Structural Systems for Office Buildings

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Abstract

There are many ways to construct a building. The designing team, structural engineers and architects, works together to find the best possible solution that will fulfill the owner's whishes. In this process a structural system needs to be chosen. There are many factors that affect the selection of the structural system, but generally the most economical system is chosen. The factors that need to be considered are related to the cost and the requirements for the building, respectively. The objective of this thesis is to study the structural systems for office buildings that are available on the market and how well they fit the factors that need to be considered.

Different structural members are combined to form the structural system. Structural systems are divided to sub-systems; vertical force resisting elements, floor systems, horizontal force resisting elements. Structural members vary in many different ways such as material, dimensions, and behavior.

In conclusion, the selection of a structural system depends on availability, economics, experience, and tradition. The market is different in many countries and therefore there is a tradition for using a certain type of structural system. However, it is important to be open for trying new solutions and learn from other countries in the field of construction. Concrete, steel and composite systems can all be designed to meet the requirements. The designer needs to know the structural members that are available and make a comparison after studying the layout of the building. Then the structural system can be chosen.

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Preface

The work presented in this master's thesis was carried out at the Division of Structural Engineering, Lund Institute of Technology, Lund University, Sweden.

I would like to express my gratitude to my supervisor, Prof. Sven Thelandersson at the Division of Structural Engineering, for his guidance during this work. I would also like to thank Eysteinn Einarsson at Línuhönnun Consulting Engineers for advising me throughout the work. I would also like to thank all the people I interveiwed for their time and kindness.

Finally, I would like to thank my parents for all of their support throughout my education.

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Ásthildur Helgadóttir

Contents

0. INTRODUCTION

0.1 Background

There are many possible ways of designing and constructing an office building. During the last fifty years or so, new structural solutions have been presented in the field of structural engineering.   The new solutions can have the purpose of simplifying the construction or saving time and money. The designing team, structural engineers and architechts, work to find the best possible solution that will meet the owner's requirements and fundamental requirements for the building respectively. A selection of the structural system is a part of this process. Structural members are combined to form the overall structural system. The structural engineer needs knowlegde of the members that are available on the market and the behavior of the members. The structural engineers also needs knowlegde of the factors that needs to be considerd in the beginning of the design process of the building. The structrual engineer will have to recongnize the advantages and disadvantages of the structural system in question.

0.2 Objective and scope

The main objective of this thesis is to study structural systems for office buildings. There are many factors that need to be considered when a structural system is chosen for a building. These factors apply to fundamental requirements for buildings and special requirements for office buildings. The selection of a structural system depends on how well these requirements will be met and the wishes of the client can be fulfilled. The report gives an overview of different structural elements that are used in the structural field today. These structural elements are combined to make the structural system of the building. Different structural systems will be discussed and advantages and disadvantages will be described. The work contains five chapters that are as follows:

1. Requirements for office buildings
The fundamental requirements for buildings in general are described according to Eurocode. The requirements for office buildings to provide appropriate work environment and meet the client's wishes.

2. What to consider
A discussion of the factors that need to be considered in the process of selecting the best suitable structural system for an office building.

3. Structural elements
The structural elements are described that are available in the market of construction

.

4. Combination of structural elements

Different structural systems are discussed and evaluated depending on the factors that need to be considered for office buildings.

5. Case studies
The work contains two case studies; a four story office building and a twenty story office building. A structural system will be chosen for the four story office building. The structural system that the designing team at Ferill Consulting Engineers has chosen for the twenty story building will be described and discussed.

The aim is to learn about different structural systems and recognize under what circumstances they might be appropriate depending on advantages and disadvantages.

1. REQUIREMENTS FOR OFFICE BUILDINGS

1.1 Fundamental requirements for buildings

According to Eurocode 4, Part 1.1, the fundamental requirements for a building are the following:

1. A structure shall be designed and executed in such way that it will, during its intended life with appropriate degrees of reliability and in an economic way:
    - remain fit for the use for which it is required; and
    - sustain all actions and influences likely to occur during execution and use.

2. Design according to fundamental requirements implies that due regard is given to structural safety and serviceability, including durability, in both cases.

3. A structure shall also be designed and executed in such a way that it will not be damaged by events like fire, explosions, impact or consequences of human errors, to an extent disproportionate to the original cause.

4. The potential damage shall be avoided or limited by appropriate choice of one or more of the following:
    - avoiding, eliminating or reducing the hazards which the structure may sustain;
    - selecting a structural form which has low sensitivity to the hazards considered;
    - selecting a structural form and design that can survive adequately the accidental removal of an individual element or a limited part of the structure, or the occurrence of acceptable localized damage;
    - avoiding as far as possible structural systems which may collapse without warning;
    - tying the structure together.

5. The above requirements shall be met by the choice of suitable materials, by appropriate design and detailing, and by specifying control procedures for design, production, execution and use relevant to the particular project. [1]

The structural system must also meet architectural requirements and fulfill the owner and user requirements. Service systems are required in every building, such as heating, ventilation and air conditioning, horizontal and vertical cabling, and other electrical and mechanical systems. For the structural system to work properly, the building, foundation and the ground must interact. Fire resistance is also a requirement, and depends on the building code used and the type of the building. The structural system is required to facilitate simple and fast erection of the building and be economical at the same time.

1.2 Requirements for an office building

Requirements for an office building can vary from time to time. The most common term, regarding the requirements is flexibility. Office concepts, such as group office, modular office, combination office, and business club should all be considered in the planning. This depends on the company requirements but it is important that changes in the use of the area are possible.

Architectural requirements are often complex in office buildings. The architectural solution must utilize and exploit the structure to the fullest extent. When a structure is expressed, it is expected to look elegant, appealing, and above all structurally correct. Harmony between structure and architectural form is the most important factor in the success of expression. Aesthetics is another important term which relates to structure through efficiency, lightness, elegance, and the principles of minimizing weight and the use of materials to control cost, among other factors.

Open office planning was developed as a means of providing organizational flexibility, encouraging interactions between people in different units, and supporting the team concept. Conventional office layouts typically contain perimeter offices for professional staff at the middle and upper management levels with support staff located directly outside the offices. Removable panels are often used to define workspaces and provide privacy.

2. WHAT TO CONSIDER

2.1 Time of Design and Planning

The procedure of planning and designing a building begins with the decision of the client/contractor to construct a building. The time of design and planning varies and can be from three to twelve months. It can depend on the urban planning and the time it takes to get license to construct the building. After the client gets permission to construct the building, the preliminary design begins. Then cost and time of the project is considered and the best way chosen depending on the client's wishes. Then the engineers make a tender and the contractor makes an offer. The project team usually spends time in finding ways to save money and that process is called value engineering. Value engineering has become an important factor in the design process. Value engineering is the structured application of proven techniques at various design phases with the primary aim of cost avoidance, without sacrificing scope and quality. The principle involves evaluating the function of the process and/or equipment and focusing on poor value items/functions. This approach requires extensive team interaction and creativity. Value engineering is linked to life cycle cost that will be discussed in section 2.4. The following steps are involved in value engineering:

- Information gathering
- Function analysis
- Creative phase
- Evaluation
- Development
- Completion [45]

The design process usually takes around six months. Currently, in the construction field it is common that the design of the building continues after the construction has started.

The key to successful construction of buildings is successful planning. Successful planning involves good communication and close cooperation between everybody involved in the project, the owner, the architect and the engineer. As soon as the contractor has been assigned to the project he should also cooperate with the other parties. In this way the constructability of the building can be addressed which is very important. Constructability affects the time of completion of a turn-key project and the final cost to the owner. [2]

2.2 Construction Time

The construction time is getting shorter and shorter. It is important that the construction time of a building is under 12 months. It depends on the building but usually it takes around 10-14 months to construct the building. If the building is very complex, it can take longer. The construction time needs to be kept to a minimum to reduce interest fees so the owner gets rate of return of the property as soon as possible.

The construction time is a big cost factor in the project and the construction field is constantly working on minimizing the time of construction. It is important that the construction can be a continuous process without time required between the phases in the construction. The construction time has been reduced by finding ways to work with many phases of the building at the same time. In concrete construction, the propping and the poring of the concrete is very time consuming. The use of multi deck form work has been used successfully in concrete construction and has the ability to save time considerably. [33]

2.3 Cost of construction

The cost of construction is affected by many factors. The cost is dependent on the factors that have already been discussed in this chapter. The cost is evaluated to calculate the profit of the project. The cost is normally divided into direct cost and total cost. Direct cost is directly attributable to the manufacturing of a product. The cost of a building can then be divided into material cost, labor cost and operational cost. The material cost and labor cost are usually similar in a building project. The most important factors of operational cost are maintenance, heating and care-taking and they are all dependent on the design of the building. Total building cost is a complex issue due to the interaction of various elements. Sometimes, the best design of one aspect conflicts with another aspect, for example services. To reach an optimum solution, the cost should be examined in an integrated manner. [33]

2.4 Life cycle cost

Life cycle cost is the total cost of a building throughout the entire duration or life cycle of the building. This term was defined in 1995 by Kirk and Dell'Isola as; *economic assessment of investment alternatives that considers all signifant costs of ownership discounted over the lifetime of a product (Öberg, 2002).*

The life cycle cost can also be defined as the present value of the total cost of a building over its operating life, including initial capital cost, occupation cost, operating cost and the cost incurred derived from the disposal of the building at the end of its life. Life cycle cost is a complicated term that has become more common in the design process because it is not relevant to only consider the initial cost of the building as design teams often do.

The initial cost can be reduced by reduction of built area, appropriate construction method, selection of structural system but it might still not be the most economical solution because cheaper materials often require more frequent maintenance. [8]

The largest part of life cycle cost is maintenance and operation cost and will usually be 50-80% of the total cost during the lifetime of the building (Chew, Tan, Kang, 2004). Life cycle cost has been more important in the designing process because buildings have become more complex, higher levels of service are required which means increased proportion of systems needed.

Life cycle cost can be applied to evaluate different solutions in the design phase. The whole building can be studied or single systems or components that are relevant in the building. Life cycle cost is essential in overall building performance.

2.5 Fire Safety

Fire protection is an important factor, which has considerable influence on the planning of the high-rise core as a result of requirements for the number and size of escape stairwells, and smoke extraction.

The fire resistance classification of a structure is determined by R (load carrying capacity), E (integrity), and I (insulation) followed by the length of time, in minutes, that the structural element would withstand a standard fire.

Fire safety in a building is rated from the following factors:

- the ability to keep fire in confined area (EI)
- the fire resistance of load carrying and stabilizing structures (R)
- the behavior of the materials regarding ignition, combustibility and build-up of smoke
- the possibilities to escape
- the fire alarm system
- active fire protection devices such as sprinklers. [32]

The following is required for a four story office building according to Swedish building codes. Structures for separating firecells shall be of class EI 60. Vertical- and horisontal load resisting systems shall be of class R60. Each storey is a separate firecell. Moreover, the stairwell-cores and the vertical installation-shafts are each a separate firecell.

Icelandic standards for fire safety require that all structural elements in the first three floors of a four story office building is required to be R60 but the elements fourth floor can be R30. The structural members in the fifteenth first floors of a twenty story building are required to be of class R120, the next four floors of class R60 and the members on the top floor can be of class R30. [34]

Concrete structures provide the best fire protection where the thickness of the concrete and the concrete cover can be adjusted to fit the fire resistance requirements. Steel structures and the steel in composite structures need protection against fire. The steel structural elements are often built in with insulation or other fire protecting material or spray painted with fire protection paint.

2.6 Acoustics

The acoustic requirements for office buildings are relatively low compared to residential buildings. The walls and floors are required to have sound barrier for average frequency sounds, such as people talking and other noise from office activity (50-70dB).

Air-bourne sound insulation, $R'_{w,}$ is the separating element's ability to reduce sound travelling through air. Air-bourne sounds are transmitted directly through elements, through flanking elements, through ventilation channels, or because of involuntary leakage in joints and openings. The lowest value recommended for air-borne sound insulation, R'_w, between rooms in an office building is 44 dB.

Impact sound level, $L'_{n,w,}$ describes the noice of tramping on the floor and depends on the slab construction and the flooring.The highest recommended value for impact sound level, $L'_{n,w}$, for an office building is 68dB.

The sound level, Lp, is the noise from installations and traffic. The sound insulation for this factor is designed with respect to duration of the disturbance. Traffic has an average equivalence sound pressure level and installations can either have long or short duration sound pressure level.

The highest allowable values for sound pressure level from installations in office buildings are:

LpA=30 dB (long duration)

LpAFma =35 dB (short duration)

The highest recommended value for sound pressure level from traffic loads is LpAFma = 40 dB.

Reverberation time, T(s), is a measure of the sound absorption in a room. Reverberation time grows the bigger the room volume is and reduces with greater sound absorption area in the room. Mineral wool and gypsum plates are sound absorption materials. This factor needs to be considered in bigger rooms or conference rooms.

Flanking transmission is when air-borne sound and impact sound pass through a partition wall through structure-borne sound (vibrations) in adjoining structural elements. The details of the joints need to be well designed to prevent this. [9]

Icelandic building codes do not include special acoustic requirements for office buildings, but it is an important factor that needs to be considered. Noise control is required to provide an indoor environment free from stress of unwanted noise and speech privacy. The following factors may be considered to provide noise control in the design of an office building

- Selection of system components to ensure minimal emissions of noise when installed in a building
- Containment of noise emissions as close as possible to the noise source
- Reduction of noise levels within the room containing the noise source
- Attenuation of noise either by absorption as it travels its path (e.g., along an air-conditioning duct) or by a combination of absorption and reflection as it passes through walls, ceilings, and roofs. [22]

2.7 Installations

There are many combinations of service systems available and the selection depends on owner's requests usually with respect to cost and the indoor climate, inside loads from the operation in the building, and outside loads, such as sun, wind and pollution.
The cost of the installations system is about 35% of the total cost of an office building. [35]

Installations can be divided into two main groups:
Climate installations

- Heating system
- Air-conditioning
- Air-cooling

Service installations

- Tap water
- Drainage
- Electricity
- Security

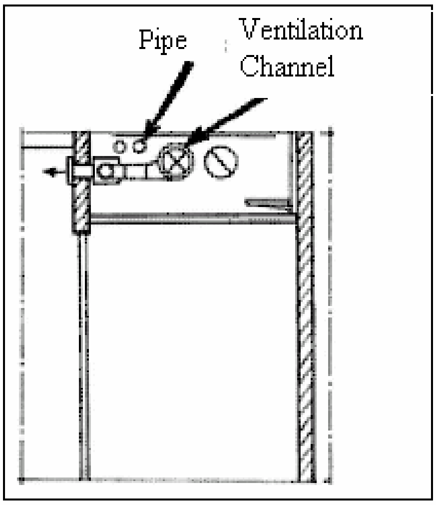
The service installations do not create problems during the construction while the climate installations are more difficult to design. The loads are constantly changing and the heating, air-conditioning, and air-cooling have to work accordingly to obtain ideal indoor climate.

Vertical pipes for water and waste water are typically installed in installation-shafts. Horizontal connection pipes for water and waste water are of smaller dimensions and they can be cast in slabs.

Heat can be provided with radiators which are in general located under windows. Pipelines for the heating system are typically placed in vertical shafts and under ceilings in corridors.

Ventilation-needs according to BBR (Swedish Standards) is that exterior air flow shall be at least 0,35 l/s per square-meter floor-area in rooms where people are situated. In addition, there are ventilating needs to get rid of heat and ozon from computers and copy-machines.

The simplest way to discharge intake air is to discharge it from an interior wall (Figure 2.1).



Ventilation system demands space for:

- Air inlet for intake air, placed on roof
- Room for fans, minimum 5 % of total floor-area
- Shafts for main channels
- Horizontal pipes are usually 400 mm in diameter
- Connection pipes are usually 160 mm in diameter
- Air terminal devices for intake air and exhaust air.

Figure 2.1: Placement of horisontal installations and air terminal devices for intake air. [35]

2.8 Structural System

The efficiency of a structural system can be evaluated for each of four major phases of the construction: design, fabrication, transportation, and erection. The evaluation of the performance of a structural system can be summarized in terms of: strength, stability, and serviceability criteria.

A structural system is expected to carry all loads acting on the building and transfer them effectively to the foundation. There are many factors that need to be considered in the selection of the appropriate structural system. The factors that need to be considered have been discussed above. From a structural stand point, the system needs to have the following functions:

- ✓ Carry and transfer dynamic and static vertical loads
- ✓ Carry and transfer lateral loads due to wind and earthquake forces
- ✓ Resist stresses caused by weather conditions and shrinkage effects
- ✓ Resist external or internal impact loads
- ✓ Resist and damp vibrations and fatigue effects

The evaluation and selection of the structural system can be summarized with the factors above and the details that are discussed earlier in the chapter. The factors above can be summarized and added to the checklist. The selection can then be made after rating the factors and dependent on the importance of the following factors.

- ✓ Architectural and owner's requirements
- ✓ Time of design and planning
- ✓ Construction Time
- ✓ Life cycle cost
- ✓ Fire safety
- ✓ Acoustics
- ✓ Installations
- ✓ Durability

2.9 Building envelope

The building envelope includes everything that separates the interior of a building from the outdoor environment, including the windows, walls, foundation, basement slab, ceiling, roof, and insulation.

An exterior wall and the facade must address a number of performance requirements in order to achieve its function of seperating the indoor environment with the uncontrolled outdoor environment. These requirements range from structural and fire performance, through building physics (heat, air, and moisture) to durability, economics, and aesthetics. Figure 2.2 illustrates the detailing where the building envelope consists of a precast sandwich element wall. In this case the building envelope is a part of the structural system.

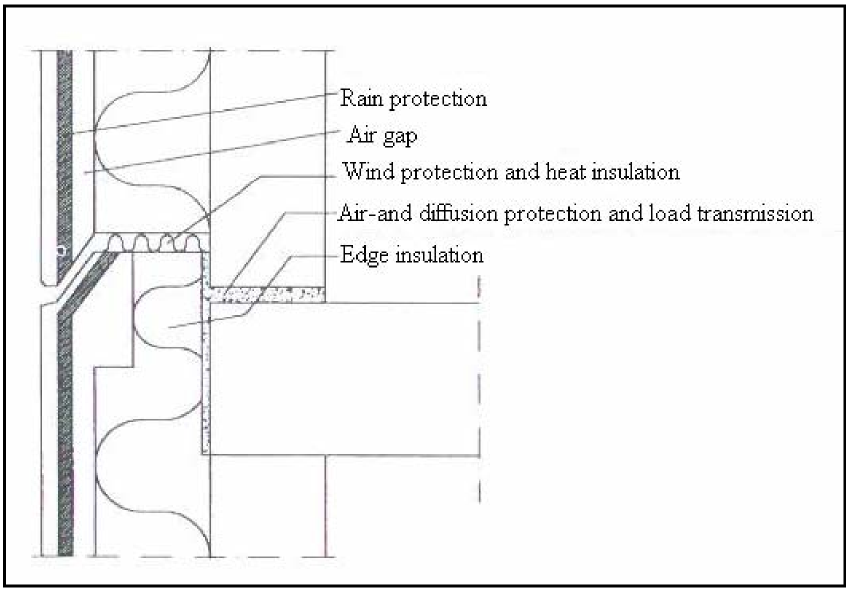


Figure 2.2: Building envelope consisting of sandwich element precast wall. [28]

The building envelope can also be a light system that is not a part of the structural system. Such a system can consist of an aluminum frame with cladding of glass or plates. Gasfilled glass is becoming more common as cladding, especially in office biuldings. Figure 2.3 shows a building envolope with glass façade.

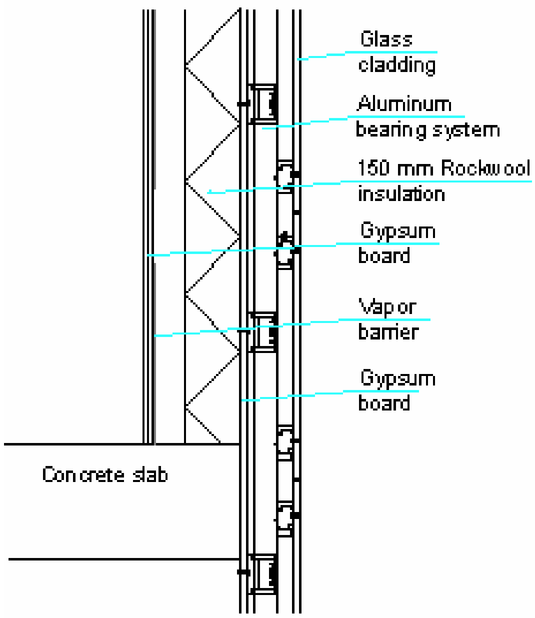


Figure 2.3: Building envelope with glass façade. [36]

2.10 Durability

The durability should be considered when choosing a building material and a structural system for a building. The designer needs to consider the effects of the environment such as freeze-thaw, chemical attack and corrosion of embedded metals. The main concern is the outer surface of the building, concrete or the cladding. Figure 2.4 illustrates the most common defects on different types of facades. In concrete the ideal approach is to make the concrete impermeable and design for high crack control.

A life time of a building is usually in the range of 50-100 years. The maintenance cost is a part of the life cycle cost and is calculated in the value engineering process. It is important to keep the maintenance cost to a minimum, but it will never be avoided completely.

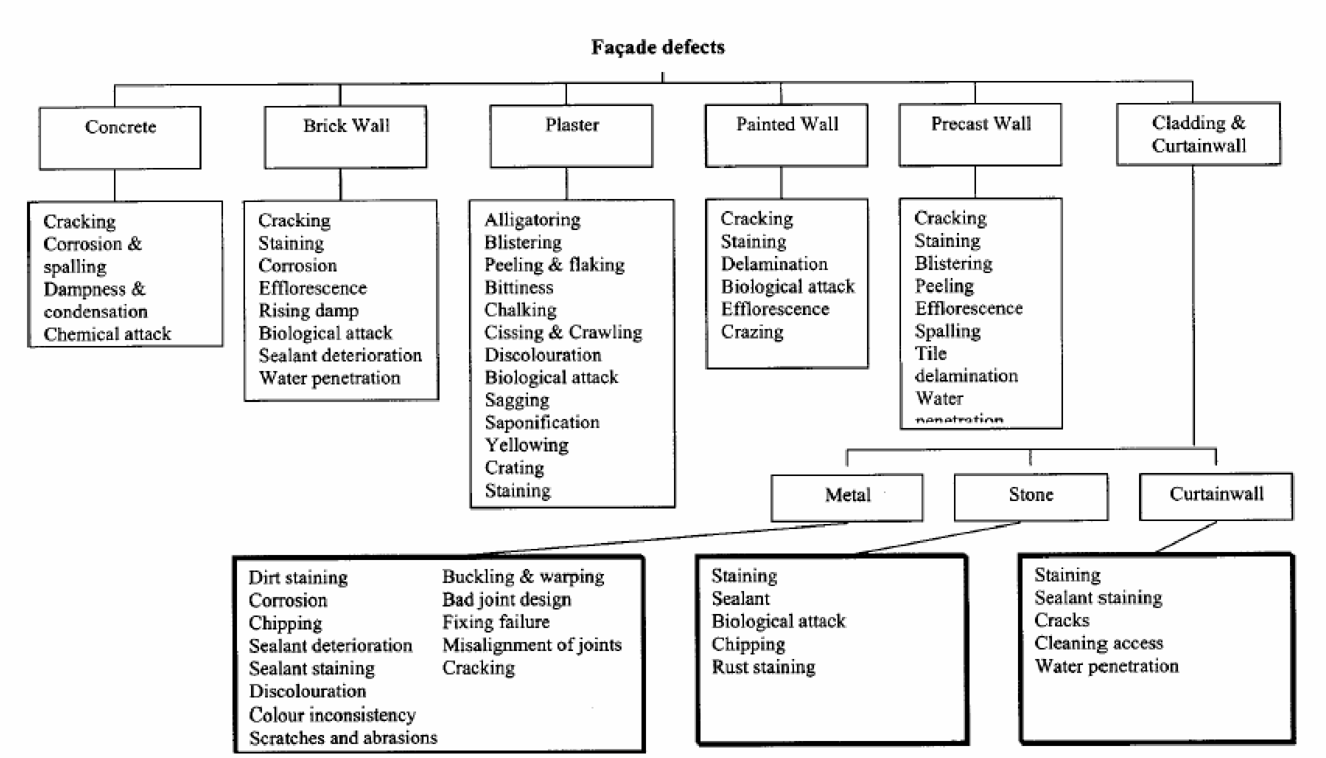


Figure 2.4: Common defects of different types of facades. [8]

3. STRUCTURAL ELEMENTS

The structural system of a building basically consists of vertical elements (columns and walls), horizontal force resisting elements (shear walls, braces, moment frames) and a floor system. The elements of the structural system must be able to transmit forces and loads to the foundation, which is generally also considered a part of the structural system. There are a number of possibilities for solutions and materials and each part of the structural system will be discussed and the possibilities addressed. Then solutions of combining these parts to complete the system will be discussed in the following chapter.

3.1 Vertical elements

3.1.1 Columns

Columns are vertical elements in a structural system and used to resist vertical forces and loads. Columns can also be a part of the lateral resisting system and are then a part of a braced frame or a moment frame.

3.1.1.1 Concrete columns

3.1.1.1.1 Cast in place concrete columns

Columns or beam-columns as they are usually referred to are structural elements subjected to axial load, shear and bending. Most reinforced concrete columns have circular or rectangular cross sections and are reinforced with longitudinal steel bars (figure 3.1). The longitudinal steel is wired together to hold it in place while the concrete is poured. A tied column has lateral reinforcement of individual steel bars, called ties. A spiral column is laterally reinforced with continuous spiral that holds the longitudinal reinforcing bars together. [5]

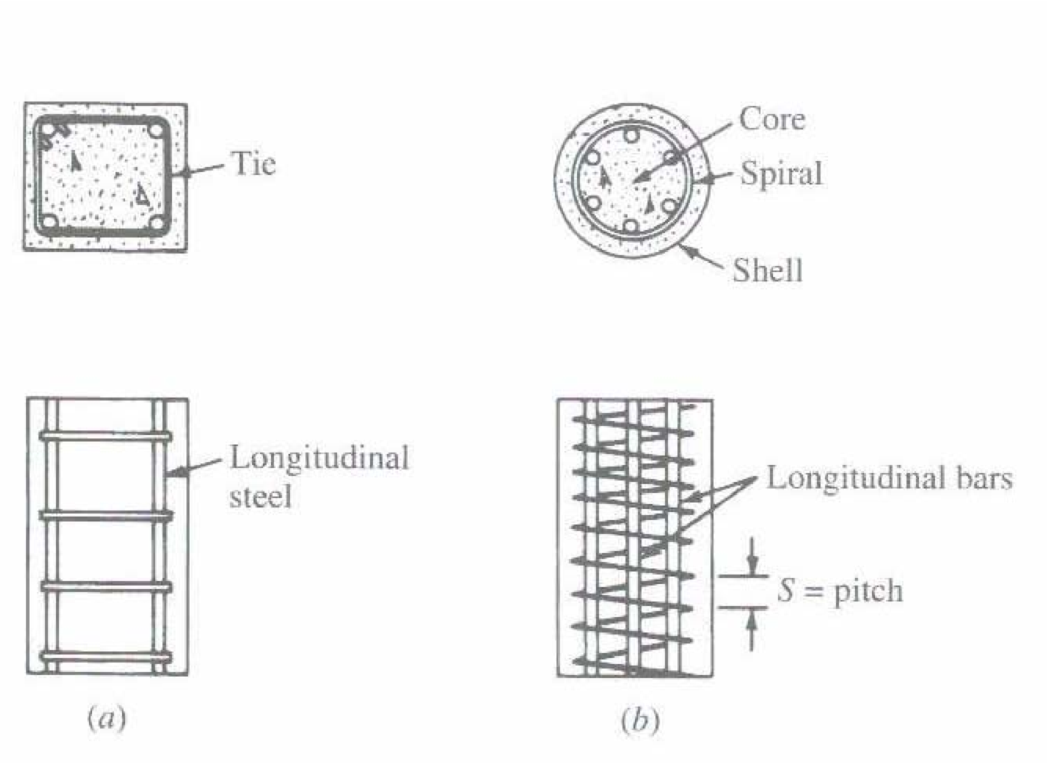


Figure 3.1: Types of columns: a) tied column, minimum of four longitudinal bars required in a rectangular column; b) spiral column, minimum of six longitudinal bars required. [5]

Columns are classified as short or slender depending on the flexibility of the column, a function of its length-to-thickness ratio and the end restraint. The design of slender columns is more difficult where the moments to be considered are primary moments and secondary moments. Primary moments are member end moments or moments due to transverse loads. The secondary moment is a product of the axial force and the deflection of the centerline of the cross section. When the secondary moments are large, the cross section must be designed for the sum of the primary and secondary moments.

Short columns have large bending stiffness and therefore very small bending deformation. The secondary moments will be very small and can be neglected in the design. Every column in a reinforced concrete frame has three internal forces, shear, moment, and axial force. Moments can be developed due to accidental eccentricities of the axial load with respect to the centroid of the column's cross section. These eccentricities can be produced by small variations in the cross sections such as voids, honeycombing, misalignment of reinforcement, and crookedness of forms. Most reinforced concrete columns are classified as slender, but failure is normally caused by overstress rather than buckling.

High strength concrete is often used in reinforced concrete columns to minimize the size of the cross section. Even though high strength concrete is more expensive the overall cost will usually not increase because smaller quantities of steel and concrete will be required. As a result, larger areas of rentable floor space will be available. [5][6]

3.1.1.1.2 Precast concrete columns

Precast columns can be either reinforced or prestressed and can be produced as either multi-storey corbelled columns or single floor to floor elements. Usually, it is most economical to have the column floor to floor (figure 3.2). Single story reinforced columns are simple to design, detail and construct. Once loads and bending moments are recognized the design process is the same as a traditional reinforced in-situ column. Eccentric loading during erection and due to localized effects at the top and bottom of the column should be taken into account in the design. Additional reinforcement is usually provided at the top and bottom of the column, these additional ties act as anti-splitting reinforcement.

Other important factors that must be considered in designing include the required beam bearing on the column. When considering this bearing area, it must be remembered that due to the corner chamfer, approximately 30 to 40 mm is lost around the perimeter.

The base connection is generally analyzed as a pin joint and due to connection details the columns tend to be conservatively sized, manufactured with high strength concrete, and reinforcement typically limited to four corner bars with nominal ties. This approach results in extremely simple components that can easily be mass produced.

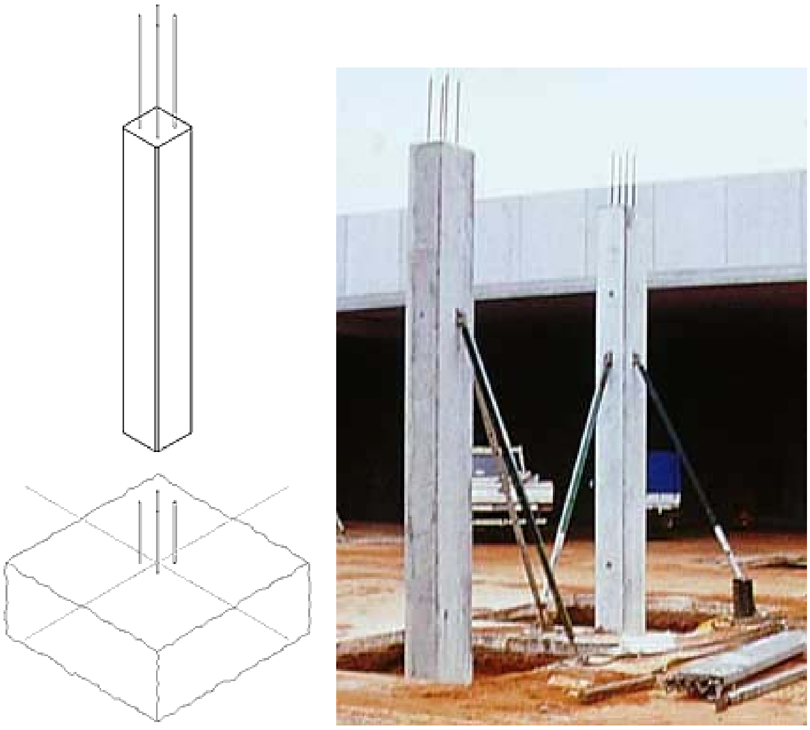


Figure 3.2: Typical precast column. [39]

3.1.1.2 Steel columns

In steel frames, the columns are usually structural members which combine the beam function of transmitting transverse loads or moments with the compression member function of transmitting axial forces. In this case, the structural member is called beam-column. The beam-column can be isolated, eccentrically loaded with simple end connections, or it may be a part of a rigid frame. In frames with simple connections, the beam-column can be treated as isolated, but in frames with rigid or semi-rigid connections the interaction between members need to be considered. Typical steel cross sections are shown in figure 3.3. [10]

Because of high strength per unit weight in steel structural members, the slenderness of members usually exceeds significantly the slenderness of similar structural members made of other traditional materials. Thus buckling becomes a serious problem, and the higher the yielding strength of the steel the greater the danger of buckling. Most structural shapes are formed by plate elements which can undergo local buckling, particularly when strained in the inelastic range. Therefore, in earthquake-resistant design, the compactness requirements for the cross section of the critical regions of structural members are more stringent than for design against normal (standard) loading condition.

The shape of the column also affects the way in which it will buckle and hollow structural-steel sections are the most efficient of all structural sections in resisting compression loads. [10] [11]

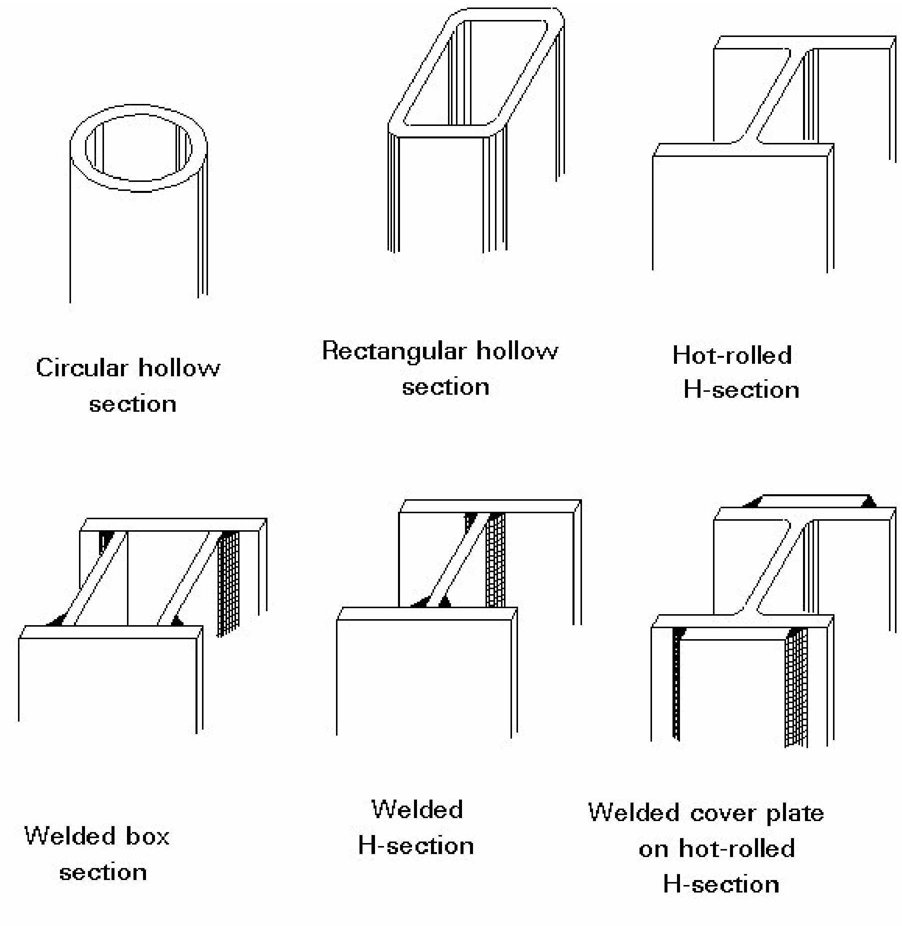


Figure 3.3: Typial steel cross sections. [29]

3.1.1.3 Composite columns

The column consists of a steel section and reinforced concrete, where the steel section is encased with concrete, a steel tube is filled with concrete, or a rolled section is partly encased with concrete.

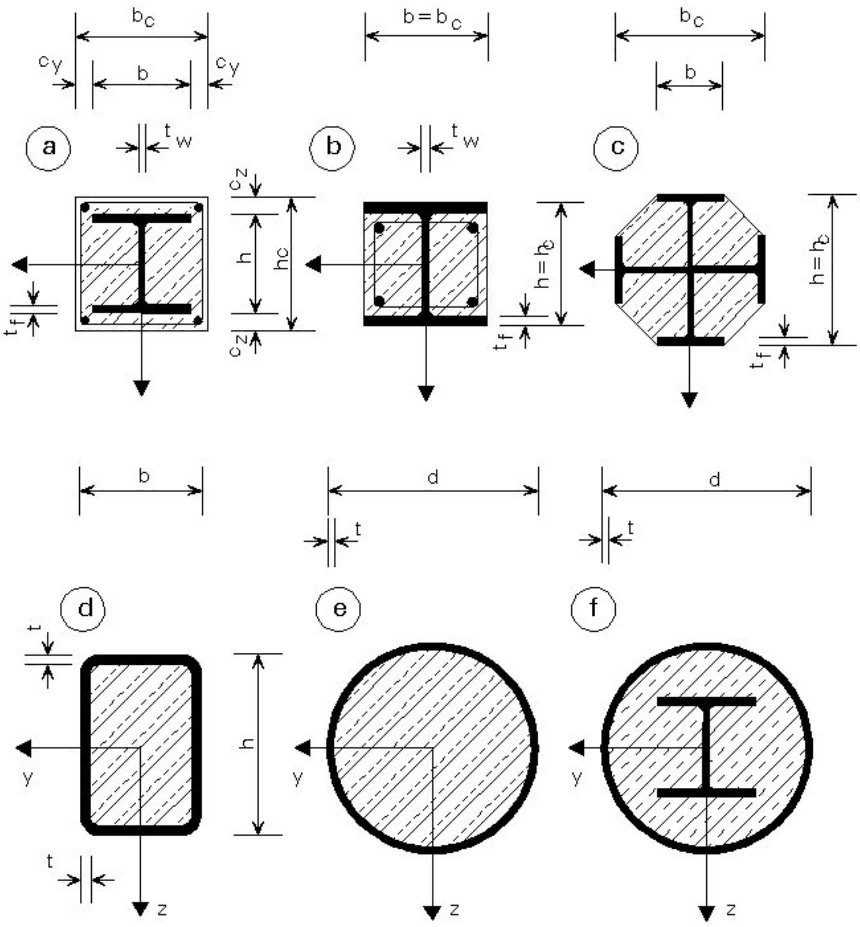


Figure 3.4: Typical cross-section of composite columns. [29]

The cross sections in figure a-c are either totally or partially concrete encased. The concrete protects the steel from corrosion and provides better fire protection. Totally encased sections (figure 3.4a) generally fulfill the technical requirements for high classes of fire protection without any additional measures. These requirements can be achieved in partly encased sections (figure 3.4b, c) as well as concrete filled sections using additional reinforcement. In the construction of partly encased sections, the concrete can be cast whilst the steel section lies horizontally and there is still considerable area of steel available for connections.

Concrete filled sections (figure 3.4d-f) provide reduction of the erection time by pouring the concrete after the frame has been constructed. The steel section works as a formwork during casting the concrete. The protective steel casing allows the concrete to achieve greater strength where the effect of confinement by the steel leads to an increase of overall resistance. Creep and shrinkage of the concrete need to be considered in concrete encased sections, where as these factors can be neglected in concrete filled sections.

The connections of composite columns must be carefully designed to ensure direct transfer of loads to both the steel and the concrete in the section. For continuous composite columns special detailing for load transfer is necessary. An example of a solution of this connection which has been proven to be efficient and economical is shown in figure 3.5. Figure 3.5(a) shows a connection of welded studs in the webs of I-profiles. Figure 3.5(b) illustrates gussets plates, punched through the steel section into the concrete filled hollow profiles. [29]

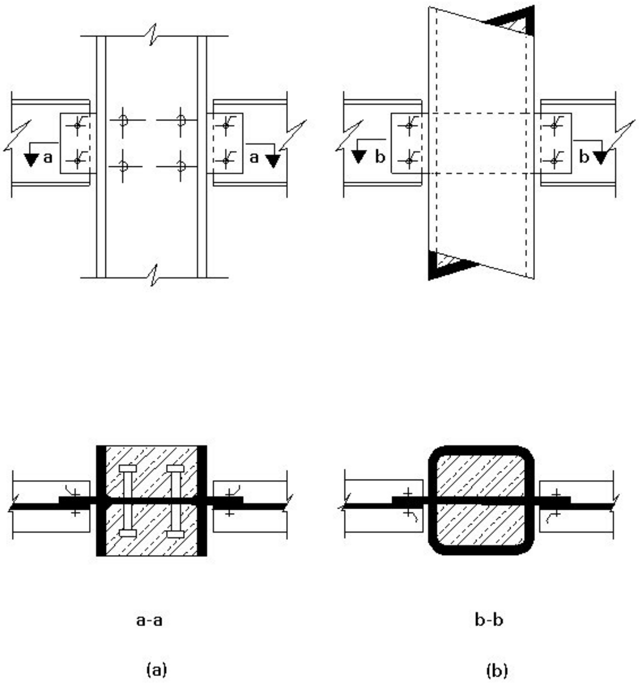


Figure 3.5: Examples connections for continuous composite columns. [29]

3.1.2 Walls

The main focus is on load bearing walls and their function as a structural element in a structural system. Load bearing walls can either be cast in place concrete or precast concrete. Walls are used to resist vertical loads and are often also used as lateral force resisting elements, referred to as shear walls. The lateral force resisting system can consist of shear walls, where the stair case or elevator shafts are made of shear walls.

3.1.2.1 Reinforced concrete walls

Reinforced concrete walls are the most traditional in buildings and have been for many years. Most concrete walls in low-rise buildings are load-bearing and support vertical loads and lateral moments. Concrete walls usually have high in-plane stiffness and are therefore convenient in resisting wind and earthquake forces. Load-bearing walls are normally rectangular cross sections and can be designed as columns subjected to axial load and bending.

In tall buildings, reinforced concrete walls are often used as shear walls. Shear walls have the purpose of resisting horizontal loads and will be discussed in section 3.3, Lateral-force-resisting elements.

3.1.2.2 Precast walls

3.1.2.2.1 Solid element walls

Solid precast concrete walls are widely used in building to speed up the construction. They have the same function as reinforced concrete walls except the connections are different. They can be either prestressed or reinforced. Precast walls can be used as shear walls and in elevator/stairwell cores. The detailing in precast wall connections is important and will be discussed in greater detail in section 4.1.2.3.
Load bearing panels must be designed to span horizontally or vertically between columns. They are designed as beams when spanned horizontally but as trusses when there are window openings regularly spaced in the wall. When they are designed in this manner it is important to have horizontal joints to prevent load transmission to panels below. When the walls are spanned vertically they are usually designed as columns where slenderness needs to be detected. In case of large openings, it may be needed to analyze it as a rigid frame. [27] [28]

3.1.2.2.2 Sandwich element walls

Sandwich element walls consist of two shells, where the inner shell will be the bearing element. The outer shell can be used as the façade of the building and is thinner than the inner shell. Insulation is placed in between the shells.
The length of the wall can be up to 8.4m and the height can be up to 4.2m. The inner shell is 0.10-0.25m and the outer shell is 0.06-0.12m. The insulation thickness is normally 0.10-0.20m. Sandwich element walls may be used only for cladding, or they may act as beams, bearing walls or shear walls. Figure 3.6 illustrates a sandwich bearing wall. [27] [28]

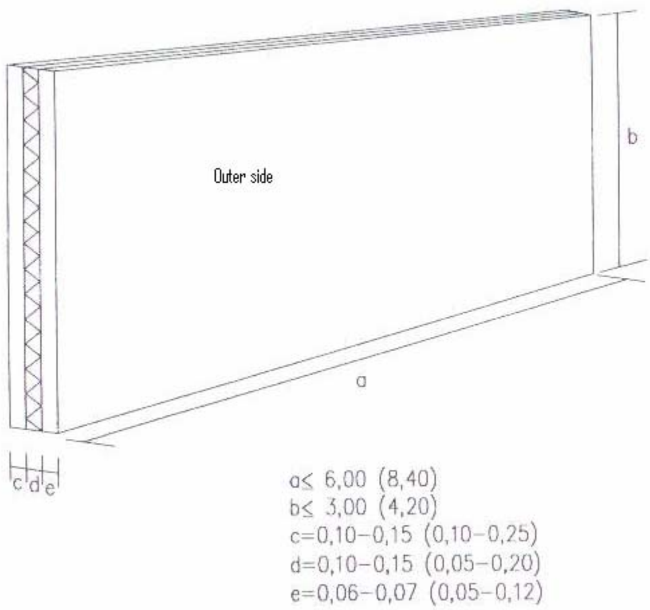


Figure 3.6: Sandwich element wall, bearing wall (dimensions in [m]). [28]

3.2 Floor systems

3.2.1 Beams

3.2.1.1 Concrete beams

3.2.1.1.1 Cast in place beams

A reinforced concrete beam is typically constructed as a part of a continuous floor system. The shapes are usually rectangular, T-shaped or L-shaped. The beams can either be simply supported or continuous but continuous beams are more common. Shallow beams are the most common elements in reinforced concrete design and the design principles can be applied to more complicated elements such as slabs, girders and continuous frames.

A reinforced concrete beam design consists primarily of producing member details which will adequately resist the ultimate bending moments, shear forces and torsional moments. Flexural strength usually controls the dimension of the beam so the beam is initially designed for moment and then checked for shear. When large moment is applied to the beam, the tensile bending stress is high and exceeds the flexural tensile strength of the concrete so that the concrete tends to crack. Once the beam cracks, the longitudinal steel reinforcement in the tension zone carries all the tensile stress. Service loads usually generate moments that are higher than the cracking moment. In regions where the moment exceeds the cracking moment, the beam will crack. The bending stiffness of a beam reduces significantly once the beam develops flexural cracks. Reinforced concrete beams must be designed to have adequate stiffness as well as strength. Deflections must be limited under service loads so attached nonstructural elements will not be damaged or rendered inoperative by large deflections. Nonstructural elements can be partitions, pipes, ceilings, or windows. In the deflection design considerations, elastic instantaneous deflections caused by applied loads and long term deflections developed due to creep and shrinkage must be considered. Deflections are minimized when beams are carefully constructed out of high-strength, low-slump concretes that are well compacted and effectively cured. In the selection of reinforcing steel the bond between the reinforcement and the concrete must be checked to prevent that slippage will take place. [5] [20]

3.2.1.1.2 Cast in place post-tensioned beams

The development of pre-stressing methods has been very important in the field of structural concrete. There are two ways of pre-stressing concrete; precast pre-tensioned and cast in place post-tensioned. Pre-stressing involves inducing compressive stresses in the zone which will tend to become tensile under external loads since the concrete is weak in tension. The compressive stress neutralizes the tensile stress so that no resultant tension exists, or only small values that can be ignored in the design. The concrete will carry load more effectively and cracking will be eliminated under working load. Therefore the sections can be lighter and span longer spans compared to conventional reinforced concrete. [18]

Post-tensioned elements in buildings have become common in some countries, especially in the US and Australia. The use of post-tensioned beams and slabs is growing in Europe and this section will focus on post-tensioned beams.
Post-tensioned beams are usually convenient in longer spans where the depth of the beam and reinforcement can be minimized by post-tensioning. Post-tensioned transfer beams or plates are commonly used in lobbies of office buildings, where a large column free space is required. The transfer beam or plate is used for the transition from small support grid to large column spacing in the lobby (figure 3.8). Post-tensioning involves the following steps: The cable ducts and reinforcement are placed in the beam formwork and the concrete is pored and allowed to cure to the required initial strength. Then the tendons are threaded through the cable ducts and tensioned to about 70% of their ultimate strength. The wedges are inserted into the end anchorages and the tensioning force on the tendons is released. Finally, the ducts are filled with grout to protect the tendons. [13][18]

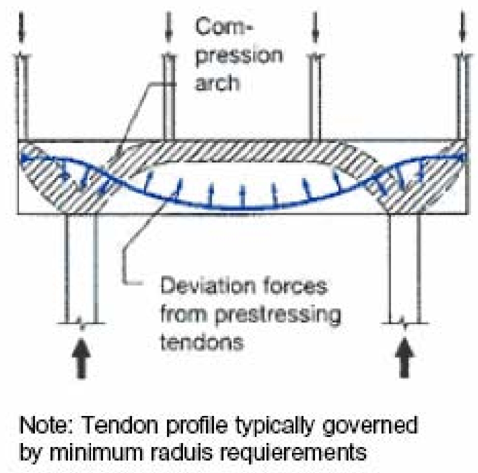


Figure 3.7: Principles of post-tensioned transfer beam [13]

Figure 3.7 shows the principles of post-tensioned transfer beam, where the column forces are transferred from the upper floors to the supports. The self weight of the beam is balanced by the upward acting deviation forces from the parabolic tendons. This will result in smaller deflection than in traditional cast-in-place beams. The post-tensioning tendons create in-plane compression stress that improves the cracking behavior of the beam.

The bending moments are mainly resisted by the post-tensioning tendons so that usually only a minimum crack reinforcement is required in the extreme faces. The reinforcement can therefore be simplified and results in reduction of construction time, which is very important in construction of a multi-story buildings. [2][13]

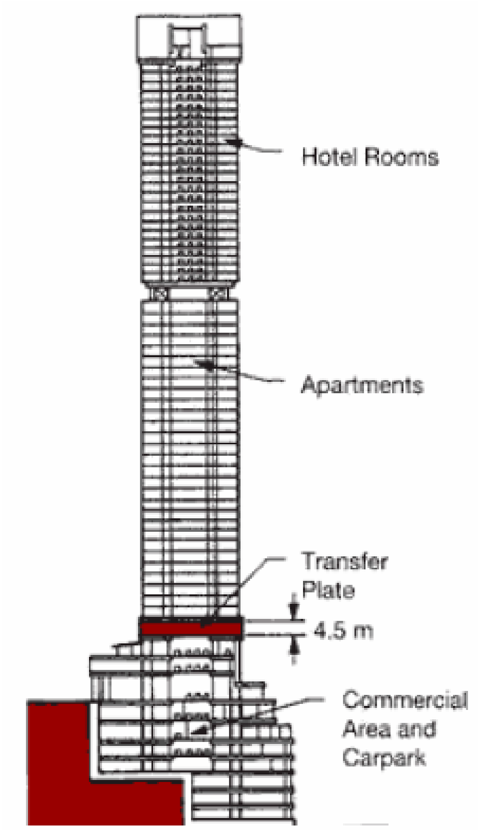


Figure 3.8: An example of use of post-tensioned transfer plate in a high rise building. [13]

3.2.1.1.3 Precast beam

Precast beams are designed as pre-stressed or partially pre-stressed and the details have been developed with simplicity and practicality in mind. In the US, typical precast beams are an inverted T- profile and designed as continuous for imposed loads in its final form, while being simply supported during the erection phase. The connections of continuous beams are quite complicated and will be discussed in section 4.1.2.3. In Europe, precast beams are designed as simply supported to avoid the complex connections. Precast beams in general are designed so that no propping is required during erection of the supported floor. The precast floor components sit directly on the ledge of the inverted T.

The beams are placed directly on the top of the columns, when columns are floor to floor (figure 3.9). The beams are connected to the column with a pin connection, where dowels from the column pass through ducts within the end of the beam. This connection is simple to construct but the connections in precast structures can be very complicated. When the beam is loaded it can have the tendency to roll on the columns so the connection needs to be designed to resist torsion.

While the use of this type of one way skeletal structure is a very simple and effective method of construction, it does require a slightly increased overall beam depth compared to slim line profiled beams or a traditional band beam system. The end result is generally that it is more economical to increase the overall building height than to reduce beam depths [27].

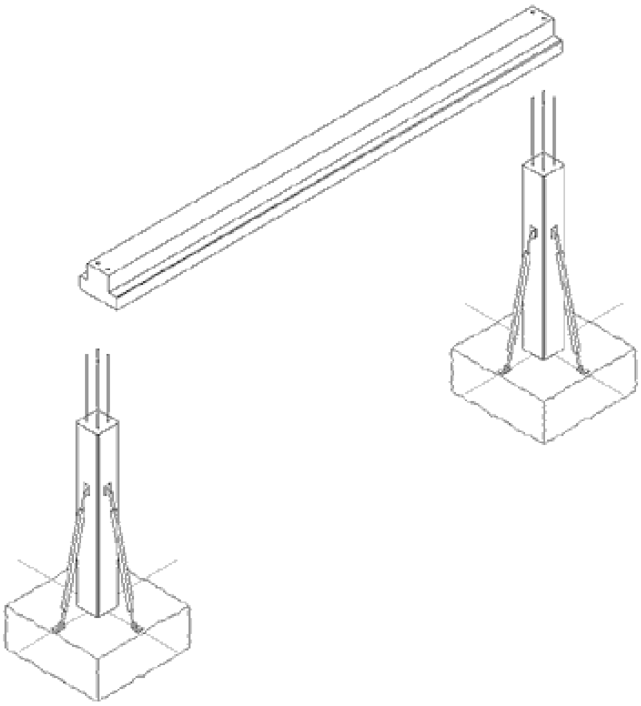


Figure 3.9: Precast beam on floor-to-floor column [39]

Table 3.1 illustrates the recommended straight precast beam sections which are often used. I-beams are also quite common, especially for longer spans.

	h (mm)					
b (mm)	300	400	500	600	700	800
200						
250						
300						
400						
500						

Table 3.1: Recommended straight beam sections. [30]

Normal dimensions are as follows:

Length: 4.8-14.4m
Width: 250-1000mm
Depth: 300-700mm [30]

3.2.1.2 Steel beams

Steel beams can be used in many different shapes in a structural frame and there are many methods to obtain the most efficient and economical cross section. Figure 3.10 illustrates typical steel beam cross sections. Thin-walled sections are most frequently used, where the material is distributed more efficiently. Thin-walled sections are usually cheaper to manufacture but tend to be weak in torsion. Rolled sections are most economical to manufacture and when they are not suitable a beam may be fabricated by connecting together a series of rolled plates. Tapered and castellated beams can also be fabricated to rolled beams. [10]

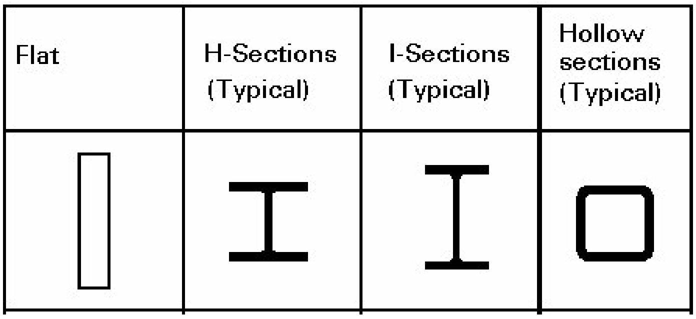


Figure 3.10: Typical steel beam sections. [29]

In buildings, the most common types of beams are joist and girders. Joists are closely spaced beams and usually act as secondary beams. Girders are deep beams that are frequently at wide spacing.

Plate girders are very commonly used as a part of a rigid frame system in buildings. A plate girder is built up from plate elements to achieve more efficient arrangement of materials than is possible with rolled beams. Plate girders may be bolted, or welded elements (figure 3.11) and are economical for long spans. Plate girders can be used for spans from 20 to up to 50m. [11]

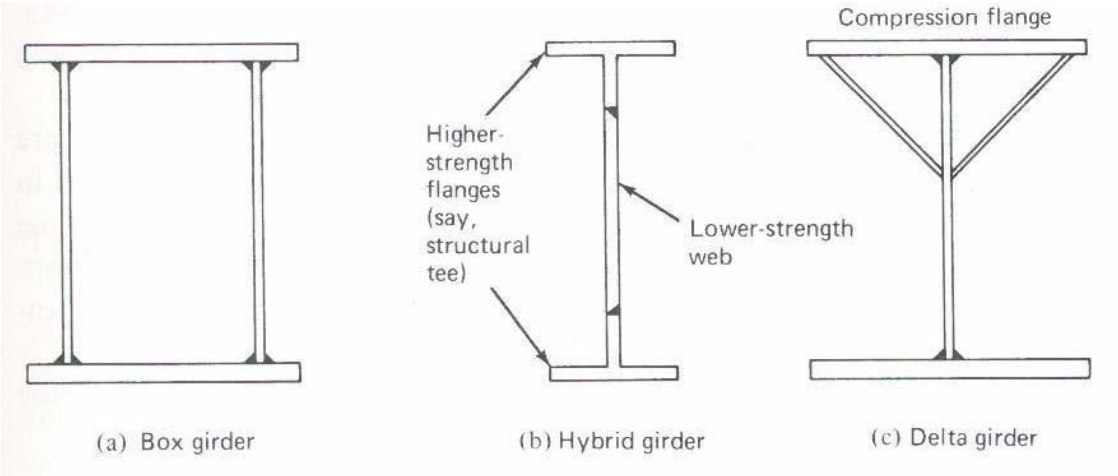


Figure 3.11: Types of welded plate girders [11]

Since the shear strength of plate girders is largely associated with the web, regularly spaced transverse stiffeners are used to increase the web's strength and stiffness. The plate girder behaves like a truss where the web carries the tension forces and the stiffeners carry the compression forces.

3.2.1.3 Composite beams

Composite beams (figure 3.12) consist of steel section and reinforced concrete, acting compositely. The beam is mainly subjected to bending, where vertical loads create sagging bending moments that cause tension in the steel section and compression in the concrete deck. The two materials are connected by mechanical shear connectors. The result of the composite action is a high stiffness beam that can carry heavy loads on long spans. The degree of the shear stud connectors is the most important factor in interaction between the steel and the concrete. Slip at the interface between the steel section and the concrete slab must be eliminated to have composite action in the sections. Typical height of a composite beam is 240-300mm for spans of 6m. For longer spans the height increases, a beam that spans 25m would have a height of around 1m.

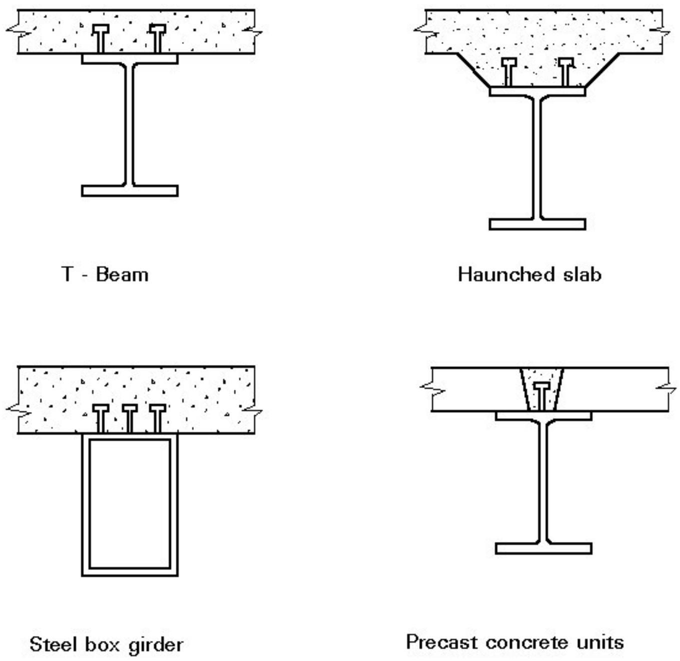


Figure 3.12: Typical beam cross-sections. [29]

The beams can either be rolled sections or fabricated. Rolled sections are usually used for spans in the range of 6-10m. Fabricated sections are sized precisely how the designer wants, where the dimensions can be fitted to the design capacity. Fabricated sections are economic for spans above 12m. Fabricated beams with tapered webs are most economical for spans from 13 to 20m. Tapered beams (figure 3.13) are designed have varying moment and shear capacity along the length of the beam and can be designed for the required resistance at all points along the beam. [29]

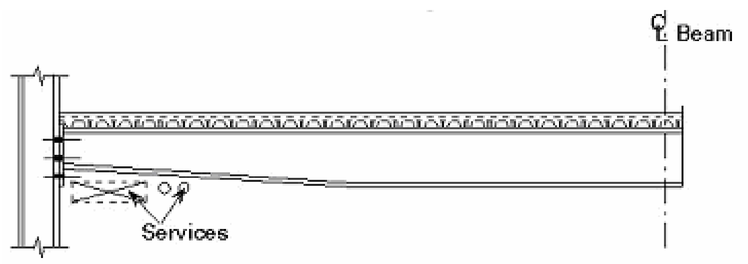


Figure 3.13: Typical tapered beam. [29]

3.2.2 Slabs

3.2.2.1 Concrete slabs

In the middle of the nineteenth century, reinforced concrete was invented and the outcome was strong, stiff, ductile, and durable construction material. Unprotected steel corrodes with time, but covering it with concrete prevents that and provides fire protection. The steel is strong in tension and reduces the negative effects, cracks and brittleness respectively. In addition, steel has higher shear strength than concrete. The negative characteristics of reinforced concrete are shrinkage and creep, but the effects of these properties can be minimized by careful design. [5][6]

3.2.2.1.1 Cast in place concrete

Reinforced concrete slabs are the most common kind of slabs in buildings. The concrete is pored in a formwork in-situ after the reinforcement has been placed. The formwork is removed after the concrete is cured. The slabs are supported by beams and/or girders that can be made of steel or concrete. The minimum slab thickness is controlled by deflection limitations. One-way slabs (figure 3.14) are supported so it bends in one direction only, called cylindrical bending. The design of one-way slabs is made by the assumption that it behaves like a series of individual beams placed side by side. The slab reinforcement is normally uniformly spaced bars of a single size.

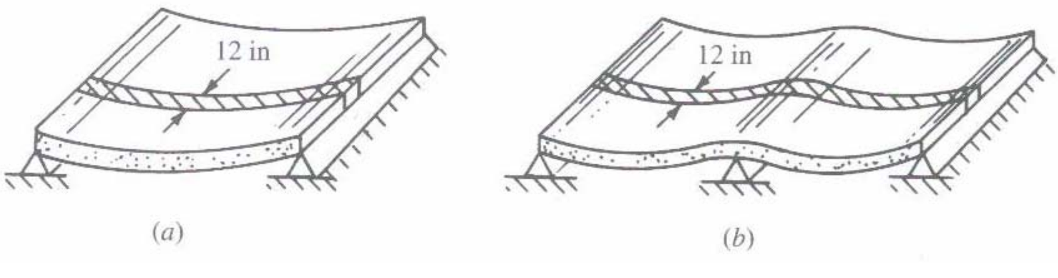


Figure 3.14: One-way slabs: a) simply supported, b) continuous. [5]

Two-way slabs (figure 3.15) require reinforcement in two directions to prevent excessive cracking and to limit deflections. Two-way slabs bend in double curvature. Two-way slabs are usually supported by columns that form a rectangular grid so a two way action develops. The rectangle formed by the columns is called a panel. The curvature of the slab determines the position of flexural steel reinforcement, where top steel is used in regions of negative curvature and bottom steel in regions of positive curvature. The most common two-way systems include flat plate, flat slab, or flat plate stiffened with beam along the column centerlines.

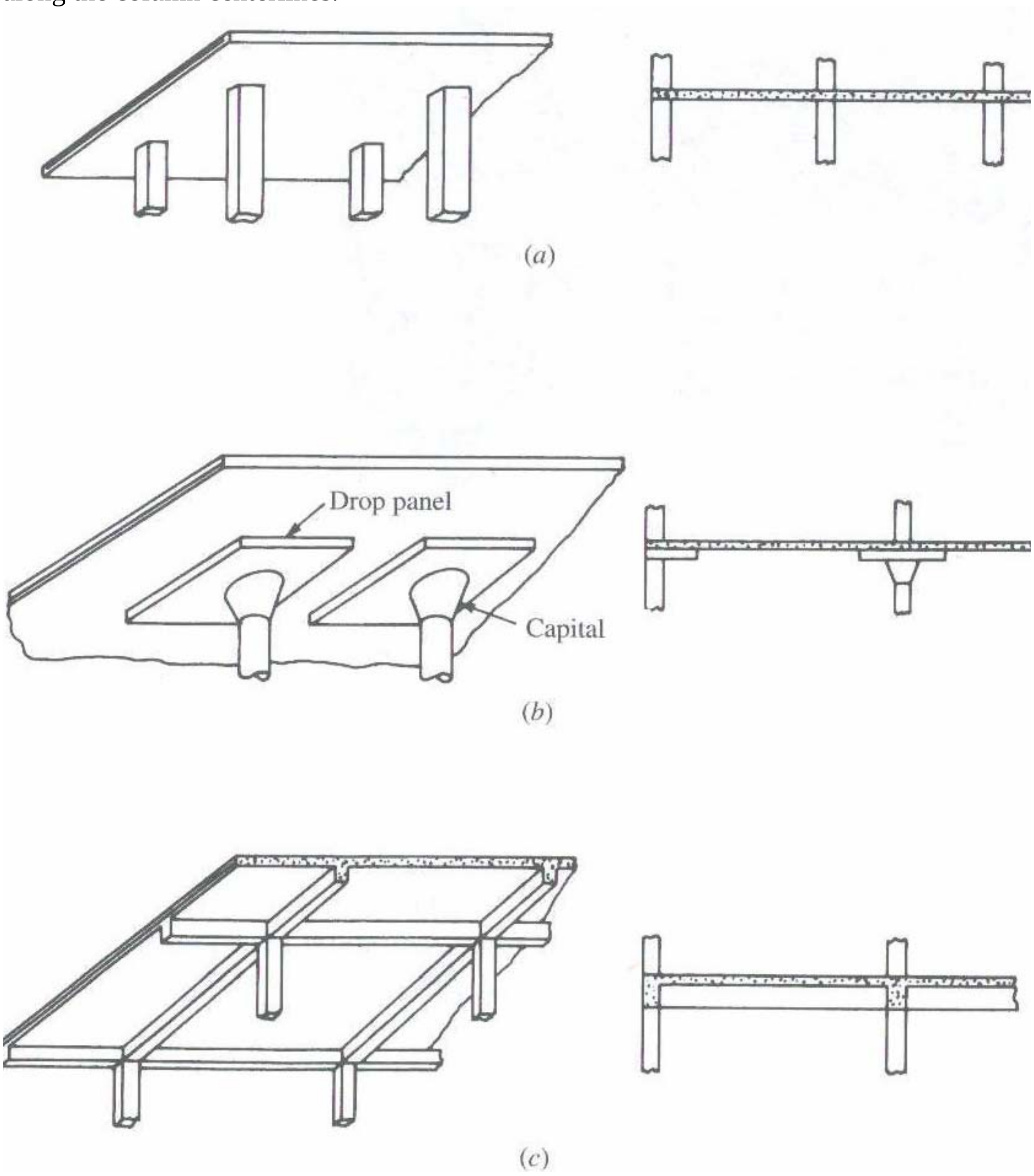


Figure 3.15: Two-way slab systems: a) flat plate, b) flat slab, c) slab stiffened with beams on column centerlines. [5]

The two-way slab is a highly indeterminate element and there are many different ways to analyze and design the slab. Strip line method and the yield line theory are methods that can be used, but finite element programs are now commonly used. Properly reinforced two-way slabs can develop large flexural capacity but deflections tend to be large because of the flexibility of the slab. The design is usually controlled by deflection limitations. The capacity to transfer loads by shear to the columns is often low in two-way slabs so failure is caused by overstress in shear at the column in systems without beams. This failure is called punching-shear failure.

In a typical plate element, large internal forces can develop. These forces act on the interior face of the slab and are in the general vertical and horizontal shear, an in-plane axial force, bending moment and torque (figure 3.16). [5]

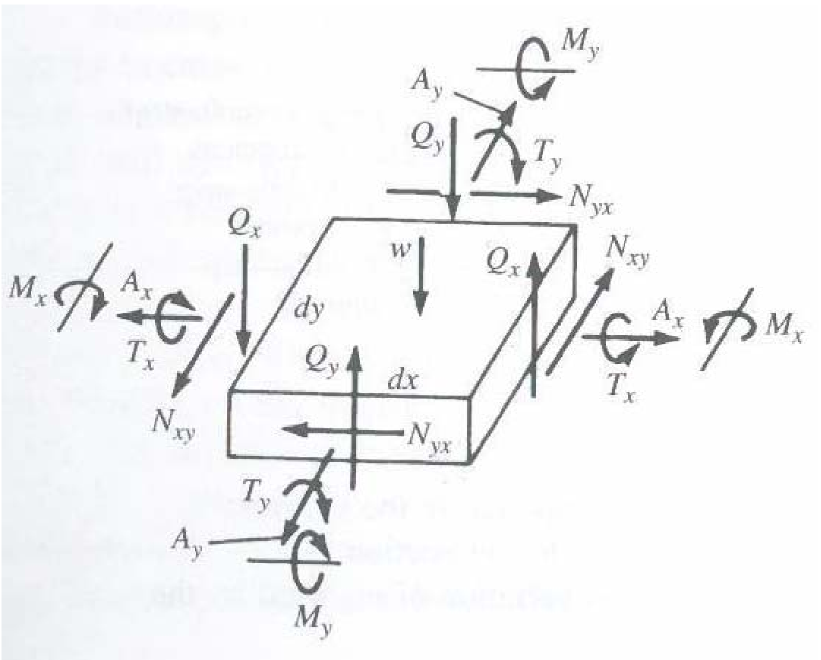


Figure 3.16: Internal forces on a typical slab element: A =axial force, N =inplane shear, Q = vertical shear, T = torque, M = bending moment, w = uniform laod. [5]

3.2.2.1.1.1 Waffle slab

Waffle slab floor system is a two-way floor system that consists of a shallow slab and a grid of beams (figure 3.17). The system is constructed by arranging square fiberglass or metal pans with tapered sides relatively closely spaced and the concrete is pored over and between the pans so the waffle shape is formed. The gap between the pans for the web of beams that are rather deep and provide large moment arms for the reinforcing bars. Waffle slabs are used for spans from 7.5 to 12m. The weight of the floor system is greatly reduced with the use of waffle slabs, without reducing the moment resistance. Waffle floors are usually made solid around columns where lack of shear resistance tends to create problems. [20]

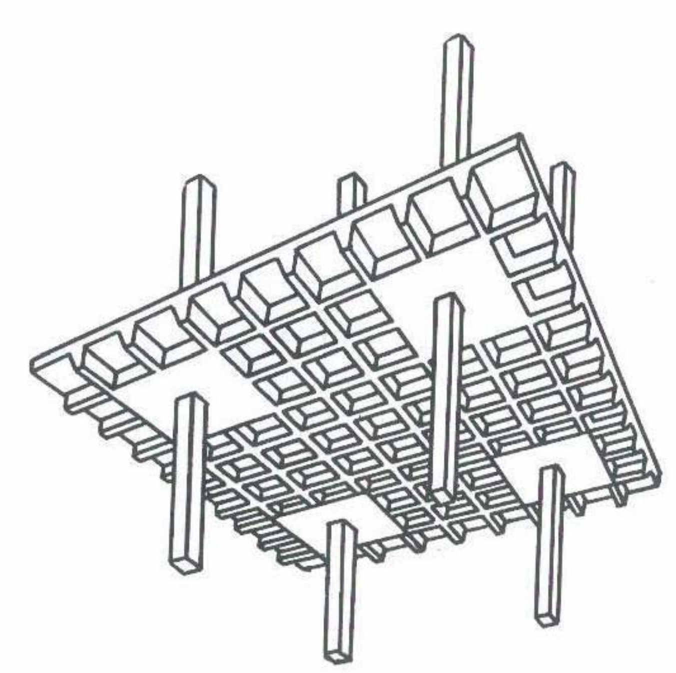


Figure 3.17: Waffle slab [20]

3.2.2.1.2 Post-tensioned concrete slab

Post-tensioned (PT) slabs are often used in medium to high-rise office buildings. These floors are particularly popular in the US and Canada. They are used only to a limited extent in Europe but are quite popular in the UK. Post-tensioned slabs are also frequently used in parking facilities where the requirements for cracking are strict. In high-rise buildings especially, constructability of floor to floor, floor height and weight are very important factors. Post-tensioning allows the floor framing to be more slender, solving the problem of the conflicting needs for long spans and small structural depth. The amount of reinforcement can be reduced significantly as well as the amount of concrete. Long span PT floors constructed from internally prestressed cast in place concrete may be up to 30% thinner than traditionally reinforced slabs and the spans can be up to 70% greater. This results in a lighter system which will reduce crate hoisting loads, form work size, column sizes and the size of the shear walls. [18][19]

The slender slabs can be designed to have sufficient strength but the small depth can lead to reduction in stiffness which can cause problems in reaching serviceability requirements such as floor deflection, vibration or cracking. The cracking of the concrete and static floor deflection of a PT slab can be avoided to a large extent by careful choice of amount and location of the prestressing tendons. The dynamic behavior of the slab cannot be avoided in the same way since that is largely governed by the slab stiffness, mass and damping on which different levels of prestressing do not have major influence. The location of the tendons must also be considered with respect to long term flexibility of the building. Remodeling of the building can be more difficult and more expensive because of the reinforcement and the post-tensioning tendons. Figure 3.18 illustrates an example of the tendon profile in a PT slab.

Low material cost and availability are factors that are an advantage of PT slabs. PT floors can typically be constructed quickly, due to the quick strengthening properties of the material. In conventional reinforced concrete, construction of successive floors must often be delayed until the concrete has gained enough strength to support its own weight, often 14 to 28 days. PT slabs can span up to 16m but in those cases the post tensioning tendon profile is difficult to design. In office buildings, the spans are often 6-8m which that would make the height of the slab around 300mm. [19]

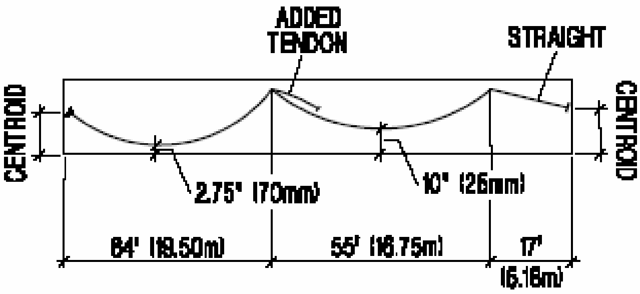


Figure 3.18: An example of post-tensioning tendon profile for a member with unequal span lengths. [19]

3.2.2.1.3 Precast and pre-stressed slabs

3.2.2.1.3.1 Hollow core slab

Hollow core slabs are pre-stressed concrete units with continuous voids provided to reduce weight and therefore cost. The width of the slabs are usually 1200mm, but can be manufactured with 2400mm width as well. Thicknesses vary from 150-500mm, where the thickness is determined by span, loading, fire rating, and cover to reinforcement. Hollow core slabs now have a market share of approximately 50% of all slabs for offices and housing. Hollow core slabs are mainly used as floor or roof deck systems. The hollow cores in the concrete floor slabs are used as heating and air-conditioning ducts and to run electric conduits. The load bearing capacity can be dominated by four different failure modes, i.e. flexure, anchorage, shear compression and shear tension.

The design of hollow core floors generally involves two stages: preliminary design and final design. In the preliminary design the general layout, overall dimensions of the hollow core plank and the typical details are chosen to suit the requirements of the building. In the final design, details of the plank, connections and embedded items are decided before the final drawings are produced. [27]

Hollow core floors are usually designed as simple one-way slabs. After the planks have been installed they interact and transfer forces from one plank to another. [26]

Advantages:

- Speed of erection. Propping is usually not necessary and the elements are ready to install when brought to site.
- Long spans, up to 16m
- Quality. The slabs are manufactured in a controlled factory.
- Good fire resistance
- Good sound insulation
- Good thermal conditions within terms of energy efficiency.
- Small total depth of floor system.

Disadvantages:

- Lack of knowledge of shear and anchorage strength.
- Additional supports are needed around openings.
- Joint arrangements are difficult
- Holes for vertical installations are difficult to arrange.

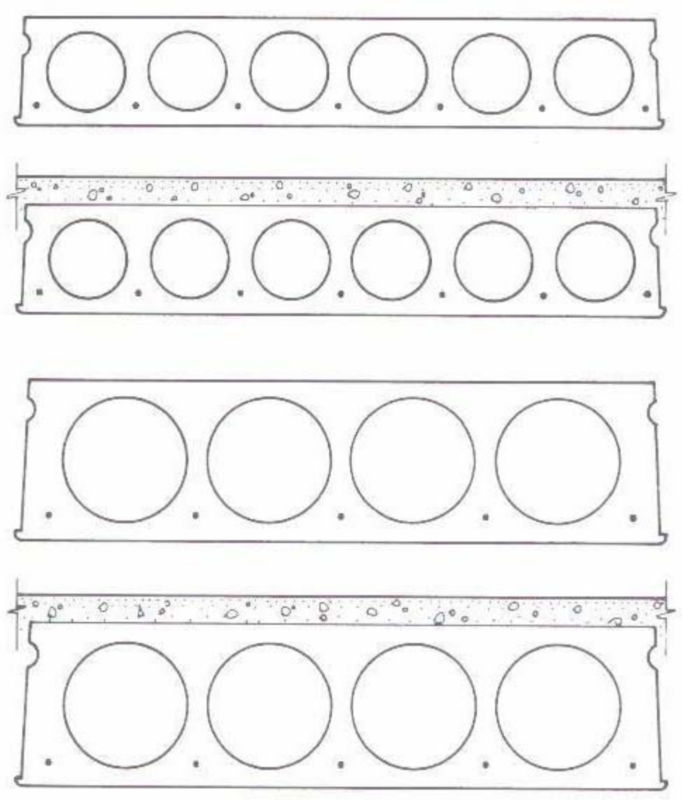


Figure 3.19: Hollow core slabs [27]

3.2.2.1.3.2 Double Tee slab.

Double Tee slab is basically a series of T-beams and is designed as such. The behavior and function is very similar to the hollow core slab. Double Tee can carry more load and span up to 16m while hollow core can span up to 12m. The height of the slab is relatively high and therefore inconvenient in some cases. Different types are available such as single Tee slab and inverted U-beam which are illustrated in figure 3.20.

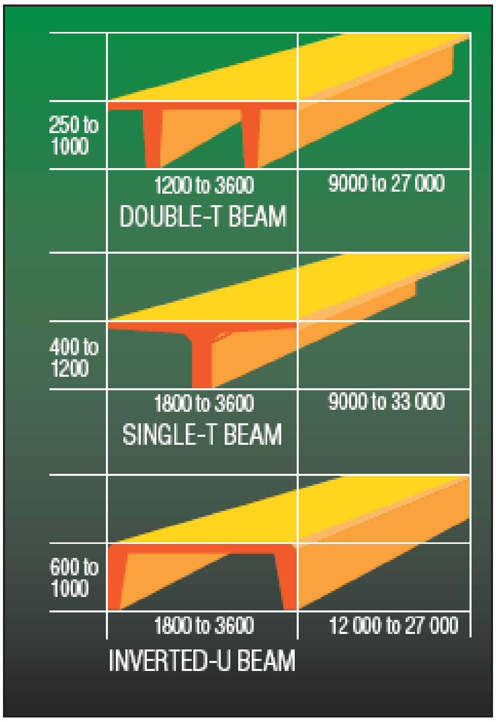


Figure 3.20: Double-T-slab, single-T and inverted-U slab. [39]

Table 3.2 summarizes normal dimensions for precast slabs.

Precast floor type	Max span (m)	Structural Depth (mm)	Most common unit width (mm)	Weight of unit (kN/m2)	Fire resistance
Hollow core	< 20	100-500	1200	2.1-4.8	120
Double T	< 24	200-800	1200-2400	2.1-5.0	120
Single T	< 30	600-1200	1500-5000	3.0-3.6	120
Inverted U	< 9	150-300	600	1.45-3.5	60
Permanent frame work	< 7.2	100-200	600-2400	2.4-4.8	120

Table 3.2: Types and properties of common precast floor units. [30]

3.2.2.1.4 Precast concrete

3.2.2.1.4.1 Bubble Deck

The bubble deck is the most recent on the market and is used mostly in Europe. The slab consists of a reinforcing mesh (bottom), hollow air balls that are made of recycled plastic, and a reinforcing mesh (top) (figure 3.21). The purpose of the balls is to eliminate the concrete that has no carrying effect in traditional reinforced concrete slabs. The bottom and top layers are then connected with concrete that is pored in-situ. The bubble deck idea is developed from the hollow core principle to have voids in the concrete to minimize weight except the voids are in both directions. Instead of having cores in two directions, the bubbles are closely spaced to obtain the effect and weight reduction. The reinforcement meshes keep the plastic balls in place and stabilize the spatial lattice. When the steel lattice unit is concreted, a "monolithic" two-way hollow slab is obtained. [40]

Figure 3.21 Bubble deck. [40]

Figure 3.22: A stack of bubble deck slabs. [40]

The weight of the slab is less than for conventional concrete, because of the bubbles in the deck, and the slab can carry load in two directions. A big advantage of the bubble deck is that openings in the slab are easy and additional support is not needed. This is because of the ability to carry loads in two directions. The obvious disadvantage is the thickness of the bubble deck and overall floor height is relatively high, or typically at least 400mm.

3.2.2.1.4.2 Precast permanent framework system

A precast permanent formwork system (figure 3.23), which consists of 70mm prestressed concrete permanent formwork panel, steel trusses that are cast in the panel, and the topping is pored concrete. The width of the elements is 1200mm and the length is typically 12m. To increase the span length, polystyrene void-formers are placed in between the steel trusses before the concrete is pored.

The steel trusses work as shear reinforcement between the precast panel and the pored concrete.

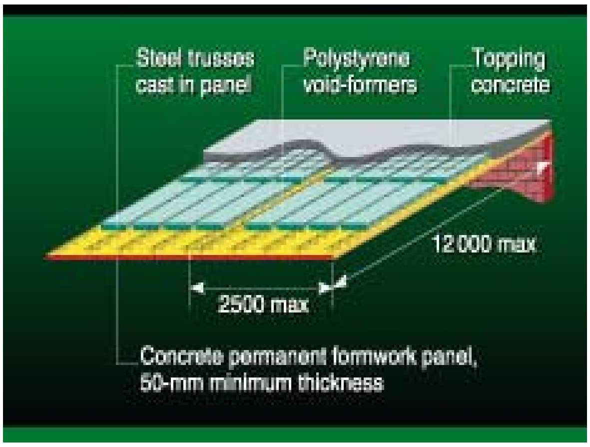


Figure 3.23: 'Transfloor'precast permanent formwork system. [39]

3.2.2.2 Composite slabs

3.2.2.2.1 Conventional

The slab consists of reinforced concrete and metal decking that acts as a formwork during concreting and tension reinforcement after construction. The combination of the profiled steel sheet and the concrete topping makes the slab resistant to horizontal shear forces at the interface of the steel and concrete. To ensure the composite action, slip must be partly or completely prevented. The metal decking is cold-formed steel sheet and provides working platform for construction, acts as a formwork for the concrete slab, and constitutes reinforcement in the bottom of the slab (figure 3.24). The use of profiled steel sheeting speeds up the construction and saves time. The weight of the floor can be reduced. Composite floor systems can be used for spans as long as 12, 15 or even 20m. They have been found to be economical and flexible for longer spans. For smaller spans, typically 6-8m the slab thickness is usually 120-160mm.

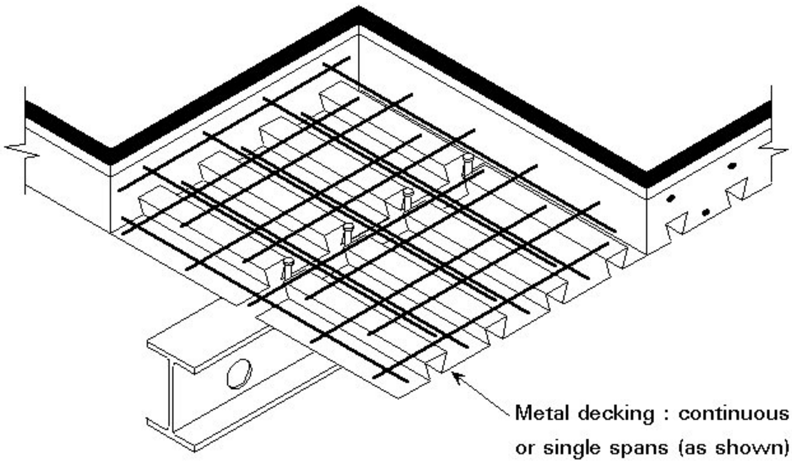


Figure 3.24: An example of a floor construction with metal decking. [29]

There are many different types of steel sheets available for composite construction and they vary in form, rip depth, rip spacing, sheet size, style of lateral over-lapping, methods of stiffening flat elements of the profile, and methods of connecting the steel sheet and the concrete mechanically (figures 3.25 & 3.26).

Normally, the thickness of the sheet is from 0.75 to 1.0mm and the height of the profiles can vary from 38mm to 80mm. The variation is usually to meet specific requirements like sound insulation, fire protection, long spans, and maximum load capacity. [29]

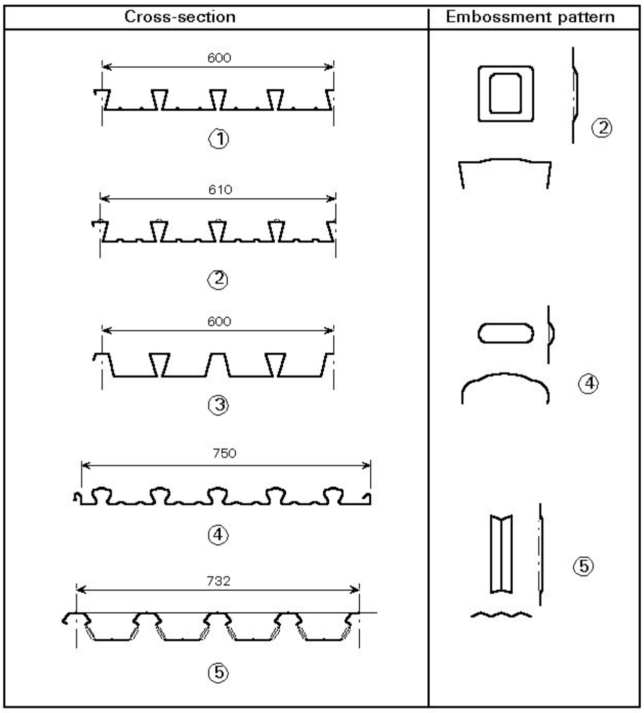


Figure 3.25: Types of sheeting profiles used in composite slabs. (Example of re-entrant types) [29]
(The right section of the figure shows the profile of the steel where the numbers indicate profile type)

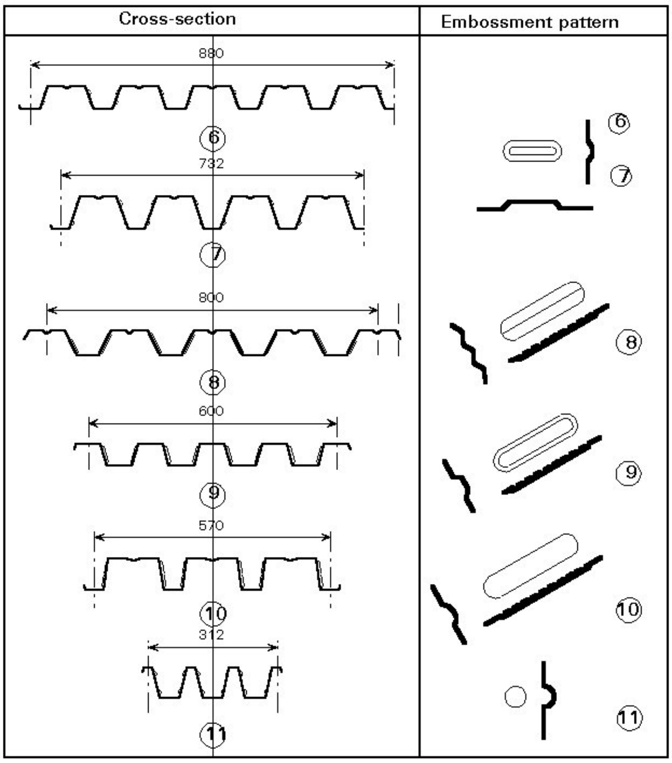


Figure 3.26: Trapezoidal sheeting profiles used in composite slabs. [29]

The connection of the steel sheet and the concrete is crucial for the composite function. The bond must be able to transmit longitudinal shear at the steel-concrete interface. There are many ways of creating this connection, such as by friction, by embossments on the flanges or ribs of the sheet, by anchorages situated at the ends of the slab, consisting of stud connectors welded through the sheet, by shot-fired shear connectors, or by deformation of the ribs. Figures 3.27-3.31 illustrate different types of connections of the steel sheet and the concrete.

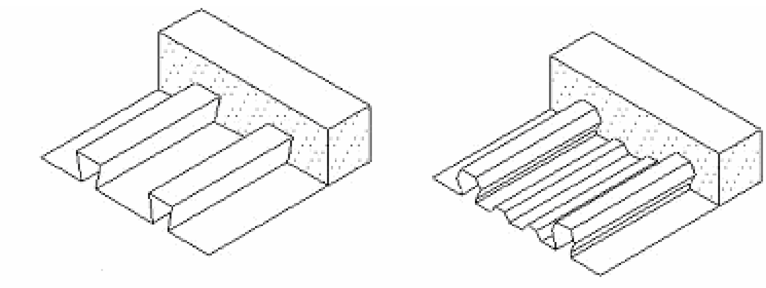


Figure 3.27: Connection made by friction of re-entrant shaped ribs. [29]

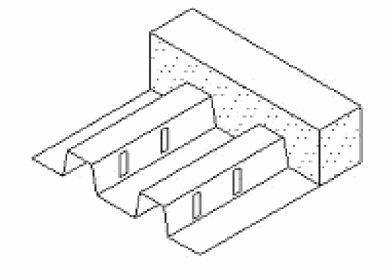


Figure 3.28: Connection made by embossments on the flanges or ribs of the sheet. [29]

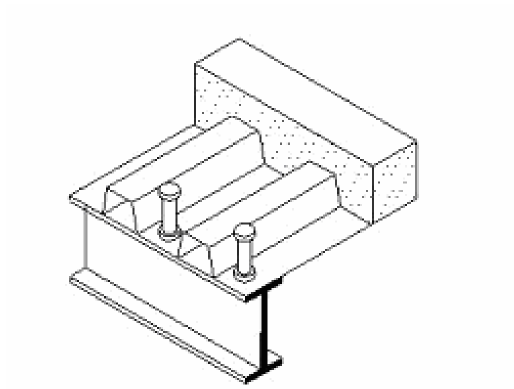


Figure 3.29: Connection made of anchorage at the end of the slab, welded shear. [29]

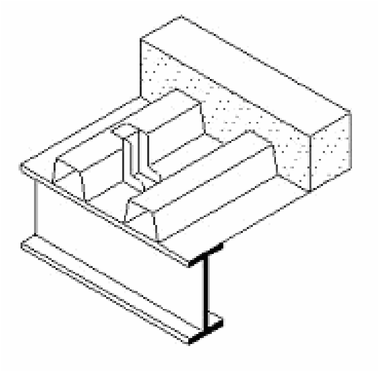


Figure 3.30: Connection with shot-fired shear connectors. [29]

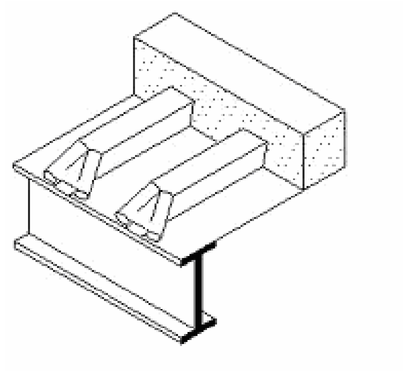


Figure 3.31: Connection by deformation of the ribs.[29]

3.2.2.2.2 Slim floor

In the recent years, a shallow floor solution has been developed, called a slim floor system. The concept is popular in the Scandinavian countries and in the UK. The steel beam is either welded on a flat plate or an asymmetric hot-rolled section. The slab can be either prefabricated concrete (figure 3.33) that lies on the lower flange of the beam or cast-in-place with a steel deck formwork (figure 3.32). The beam is partially encased within the concrete, which provides better fire protection and reduces the total height of the system. The slab is sustained directly by the primary beam, forming the part of the composite beam that works together with the steel beam. This offers an opportunity of savings in construction cost, compared with a traditional composite frame system with primary-secondary beam system. [8]

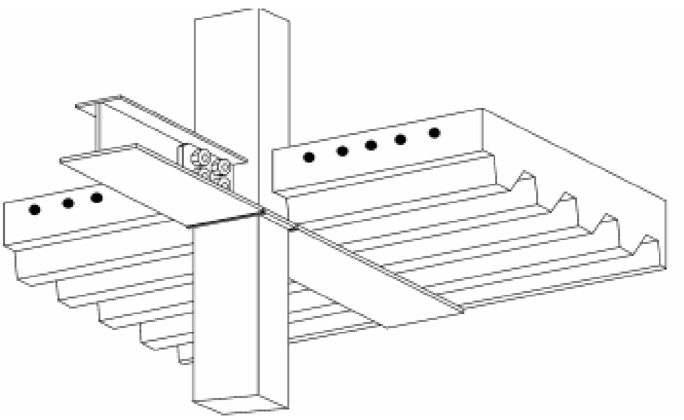
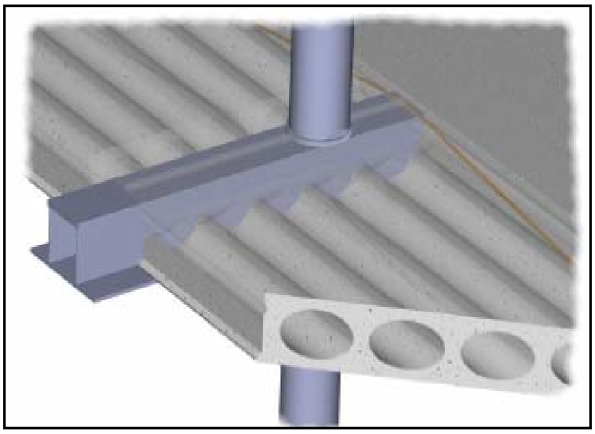


Figure 3.32: An example of slim floor system with cast-in-place concrete slab. [29]



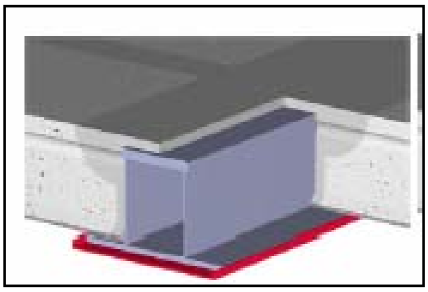


Figure 3.33: Hollow core connected to HSQ-beams inside the building and its fire resistance. [37]

3.3 Lateral Force Resisting Elements

Lateral-force-resisting elements must provide strength against wind loads and seismic forces. There are three principal types of resisting elements which are shear walls, braced frames and moment-resisting frames. A combination of these three types is also possible to provide adequate lateral resistance.

3.3.1 Shear walls

Shear walls are used in building frame systems to resist lateral loads and provide lateral stiffness against excessive side-sway. Shear walls are often used in a combination with a steel braced system to provide lateral strength and stiffness. Shear walls can be constructed from wood or reinforced concrete, but the latter is more common in commercial buildings. Lateral loads are distributed to each shear wall in proportion to its rigidity. Shear walls are usually designed for lateral loads in only two orthogonal directions. [27] [31]

The lateral forces are distributed to shear walls by floor and roof systems acting as diaphragms (figure 3.34). Floor and roof systems must be able to transmit lateral forces to the shear wall without exceeding a deflection which would cause distress to vertical elements. This load transmission is dependent on connections between the diaphragms and the shear walls.

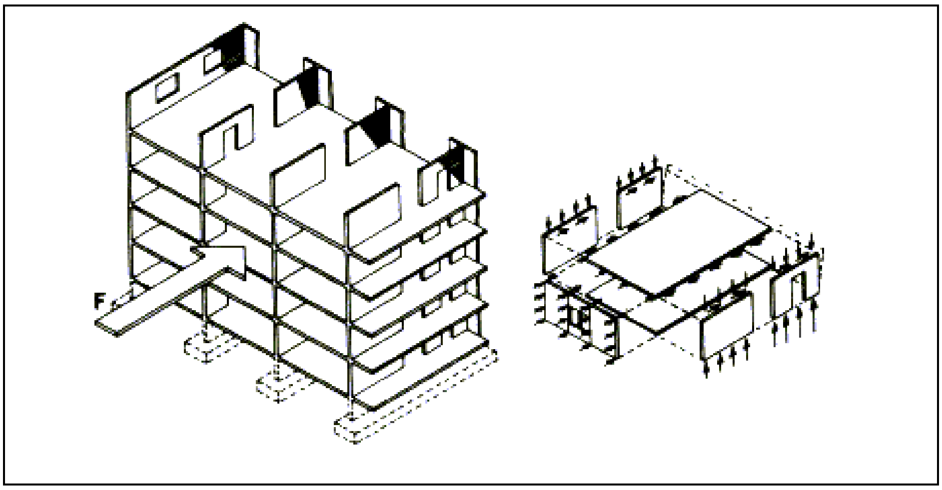


Figure 3.34: Diaphragm action of horizontal forces. [41]

A lateral horizontal system with combination of a rigid frame and shear walls exhibit different responses to lateral loads, especially in high-rise buildings. The frames bend predominantly in a shear mode as shown in figure 3.35 a, while the shear wall deflects predominantly in a cantilever beam mode, figure 3.35 b. This behavior is usually exhibited by elevator shafts, stairwells and concrete walls. This can create confusion in determining the mode of deflection. A shear wall can act as a frame if it's weakened by openings and a frame can deflect in a bending mode. The load distribution in a system of both frames and shear walls is more complex because of this difference in bending mode. The loads can be distributed to the units in proportion to their stiffness if all vertical elements are in frames or all in shear walls and all produce the same behavior under load.

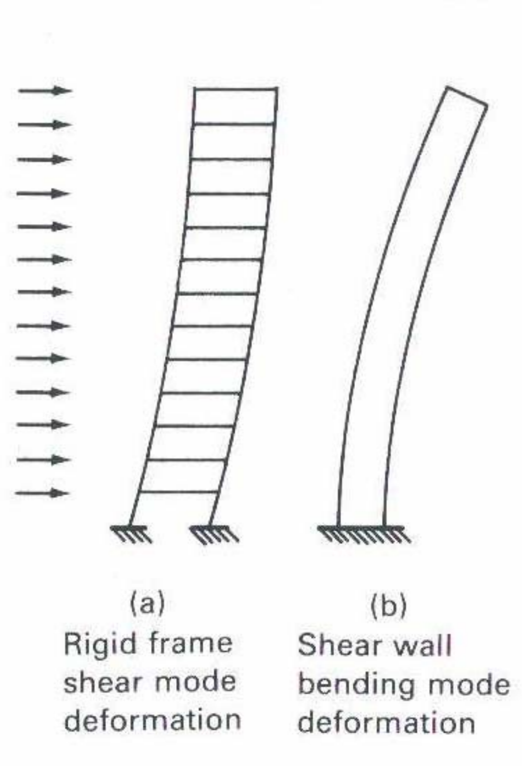


Figure 3.35: Deformation modes of a rigid frame and a shear wall system. [27]

In tall buildings, coupled shear walls (figure 3.36) are often used to provide lateral resistance. Coupled shear walls are two shear walls that are connected by coupling beams. The coupling beams are often made of reinforced concrete and are normally subjected to very high bending and shear stresses. The design of the beams is the complicated part of the design of coupled shear walls because of lack of shear capacity in reinforced concrete beams.

The effect of coupling will increase the stiffness by transfer of shear through the coupling beam. A frame action is developed that will change the curvatures of the walls. [27]

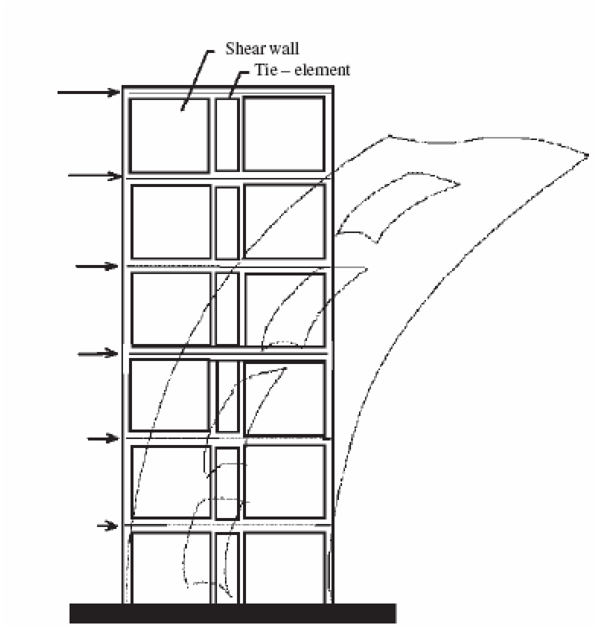


Figure 3.36: A typical coupled shear wall. [31]

3.3.2 Braces

Steel bracing is used to increase seismic strength and stabilization of structural frames. Steel bracing is more frequently used in steel structural frames but can also be used in reinforced concrete structures instead of shear walls or in combination with shear walls. Braced frames are essentially vertical, cantilevered trusses and may be either concentric or eccentric in configuration. In concentric frames, the lateral loads act along the direction of the longitudinal axis of the diagonal braces. Eccentrically braced frames use both axial loading of braces and bending of sections of horizontal beams to resist lateral forces. Figure 3.37 illustrates the most common types of bracing systems. [23]

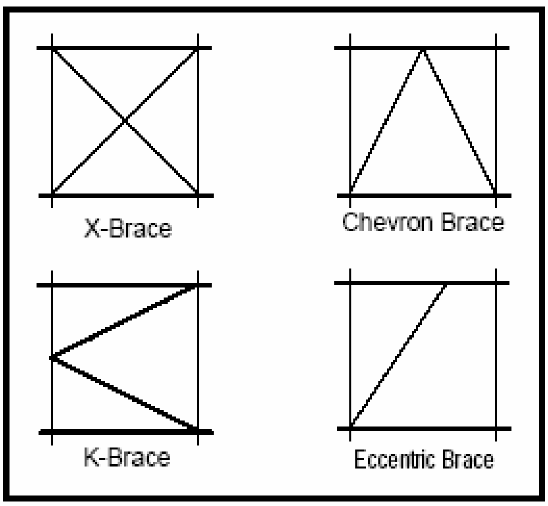


Figure 3.37: Different types of braced frame elements. [7]

3.3.3 Moment-resisting frames

Moment-resisting frames are usually constructed of steel, concrete or masonry. They carry vertical loads with a space frame throughout the building. The frame elements, which consist of beams and columns, carry the lateral forces. In the design of moment frames, ductile behavior of beam-to-column joints needs to be ensured. Moment resisting frames are designed to deform well into the inelastic range during earthquake loadings. The beam-to-column joint is essential in the behavior of the frame and the formation of hinges in beam is preferred rather than formation of hinges in column. [17]

3.3 Foundations

Foundations are structural elements that support the main load-bearing members, columns and walls and transmit the loads from the building into the ground. Foundations must reduce the pressures applied directly to the soil since soil can sustain much smaller bearing pressures than the compressive stresses in columns and walls. Foundations spread the supported loads over an area large enough to prevent rupture or excessive deformation of the soil.
The following factors influence the selection of the type of foundation:

1. The strength and compressibility of the various soil strata at the site.
2. The magnitude of the column loads.
3. The position of the water table.
4. The need for a basement.
5. The depth of foundation of adjacent buildings. [5]

Foundation systems are almost without exception constructed of concrete and different kinds of systems will be described briefly below.

3.4.1 Pile Foundation

A pile foundation (figure 3.38) consists of vertical structural members that are forced into the ground by impact. A machine called a pile driver is used to force the piles into the ground. The pile is driven into the ground until the soil is strong enough to resist the pile. Steel or concrete have been used since the beginning of the 20th century when it was found to be more practical than wood.

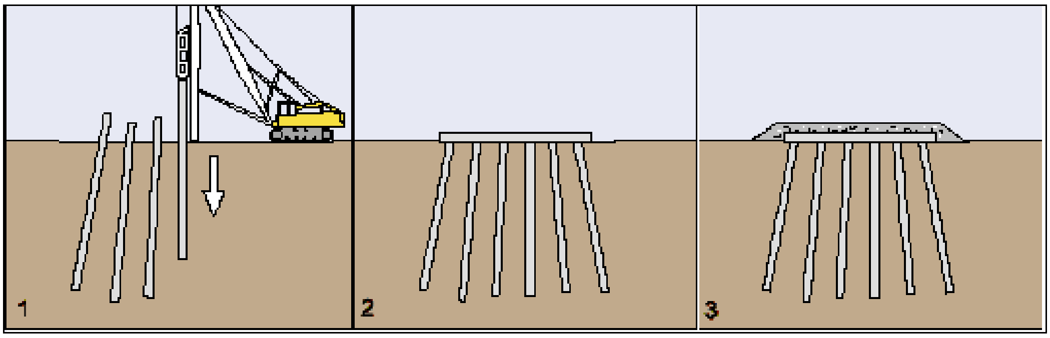


Figure 3.38: Piles driven into the ground [42]

3.4.2 Drilled shaft Foundation

Drilled shaft foundations (also known as Caisson foundations), are very similar in form to pile foundations, but are constructed in a different way. The foundation is created by drilling a deep hole into the ground, and then filling it with concrete. Steel reinforcement is placed into the whole before poring if needed. The shafts are either drilled to bedrock or deep into the underlying soil strata if the soil has adequate strength (figure 3.39).

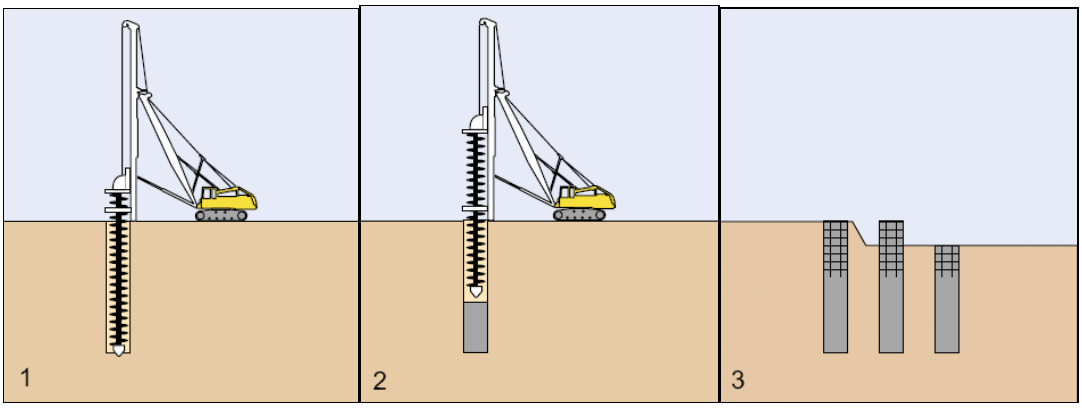


Figure 3.39: Drilled shaft foundations. [42]

3.4.3 Mat Foundation

Mat foundations (also known as “raft foundations”) consist of a large continuous footing which lies under the entire building. This foundation system is used where soil is week and the bedrock is extremely deep. “Floating or compensated mat foundations” are sometimes used under these circumstances. The amount of soil removed and the resulting uplift caused by groundwater is equalized by the downward forces of the building and the foundation. A mat foundation system can also be constructed in combination with drilled shafts or piles. Figure 3.40 shows a mat foundation.

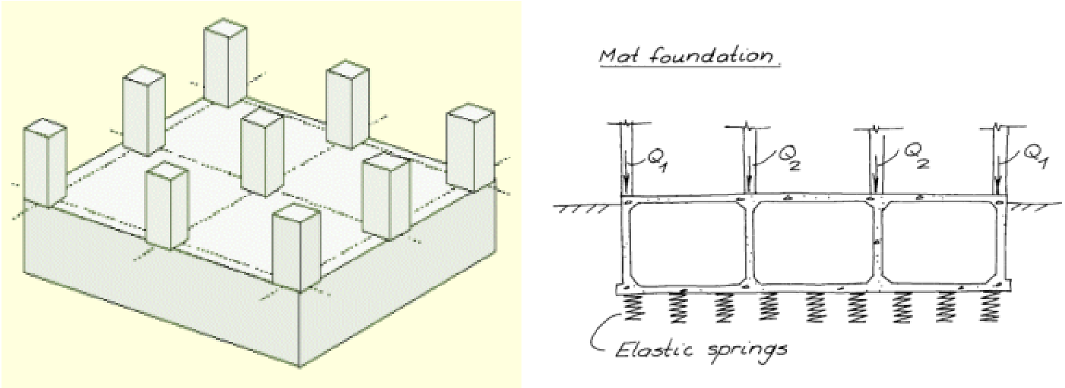


Figure 3.40: Mat foundations. [44]

3.4.4 Spread Foundation

Spread foundations (also known as footing foundation), consist of footings spread out over a broad area under the building. Horizontal mats are used to anchor the building or individual columns or walls. Spread foundations are often used in low-rise buildings.

4. COMBINATION OF STRUCTURAL ELEMENTS

Structural elements can be combined in many different ways to form the structural system. The structural elements are combined into sub-systems; vertical load resisting elements, floor systems, horizontal load resisting elements, and connections. So far, connections have not been discussed in the report but will be discussed in this chapter relevant to combining the structural elements. The sub-systems can also be combined in different ways to form the complete structural system. In the following chapter some of the possibilities will be discussed.

4.1 Concrete systems

4.1.1 Cast-in-place structural system

Reinforced concrete structural system is probably the most widely used system in the world. Reinforced concrete is a relatively simple structural material and reinforcing bars usually have wide availability. The material cost is low compared to other structural materials. In many countries, reinforced concrete has the longest history in the structural field and the engineers have a long experience of designing concrete structures. The strong tradition of concrete can affect the selection of structural system and even prevent that other solutions are chosen. Time of construction has become an important factor which is not in favor of a cast-in-place concrete structural system.

4.1.1.1 Vertical and Horizontal Load resisting system

The structural system can either be a moment frame or a shear wall system. In a moment frame, the system is constructed of reinforced concrete where the floors are interconnected with columns by continuous reinforcement to form rigid joints. The design of the floor system depends on the column spacing and magnitude of the design loads. For office buildings, it’s important to minimize the number of interior columns, so the spans may need to be longer. Average spacing for columns is 5.5-5m. The grid of columns and beams needs to be practical and economical and then the floor system is chosen. A moment frame system is often designed as dual system, where shear walls carry the lateral loads. A shear wall system is more common in Iceland, where there is a system of beams that carry a flat slab. The shear walls are located in elevator/stair cores or along the outer lines of the building. Scattered shear walls can even be required to resist applied loads.

4.1.1.2 Floor system

The slabs are traditional in-situ reinforced concrete slabs and reinforced concrete beams. It is simple and economical to construct a concrete slab and the ceiling requires little finish, but its ability to transfer shear into the column is poor. The slabs have the tendency to deflect excessively, so it is important that the slabs are as light as possible. The capacity of the floor system can be increased by thickening the underside of the slab around the columns (this is called a drop panel), or an extra support can be added on the top of the column, called a capital. Beams can also be added along the centerlines of the column to increase the load capacity of the system. If spans are large, intermediate beams can be added to support the slab. The intermediate beams behave like continuous beams supported vertically by girders. The slab acts both with the intermediate beams and the girder to form a T-beam in regions of positive moment. If the requirements are to have no interior columns, the slab is supported by deep girders spanning between columns on the perimeter of the building. If the spacing between the girders is large, shallow beams may be spanned between the girders to support the slab. These beams are called joists. [5]

4.1.1.3 Connections

Connections in reinforced concrete structures need to be ductile and the details need to be carefully constructed. The beam-to-column connections can be difficult to design. Connections are classified as exterior, interior, and corner joints. For connections in nonseismic areas confinement needs to be provided, shear needs to be limited in the joint, and the bar size needs to be limited to fit in the concrete section. For best results, the longitudinal column reinforcement should be uniformly distributed around the perimeter of the column and at least two layers of transverse reinforcement provided between longitudinal reinforcement.
Beam-to-column corner connections in moment frames are either called opened or closed depending on how the bending moment is applied to the joint. Opening joints are located at corners in moment frames. Large tensile stresses occure at the reentrant corner and in the middle of the joint. Reinforcement needs to be provided to prevent diagonal cracking in the joint as shown in figure 4.1.

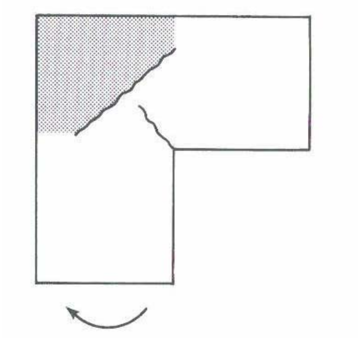


Figure 4.1: Cracking of opening corner joint [20].

Experiments have shown that the reinforcement detailing in the connection illustrated in figure 4.2 can effectively resist bending moments without excessive deformations [20].

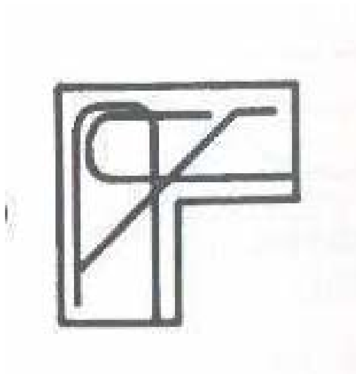


Figure 4.2: Satisfying reinforcement of opening corner joint [20].

Closing joints are subjected to the opposite elastic stresses to the opening corner joints. The cracks illustrated in figure 4.3 need to be prevented with reinforcement but with proper detailing the efficiency of the joint can be between 80-100% (MacGregor, 1997).

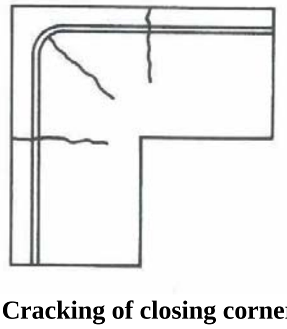


Figure 4.3: Cracking of closing corner joint [20].

A connection between a flat reinforced concrete slab on columns is subjected to high transverse stresses concentrated at the columns. This stress can lead to nonductile, sudden and brittle punching failure. The maximum effects of flexural and shear loads are in the area of slab and column connection. The connection needs to have flexural ductility which is usually provided with longitudinal reinforcement in the bottom of the slab. Punching shear capacity provides protection against rotation in the joint; this can be solved by placing transverse shear reinforcement in the slabs.
The slab is normally designed to have diaphragm action where the connection needs to transfer lateral loads to the lateral load resisting system.

4.1.1.4 Method of erection

The formwork is constructed before the concrete is pored. The formwork needs to hold the concrete in place until it hardens. Additional support such as falsework or shoring may be needed to keep the formwork in place. Formwork is expensive and adds up to one-third to two-thirds of the total cost of a reinforced concrete structure in the US, with an average value of about 50% (McCormac & Nelson, 2005). The reinforcement is placed and then the concrete is pored. The formwork can be removed when the concrete members have gained sufficient strength to support themselves. It usually takes 28 days for the concrete to gain full strength. [21]

Check list

- ✓ Architectural and owner's requirements
  Requirements can usually be met by using cast-in-place concrete structural system. The sizes of members can be large which can reduce the usuable space. The overall floor height can also be so large that the designer is forced to choose another solution.
- ✓ Time of design and planning
  The procedure of design and planning takes around six months.
- ✓ Construction time
  The construction time is generally about one year. The construction time can be reduced by the use of modular formwork.
- ✓ Life cycle cost
  There are no particular additions to life cycle cost when a cast-in-place structural system is used.
- ✓ Fire safety
  Concrete has good fire resistance qualities.
- ✓ Acoustics
  Acoustics requirements can be met in a simple way.
- ✓ Installations

Horizontal installations are cast in slabs or placed in the ceiling, while vertical are usually placed in installation shafts. Vertical cables can be run through the slabs by making small holes in the slab.

- ✓ Durability

  Concrete has good durability.

Advantages:

- **Cheap building material**
- **Versatility:** Ideal for irregular building shapes and flexibility of design on site
- **Durability**
- **No lateral bracing required**
- **Fire Safety**

Disadvantages:

- **Large column and beam dimensions**
- **More on site construction**
- **Slow speed of erection**
- **Quality control**

4.1.2 Precast structural system

The use of precast concrete systems is growing but they became a major construction method in some countries in Europe, especially in the middle of the twentieth century. They are still used extensively in eastern and northern Europe. [3][4]

4.1.2.1 Vertical and Horizontal Load resisting system

Vertical forces are normally resisted by columns and walls, where forces applied on floors are transmitted to vertical elements. The detailing of connections between these elements is complicated and will be discussed in section 4.1.2.3.
The horizontal load resisting system is usually a system of shear walls. The shear walls can be exterior walls system, interior walls, or walls of elevator, stairway, and mechanical shafts. The lateral forces are transferred to the shear walls via diaphragm action of the floors through the connections or by direct bearing. The shear walls act as vertical cantilever beams which transfer the lateral loads to the foundation of the building.

4.1.2.2 Floor system

The floor system consists of slabs and beams that carry the live load. The slabs usually work as diaphragms and transfer loads to shear walls or lateral bracing. The slabs can be of various types that are discussed in section 3.2.2.3.1. The beams are commonly an inverted T-beam where the slab rests on the flange of the beam.

4.1.2.3 Connections

The design of connections is very important in a precast structural system. The details must be carefully designed and constructed to obtain a successful function of the system. The types of connections to be used should be determined during the preliminary analysis because it may affect the component dimensions and the overall structural behavior. [27] To improve the overall integrity of the building, each member of the structure must be tied together effectively so the detailing of the reinforcement and the connections is very important. This is achieved by providing tension ties in the transverse, longitudinal, and vertical directions, and around the perimeter of the structure.
In precast systems, beams and deck members are most economical when they are connected and designed as simple-span members. The positive moment-resisting capacity is much easier and cheaper to attain than negative moment capacity at supports. Continuous connections at supports are very complex and expensive. Therefore, it is preferred to design precast structures with connections that allow lateral movement and rotation and design the structure to achieve lateral stability through diaphragms action. Typically, the members are connected into the load path of the lateral load resisting system to meet the tie requirements. The lateral load resisting system is designed to have a continuous load path to the foundation.

Moment connections are designed to transfer shear and moment and usually connect elements in the lateral load resisting system. The lateral load resisting system can consist of a frame or a combination of shear wall and frame action. The tension force for the moment resistance can be provided by inserting headed studs or deformed bar anchors. Ductile behavior is essential in this type of connections. Therefore, moment resisting connections are usually designed to be partially fixed where a certain rotation is allowed. Fully fixed connections are difficult to design because of volume changes in the concrete that create large forces in the connections. Typical moment connections are shown in figure 4.4. [27][30]

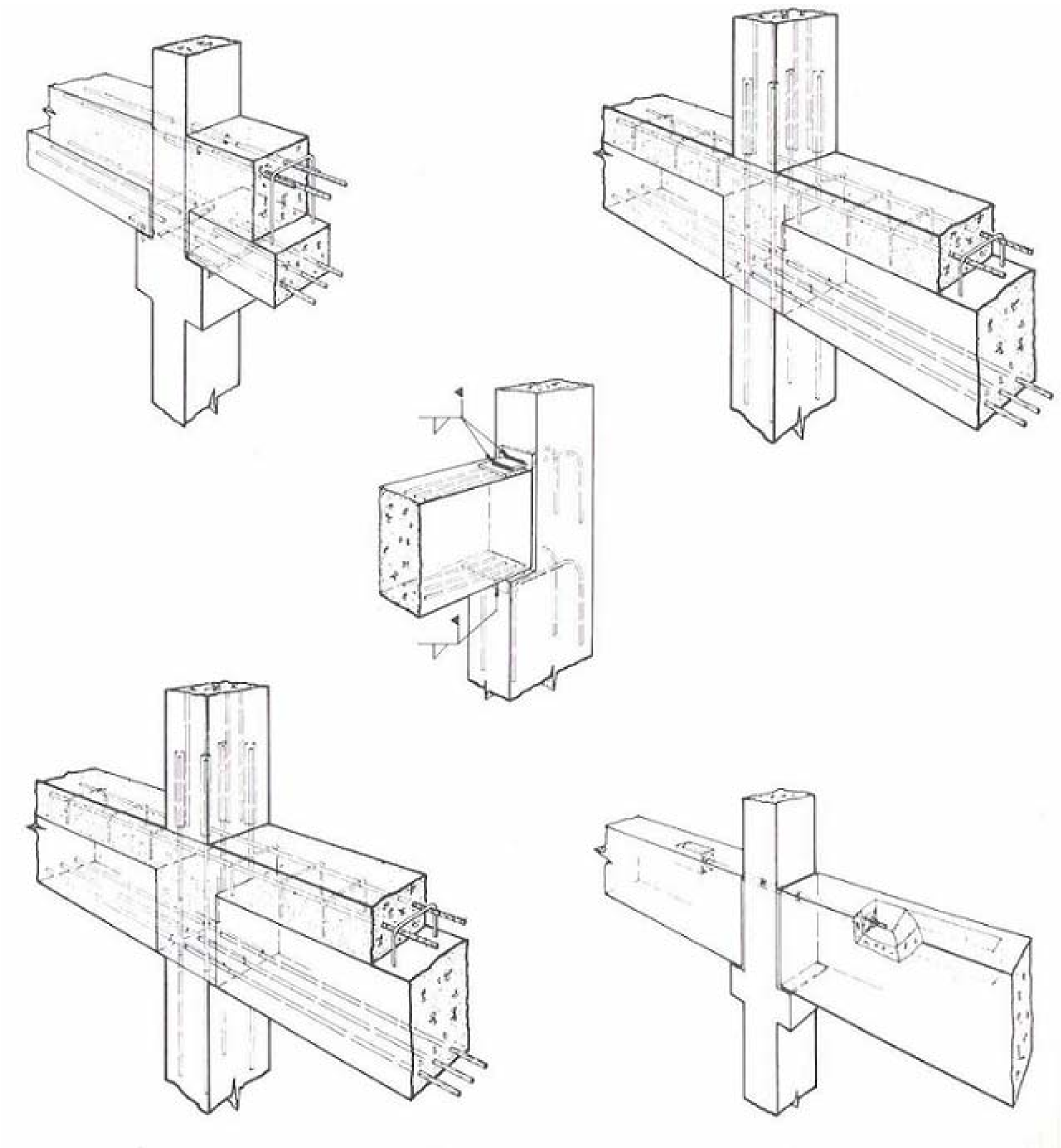


Figure 4.4: Different types of moment connections. [27]

Bearing connections must transfer dead, live, wind and earthquake loads, and be able to resist effects of volume changes as well. The joint can be a connection of a horizontal and a vertical member so forces are applied in many directions. Superposition of forces and various combinations of panel and joint assemblies must be considered. The load distribution of lateral forces to shear walls is largely dependent on the floor to wall connections. The vertical joints may also need to resist shear forces induced by differential loads on adjacent panels.

4.1.2.4 Method of erection

The precast elements are transported to the site, usually with trucks. The size and weight of the elements varies so the transportation is important in the erection process. A crane is used to put the elements at the right place and then the elements are combined. The selection of crane type and size is an important ingredient to the viability of the precast structure. Mobile cranes are generally the most economical. The combination of elements is key in the construction. The elements are usually connected with reinforcement which is then covered with concrete.
A small cover of concrete is pored on the slabs to get rid of rough surface, typically around 50mm. Figure 4.5 shows a precast frame under construction.

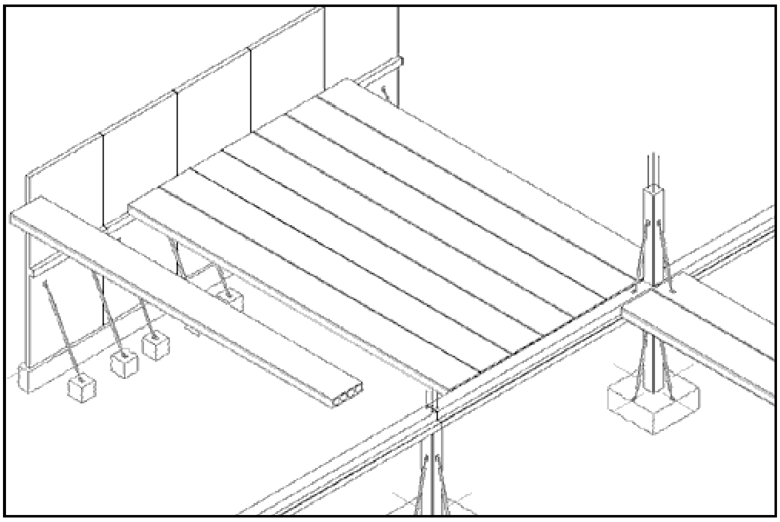


Figure 4.5: Precast frame in construction. [39]

Check list

- ✓ Architectural and owner's requirements
  All requirements can usually be met by using a precast concrete structural system. If there are certain requirements that cannot be met, another system is chosen. Irregular shapes can be hard to construct with precast concrete, but they are not common in office buildings.
- ✓ Time of design and planning
  The procedure takes around six months. The design precedure can take shorter time but the planning takes longer than for exemple cast-in-place system. The project planning is very important and can save time in the overall construction.
- ✓ Construction time

The use of precast allows not only the speedy erection of the structure. A minimum amount of propping allows the following trades to commence work on the structure earlier than conventional construction methods.

- ✓ Life cycle cost

  There is usually no additional life cycle cost when precast system is used.
- ✓ Fire safety

  Precast concrete has good fire protection qualities, since the reinforcement is protected in the structural frame.
- ✓ Acoustics

  Concrete has good acoustic qualities.
- ✓ Installations

  Horizontal installations are placed in the concrete finishing layer of the slab and air conditioning ducts are placed in the ceiling. Vertical installations are generally placed in shafts.
- ✓ Durability

  Concrete has good durability

Advantages:

- **Speed of Construction**
- **Off-site Manufacture**
- **Quality Control**
- **Fire Protection**
- **Acoustic**
- **Appearance and Finishes**

Disadvantages:

- **Connections**
- **Transportation**
- **Cranage**

4.2 Steel frame structural system

Structural steel has been used in the construction field for around 120 years. Iron was used until it was prohibited in the beginning of the 20th century, but had then been used since antiquity. Developments in production of steel have improved the efficiency and quality during the past century, energy consumption has been reduced and environmental factors improved. [29]

4.2.1 Vertical and Horizontal Load resisting system

The framework is a steel skeleton that supports the secondary elements such as floor slab and cladding. The frame is usually a moment resisting frame system or braced frame system. Braced frame is simpler and therefore the most economical. Vertical steel bracings, (X, K or V shaped) are formed by diagonal members in the steel frame. This is discussed in section 3.3.2. Shear walls or cores can also be used as a part of the structural steel systems, these systems are called dual systems. In dual systems, the vertical forces are transmitted by the steel skeleton and the horizontal forces transferred by the shear walls or cores. In non-dual systems, all external loads are transmitted to the foundation by means of the steel frame work. The frame is mainly composed of columns and beams which may be connected together in different ways. In a braced frame system, the connections act as hinges and are therefore very simple. Sway deformability of the structure is limited by the bracing elements. Interaction between axial forces and bending moment in the column is not of concern. On the other hand, foundation of braced frames can be complicated because it must resist the overall horizontal forces with a very small amount of axial compression. The values of eccentricity will be high which require large dimensions of the contact area under the foundation.

A moment resisting frame system is more complex and the connections are expensive. The system is a combination of beams and columns and no bracing is required. The beams and columns act together to resist axial, bending and shear forces. The beam-to-column connection must be designed as rigid to obtain the moment resisting frame behavior. As a result, the interaction between axial forces and bending moments is critical in column design. The overall sway deformability of the structure can be too large, as it depends only on the inertia of the columns. The beam-to-column connections will be discussed further in section 4.2.3.

4.2.2 Floor system

The floor system in a structural steel system can be cast-in-place concrete, precast concrete or composite slabs using steel decking. The floor slabs are required to resist vertical loads applied directly on them. The slabs are usually supported by secondary steel beams. The floor plan is created depending on the required load resistance of the system. The slabs also need to transfer the horizontal loads to the points on the framework where the bracing members or shear walls are located.

4.2.3 Connections

The connections in a braced steel frame (pin-ended) are relatively simple. The beam-to-column joints must only resist axial and shear forces. These connections are usually bolted between the beam web and the column flange, a double end connection (figure 4.6). They are simple to construct and are more economical than fully welded connections for rigid structures. Type (e) and (f) in figure 4.6 are double angle, bolted connections between the web and the column flange and are the most common.

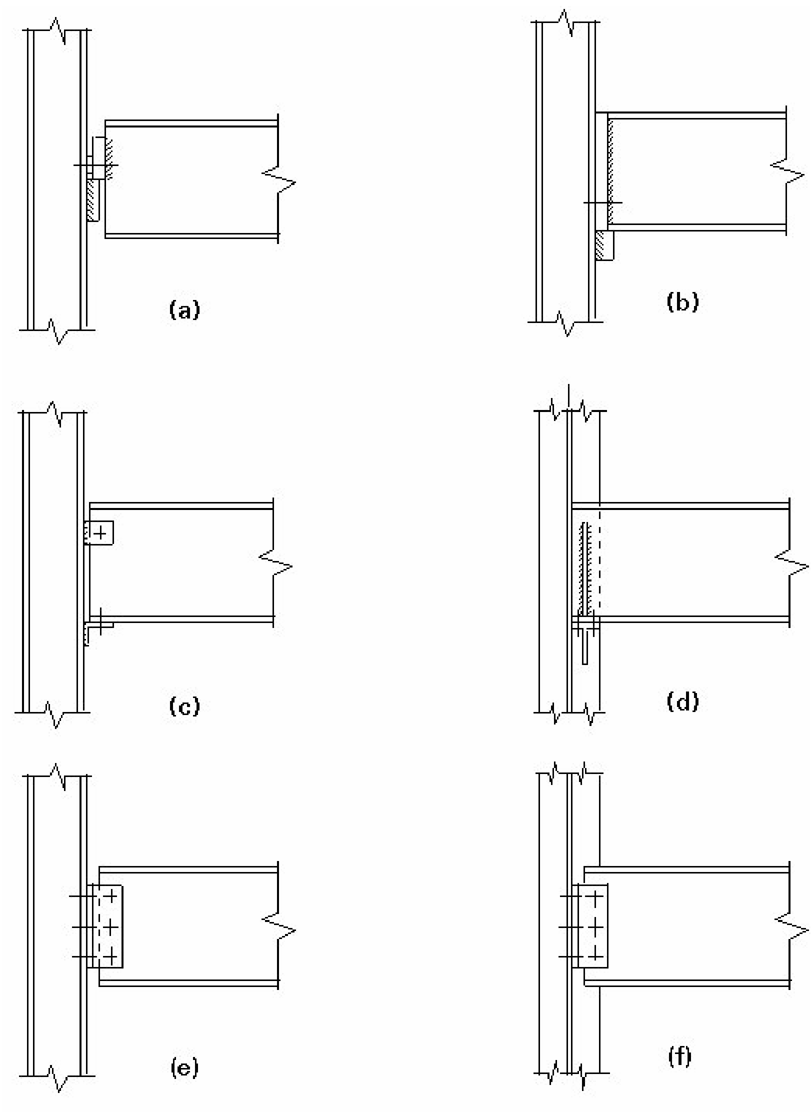


Figure 4.6: Steel beam-to-column connections in a braced steel frame [29]

As mentioned before, the joints in a moment resisting frame are complicated and expensive. The beam-to-column connection must be rigid and needs to transfer bending moments from the beam to the column. These joints are illustrated in figure 4.7, where type (a) can only transfer limited bending moments because of risk of buckling in the web due to local concentration effects. Type (b) is designed with horizontal stiffeners which make the column web only applied to shear force.

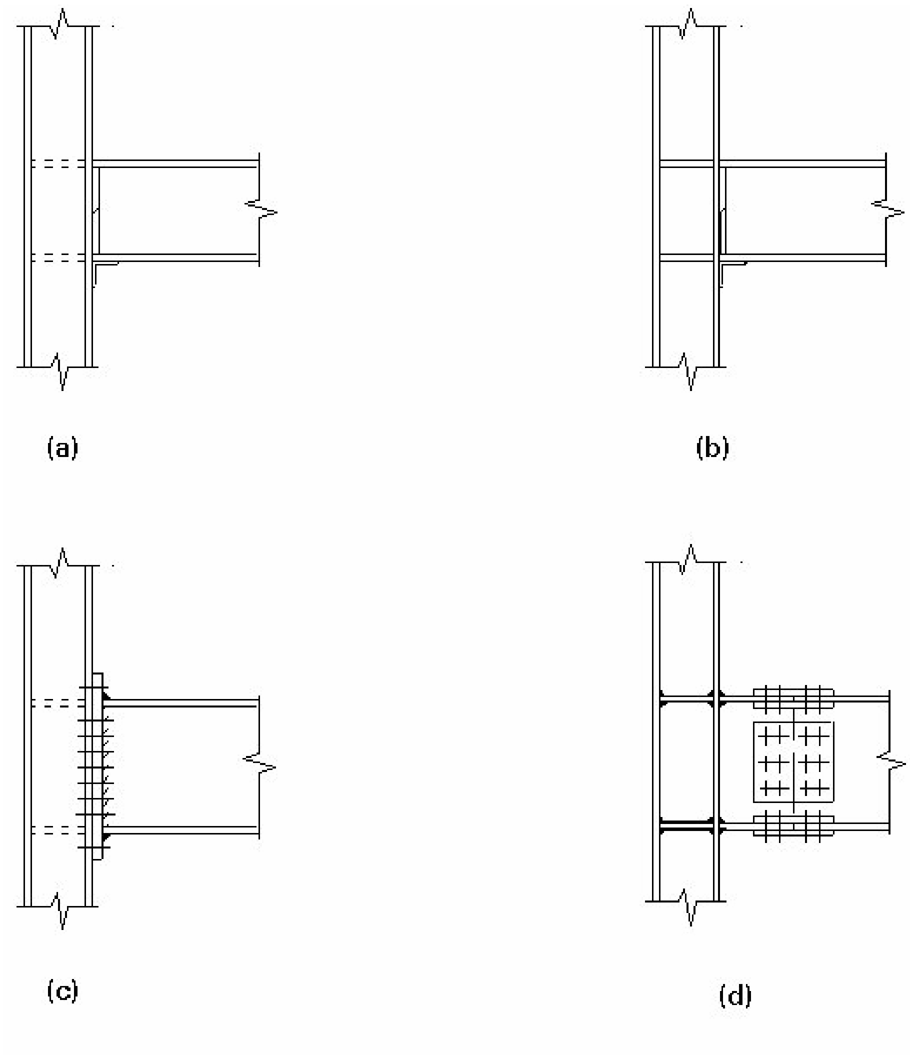


Figure 4.7: Steel beam-to-column connections in a moment resisting steel frame. [29]

Types (a) and (b) require the execution of welding operations on site. Welding on site is not always dependable and can possibly cause delay in the erection. Bolted connections are preferred and types (c) and (d) in figure 4.7 are typical solutions for rigid frame connections. Type (c) is the extended end plate joint and type (d) is the cover plate joint. [29]

4.2.4 Method of erection

Steel buildings are erected story by story and the construction time is relatively short. The lower floors will be completed early and enables other work being completed on the floor while working on upper floors. A single tower crane may be used for lifting the steel elements. The position of the crane can be fixed (figure 4.8) and is independent of obstructions constructing the basement slab or ground slab. This independency can also provide certain freedom in overall planning of the construction. However, the fixed location of the crane can affect the lifting capacity because of the fixed arc of the crane so site splices need to be provided to keep the weight of the elements to minimum. The construction rate is controlled by many factors that are out of control of the design engineers. The factors that the design engineers can control include the following:

- Type of end connections.
- Extent/type of bolting or welding.
- Number of separate pieces. [29]

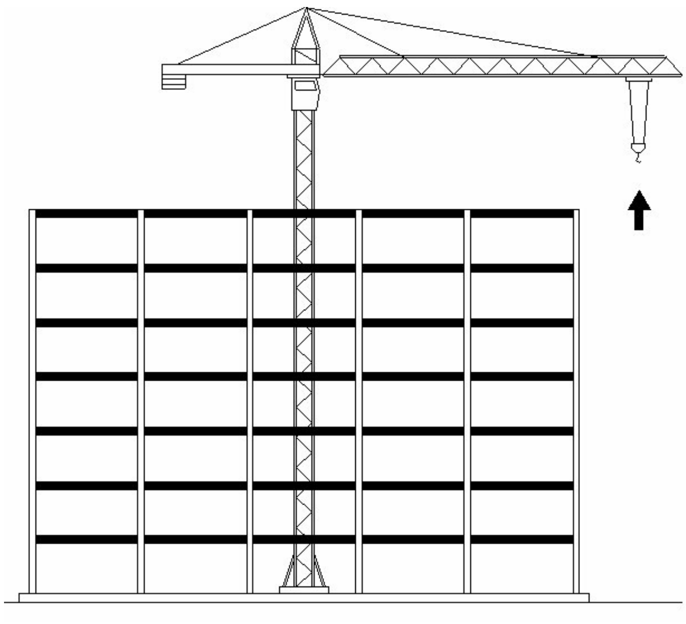


Figure 4.8: A steel multi-frame building constructed with fixed tower crane. [29]

Check list

- ✓ Architectural and owner's requirements
  All requirements can be met by using steel structural system
- ✓ Time of design and planning
  The procedure takes around six months.
- ✓ Construction time
  The construction time can be reduced and is one of the advantages of steel structural systems.
- ✓ Life cycle cost
  Additional life cycle costs are because of fire safety requirements. The fire protection needs to be inspected and maintained.
- ✓ Fire safety
  Steel needs to be fire protected by building in the members or with fire protection paint.
- ✓ Acoustics
  The acoustic qualities of the system depends on the floor slabs and the wall system. The detailing of slabs and walls needs to be designed to meet acoustic requirements.
- ✓ Installations
  Smaller horizontal installations are placed in the slab while larger installations are placed in the ceiling. It is possible to make holes in the web of beams to place horizontal ducts. Vertical installations are placed in shafts.
- ✓ Durability
  Steel structures have good durability.

<u>Advantages:</u>

- **Speed of erection**
- **Light weight structure**
- **Less on site construction**
- **Quality control**

<u>Disadvantages:</u>

- **Fire protection**

4.3 Steel-concrete composite system

Composite structures were first used in bridge construction in the US and European Countries in the 1950s when the use of welded headed studs were presented. From that time these structures have been researched and used in the building industry with good experience. A dramatic increase in the use of composite steel-concrete framing systems for mid-rise and high rise buildings occurred during the period 1982-1992. The reasons for the increase were improved economy resulting from better construction methods and improved design specifications. [25]

The main topics of interest in research are the function of composite structures in seismic areas and fire resistance. [29]
Steel-concrete composite systems are constructed of steel and concrete elements that interact to obtain the required structural strength, stiffness and stability to the system

4.3.1 Vertical and Horizontal Load resisting system

The vertical load resisting elements are usually a system of composite columns as discussed in chapter 3.1.1.3. There are different types of columns and the designer chooses the type that fits best to transfer vertical loads to the foundation. The columns form a frame structure together with beams and can be either rigid or flexible, depending on the relative rigidity of beams with respect to columns. The frame system also transmits lateral forces to the foundation and is often combined with a shear wall system that helps transmit lateral forces to the foundation. In rigid frames the beams and columns are connected rigidly and the slabs provide transverse stiffness to the entire system. The shear walls can be either reinforced concrete or prefabricated elements and are typically used as core for elevators or stairs. A combination of a frame system and shear walls is widely used as transmitting system for both vertical and lateral forces.

In tall buildings, slenderness, flexibility and sensitivity to different effects need to be considered. It is more difficult to design for stability and additional resisting elements may be needed. Another shear wall core can be added or the frame structure can be braced in different ways as mentioned in chapter 3.3.2.

4.3.2 Floor system

The floor system consists of slabs and beams. Depending on span lengths and loads, secondary beams may be required, often called joists. The most efficient floor plan is rectangular where primary beams span between columns and secondary beams span between the secondary beams as shown in figure 4.9.

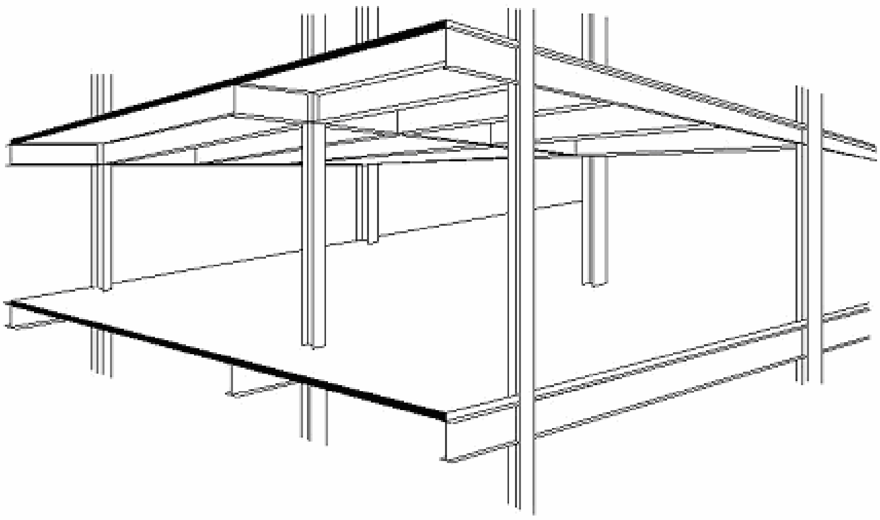


Figure 4.9: Typical floor arrangement in a composite building. [29]

Different floor systems are shown in figure 4.10 and are discussed in 3.2.2.2. The most common type consists of metal decking, where shear connectors provide the composite action between the beam and the slab. The shear connector is welded through the metal decking onto the beam flange (figure 4.10). This type of system is widely used because the low weight metal decking has enough strength and stiffness to carry the slab while the concrete hardens. When long spans are required, the slab depth is increased, but that also requires deeper beams to carry the increase in weight. This influences the structural depth, which is preferably as low as possible. The most efficient span between floor beams acting with slab with metal decking is 2.5-3.5m which results in slab depth of 120-150mm.

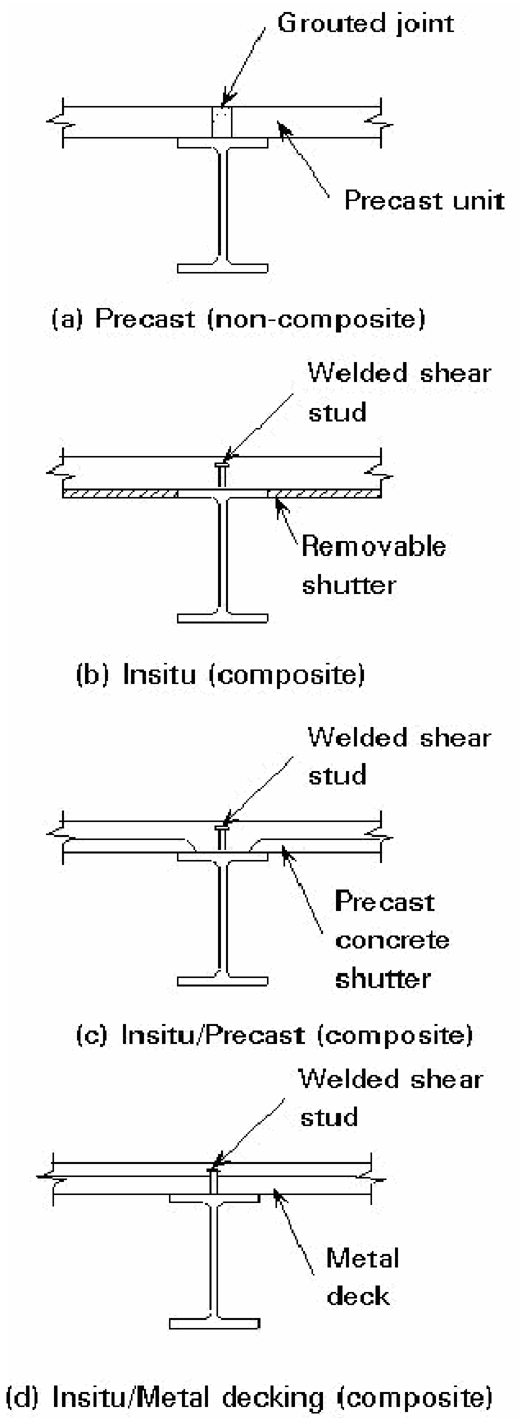


Figure 4.10: Different composite floor systems. [29]

4.3.3 Connections

Connections in reinforced concrete-steel buildings have created some concerns in the structural field, especially in seismic areas. The beam-to-column connections are very important for stability in any structural frame. Connections in composite structures are in general very similar to connections in steel structures and designed in a similar manner. There are two failure modes: shear failure and bearing failure. The shear failure is comparable to reinforced concrete connections and steel connections except for the interaction of steel and concrete. Bearing failure occurs where compressive stress is high and creates rigid rotation of the steel beam within the concrete column. Bearing failure should be avoided in seismic areas [24].

The difficulty of designing composite beam to steel column connections is the behavior of the slab when it interacts at the joint. Under gravity loading, a positive bending moment develops in the mid-span of the beam, but negative moment at the end of the beam. The slab applies lateral loads to the joint and the negative moment at the beam end becomes positive which transmits on to the column face and creates torsion. The problem can be solved by using a semi-rigid joint and placing the longitudinal reinforcement in the slab close to the column. [14] [24]

Rigid or semi-rigid connections allow the beam-bending moment to be distributed more uniformly, which results in reduction of deflection and reduced depth of the beam. [15].

4.3.4 Method of erection

There are two basic methods of erection for composite steel and concrete structural systems: shored and unshored. The methods are basically how the composite floor is constructed. The difference in the two methods is that in a shored system, the beams are supported or propped when the concrete is pored. The supports can be removed when the concrete reaches 75% of its compressive strength. Deflection is reduced by supporting the beam but this method is more time consuming than the other. In an unshored construction, the beams and girders carry the loads until the slab has obtained strength. The beams and girders deflect when the concrete is pored. Studies have shown that the beam/girder has the same flexural strength regardless which method is used. Unshored construction is usually preferred because of reduced construction time and of the cost of installing and removing the supports. [25]

Check list

- ✓ Architectural and owner's requirements
  All requirements can be met by using composite structural system.
- ✓ Time of design and planning
  The procedure takes around six months.
- ✓ Construction time
  The construction time can be reduced by carrying out work at different floors simultaneously.
- ✓ Life cycle cost
  Fire protection will increase the life cycle cost.
- ✓ Fire safety
  Steel members in the structural system need fire protection.
- ✓ Acoustics
  Acoustic requirements can be fulfilled with insulation and carefully designing details.
- ✓ Installations
  Horizontal installations are placed in slabs and under the ceiling. Holes can be made in the web of beams if the height of the beams is large. Vertical installations are placed in shafts.
- ✓ Durability
  Composite structures have good durability.

Advantages:

- **Less on site construction** (steelwork, prefabricated structural elements)
- **High quality** (steel elements manufactured under controlled factory conditions)
- **Speed of erection** (steel erection, metal decking and stud welding, concreting, fire protection, cladding, facade work, services and finishing can be carried out at different floor levels simultaneously.
- **Spans can be 12, 15 or even 20m.**
- **Economical for longer spans.**
- **No formwork required.** The use of profiled steel sheeting speeds up the construction.

Disadvantages:

- **Connectors** (at the steel-concrete interface)

5. CASE STUDIES

5.1 Four story office building

In this case study, a structural system will be chosen for the building. The project was a part of the course Building systems at Lunds Tekniska Högskola which was solved with two of my fellow students, Inga Rut Hjaltadottir and Fjalar Hauksson.

5.1.1 Description of the building

The building is an office building in Malmö, Sweden. The building is four story and all regular office requirements apply to the building. The construction site is surrounded with relatively old buildings and there is limited space around the building that can be used during the construction. The ultimate bearing capacity for the ground is $q_{Rd} = 200kPa$.

The structural system consists of steel and prefabricated concrete elements, load bearing steel columns, MKC steel beams in the structural envelope of the building, interior columns, HSQ beams (hat profiles) and HD/F slim floor (hollow core).

5.1.2 Structural system

A composite structural system is chosen for this building. The layout of plan 2 of the building is shown in drawing 1 in Appendix A and the layout for plan 4 is illustrated in drawing 2 in Appendix A. Drawing 3 in Appendix A illustrates a plan of the foundation of the building.

5.1.2.1 Vertical load resisting system

The load bearing columns in the exterior walls are made of rectangular hollow steel profiles with 120 mm width. Therefore, they can be built inside the exterior walls. The columns are located with 4.8 meters interval.

The inner columns are composite columns, consisting of a closed steel cross-section filled with reinforced concrete. Mechanical connections are used to ensure a complete interaction. The connections are at the columns ends and where the loads are applied.

5.1.2.2 Floor system

The chosen floor system is a prefabricated slim floor with HD/F plates (hollow core). In the exterior walls, continuous MKC-beams are used. The prefabricated concrete lies on the lower flange of the beam. The HSQ-beams (hat profiles, see figure 3.33) are used inside the building (Drawing 1 in Appendix A). The steel beam is welded on a flat plate. The slab is sustained directly by the primary beam, forming the part of the composite beam that works together with the steel beam. The columns in the outer walls are two-storey high (continuous) and the beams are simply supported. The inner columns are one storey high and the beams are continuous.

5.1.2.3 Horizontal load resisting system

To stabilize the structure, prefabricated walls (shear walls) are used. The stairwell and the lift shaft in the building consist of shear walls that stabilise the building. The floor systems are designed to act as horizontal diaphragms to transfer horizontal loads to the shear walls that act as vertical cantilevers in resisting horizontal forces. In general, the horizontal force is carried to the foundations by each shear wall in proportion to its relative stiffness.

<u>Dimensions of members:</u>

HSQ-BEAMS (INNER BEAM)

200x440 and a steel area $A_s = 18.800mm^2$ has a moment resistance of $M_{Rxd} = 631kNm$ and a shear strength of $V_{rd} = 432kN$.

MKC-BEAMS (OUTER BEAM)

MSC(SV.)-265 (C-profile) beam with dimensions 60x160 and a steel area $A_s = 7.200mm^2$

Moment resistance of $M_{Rxd} = 185kNm$ and a shear strength of $V_{rd} = 811kN$.

Outer column

VKR 120x120x8,0 and $i = 53mm$

Inner column

DIN2448, (circular profile) with outer diameter $d_y = 323,9mm$ and $i = 112mm$

Shear walls

Precast solid element walls of thickness of 300mm.

Hollow core slab

HD/F/120/27

Moment resistance of $M_{Rxd} = 190kNm$ and a shear strength of $V_{rd} = 70kN$.

The bearing length is at least *80mm*.

5.1.2.4 Comments

In real life, the building was constructed by using a steel beam-column structural system with slim floor system. The elevator and stair cores were constructed of precast concrete walls. The structural system is in principle the same, the only difference is that we used composite columns instead of steel columns.

The reason for our selection of a composite structural system with slim floor system and precast shear walls is that we would get smaller dimensions of columns and smaller floor height with the beam built in the slab. Furthermore, we wanted to minimize transportation to the site because of the traffic problems at the area of the building. The disadvantages of using composite system are the additional fire protection on the steel required which will need inspection and maintenance.

The use of the MKC beams that are C-profile steel sections allows the slab to rest on the lower flange of the beam. We thought this was a good solution and had not seen it before. We were also fascinated with the use of "hat profiles" in the slim floor instead of a regular I-section. An I-section is usually used in Iceland so this project was a good experience and will hopefully come to a good use while practising structural engineering in Iceland.

5.2 Twenty story office building

This case study will be solved with a different approach, the actual solution will be described and then different options regarding the structural system presented. The structural design of the building is carried out by Ferill consulting engineers in Iceland.

5.2.1 Description of the building

The building will be located in Kopavogur, Iceland. The tower will be in the middle of the second biggest service center in Iceland. The first floor of the building will be used as a shopping center and will cover a larger area than the tower itself or to be exact 4006 m^2 while the rest of the floors will be 431 m^2. There is a basement under the entire first floor (drawing 4). The building will be the tallest office building in Iceland with a total of eighteen floors.

The design of the building is challenging because the owner has special requirements regarding the appearance of the building and required maintenance kept to a minimum. The façade will be of glass. Flexibility and easy adjustment to the user's needs are also required. The building is shown in figure 5.1.

Figure 5.1: Smáratorg, office tower. [38]

5.2.2 Structural system

The designing team in Iceland has selected cast-in-place concrete structural system for the whole building.

5.2.2.1 Vertical load resisting system

The vertical load resisting system will consist of columns and shear walls that are located in the elevator and stair cores of the building. The columns are located in the façade of the building and carry the slab. The columns are circular with a radius of 620mm at the bottom but 540 at the upper floors of the building. The shear walls in elevator and stair cores carry vertical loads from the roof and from slabs.

5.2.2.2 Floor system

The floor system will consist of reinforced concrete slabs that rest on the columns at the outer core of the building and are fixed at the elevator and stair shafts (drawing 5). The thickness of the slab is 260mm at the largest span or where there is a high risk of deflection. At the shorter span, the thickness of the slab is 220mm. The reinforcement will be about 70kg/m^3. The reinforcement of the slab has not been fully designed so further details cannot be presented.

5.2.2.3 Horizontal load resisting system

The horizontal forces are resisted by the shear walls located at elevator and stair cores. The forces are distributed to the footing of the building. The basement of the building is designed as the foundation of the building with additional anchors to the ground. The shear walls at the bottom have a thickness of 350mm and 250mm at the upper floors of the building. The shear walls are designed to have the required stiffness at the bottom to stabilize the building. The floor slabs transfer forces to the shear walls that transfer them to the foundation. [38]

5.2.2.4 Comments

The structural design of the building is quite complicated. In tall buildings the stabilization is a big concern and the designing team has spent a lot of time on solving that. In a tall building, the elevator/stair cores are often used as a stabilizing system. Cast-in-place shear walls are simplest to design in this case, especially because of connections to foundation and to the floor slabs. The difficulty with designing the shear walls is to get the required stiffness at the bottom of the walls where the walls must resist a large moment. The designing team did not consider a bracing system for the stabilization because of the glass façade, since the bracings can be difficult to hide in the structure.

The designing team considered several floor systems, bubble deck, composite, and hollow core slabs but came to the conclusion that reinforced concrete slab was the most economical. Also, the reinforced concrete slab had the best fire resistance and acoustic qualities. The floor system is interesting since there are no beams. The slab rests on the columns which makes the overall floor height relatively small. The bubble deck would have a height of at least 400mm, which is a disadvantage compared to a reinforced slab. A composite slab would require a system of beams as well and the overall height would be greater even though the slab thickness would be smaller. The hollow core slab would also require the use of beams since it cannot be designed as a two-way system.

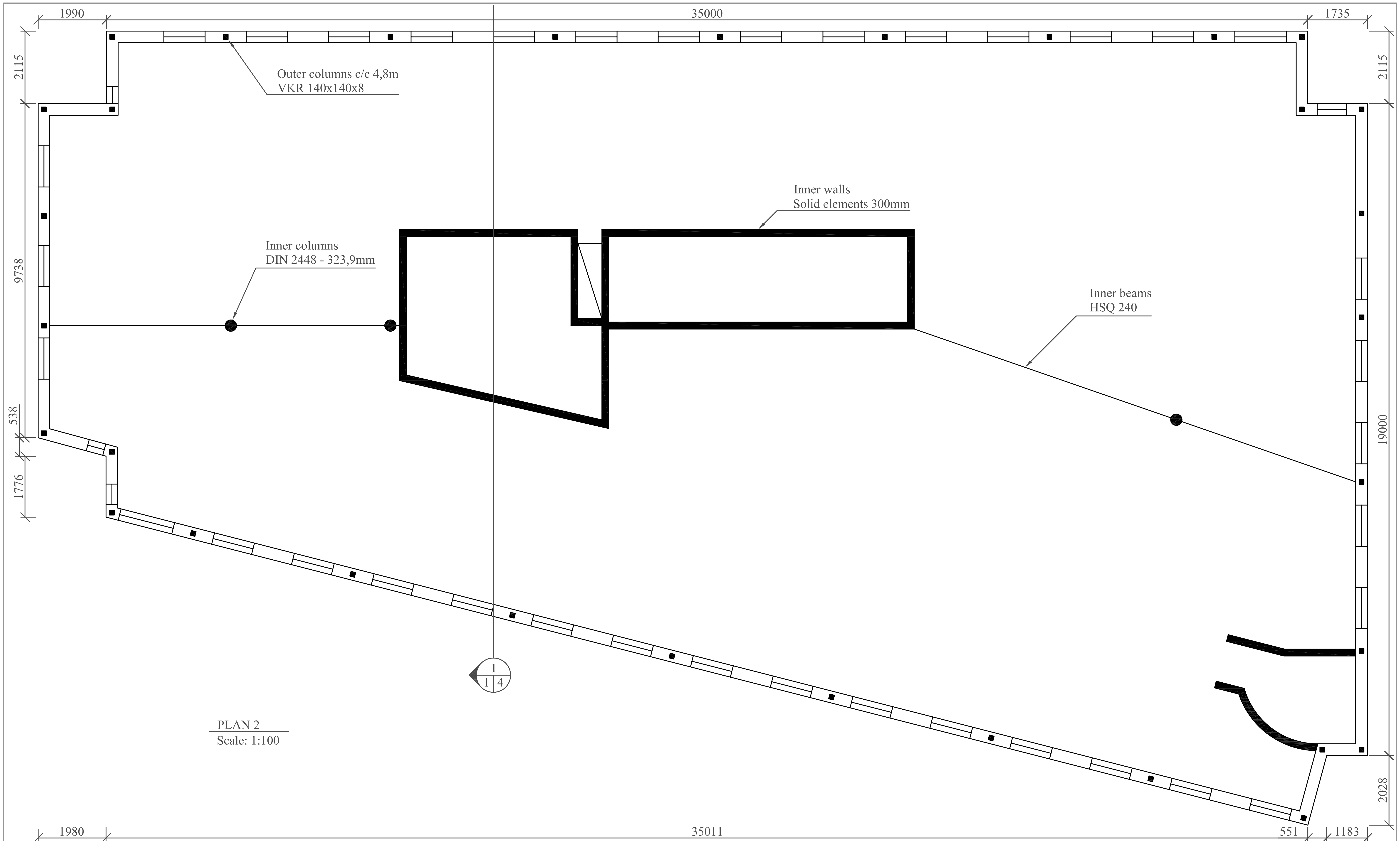
There are not few tall buildings in Iceland, and this building will be the tallest office building in the country. The need for taller buildings is growing in Iceland and two twenty story buildings will be constructed in this service area in the nearest future. It will be interesting to follow the design and construction of these buildings. In Iceland, there is a tradition for cast-in-place structural system, but now more and more different systems are chosen. Only a few office buildings have been constructed with a composite structural system, but they have all been successfully designed and made a positive impression.

6. Conclusion

The objective of this thesis was to study structural systems for office buildings. That involves learning about the majority of the structural members that are available on the market. Different structural members are then combined to form the overall structural system. Information was gathered from all over the world and it was interesting to acknowledge the cultural difference in the field of structural engineering. A lot of research has been made on buildings in countries like USA and Japan, which both have large seismic areas. These countries also have big populations and a great variety of buildings which allows a large market of construction. The market in Iceland, or even in Sweden, is much smaller so new solutions take longer to be accepted.
In conclusion, the selection of a structural system depends on availability, economics, experience, and tradition. The market is different in many countries and therefore there is a tradition for using a certain type of structural system. However, it is important to be open for trying new solutions and learn from other countries in the field of construction. Concrete, steel and composite systems can all be designed to meet the requirements. The designer needs to know the structural members that are available and make a comparison after studying the layout of the building. Then the structural system can be chosen.

Appendix A: Drawings

Drawing 1: Four story office building, Plan 2.
Drawing 2: Four story office building, Plan 4.
Drawing 3: Four story office building, Foundation, plan.
Drawing 4: Twenty story office building, Basement, plan.
Drawing 5: Twenty story office building, Layout of upper floors.



BYGGSYSTEM - VBK 055

Students: Asthildur Helgadottir
Fjalar Hauksson
Inga Rut Hjaltadottir

Teacher: Miklos Molnar

05.05.20

Scale: 1:100

Drawing 1

Plan 2

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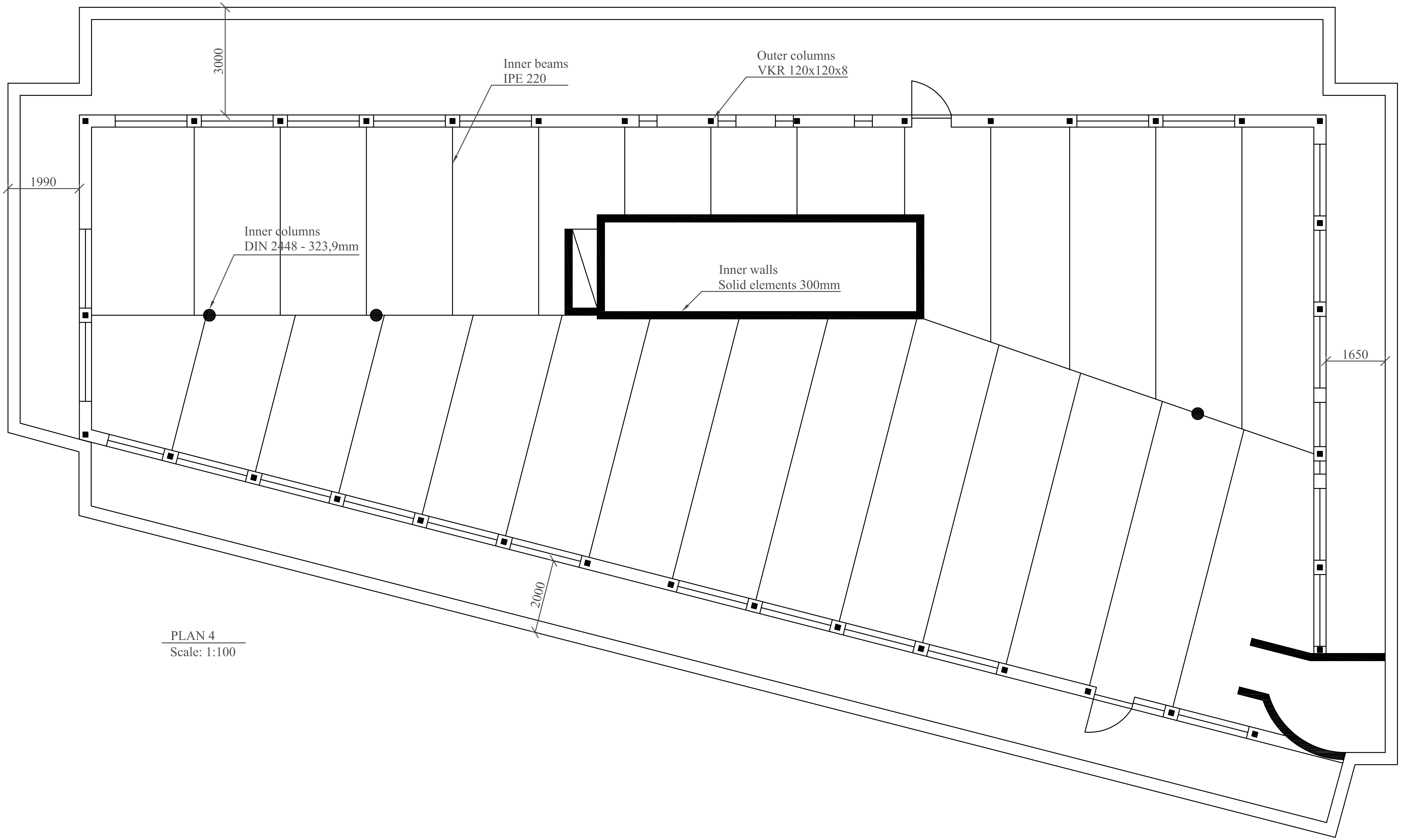

PLAN 4
Scale: 1:100

BYGGSYSTEM - VBK 055

Students: Asthildur Helgadottir, Fjalar Hauksson, Inga Rut Hjaltadottir	05.05.20	Scale: 1:100
	Drawing 2	
Teacher: Miklos Molnar	Plan 4	

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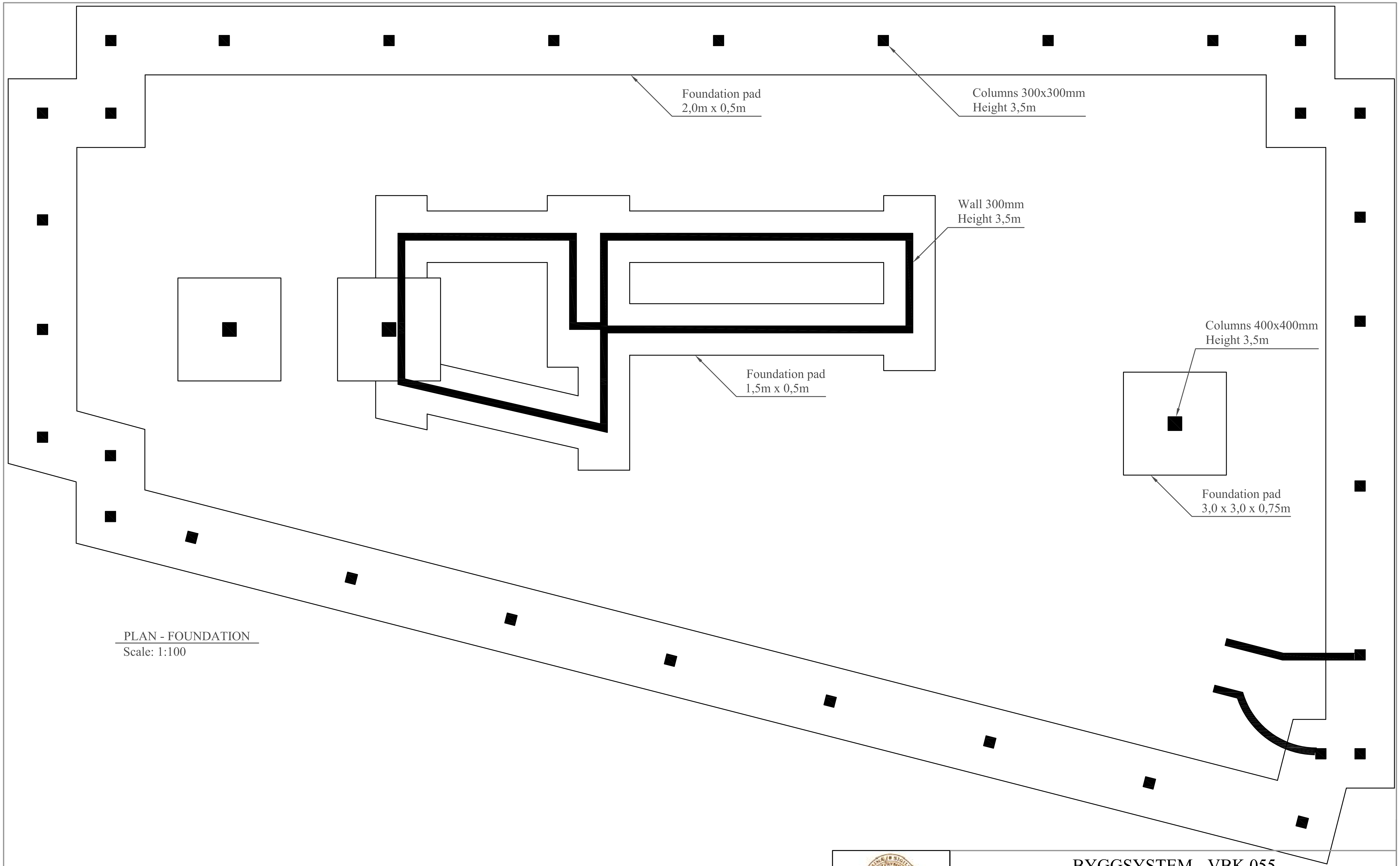

PLAN - FOUNDATION
Scale: 1:100

BYGGSYSTEM - VBK 055		
Students: Asthildur Helgadottir, Fjalar Hauksson, Inga Rut Hjaltadottir	05.05.20	Scale: 1:100
Teacher: Miklos Molnar	Drawing 3	
	Foundation. Plan.	

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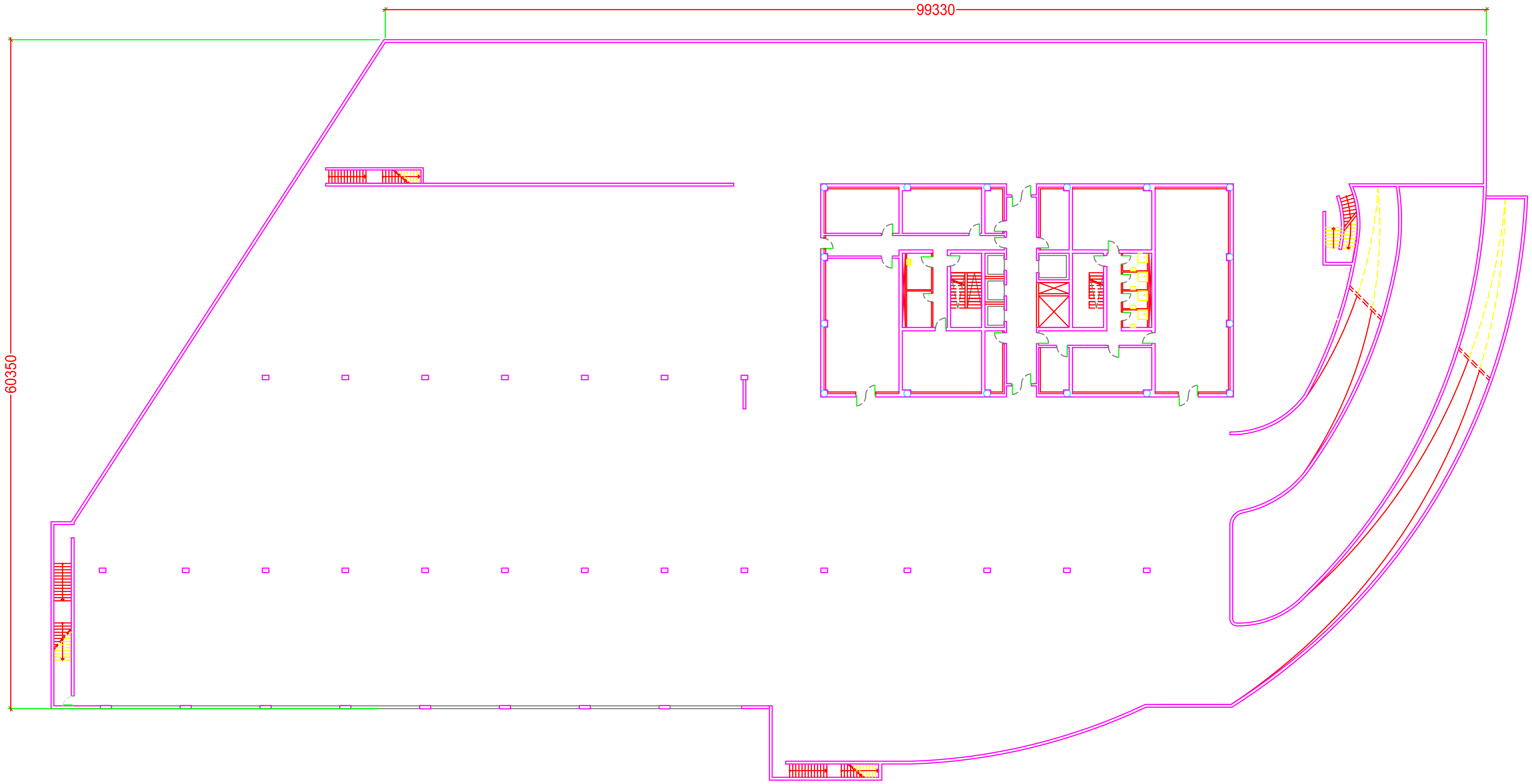
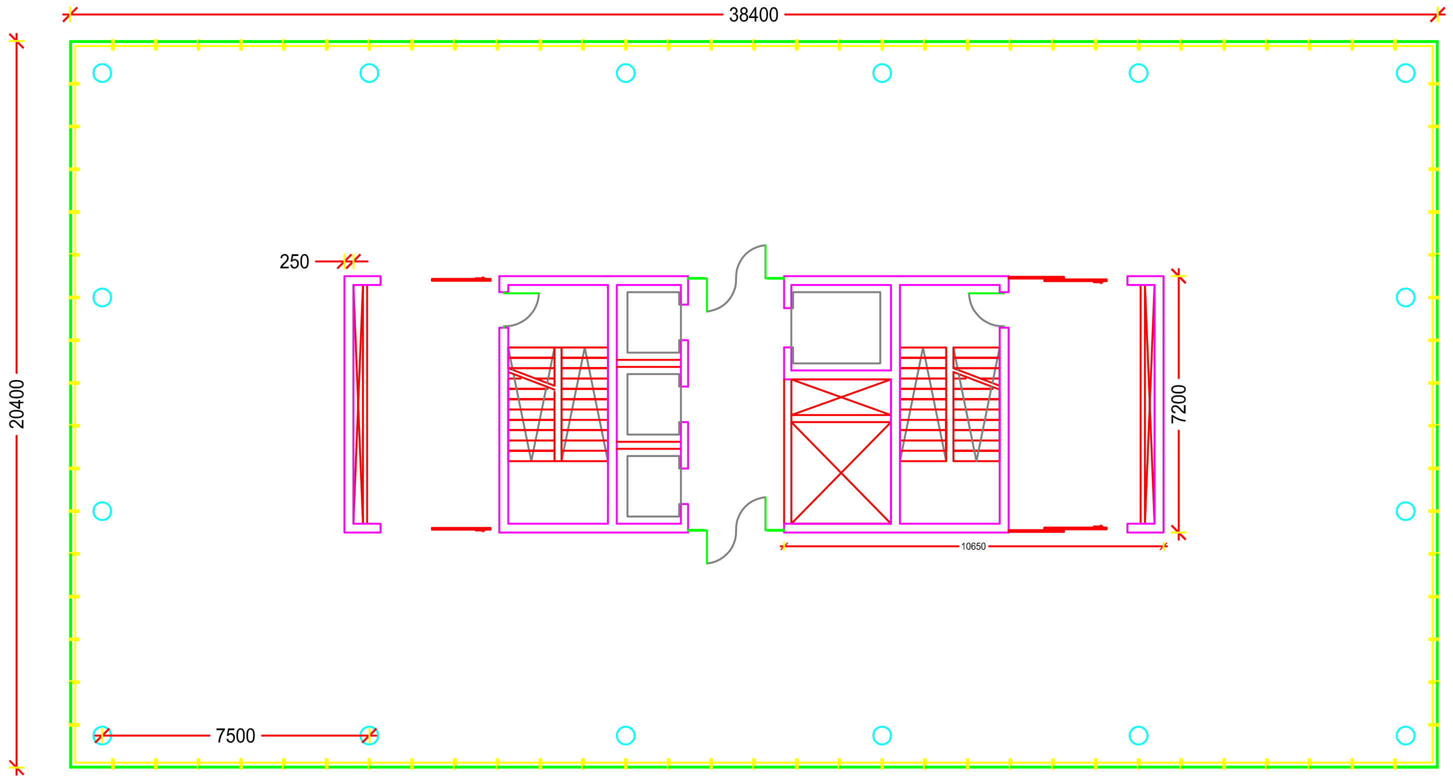


Drawing 4
Basement
Case study II



Drawing 5
Layout of upper floors.
Case study II

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