shape of the system shown in Figure 9.36.

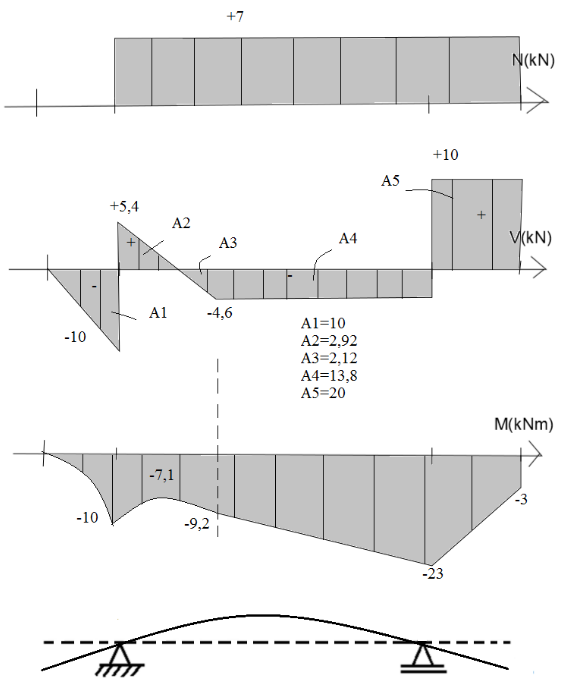


Figure 9.37. N,V,M diagrams and deflected shape of the system in Figure 9.36

Example 9.2. Draw the N,V,M diagrams and the deflected shape of the system shown in Figure 9.38.

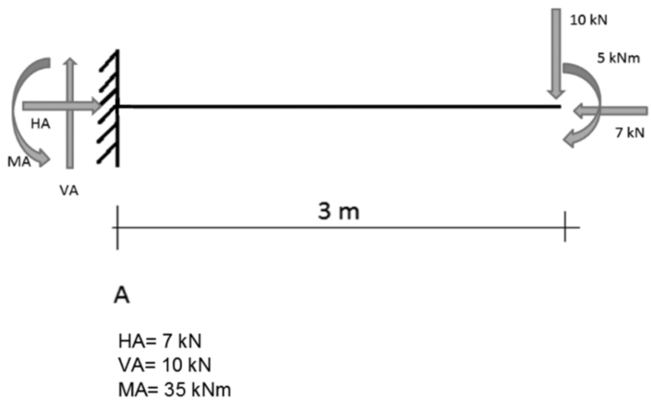


Figure 9.38. Another system to draw N,V,M diagrams and deflected shape

Figure 9.39 shows the N,V,M diagrams and deflected shape of the system shown in Figure 9.38.

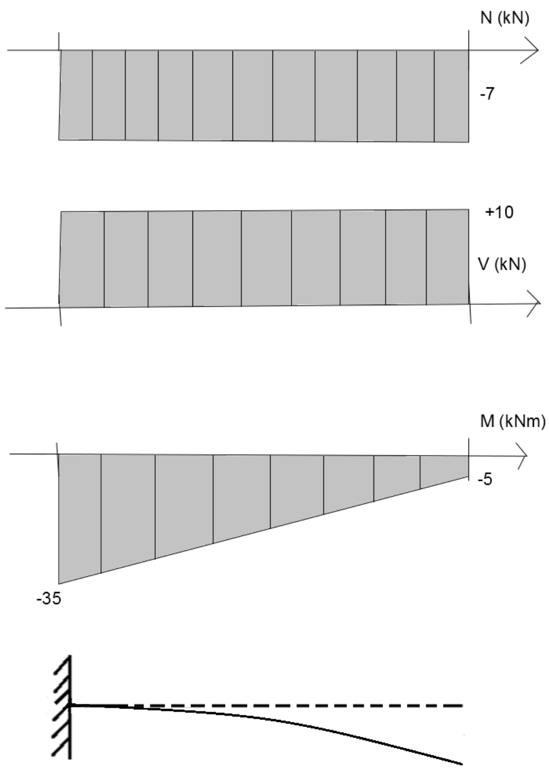


Figure 9.39. N,V,M diagrams and deflected shape of the system in Figure 9.38

The determinate systems can also have columns. As seen in Figure 9.40 there can be three types of columns according to the support type they have.

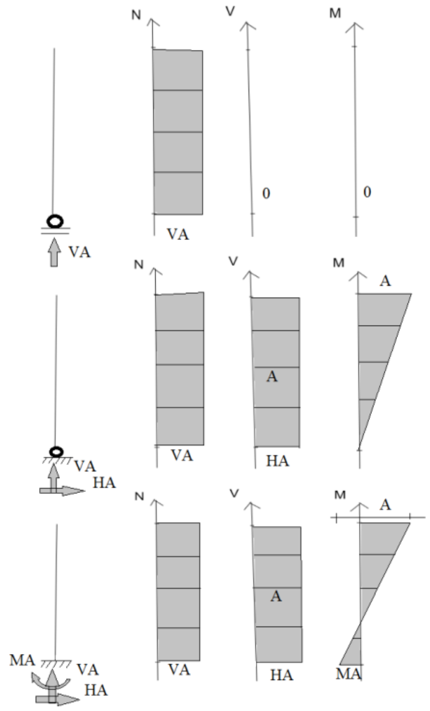


Figure 9.40. Types of columns in determinate systems

The N,V,M diagrams and deflected shape of these columns are also drawn in the same way. The left side of the column is accepted as the positive side and the right side is accepted as the negative side. The axial force in columns is seen as shear in beams, and the shear force in columns is seen as an axial force in beams. Thus, there is no relationship between the columns and beams while drawing N and V diagrams. However, this is not true for the M diagram. The M value in columns effects M value in beams. While drawing M diagrams one should consider the equilibrium of joints.

Example 9.3. Draw the N,V,M diagrams and the deflected shape of the system shown in Figure 9.41.

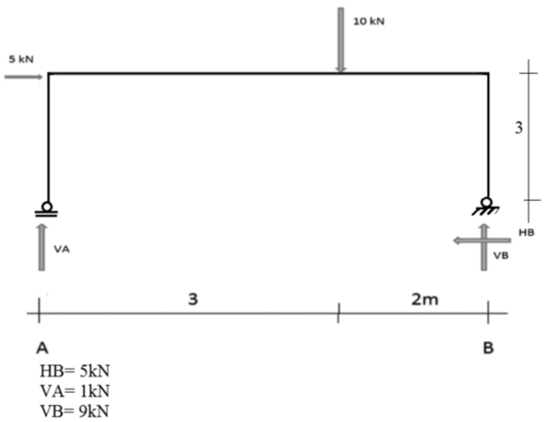


Figure 9.41. A system with columns to draw N,V,M diagrams and deflected shape

Figure 9.42 shows the N,V,M diagrams and deflected shape of the system shown in Figure 9.41.

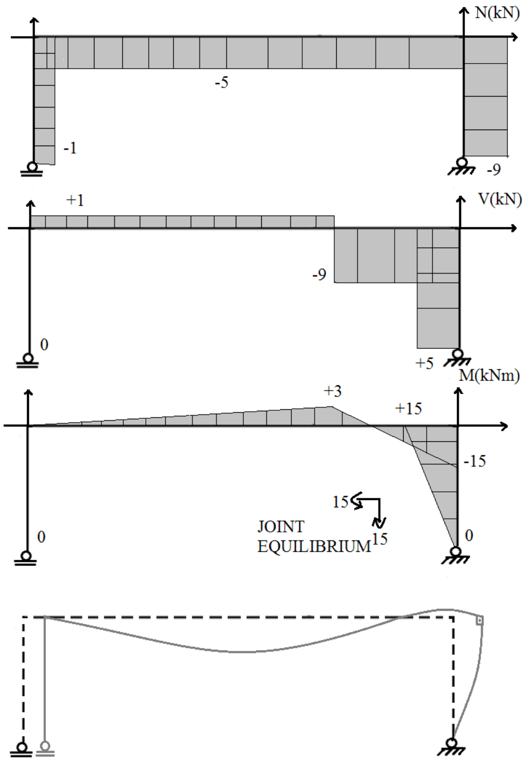


Figure 9.42. N,V,M diagrams and deflected shape of the system in Figure 9.41

Example 9.4. Draw the N,V,M diagrams and the deflected shape of the system shown in Figure 9.43.

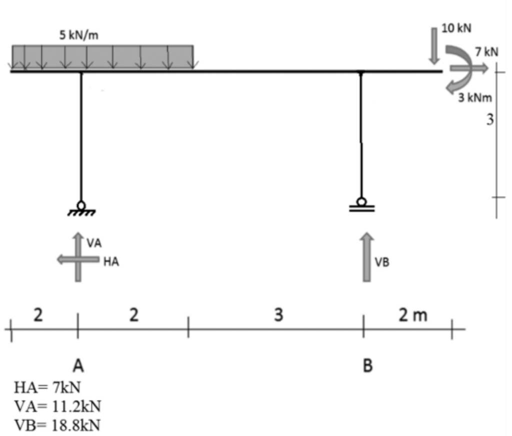


Figure 9.43. Another system with columns to draw N,V,M diagrams and deflected shape

Figure 9.44 shows the N,V,M diagrams and deflected shape of the system shown in Figure 9.43.

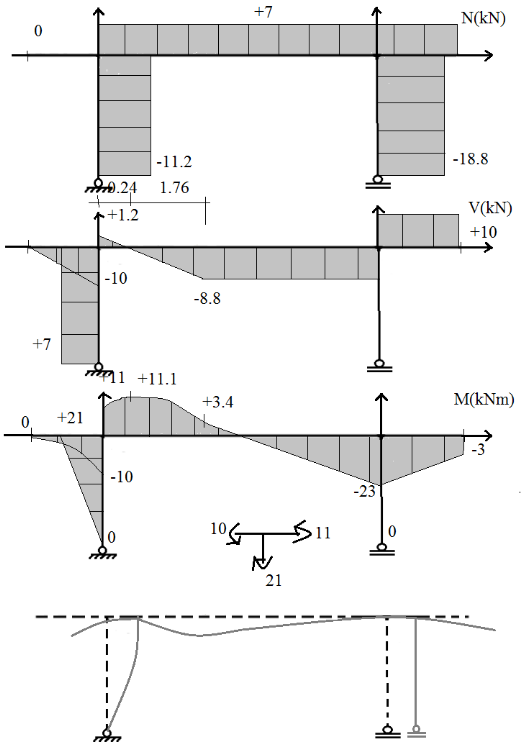


Figure 9.44. N,V,M diagrams and deflected shape of the system in Figure 9.43

The Portal Method

The Portal Method is an approximate method of analysis of the effect of horizontal forces on frame systems which are not slender. It is used if the height of the structure is less than three times the width of the structure (h<3.w). According to T.Y. Lin and S.D. Stotesbury`s (1981: 224) description of the method, the major assumptions of the Portal Method contain the following items:

1. The moment at the top and bottom of each column are equal to each other and the moment values at the middle of the columns are equal to zero.

2. The moment at the left and right side of each beam are equal to each other and moment values at the middle of the beams are equal to zero.

3. Shear values in interior columns are twice the shear values of exterior columns.

The steps of the Portal Method are as follows:

a. Determine the shear in the columns by considering that the shear in inside columns will be twice of shear in outer columns (see Figure 9.45) Consider that these shear forces should balance the horizontal loads.

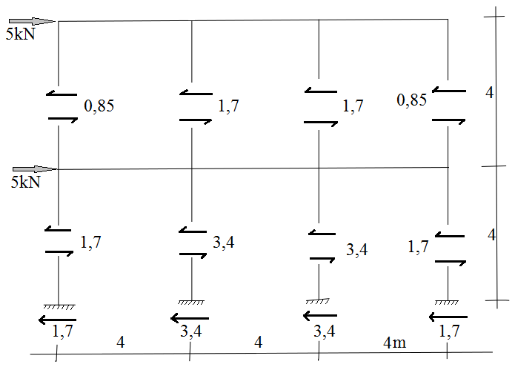


Figure 9.45. Finding shear in columns

b. Find the moment in the columns by considering that M = V. (l/2) where V is shear in the column and l is the length of the column (see Figure 9.46).

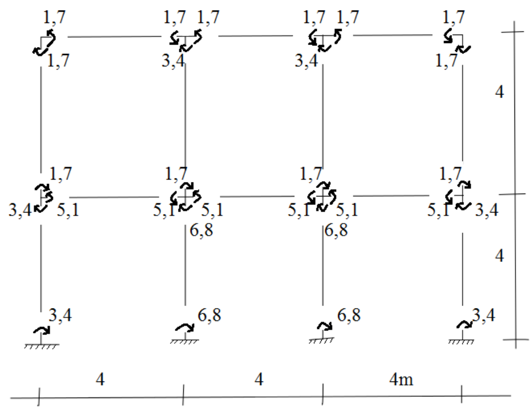


Figure 9.46. Finding moments in columns and beams

c. Find the moment in beams by considering the joint equilibrium. Consider that positive moment presses the top of the element, whilst negative moment presses the bottom of it. (See Figure 9.46)

d. Find shear in beams by considering that V= M / (l/2) where M is moment in beams and l is the length of the beam. (See Figure 9.47)

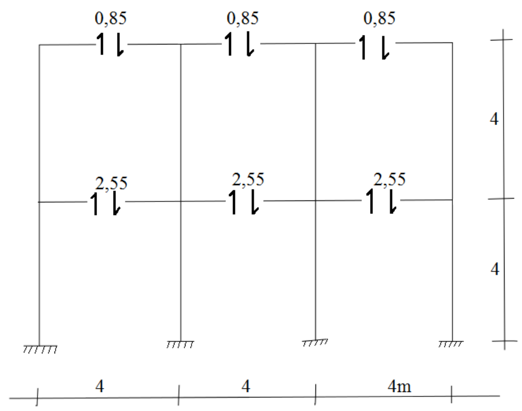


Figure 9.47. Finding shear in beams

e. Find the axial force in the columns by considering joint equilibrium. (See Figure 9.48)

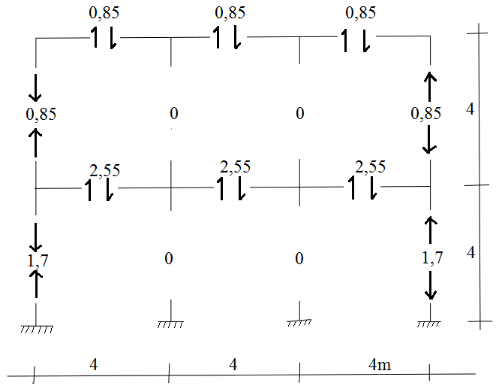


Figure 9.48. Finding axial force in columns

f. Find the axial force in the beams by considering the joint equilibrium. (See Figure 9.49)

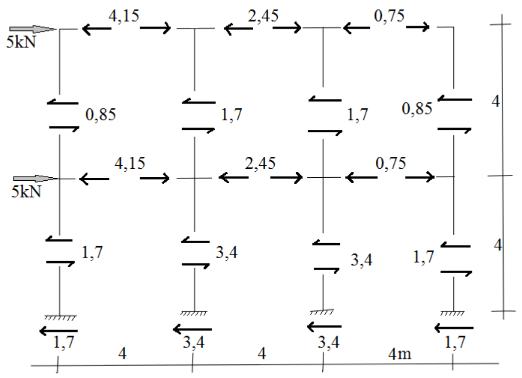


Figure 9.49. Finding axial force in beams

The N, V, M diagrams and the deflected shape of the frame will be as seen in Figure 9.50.

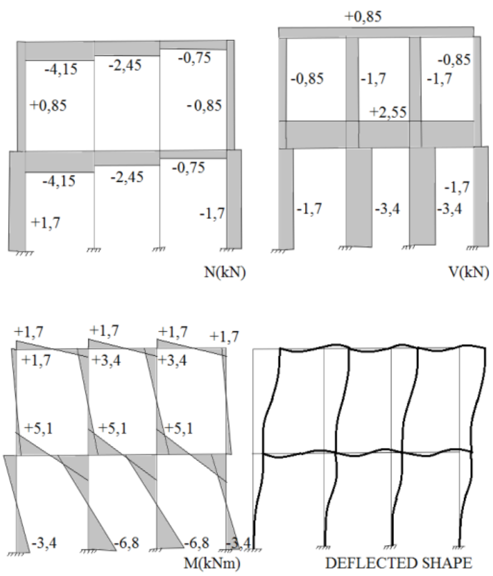


Figure 9.50. N, V, M diagrams and the deflected shape of the frame

Example 9.5. Draw the N,V,M diagrams and the deflected shape of the system shown in Figure 9.51.

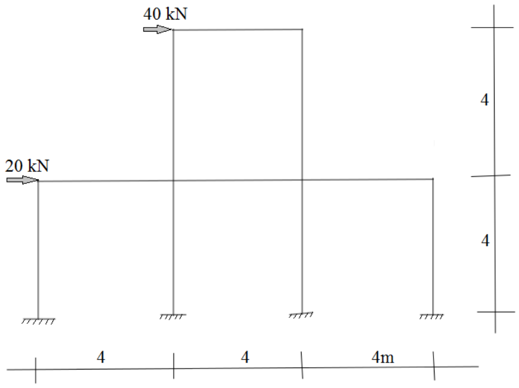


Figure 9.51. A frame to draw N,V,M diagrams and deflected shape

Internal forces in the elements of the frame can be found as shown in Figure 9.52.

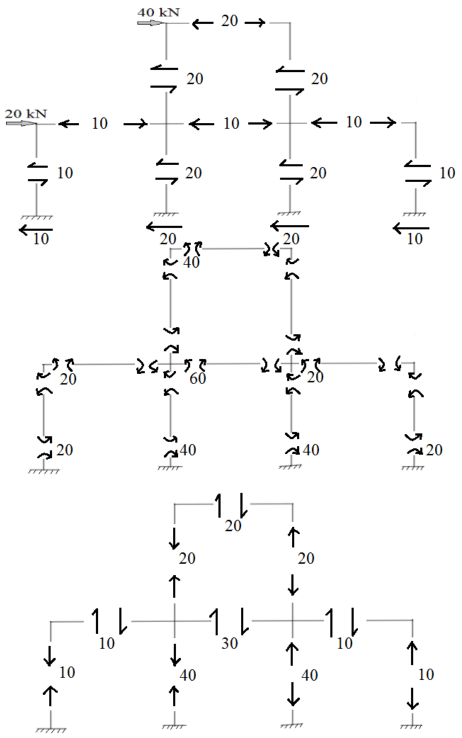


Figure 9.52. Finding internal forces in the elements of the frame

The N, V, M diagrams and the deflected shape of the frame is shown in Figure 9.53.

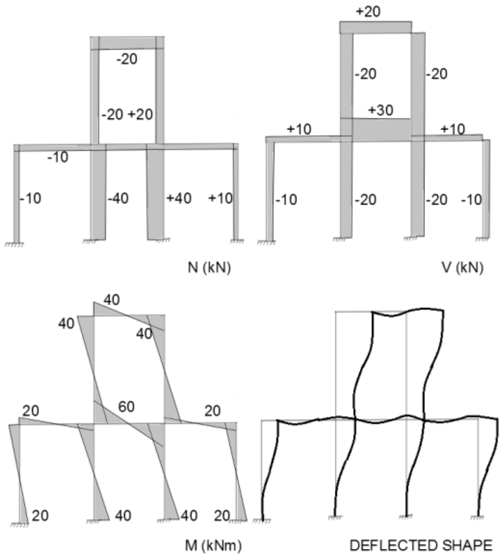


Figure 9.53. N, V, M diagrams and the deflected shape of the frame

When Do We Use Frame Systems?

The preference for frame systems can be based on economy and/or limitations of certain spans of slabs/beams and certain height ranges of the building.

As aforementioned, the limits of reinforced concrete and steel beams and slabs are seen in Table 9.1.

Table 9.1. Limits of reinforced concrete and steel beams and slabs

Material	**Structural element**	**Span**
Reinforced concrete	Beam Simple slab Ribbed/waffled slab	Up to 15m (if high strength reinforced concrete is used) Up to 7x7m Up to 15x15m (can reach 25 m with triangular waffled slab)
Steel	Beam Box girder	Up to 20m Up to 200m

Reinforced concrete frame systems are economical up to 20 storeys. If they are used together with shear walls, then they become economical up to 50 storeys (Mir, 2001). Steel frames are economical up to 30 storeys. If they used with steel shear walls, then they become economical up to 40 storeys. If they are used with steel shear walls and belt trusses, then they become economical up to 55 storeys (Dallaire, 1983). Economic limits of various applications of frames can be seen in Figure 9.54.

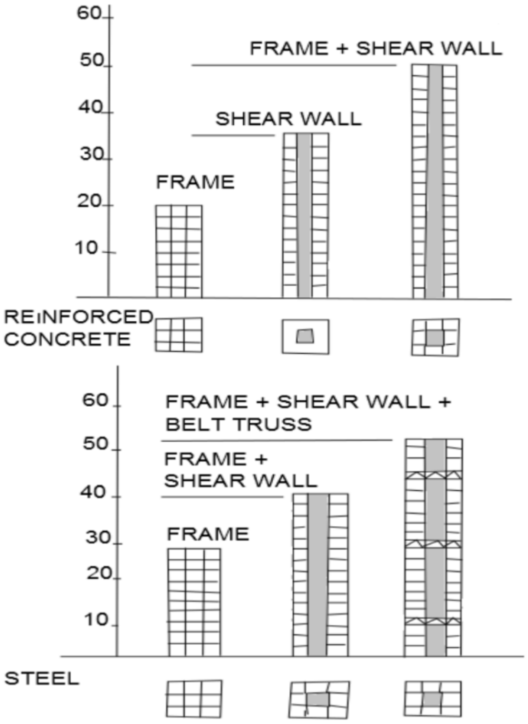


Figure 9.54. Economic height limits of various frame applications

Organization of Elements

Beams, columns, shear walls, slabs, stairs, foundations and partition walls take place within a system in order to form a structure for a building. They are not arbitrarily placed. They have to transfer load to each other and act in unity against loads. Thus, their continuity should be provided. Load is transferred from slabs to beams, from beams to columns and finally from columns to foundations as shown in Figure 9.55.

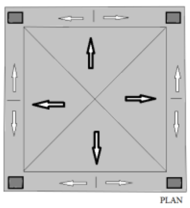


Figure 9.55. Transfer of load to foundations

Beams, columns and foundations come together to form frames and frames come together to form three dimensional frame systems as seen in Figure 9.56. Each two dimensional frame within this three dimensional frame is analyzed separately by structural engineers.

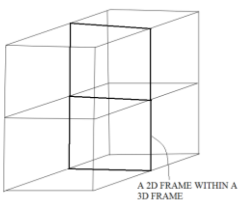


Figure 9.56. Two and three dimensional frame systems

Each two dimensional frame forms a column axis in plan. There can be straight, curved and broken axes as seen in Figure 9.57.

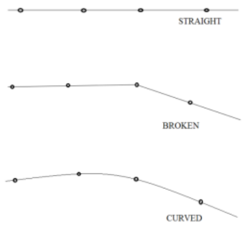


Figure 9.57. Types of column axes

Column axes might also have different angles with respect to each other. However, the structures which contain column axes with various angles will be more expensive than the structures with regular orthogonal axes, because building codes, such as the Turkish building code, might ask for more loading for the structural analysis of irregular axes (Ministry of Public Works and Settlement Government of the Republic of Turkey, 2007).

In a well-designed frame system all column axes start from one end of the structure and end at the other end as seen in Figure 9.58. It is not good to have intersecting beams and unconnected frame pieces within a frame system. Intersecting beams cannot transfer horizontal loads to the columns directly. Unconnected frame pieces cannot behave in unity against horizontal loads.

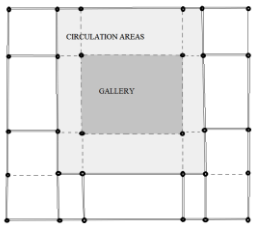


Figure 9.58. Column axes starting at one end of the structure and ending at the other end

Earthquake Resistant Design of Frame Systems

Frames should be resistant against dead load as well as horizontal loads, such as wind loads and earthquake loads. Building codes suggest different applications for high and low earthquake risks. Places of the world with a high earthquake risk are shown in Figure 9.59. As seen from this figure, the shores of Pacific Ocean, south Europe, Middle East, mid Asia and Japan islands form the high risk earthquake regions (University of California, Seismological Laboratory, 2008).

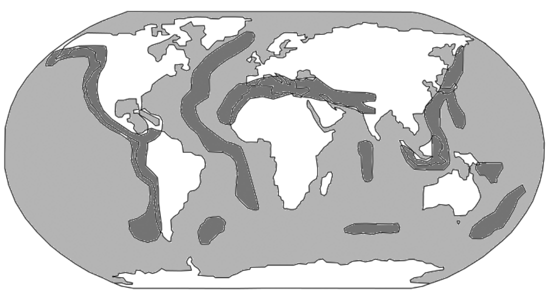


Figure 9.59. Earthquake map of the world (drawn with the help of URL1, n.d.)

The earthquake load is proportional to the mass of the building. The Peru building code suggests reducing weight in order to combat earthquake load (NTE E.030, 2003).

There are many structural engineering books about earthquake resistance of buildings such as A.W. Charleson`s (2008) "Seismic Design for Architects: Outwitting the quake." These books and reports written after earthquakes cover many problems in buildings that are affected during earthquakes. This book will describe the problems which can be eliminated or reduced through architectural design. The following problems are addressed and categorized with the help of International Building Code (ICC, 2000) and Turkish building code (Ministry of Public Works and Settlement Government of the Republic of Turkey, 2007). However, the International Building Code of 2012 (ICC IBC, 2012) does not contain these categories and structural analysis is preferred as a tool to eliminate potential problems.

- Dimensions of columns in relation to dimensions of beams,
- Plan irregularities,
    - General shape of plan,
    - Total area of galleries,
    - All discontinuities in a horizontal force resistance path,
    - Twisting instability,
- Vertical irregularities,
    - Soft storey,
    - Weak storey,
    - Short column,
    - Weight irregularity,

If the earthquake risk is high and the building is over 80 meters in height, the International Building Code does not allow any irregularities to exist in an architectural project. If the building is under 80 meters, then extreme twisting instability, extreme soft storey and weak storey problems should be avoided in regions with high earthquake risk. The other problems are considered during the structural analysis by increasing the load acting on the building.

Dimensions of Columns in Relation to Dimensions of Beams

Horizontal loads directly cause shear and moment forces in the columns. Thus, the architectural dream of having very few and slender columns might not be realized if there is a high earthquake risk. However, if the earthquake risk is low, having slender columns is possible for low rise structures. 25 cm by 25 cm columns can be sufficiently strong for this type of structures.

There can be two strategies to follow in high risk earthquake regions:

- Using shear walls in a systematic way together with slender columns,
- Making the columns thicker.

Different building codes of different countries suggest these solutions depending on the economic condition of the country. For example, as aforementioned, Japanese building code suggests the first strategy (Paz, 1994), while Turkish building code suggests use of shear walls if the building is higher than 13 meters. For shorter buildings the second strategy of having thicker columns is suggested (Ministry of Public Works and Settlement Government of the Republic of Turkey, 2007).

According to the Turkish building code, columns should be able to carry 20 % more moment in comparison to the moment carried by beams. The author of this book suggests that architects may translate this condition into physical terms by saying that column dimensions should be similar to beam dimensions. For example, if two columns carry a 5 meters long reinforced concrete beam, which is 50 cm deep, then the dimensions of these columns can be 25 cm by 50 cm, having the 50 cm similar to the depth of the beam. It is possible to have one or two slender columns within a structure. However the majority of the columns should have similar dimensions to the beams.

Plan Irregularities

Plan shapes, which contain deep recesses, are not recommended if there is a high earthquake risk. It is better to separate these deep recesses from the rest with the help of expansion joints as seen in Figure 9.60. According to the Turkish building code these recesses should not exceed 20 % of the whole length of the building (Ministry of Public Works and Settlement Government of the Republic of Turkey, 2007).

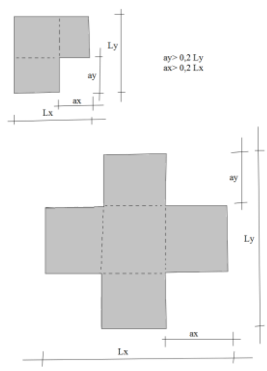


Figure 9.60. Avoiding deep recesses with the help of expansion joints

It is not recommended to have *large galleries* in slabs. The area of galleries in a slab should not exceed 1/3 of the slab area. Abrupt discontinuities in these slabs eliminate the diaphragm behaviour of the slabs. Figure 9.61 shows some problematic conditions in the organization of galleries.

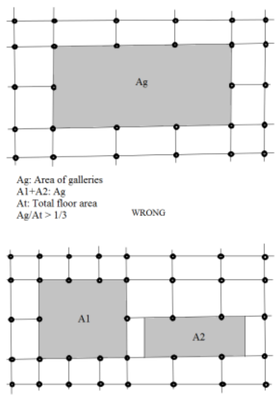


Figure 9.61. Some problematic arrangements of galleries

As stated previously, all *discontinuities in a horizontal force resistance path*, such as having discontinuous axes, beams intersecting each other and having non-parallel axes, are also not recommended.

Twisting instability is one of the major irregularities, which frequently cause problems in earthquakes. Buildings can be twisted around themselves during earthquakes. To understand twisting instability it is necessary to know to where on plan the earthquake force is applied and from where the structure`s resistance comes. The earthquake force is applied to the centre of the geometry of the plan, while resistance of the structure comes from the centre of gravity of the structural plan as seen in Figure 9.62.

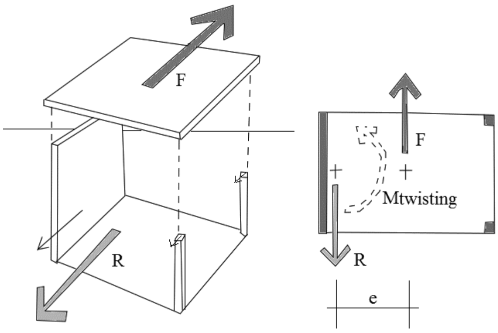


Figure 9.62. Earthquake force F and resistance of structure R

The distance between the two forces is called eccentricity (e). If eccentricity is high, the two forces act as a couple to create a twisting moment. This problem can be solved in two different ways:

- Designing the structural plan as symmetrical,
- Reducing eccentricity by balancing the structural plan as seen in Figure 9.63.

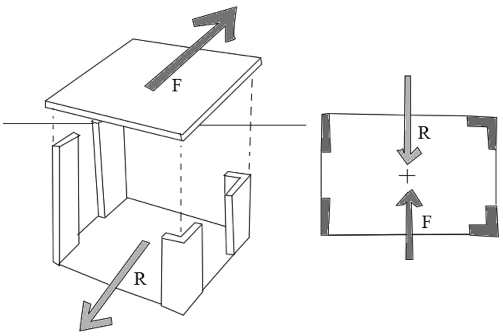


Figure 9.63. Reducing eccentricity

Vertical Irregularities

Soft storey problem is one of the major vertical irregularities which cause problems in earthquake. Frames are flexible structures, but rigid partition walls (such as brick walls) eliminate the flexible movement of frames. Thus, the placement of rigid partition walls in frames can cause significant problems. Figure 9.64 shows some acceptable and unacceptable arrangements of rigid partition walls and windows within frame systems.

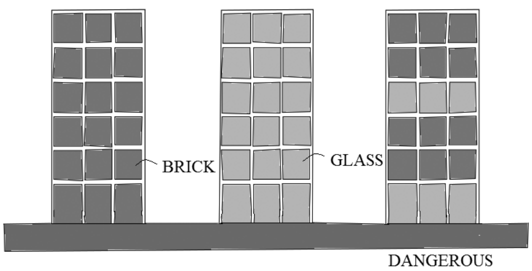


Figure 9.64. Acceptable and unacceptable arrangements of rigid partition walls and windows within frame systems

If the bays of the frame are filled with windows, this will be a flexible but acceptable structure. If the bays are filled with rigid partition walls, this will be a rigid and acceptable structure. However, if one of the lower floor`s bays are filled with windows and the bays of the rest of the structure are filled with rigid partition walls, then the floors with windows is called soft storey. Stiffness of this floor is considerably less than the stiffness of other floors.

Columns of the floors with rigid walls cannot bend, while the columns of the soft storey are bent too much. These columns might collapse due to excessive bending.

The soft storey problem can be solved in the following ways:

- Replacing rigid partition walls with more flexible walls, such as metal panels,
- Using bracing for the soft storey (see Figure 9.65.a)
- Increasing the thickness of columns at the soft storey level (see Figure 9.65.b)
- Increasing the number of columns at the soft storey level (see Figure 9.65.c)
- Adding shear walls to the system (see Figure 9.65.d),
- Decreasing the size of openings at the soft storey level (see Figure 9.65.e),
- Placing elastic material between the structural elements and the rigid walls and letting movement of elements free everywhere (see Figure 9.65.f).

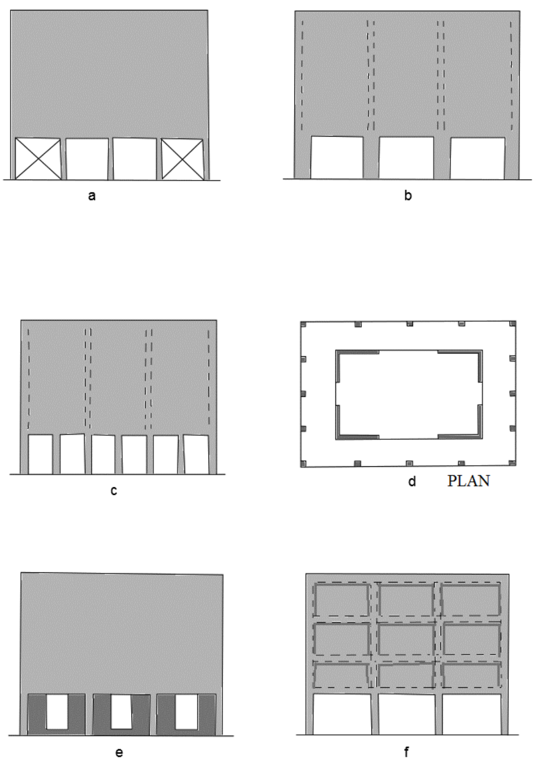


Figure 9.65. Some ways of solving the soft storey problem

Except for increasing thickness of columns, all of the other solutions are architectural solutions. If the problem cannot be solved otherwise, then the thickness of soft storey columns can be increased under the control of structural engineer.

Weak storey problems occur if the strength of a floor against horizontal loads is under 80 % of the strength of the floor above (ICC, 2000). This problem can occur if the dimensions of columns and shear walls are reduced at an intermediate level. Another cause of the problem can be due to removal of rigid partition walls at one intermediate level.

Short column problems are also due to incorrect use of rigid partition walls within a flexible frame. It can also be stated that one reason of the short column problem is the form of openings within these rigid partition walls. As seen in Figure 9.66 most forms of openings are acceptable, however ribbon windows cause short column problems.

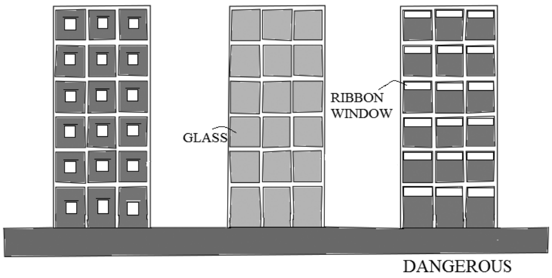


Figure 9.66. Form of openings and short column problem

Since the rigid walls eliminate deflection of the columns' lower parts, there occurs a concentration of shear within the columns' upper parts beside the ribbon windows. These columns can be cut due to excessive shear. It is possible to make the toilet paper analogy here. Because of the holes organized over lines, it is easier to tear the toilet paper through these lines.

Short column problem can also occur at various different situations, where the height of the column is reduced for some reason. Figure 9.67 shows that short column problem might occur at stair-cases and inclined sites.

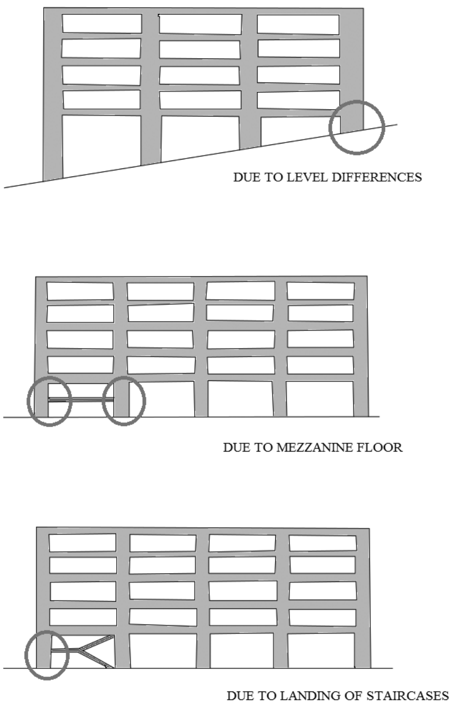


Figure 9.67. Some other causes of short column problems

If the short column problem exists due to the form of openings, then it can be eliminated by taking the following precautions:

- Replacing rigid partition walls with more flexible walls, such as metal panels,

- Changing the form of the opening,
- Increasing the thickness of short columns,
- Adding shear walls to the system,
- Placing elastic material between the structural elements and the rigid walls and letting movement of elements free everywhere.

Weight irregularity problem occurs if the weight of one storey is more than 150 % of the adjacent storeys.

Structural Guidelines for Frame and Shear Wall Systems

Structural guidelines for frame and shear wall systems can be presented under the following three categories:

- General structural guidelines for all structural materials,
- Structural guidelines for reinforced concrete frame (and shear wall) systems,
- Structural guidelines for steel frame (and shear wall) systems.

Table 9.2. General structural guidelines for frame (and shear wall) systems with any structural material

Structural guidelines	**Value system**
Elements of frame systems should be continuous. The loads from slabs should be directly transferred to beams, the loads from beams should be directly transferred to columns, and the loads from columns should be directly transferred to the foundations.	Safety
The form of the elements of frame systems should be designed to reduce bending moment in them.	Economy
It is less problematic not to have strongly curved beams or beams with corners in order to avoid twisting.	Economy
Columns should not be slender in order to avoid buckling.	Safety
Columns and shear walls should reach foundations.	Safety
Directions of columns and shear walls should be well distributed on plan.	Safety
Rigid partition walls should be placed over beams.	Safety
Building parts with considerable height differences should be structurally separated by expansion joints.	Economy
It is better to separate building parts with different structural material / structural system with the help of expansion joints.	Economy
If there is high earthquake risk and if the plan shape contains deep recesses, these parts should be separated from the main body with the help of expansion joints.	Economy
If the plan is longer than 30 m by 30 m then the structure should be divided into different parts with the help of expansion joints.	Economy
Minimum width of an expansion joint is 3 cm. If the building is higher than 6 m, 1 cm should be added to this value for each 3 meters of height.	Safety
Slabs adjacent to stairs should be surrounded by beams.	Safety

Column axes should start from one end of the building and end at the other end to be able to resist horizontal loads. It is better not to have any intersecting beams and unconnected frame pieces, if there is a high earthquake risk.	Safety
Building weight can be reduced to decrease earthquake load.	Economy
If there is high earthquake risk and if the building height is over 80 m, there should be no irregularity problems in the structure.	Safety
Either shear walls should be used systematically, or columns should have similar dimensions to beams in order to resist earthquake loads. If the building height is over 13 m, than there should be shear walls.	Safety
If there is a high earthquake risk, area of galleries should not be over 1/3 of the slab area. There should not be abrupt discontinuities in the slabs to be able to distribute earthquake load evenly to the vertical elements of the structure.	Safety
If there is a high earthquake risk, then the twisting instability problem should be solved either by designing a symmetrical structure or by balancing it to reduce eccentricity.	Safety
If there is high earthquake risk, soft storey problem should be eliminated.	Safety
If there is high earthquake risk, weak storey problem should be eliminated.	Safety
If there is a high earthquake risk, it is better to eliminate short column problems during the architectural design stage.	Economy
If there is a high earthquake risk, it is better to solve weight irregularity problem during the architectural design stage.	Safety

Table 9.3. Structural guidelines for reinforced concrete frame (and shear wall) systems

Structural guidelines	**Value system**
Minimum depth of reinforced concrete beams can be length/15. The minimum depth can be 30 cm.	Safety
Minimum width for reinforced concrete beams should be 20 cm.	Practicality
High strength reinforced concrete beams can span up to 15 m.	Safety
Optimum span for reinforced concrete beams is 4,5 – 5 m.	Economy
Minimum dimensions of a reinforced concrete column can be 25 cm by 30 cm.	Safety
Shorter span of one way and two way slabs can be maximum 7 m.	Economy
One way slabs are used for rectangular slabs and two way slabs are used for forms close to square.	Economy
Depth of one way slabs can be between length/20 and length/30 and depth of two way slabs can be between length/30 and length/40. Minimum depth for these types of slabs is 9 cm.	Economy
Pre-stressed flat slabs can span up to 8 to 12 m. However, it is better not to exceed 4 m, if there is high earthquake risk.	Safety

Ribbed and waffled slabs are used for spans longer than 7 m. Waffled slabs can span up to 15 m.	Economy
Span to depth ratio of waffled slab can change between 15 and 20.	Economy
It is not good to have very deep and very shallow (but wide) beams.	Safety
Minimum thickness of reinforced concrete shear walls is 20 cm. Minimum length of shear walls is 7 times their thickness.	Safety
In a shear wall structures the ratio of shear wall area to floor area can be between 5 % and 10 %.	Safety
Reinforced concrete frame systems can be economic up to 20 storeys. If they are used together with shear walls, then they can be economic up to 50 storeys.	Economy

Table 9.4. Structural guidelines for steel frame systems

Structural guidelines	**Value system**
Depth of a steel beam can be length/20.	Safety
Optimum span of steel beams is 7 m. However, they can span up to 20 m.	Economy
Box girders can span up to 200 m.	Economy
Secondary beams of steel slabs can be 7 to 20 m long and they can be placed in every 2 to 5 m. Secondary trusses can be spaced 1 to 3 m.	Economy
Steel frames can be economic up to 30 storeys. If they are used with shear walls, then they can be economic up to 55 storeys.	Economy

Case-studies

Case-study 12: Villa Savoye, Poissy, France

The most important architectural characteristics of Villa Savoye are its simple geometric form, the presence of pilotis which raise the building mass over columns, and the use of ribbon windows (See Figure 68 and 69). Le Corbusier said that it is possible to see the horizon continuously without any break through these windows (Leatherbarrow, Mostafavi, 2005: 42-43). Since there were few buildings with frame systems in 1928, this was a strikingly different architectural characteristic. Le Corbusier was providing continuity between indoor and outdoor spaces. He was also providing continuity between the different indoor spaces. Such continuity was becoming possible because of the tectonic characteristics of frame systems. Since it is possible to remove the partition walls, continuity can be achieved. Buildings with frame systems are much lighter than buildings with masonry systems. The dominant physical entity in achieving the tectonic qualities of Villa Savoye is structure.

When the characteristics of Villa Savoye are examined with the help of structural guidelines shown in Table 9.2 and 9.3, it can easily be seen that such a building cannot be built if there is high earthquake risk. Pilotis cause soft storey and weak storey problems and ribbon windows cause short column problems. Furthermore, the columns are slender and not as strong as the beams. Although the building is nearly symmetrical, these problems do not allow the same style to be applied in risky earthquake regions. However, since Villa Savoye is not in a high risk earthquake region, it can be stated that it has an affirmative relationship with structural guidelines, because it achieves its tectonic qualities without making any contrast to them.

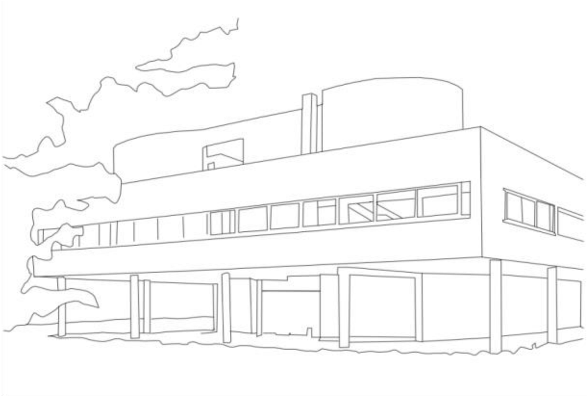


Figure 9.68. A sketch of Le Corbusier's Villa Savoye, Poissy, France, 1928 (drawn with the help of URL2, 2011)

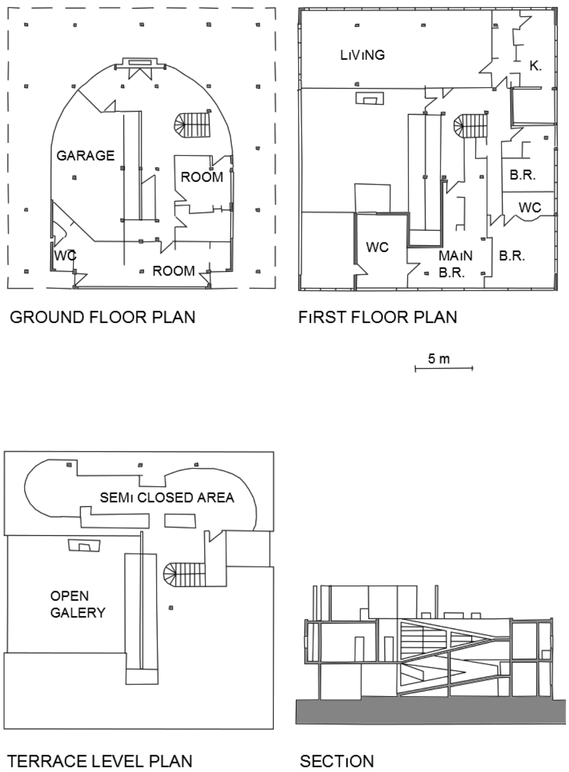


Figure 9.69. Plans and section of Villa Savoye (drawn with the help of URL3, 2011)

Case-study 13: National Assembly, Dacca, Bangladesh

Louis Kahn did not try to achieve simple geometric forms. He was dividing the mass into pieces by separating different types of functions from each other (Leatherbarrow, Mostafavi, 2005: 215-226). He was also surrounding these masses with a wall, which forms an envelope as part of a climatic response (See Figure 70 and 71). Kahn used frames and shear walls together to form the structure of his buildings. Kahn's structures were not economic because some structure axes were too close to each other (Frampton, 2001: 232-233).

The indoor spaces between the masses of the National Assembly building in Dacca have the characteristics of outdoor spaces. Street furniture is used in these spaces and natural light penetrates in from the roof. The walls surrounding the National Assembly building are stone and they have a haptic effect. However, the openings on these walls have simple geometric forms, which are optic. Thus having optic openings on haptic walls makes a contrast. The dominant physical entities in achieving the tectonic characteristics of the National Assembly are materials, details (such as the details of openings) and structure.

When the plan and section of National Assembly is analysed with the help of structural guidelines shown in Table 9.2 and 9.3, it is understood that there should be some expansion joints separating the structure into various parts because this is a large building and the hall at the middle has a different roof structure.

There are large galleries between the masses which form the building. Since the building is in a seismic zone, it could have been difficult to achieve such large galleries. However, one can guess that there are expansion joints between the masses and since the galleries take place between these masses, they do not work as galleries dividing horizontal diaphragms into pieces. The problem created as a result of the design was compensated with the help of expansion joints. The relationship of National Assembly to the structural guidelines is contravening, because it achieves some interior spaces which are difficult to achieve in earthquake regions.

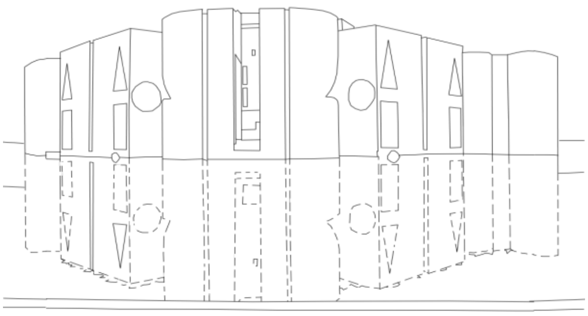


Figure 9.70. A sketch of Louis Kahn's National Assembly in Dacca, Bangladesh, 1962 to 1974
(drawn with the help of URL5, 2004)

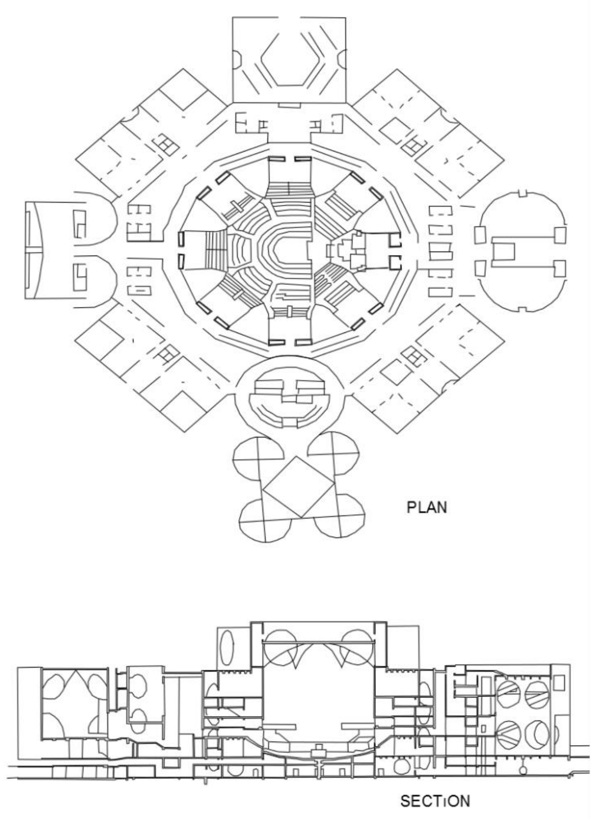


Figure 9.71. Plan and section of National Assembly (drawn with the help of URL4, 2014)

Case-study 14: Church of Light in Sunday School, Osaka, Japan

Tadao Ando's projects and especially the Church of Light and Sunday School form successful tectonic examples of reinforced concrete shear walls. The most striking tectonic characteristic of these buildings is the form of its windows (See Figure 9.72 and 9.73). One is in the form of a cross and the other is between the two shear walls with different angles. The mullions of these windows are also designed not to be seen from inside or outside. If one searches for the interior photographs of this building, s/he sees that interesting light effects have been created by these windows. Thus, it can be stated that the dominant physical entities in achieving the building's tectonic characteristics are details and materials. The window details contribute to tectonic qualities of the building as well as the continuous concrete surfaces.

However, the window in the form of a cross cancels a shear wall. The shear walls with different angles should be connected to each other through horizontal elements in order to avoid movement of them in different directions. Since there is a high seismic risk, the structure of the building should have been designed in unity. Another tectonic characteristic of the Sunday School is the brutalist expression of shear walls with the construction marks on them. The Sunday School has a contravening relationship with the structural guidelines for shear wall structures.

Figure 9.72. A sketch of Tadao Ando`s Church of Light in Sunday School, Osaka, 1999 (drawn with the help of URL6, 2006)

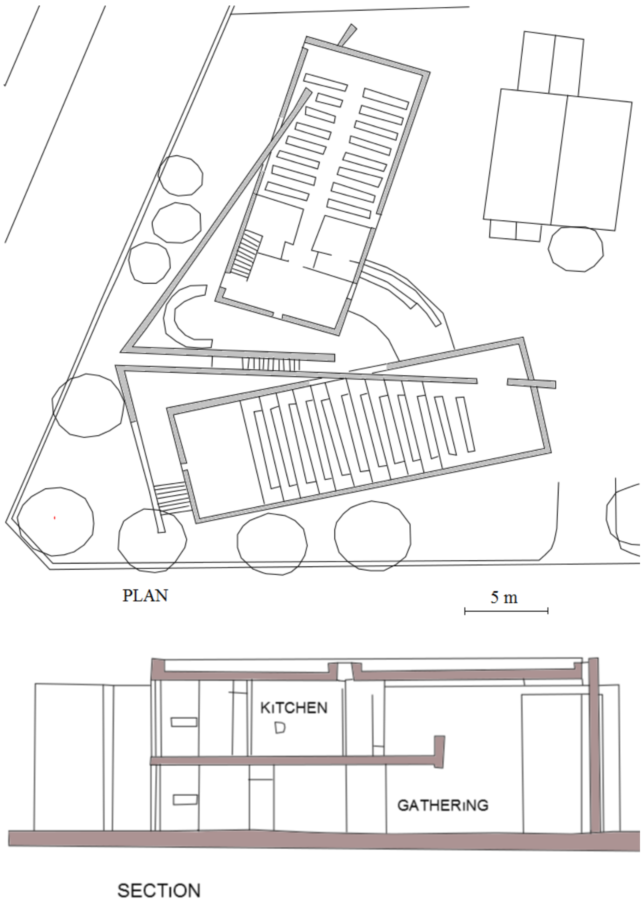


Figure 9.73. Plan and section of Church of Light and Sunday School (drawn with the help of URL7, 2012; URL11, 2014)

Case-study 15: Barcelona Pavilion, Barcelona, Spain

The architectural concept of Barcelona Pavilion is based on the idea of a steel frame (See Figure 74 and 75). Mies van der Rohe tried to express the tectonic qualities of steel frames. However, although he was trying to express the steel frame, he covered his steel columns with chrome and he hid the steel beams of the slab. He thought that the best way of expressing the steel frame was hiding its elements and showing them in a different way (Frampton, 2001: 177). Thus, the dominant physical entities in this building were its structural system and details.

There are also false stone walls inside and outside the building. These walls are not structural and they do not have any functional role. Mies thought that there is no reason for the presence of these walls and they are there only to give presence (Hartoonian, 1994: 68-80) These walls are used very close to columns and at two places the columns are placed symmetrically in front of the walls (Frampton, 2001: 175).

When Barcelona Pavilion's plan and section are evaluated according to the structural guidelines shown in Table 9.2 and 9.4, it can be seen that the columns are very slender and they do not have similar dimensions to the beams. However, Barcelona Pavilion does not take place within area of high seismic risk. These columns should have been checked against buckling only. Thus, it can be stated that Barcelona Pavilion has an affirmative relationship with structural guidelines because it follows the structural guidelines which are valid if there is no earthquake risk.

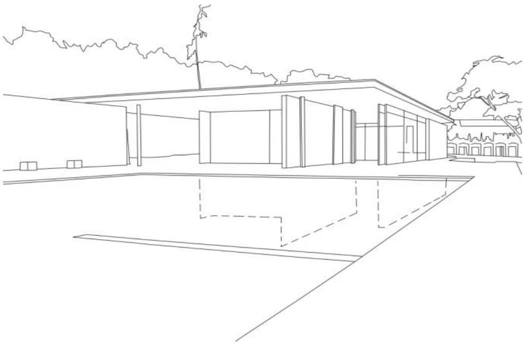


Figure 9.74. A sketch of Ludwig Mies van der Rohe's Barcelona Pavilion, Barcelona, Spain, 1928-1929 (drawn with the help of URL8, 2012)

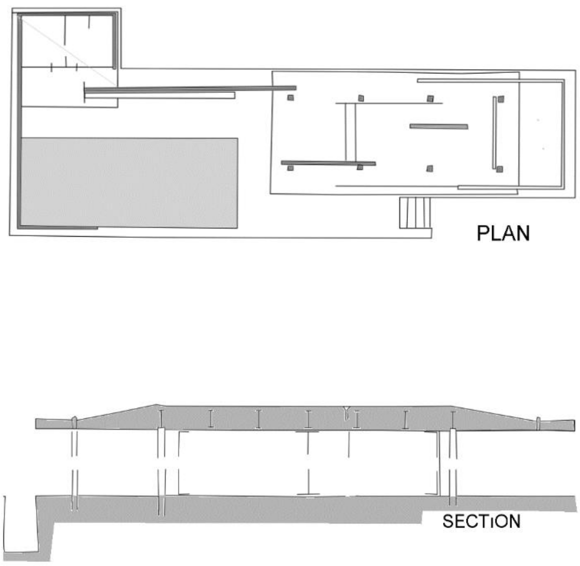


Figure 9.75. Plan and section of Barcelona Pavilion (drawn with the help of URL9, 2003 and URL10, 2011)

Discussion on Case-studies of Frame and Shear Wall Systems

When the four case-studies within this chapter are studied, it can easily be understood that the structure of the buildings in regions of high seismicity can be very different to the ones in regions of low seismicity. Thus, the architectural styles used in areas with low seismic risk should be used very carefully in areas with high seismic risk. Because problems such as soft storey, short column and slender columns have to be solved without disturbing the architectural quality.

When the two case-studies built in highly seismic zones; National Assembly and Sunday School; are examined, it can be seen that their tectonic qualities have been achieved very carefully. National Assembly's large galleries have been achieved with the help of a detail; expansion joints; which separate the different masses in the building. The tectonic effect of the Sunday School is not based on structural form. Instead, tectonic qualities are achieved with the help of space quality and details, such as the window details and construction signs on the reinforced concrete shear walls. Thus, it can be stated that tectonic qualities can also be reached with the help of details.

Tectonics of Frame Systems

The tectonic qualities of frame systems are very different than that of masonry systems. Continuous surfaces with small openings formed the basis of the tectonic characteristics of masonry structures together with the symmetry and sculptural effects of cross-walls and buttresses. Also the texture of stone, brick, adobe or timber surfaces were very effective in determining the tectonic quality of these buildings.

The most dominant tectonic quality of frame systems is their lightness in comparison to masonry structures. All the partition walls can be replaced by glass surfaces to achieve maximum transparency. However, this lightness can also be compared with the strong desire of structural engineers to create structures with the appearance of lightness. This is achieved through using the minimum amount of structural materials, while lightness in architecture can be achieved by reducing the amount of walls within the building.

Continuity between indoor and outdoor spaces as well as continuity between the interior spaces also became possible with the use of frame systems.

Form is also used as a tectonic characteristic in buildings with frame systems. The early buildings with frame systems have simple geometric forms (e.g. Villa Savoye of Le Corbusier). Later, form was divided into pieces to form assemblages of forms (e.g. National Assembly of Louis Kahn). The use of natural forms is also seen as desirable by many architects (e.g. the roof structure of Ronchamp Chapelle by Le Corbusier). The architecture of 1990's used the form in a different way by creating kind of formlessness (e.g. Guggenheim Museum of Frank Gehry). The tectonics of contemporary architecture (which is stamped by the tectonics of frame systems) can be more playful than the tectonics of traditional architecture (which is stamped by the tectonics of masonry structures) and the tectonics of engineering structures.

Thus, the general tectonic characteristics of frame systems can be listed as follows:

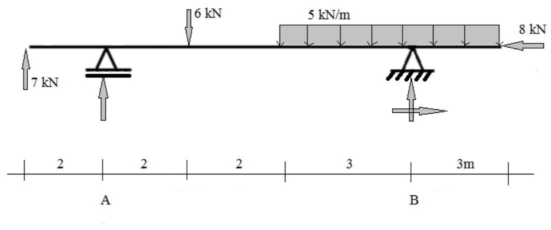
- Lightness,
- Continuity of spaces,
- Importance of form.

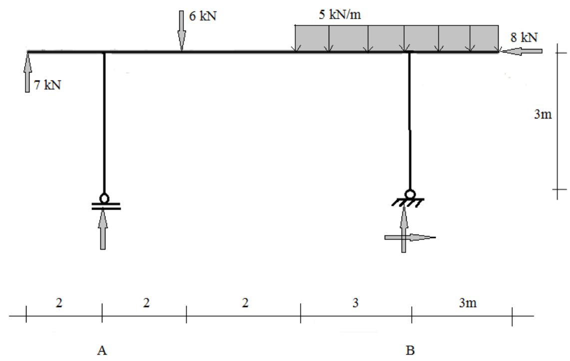
When these characteristics are brought together with the structural guidelines shown in Table 9.2, 9.3 and 9.4, it can be seen that they have a very critical relationship with earthquake resistant architectural design. The demand for lightness results in the use of slender columns and the removal of partition walls. The demand for continuity might result in the presence of large galleries to connect different floors to each other. Being playful about the form can easily cause twisting instability problems, because of the lack of symmetry.

It can even be stated that the relationship between designers and structures has been changed considerably after the invention of frame systems. Previously, there was a tendency to design small scale traditional structures in line with structural guidelines about earthquakes. Designers were going against guidelines only if there was a strong reason or demand for it. However, contemporary small structures –it might even be better to say contemporary styles- are rather against structural guidelines about earthquakes. Symmetry is disliked. Slender columns are favorites. Large galleries are spacious. Thus, the architects, who design within risky earthquake regions, should be very careful with the contemporary architectural styles.

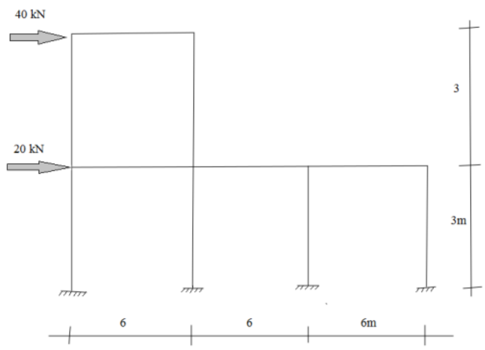
Problems to Solve

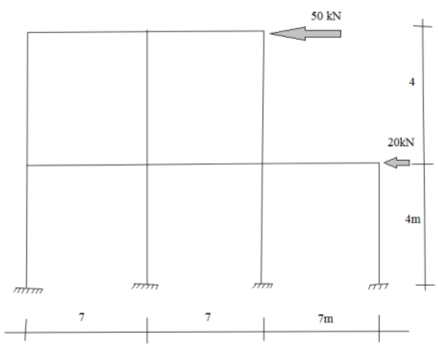
9.1. Draw N, V, M diagrams and the deflected shape of the following two systems.





9.2. Draw N, V, M diagrams and the deflected shape of the following two frames.





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