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SCHOOL OF BUILDING AND ENVIRONMENT

DEPARTMENT OF ARCHITECTURE

UNIT – I - Steel in Architectural Design – SAR1613

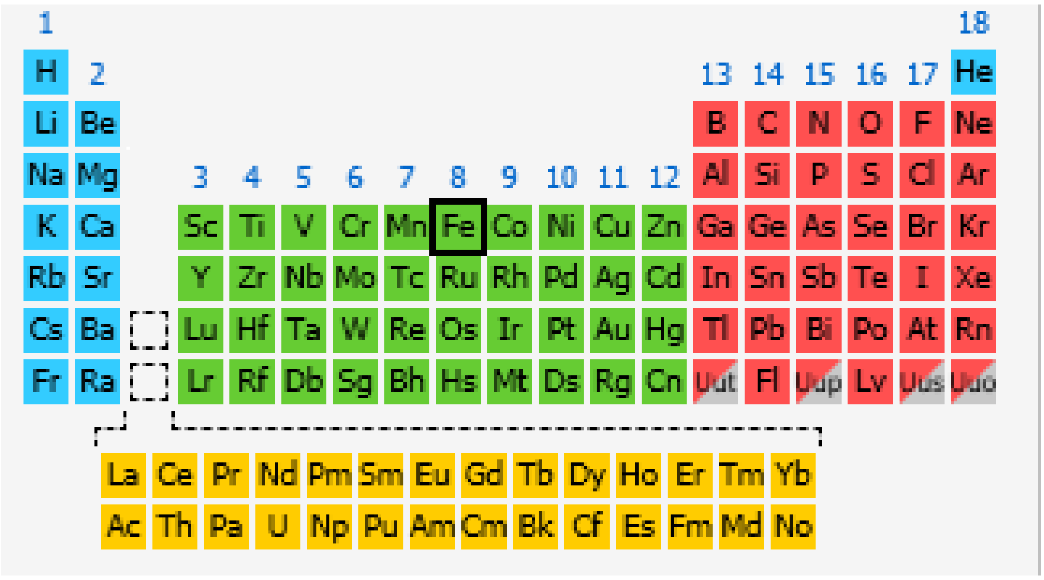
Steel Structures

UNIT 1 - Standard structural steel - thermal properties - Fireproofing Methods - Steel Sheeting - Types of Sheeting Light roofing materials (Recent trends in roofing materials like Corrugated GI Sheets, Pre-coated metal sheets, Polycarbonate sheeting, Teflon coated sheets, PTFE Steel alloys properties and uses) - Long span structures using steel - Steel Roofing namely cable structures - Cable suspended roof, Hyperbolic paraboloid roof, Catenary, Pneumatic & Membrane roof -mention their Concept, Development, Laws of formation, Merits and Demerits- Vertical, Horizontal & Hexagonal joints.

1.1. What is steel?

Steel is one of the commonly known building material, in the present times.

- Comes from our Earth's crust – 6% is iron
- An alloy of iron (Fe-26) and other elements, primarily carbon (C6)
- Manufactured to specs - After iron ore is mined, its melted at 2,800 F
- Carbon and other elements are then added

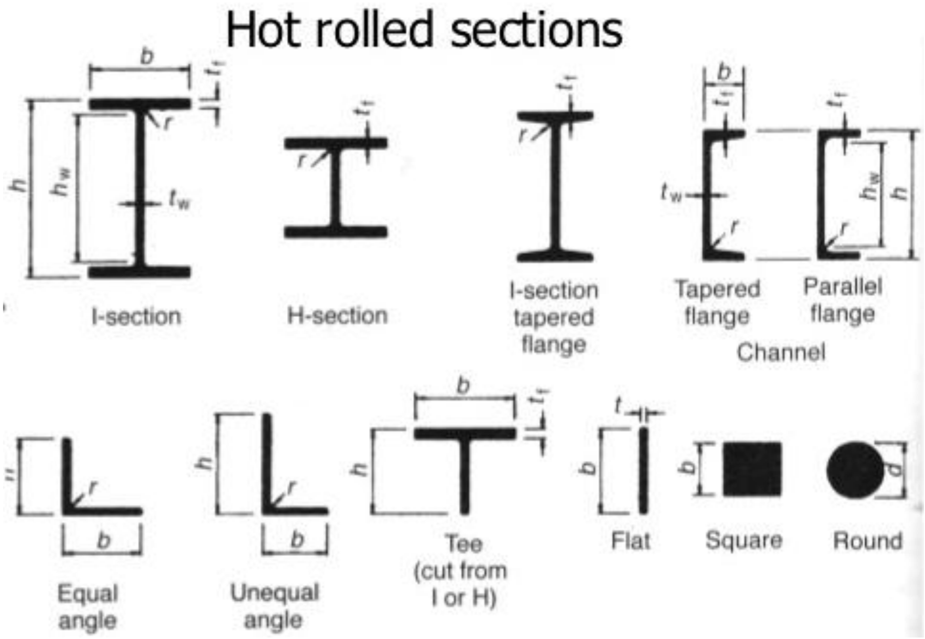


1.2. Structural Steel

Grades of steel that are used for construction of buildings are termed as structural steel

Aggregates may affect the following properties of concrete

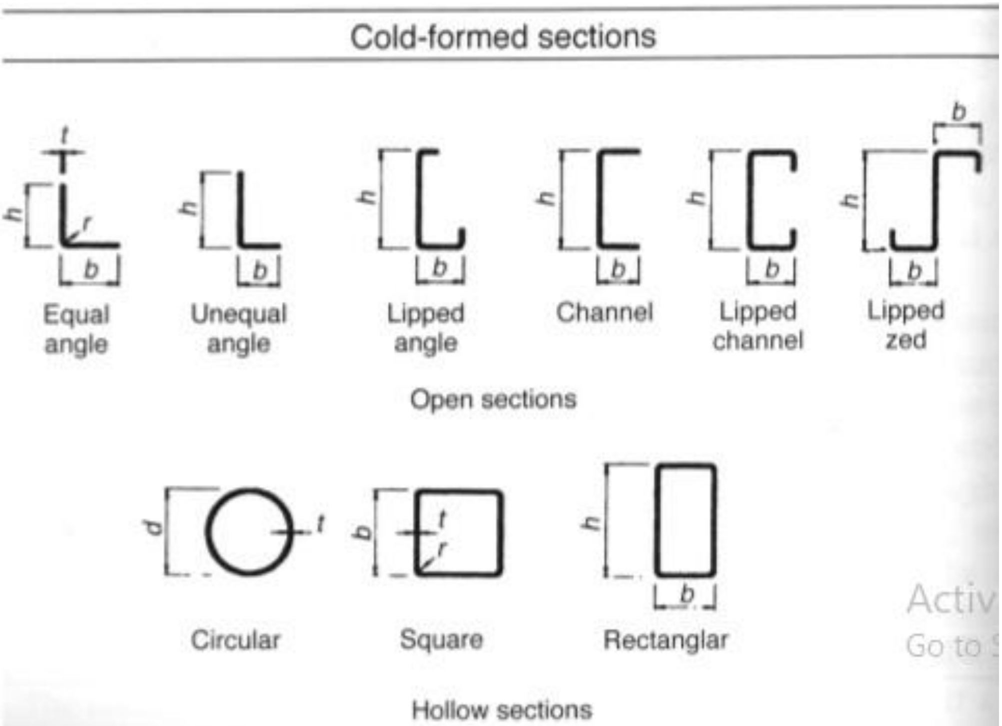
- Man-made metal derived from irom, Iron being the major constituent
- Remaining components are elements, added in small quantities
- These additional elements are added to improve quality and Structural Performance
- Basic products of a steel mill are plates, rods and bars
- Structural steel refers to the fabricated members such as beams, girders, columns, ties and composite sections



There are different types of steel, based on its carbon content

- Dead Mild steel – Less than 0.15% carbon
- Mild steel – 0.15% to 0.3% carbon
- Medium carbon steel – 0.3% to 0.8% carbon
- High carbon steel – 0.8% to 1.5% carbon

- Cast steel / Carbon tool steel – More than 1.5% carbon



In general, more than carbon content, better the performance of steel –
steel that is high in carbon …

- resists corrosion better
- Structure becomes lighter
- Steel becomes tougher and more elastic

Other than the above carbon content based classification, steel is also classified based on the kind of elements used (other than carbon) – These steel are called as Alloys of steel

Alloy steel are further classified in to

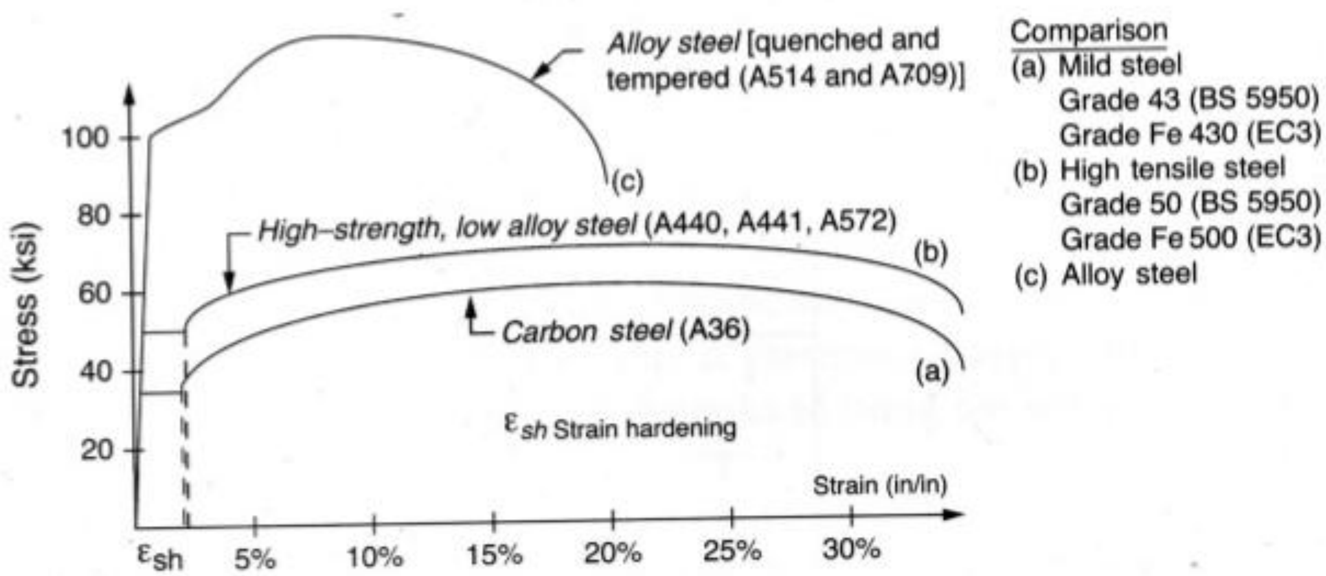
- Ferrous alloys – Chromium, Nickel, Vanadium, Tungsten, Molybdenum, Manganese
- Non- Ferrous alloys –Aluminum, lead, Copper, Zinc based alloys are non-ferrous

Ferrous Metals

Ferrous metals may include a lot of different alloying elements. Some examples are chromium, nickel, molybdenum, vanadium, manganese. Those give ferrous steels material properties that make them widely used in engineering.

- Durable

- Great tensile strength
- Usually magnetic
- Low resistance to corrosion
- A silver-like colour
- Recyclable
- Good conductors of electricity



These qualities make them usable in constructions of long-lasting skyscrapers. On top of that, they are utilised in making tools, vehicle engines, pipelines, containers, automobiles, cutlery etc.

Non-ferrous metals

They do not contain iron. They are softer and therefore more malleable. They have industrial uses as well as aesthetic purposes – precious metals like gold and silver are both non-ferrous. Actually, all pure metal forms, except for pure iron, are non-ferrous.

Non-Ferrous Metals' Properties

Non-ferrous metals' advantages make them usable in many applications instead or iron and steel.

- High corrosion resistance
- Easy to fabricate – machinability, casting, welding etc
- Great thermal conductivity
- Great electrical conductivity

- Low density (less mass)
- Colourful
- Non-magnetic

1.2.1. Advantages of Steel

Steel is the Building material of the 20th century – gives broader parameters to explore ideas and develop fresh solutions, and has outstanding material properties

- **High Strength** – Dense and strong.
- **Durability** – stays longer if taken care well.
- **Slender structures** – height to least lateral dimension.
- **Beauty** – When repeated in patterns.
- **Longer spans -** large open spaces, free of intermediate columns or walls.
- **Factory-finished** to specifications under highly controlled conditions, steel's final outcome is more predictable and repeatable, eliminating the risk of on-site variability.
- **Malleability & Ductile**– can be used as rods, sheets, deck slabs, and sections.
- **Ease of fabrication** – There are fabricators in each corner of the street.
- **capacity to bend** to a certain radius, creating segmented curves or free-form combinations for facades, arches or domes sets it apart.
- **Design freedom** – Colour, texture, Shape, Size.
- **Recyclable -** It's the most recycled material on the planet.

1.2.2. Disadvantages of Steel

- **High production cost** – mining, excavation, transportation, factory investment.
- **Energy consuming process** – Distress to environment.
- **Transportation cost** – From factory to factory, and then factory to site.
- **Skilled and qualified workmen** – needs skilled and qualified design engineers, fabricators, site supervisors and workmen.
- **Shop work Precision** – extra care on shop drawings and need for additional supervision / Quality checks.
- **Assembly equipments** – Due to heavy weight, needs huge cranes and equipments at site during assembly.

- **Corrosion** – gives broader parameters to explore ideas and develop fresh solutions.
- **Joint failure** – Steel structures fail mostly at the joints, poor workmanship is the cause
- **Impact of Failure**– an accident at any of stages is lethal, lots of workers were injured or died involved in accidents related to steel

1.3. Thermal and Fire Protection

- Material properties of all types of building materials can be damaged when they are exposed to high temperatures for a considerable time.
- Steel members can be damaged by heat, causing considerable plastic deformation. The structural strength of steel decreases by as much as half at 600°C .
- Insulating the steel enables the continued ability to resist collapse, while preventing flame penetration through partitioning walls, slabs and ceilings as well.
- Expected properties of Insulation – lesser heat conductivity coefficient, lesser reaction to fire, ability to act as a heat bridge, high dimensional stability, high resistance to water vapor, resistance to bending, resistance to compression, and fixing arrangements.
- Most insulated panels are proprietary products, relevant manufacturer's literature should be consulted as a way of ascertaining specific properties and usage recommendations.

Behaviour of Steel under fire

- Steel loses strength and stiffness at high temperature levels just like any other building materials.
- During design, effective yield stress is taken as zero at 1200 ‘C, in actuality the yield value does not fall to zero unless the steel reaches its melting point, 1550 ‘C.
- This melting point hardly will be reached in building fires. Although the steel is a non-combustible material itself, it has a high heat conducting value, which adversely affects the structural performance during a fire exposure.
- That is why it is important to create a fire design for the steel buildings. Fire proofing to following.

1.4. Passive Fire-proofing methods

Advanced design and analysis techniques allow precise specification of fire protection requirements of steel-framed buildings.

A wide range of fire protection systems are available today.

Water sprinkler systems and water-filled structural member systems are considered to be active fire protection systems. (Not in-scope of this lesson)

Integrated structural members, insulating boards, sprayed coatings, intumescent coatings, suspended ceilings, concrete covers and composite member protections are considered to be passive fire protection systems. (Detailed below)

Because light gauge sheets are so thin, they do not possess much inherent fire resistance if exposed directly to elevated temperatures

Thin film intumescent coatings are the most popular form of fire protection

Latest trend is towards Pre-engineered steel flooring systems have been designed to achieve 60-minutes of fire resistance, without additional fire protection

1. Concrete Encasement –

Until the late 1970s, concrete was by far the most common form of fire protection for structural steelwork.

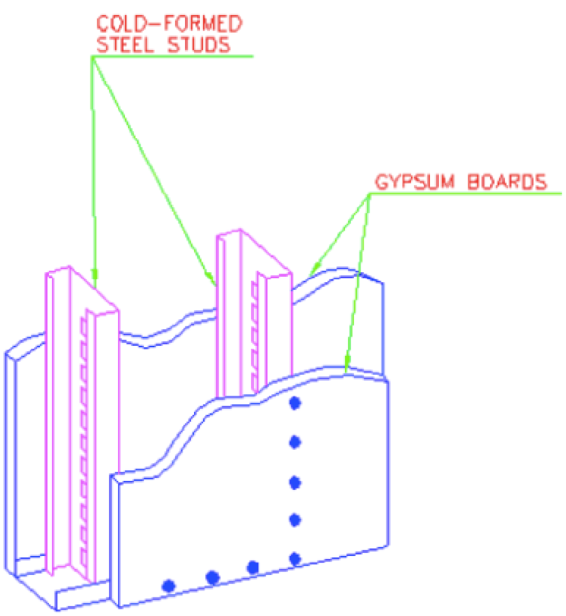
However the introduction of lightweight, proprietary systems such as boards, sprays and thin film intumescent coatings has seen a dramatic reduction in its use. Nevertheless, concrete encasement has its place and it continues to have a small percentage of the fire protection market.

The principal advantage of concrete is durability. It tends to be used where resistance to impact damage, abrasion and weather exposure are important e.g. warehouses, underground car parks and external structures. The principal disadvantages are:

Cost - compared to lightweight systems;

Space utilisation (large protection thicknesses take up valuable space around columns)

Weight.



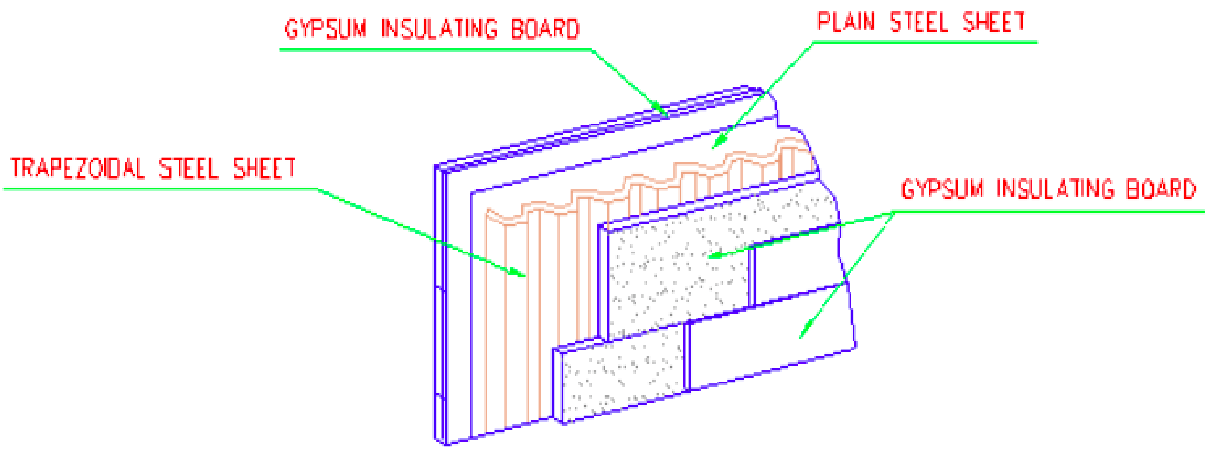
2. BOARDS

2a. integrated structural member systems–

Load bearing column and beams are embedded into the wall and floor assemblies, by the use of ceiling and wall boards; that can protect up to two hours depending upon the fire ratings and thickness of these covering materials.

2b. insulating boards –

Gypsum-based boards, mineral fibre boards or covers made with light aggregates like perlite or fibre silicate are the insulating materials that can supply the required

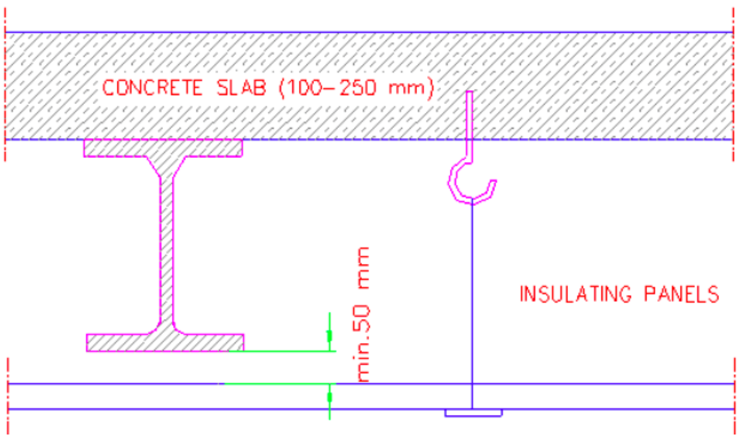


structural fire protection for steel members.

3. suspended ceiling assemblies –

Suspended ceilings can be used as a fire insulation layer acting as a protective cover on the bottom face of the floor beams. Their fire rating values must be known prior to design and use.

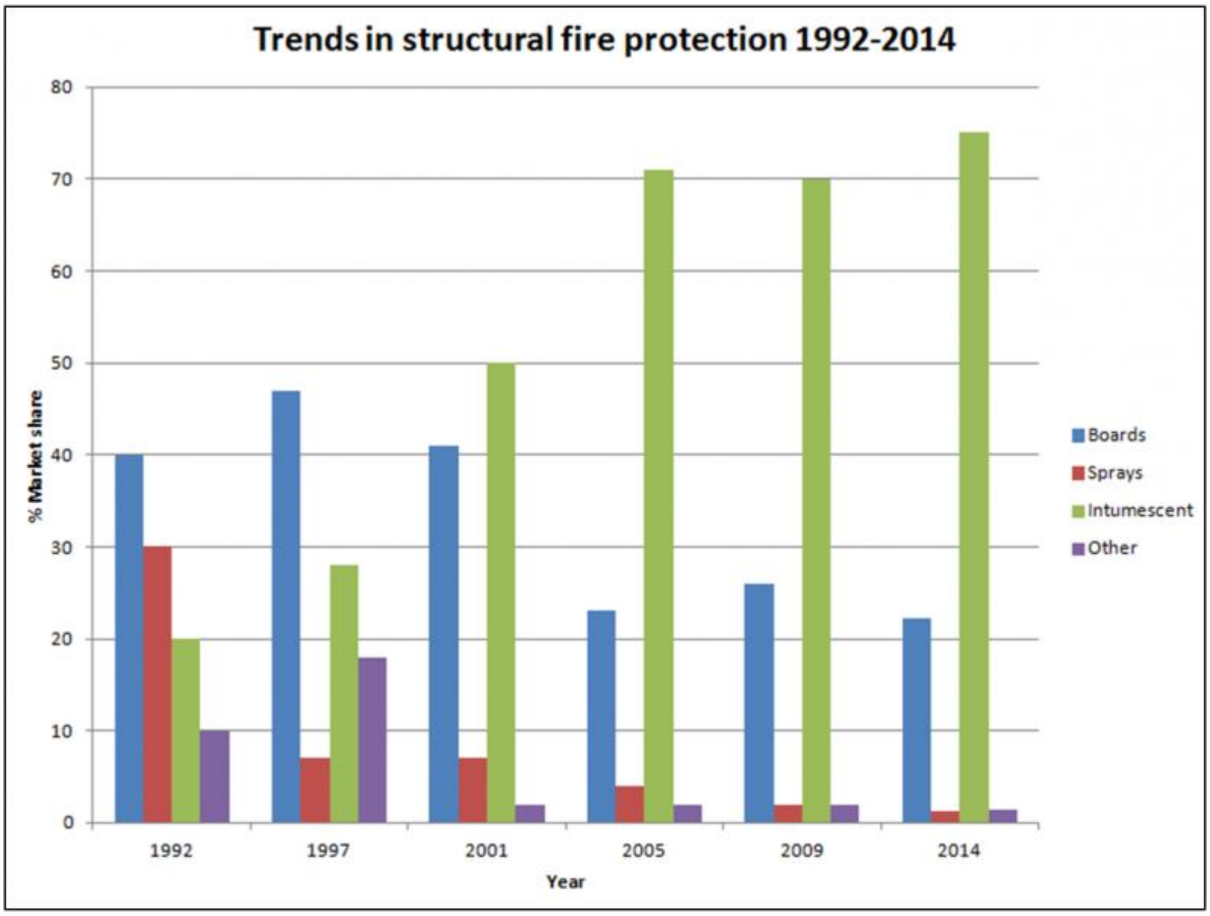
Rock wool or mineral wool insulation materials can be used in ceiling or floor member cavities which are quite fire resistant. On the other hand, suspended ceilings also can be



used to hide the plumbing lines and other conduits.

4. Thin film intumescent coating –

- They are mainly used in buildings where the fire resistance requirements are 30, 60 , 90 and 120 minutes. They can be applied either on-site or off-site. In general, most on-site application is carried out using water based materials. However, where the structure to which the material is applied is not to have an end use in a dry, heated environment, solvent based materials are commonly used.
- They have three components, a primer, a basecoat (the part which reacts in the fire) and a sealer coat. The basecoat usually comprises the following ingredients: A catalyst which decomposes to produce a mineral acid such as phosphoric acid.
- A carbonific such as starch which combines with the mineral acid to form a carbonaceous char.
- A binder or resin which softens at a predetermined temperature.
- A spumific agent which decomposes together with the melting of the binder, to liberate large volumes of non-flammable gases. These gases include carbon dioxide, ammonia and water vapour. The production of these gases causes the carbonaceous char to swell or foam and expand to provide an insulating layer many times the original coating thickness.



1.5. Common Applications

Steel is generally used as reinforcements for Reinforced cement concrete (RCC)

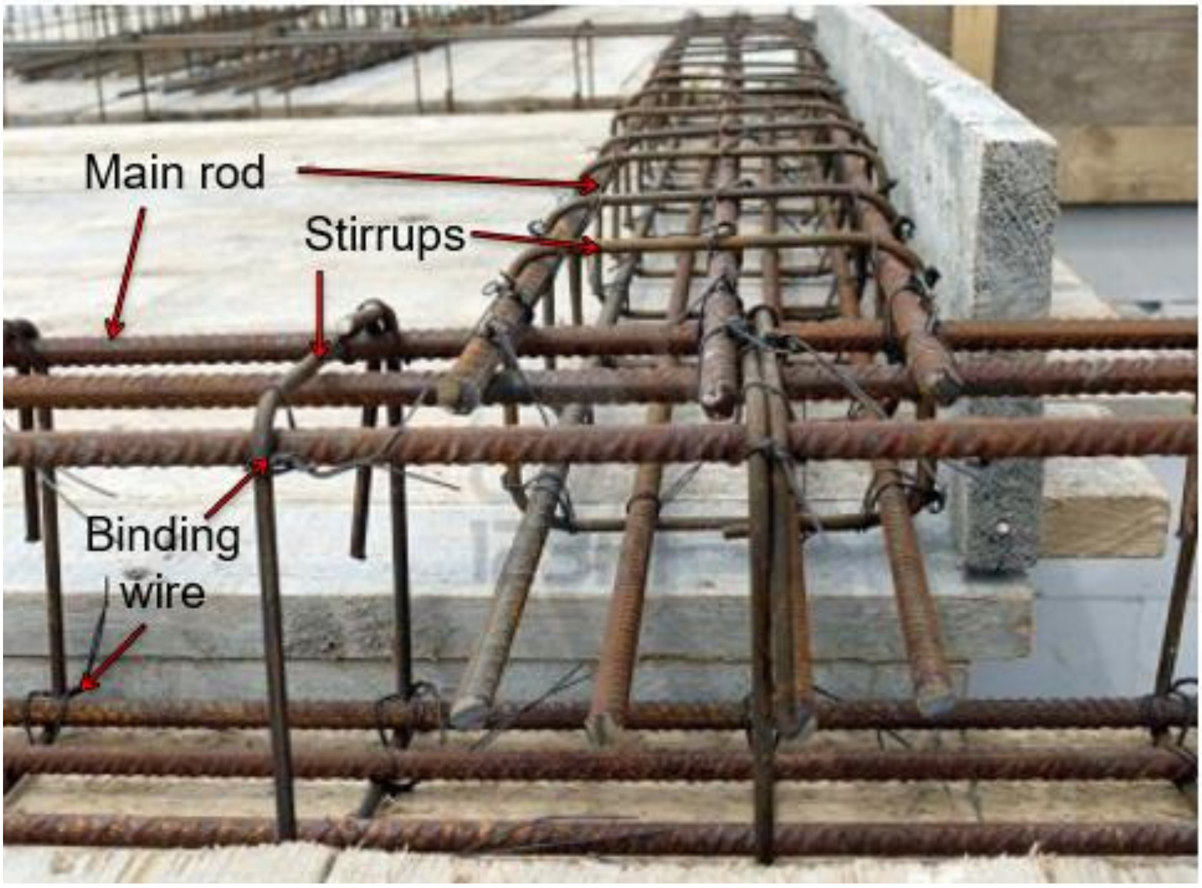
Recent advancements to material technology has introduced various other reinforcements, in place of steel,

FRP rods, bamboo, can also be used as reinforcements

Steel reinforcements are of three categories

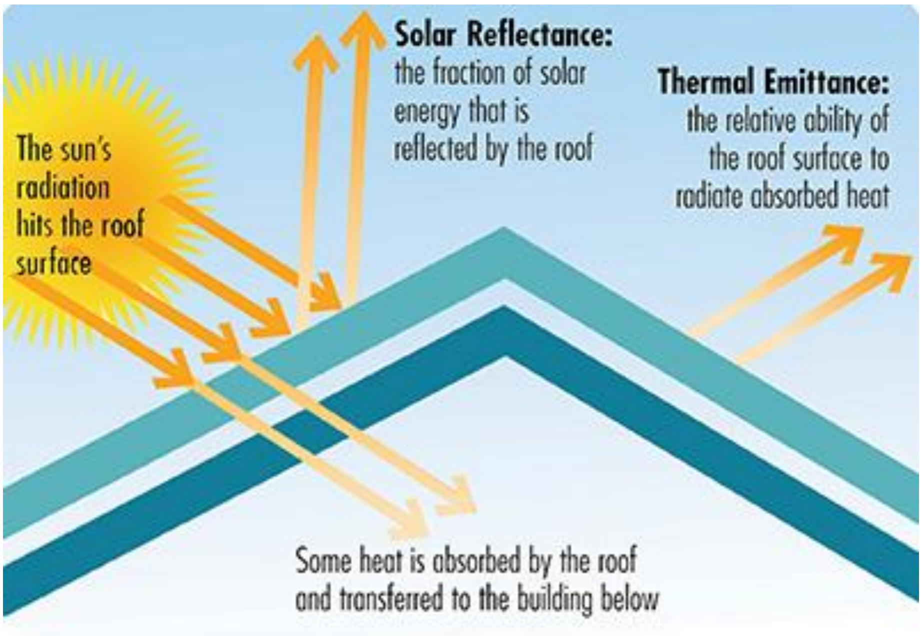
- Steel rods – main reinforcement
- Stirrups – holds all the steel rods and keeps them in place
- Binding wires – helps in binding the steel rods and stirrups together – after binding they are mostly welded, to avoid breaking lose

BINDING WIRE STEEL BARS STIRRUPS



1.6. Steel Sheeting

The coming years promise to bring in more types of fibreglass, asphalt and metal roofing options for those tired of their conventional roofs. The usage of RCC roofs, GI roofing sheets and asbestos-cement sheets for roofing purposes are still around and are here to stay.



There has been a considerable rise in the quality of clip-on systems, fasteners, trimmings and hardware fixings to make roofing structures look neater and more attractive than before. Buyers are now opting for roofs with innovative shapes, long life-span and roofs with FRP skylights to add more value to their structures. Tiles and shingles are trending too; thereby making fibreglass and metal roof an important part of residential and commercial setups in India.

- Types of Sheeting roofing materials - A metal roof can be manufactured in four different styles or profiles, including:
- Standing Seam: The most commonly recognized metal roofing profile, this option has continuous panels that run from the ridge of the roof all the way down and seams connected by fasteners, which are raised between panels.
- Metal Shingle/Slate: This style creates the distinctive look of slate tiles or even classic asphalt shingles with the added benefits of metal.

- Metal Tile: Standard concrete tile roofs are heavy, yet fragile and costly to maintain. Metal Tile, however, has the graceful curves of classic tile, but the lightness and strength of steel.
- Metal Shake: This offers an investment-grade alternative to traditional wood shake roofs, presenting an authentic look of wood, while gaining a variety of color choices with longer lasting, fireproof metal.
- With the variety of looks and finishes available, it's possible that you've seen many metal roofs on homes, but didn't recognize them as they have the ability to "hide in plain sight."

1.6.1. Corrugated GI Sheets

- Galvanised steel sheets form the base material for different types of corrugated sheets, such as the ones coated with polyester paint or protected by PVC plastisol coated roof sheets.
- corrugated roofing sheets feature repetitive folds on their surface. Because of their unique shape, they offer years of reliable utility and enhanced strength. Their corrugated wavy

design with ridges and grooves make them stronger.

- Because of the special corrugated shape, flimsy and lightweight metals like aluminium can also be equipped to undergo decades of weather beating.

- As per the pollution levels prevailing where they are installed, corrugated sheets have to be maintained every 5-10 years. Durable and eco-friendly roofing sheets are also available in market.

- *The affordable price of GI sheet is still capturing the attention of buyers for more reasons than one.*

1.6.2. Pre-coated metal sheets

- Available Finishes
- PLAIN GALVANISED
- POLYESTER LIGHT GREY
- POLYESTER PAINT: Slate, Van Dyke Brown, Juniper Green,
- PVC PLASTISOL: Slate, Van Dyke Brown, Juniper Green, Black, Goosewing Grey, Terracotta, Merlin Grey, Olive Green

1.6.3. Polycarbonate sheets

- Manufactured from best-quality high-impact polypropylene resins.

- Polycarbonate roofing sheets have insulation properties and high strength quotient, Completely weather-resistant, easy to install, extremely durable, their maintenance cost is very low, UV-resistant and fire-resistant. However, these roofing sheets aren’t scratch-resistant. Therefore, installers have to be very careful while going about their installation

- effective roofing solutions in places such as swimming pool areas, sky lighting, walkways and display signboards. Foam backed polycarbonate and clear polycarbonate roofing options are the most commonly used types of polycarbonate sheets.

- Foam-backed polycarbonate roof sheets are lightweight and durable. They are installed in industrial buildings, like warehouses, because of their longevity and strength. Homeowners use them to build sheds, carports and roofs with a minimal slope.

- Clear polycarbonate sheets are installed in patios, sunrooms and places that need natural light through the roof. These roofing panels often feature protective film layers for filtering out harmful UV rays of the sun.

1.6.4. Teflon coated / PTFE steel alloys

- PTFE is a synthetic fluoropolymer of tetrafluoroethylene discovered accidentally by Dr Roy Plunkett . PTFE is a thermoplastic compound noted for its very significant chemical inertness and heat resistance. Commonly encountered as a non-stick coating for pots and pans it is sometimes referred to by the trade name ‘Teflon’ or 'Syncolon'. It is widely used for a variety of engineering and chemical applications.

- With a high molecular weight, it consists entirely of carbon and fluorine. Displaying reduced stress cracking and corrosion, it is also hydrophobic, it cannot be wetted by water or water-containing liquids. It also displays one of the lowest coefficients of friction of any solid so that even geckos and insects cannot crawl up it.

Properties

.1. Very low friction coefficient.

.2. Resists corrosion.

.3. Significantly chemically inert.

.4. Withstands wide temperature ranges.

.5. Good abrasion resistance.

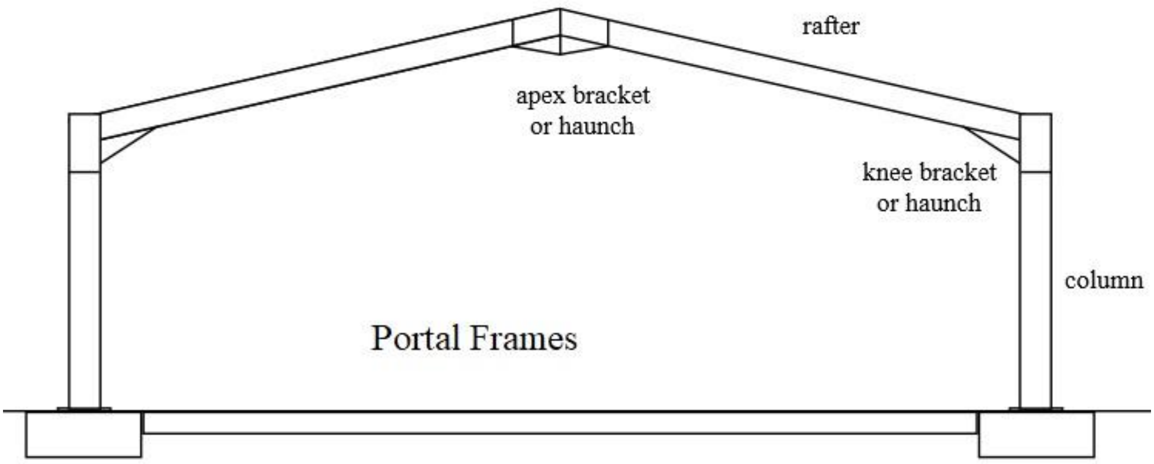
.6. Non-porous.

1.7. Long span structures using steel

- Building material of the 20th century – Steel can be used to cover long spans without the need for intermediate columns. Few of the widely used structures are - Portal frames, trusses, space frames, monitor roofs, fabric structures, long span arches / barrel vaults and suspension roofs

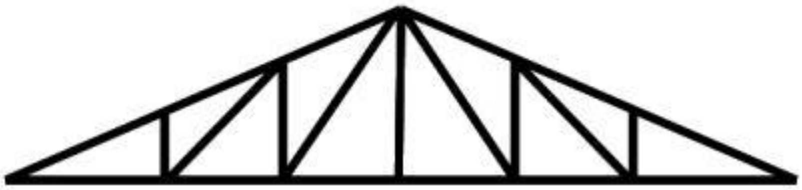
1.7.1. Portal frames

Portal frames are a type of structural frame, that, in their simplest form, are characterised by a beam supported at either end by columns, however, the joints between the beam and columns are 'rigid' so that the bending moment in the beam is transferred to the columns. This means that the beam can be reduced in sectional size and can span large distances. Typically, the joint between the beam and the columns is made 'rigid' by the addition of a haunch, bracket, or by a deepening of the section at the joints.

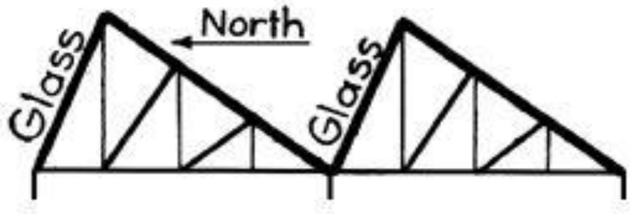


1.7.2. Trusses

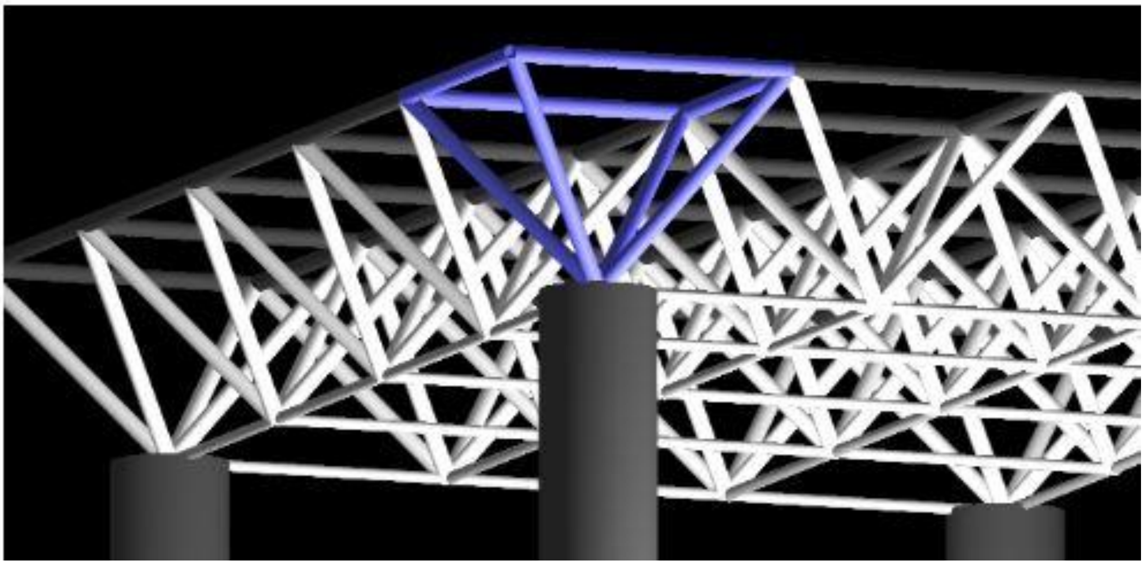
Pitched truss



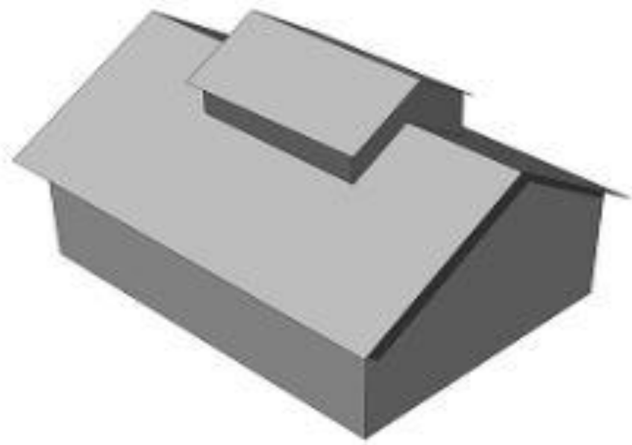
Saw-tooth roof



1.7.3. Space Frames



Monitor roofs



1.7.4. Monitor roofs

1.8. Steel Roofing

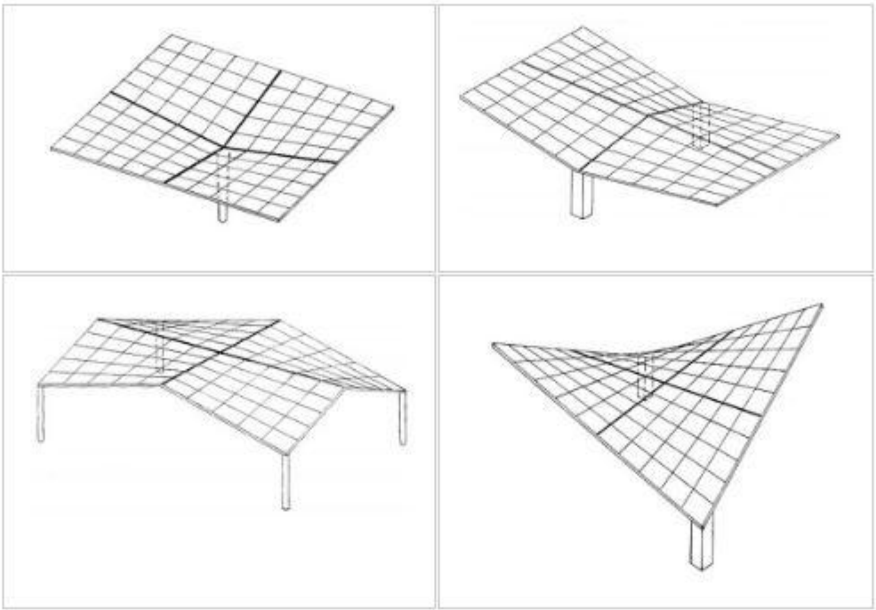
1.8.1. Cable suspended roof

- Cable suspended roof - In recent years, design and construction of structures with cable-supported and cable-suspended roofs has increased. cable roof structures permit economical, column-free construction over large spans. Cable roofs also decrease the stresses on the superstructure, supporting members and the foundation, thereby permitting the use of fewer and lighter materials.
- A loose description of a cable roof structure is any roof structure which uses steel cables as load-bearing, structural elements. Most roofs fall into one of two categories: (1) cable-suspended; or (2) cable-supported.
- Cable-suspended roof uses cables to directly carry the roof load. There are two variations of this principle: (1) cases where the roof deck is carried directly on the cable; and (2) cases where additional loads, such as ceiling frames, are suspended directly from and below the cable.
- Cable-supported system, the roof loads are generally carried by rigid structural members. In this case, the cables serve as added support.
- The architectural forms of suspension roofs are numerous. If adequately treated in the conceptual design stage, structural suspension systems offer numerous architectural forms, not only for roofs, but for the entire building. The following are the most common types of suspension roofs.

1.8.2. Hyperbolic paraboloid

- Hyperbolic paraboloid (sometimes referred to as ‘h/p’) is a doubly-curved surface that resembles the shape of a saddle, that is, it has a convex form along one axis, and a

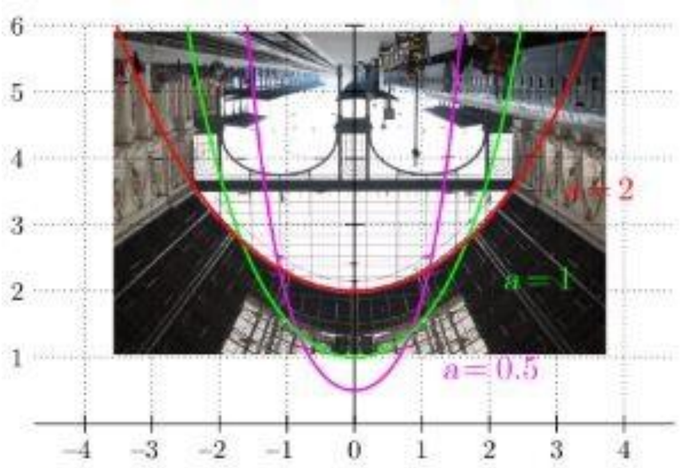
Hyperbolic paraboloid in construction



concave form on along the other. It is also a doubly-ruled surface, that is, every point on its surface lies on two straight lines across the surface. Horizontal sections taken through the surface are hyperbolic in format and vertical sections are parabolic.
- The fact that hyperbolic paraboloids are doubly-ruled means that they are easy to construct using a series of straight structural members. As a consequence they are commonly used to construct thin ‘shell’ roofs.
- By being both lightweight and efficient, the form was used as a means of minimising materials and increasing structural performance while also being capable of achieving impressive and seemingly complex designs.
- Rather than derive their strength from mass, like many conventional roofs, thin shell roofs gain strength through their shape. The curvature of the shape reduces its tendency to buckle in compression (as a flat plane would) and means that they can achieve exceptional stiffness.

1.8.3. Catenary

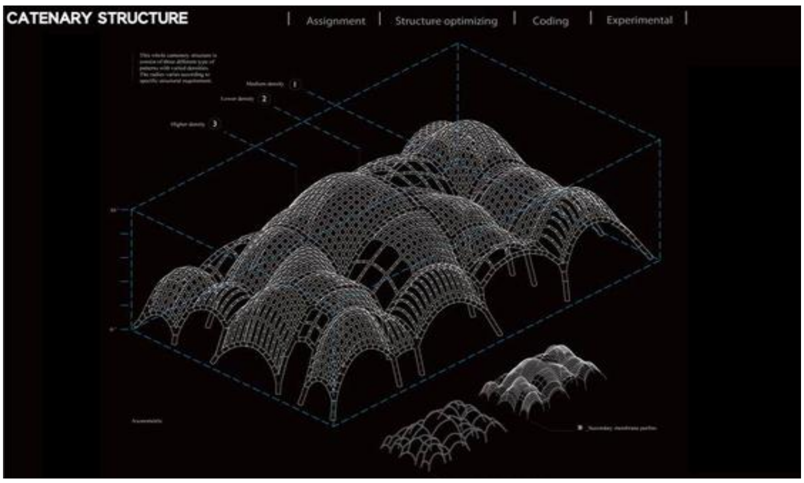
- In physics or geometry, a cable or a chain hanging freely and acting under its own weight, supported only at its end points (not in a vertical line) and with no other load, takes the form of a catenary. This is different to the loaded cables supporting a suspension bridge, which take the form of a parabola.



The cross-section of the roof of the Keleti Railway Station forms a catenary@ Budapest

Catenary[27] arches under the roof of Gaudí's *Casa Milà*, Barcelona, Spain.

- Although the two forms look very similar, they are mathematically different. In mathematical representation, the catenary uses a hyperbolic cosine while the parabola is far easier to represent with just a polynomial. Engineers may sometimes use the mathematics for a parabola when considering a catenary.
- Both forms are always in tension and may be described as funicular forms, which are the forms assumed by cables (or chains) under any given load: the catenary is funicular because it bears only its own load, while the parabola is funicular because it carries load, as in a suspension bridge. A catenary can also be called alysoid or chainette.



- In architecture and engineering, catenaries are used in bridge and arch
- design to avoid bending moments.

1.8.4. Pneumatic & Membrane roof

- **Concept -** Covering both large and small spans, air-supported roofs resemble balloons in both appearance and function. The materials used are similar to those used in tensile structures, namely synthetic fabrics such as fiberglass and polyester. In order to prevent deterioration from moisture and ultraviolet radiation, these materials are coated with polymers such as PVC and Teflon.
- **Development** - When the roof is inflated, the cable network restrains the fabric from excessive stretch and also provides structural support for lighting, sound and HVAC systems, service walkways and visual effects such as scoreboards. In case of deflation in a stadium, the cables, although in a relaxed position (a catenary), still support all the apparatus, as well as the fabric
- **Laws of formation** -The main loads acting against the air-supported envelope are internal air pressure, wind, or weight from snow build-up. To compensate against wind force and snow load, the structure's inflation is adjusted accordingly. The air pressure on the envelope is equal to the air pressure exerted on the inside ground, pushing the whole structure up. Therefore, it needs to be securely anchored to the ground.
- The danger of sudden collapse is nearly negligible, because the structure will gradually deform or sag when subject to a heavy load or force. Only if these warning signs are ignored, then the build-up may rupture the envelope, leading to a sudden deflation and collapse

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SCHOOL OF BUILDING AND ENVIRONMENT

DEPARTMENT OF ARCHITECTURE

UNIT – II - Steel in Architectural Design – SAR1613

Composite construction using structural steel

A composite material is made by combining two or more materials – often ones that have very different properties. The two materials work together to give the composite its desired properties. However, you can easily tell the different materials as they do not dissolve or blend into each other - Most composites are made of just two materials. One is the matrix or binder. It surrounds and binds together fibres or fragments of the other material, which is called the reinforcement.

1.1. A background

ADVANTAGES

- The biggest advantage of modern composite materials is that they are light as well as strong.
- By choosing an appropriate combination of matrix and reinforcement material, a new material can be made that exactly meets the requirements of a particular application.
- Composites also provide design flexibility because many of them can be moulded into complex shapes.
- Will not corrode electrochemically (durability)
- High strength-to-weight ratio
- Electromagnetically inert
- Ease and speed of installation
- Ability to tailor mechanical properties (versatility)
- Low thermal conductivit

DISADVANTAGES

- The downside is often the cost. Although the resulting product is more efficient, the raw materials are often expensive.

1.1.1. Early composites

- People have been making composites for many thousands of years. One early example is mud bricks. Mud can be dried out into a brick shape to give a building material. It is strong if you try to squash it (it has good compressive strength) but it breaks quite easily if you try to bend it (it has poor tensile strength). Straw seems very strong if you try to stretch it, but you can crumple it up easily. By mixing mud and straw together it is possible to make bricks that are resistant to both squeezing and tearing and make excellent building blocks.

- Another ancient composite is concrete. Concrete is a mix of coarse aggregate, cement and sand. It has good compressive strength, adding metal rods or wires to the concrete can increase its tensile (bending) strength.

1.1.2. Natural composites

- Natural composites exist in both animals and plants. Wood is a composite – it is made from long cellulose fibres (a polymer) held together by a much weaker substance called lignin. Cellulose is also found in cotton, but without the lignin to bind it together it is much weaker. The two weak substances – lignin and cellulose – together form a much stronger one.

- The bone in your body is also a composite. It is made from a hard but brittle material called hydroxyapatite (which is mainly calcium phosphate) and a soft and flexible material called collagen (which is a protein). Collagen is also found in hair and finger nails. On its own it would not be much use in the skeleton but it can combine with hydroxyapatite to give bone the properties that are needed to support the body.

1.1.3. Modern Composites

- The first modern composite material was fibreglass. The matrix is a plastic and the reinforcement is glass (made into fine threads and often woven into a sort of cloth) On its own the glass is very strong but brittle and it will break if bent sharply. The plastic matrix holds the glass fibres together and protects

- Some advanced composites are using carbon fibres instead of glass. These materials are lighter and stronger than fibreglass but more expensive to produce. They are used in aircraft structures and expensive sports equipment such as golf clubs.

- Carbon nanotubes have also been used successfully to make newer composites.

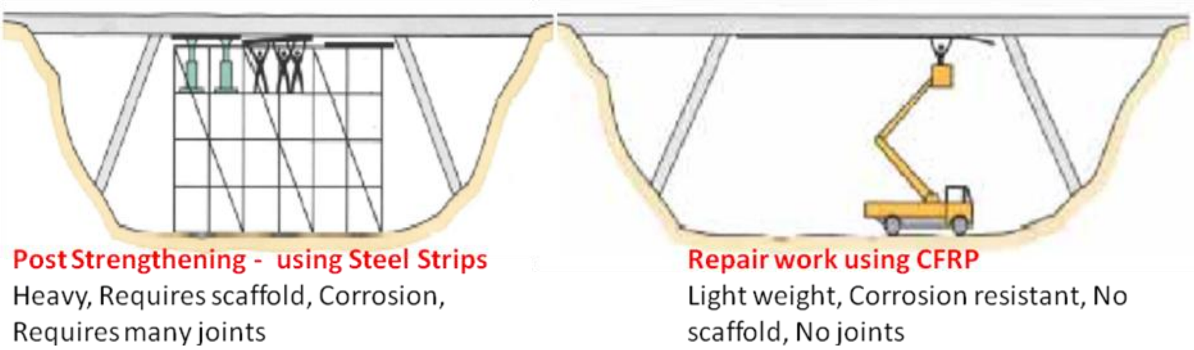
Common fibers used in composites :

- Fiberglass
- Carbon fiber
- Aramid Fiber
- Boron fiber
- Basalt fiber
- Natural fiber (wood, flax, hemp, etc.)

Common plastic resins used in composites :

- Epoxy
- Vinyl Ester
- Polyester
- Polyurethane
- Polypropylene

1.2. Carbon – Fiber reinforced Plastics (CFRP)



CFRP can be used to strengthen Steel bridges and decks without disturbing the structure and the traffic flowing on the bridge decks

Reasons for strengthening

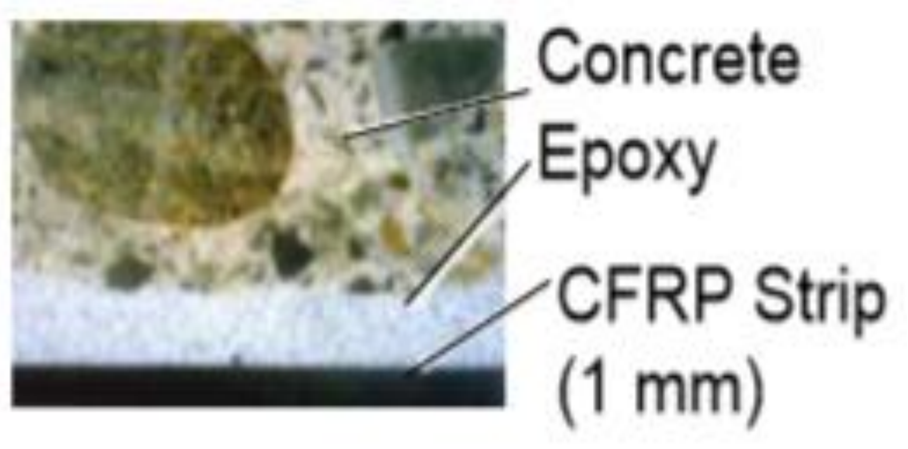
-Aging of our structures

-Renewal is too expensive

-Higher loads (railway bridges, …)

-Natural hazards (earthquake, …)

-Man made hazards (terror attacks, …)



1.3. Flitch Beams

- ***Steel Flitch Plates*** are stronger wooden beam without increasing the wooden beams size.
- Construction jobs often have repairs, restoration work or even new construction that require longer spans of support beams.

- Steel Flitch plates are perfect for larger open spaces or stronger header beams for room additions or upper level additions that may result in higher structural load requirements.

- Combing the strength of *steel flitch plates* with wooden support beams and header beams can meet those higher strength requirements. Creating a stronger support beam or header beam is done by sandwiching one steel flitch plate on either side between two wooden members (wood/steel/wood) and through bolting all pieces together. Optionally you can even use two steel flitch plates and sandwich them between three wooden members (wood/steel/wood/steel/wood) and through bolting each of the steel and wood pieces together. This style flitch beam is often used and highly desired, is easy to work with and install in your construction job.

1.4. FOAM Concrete

- Foam concrete is a type of lightweight concrete that is manufactured from cement, sand or fly ash, water, and the foam. Foam concrete is in the form of foamed grout or foamed mortar.

- The production of foam concrete involves the dilution of surfactant in water, which is passed through a foam generator that will produce foam of stable form. The foam produced in mixed with the cementitious mortar or the grout, so that foamed quantity of

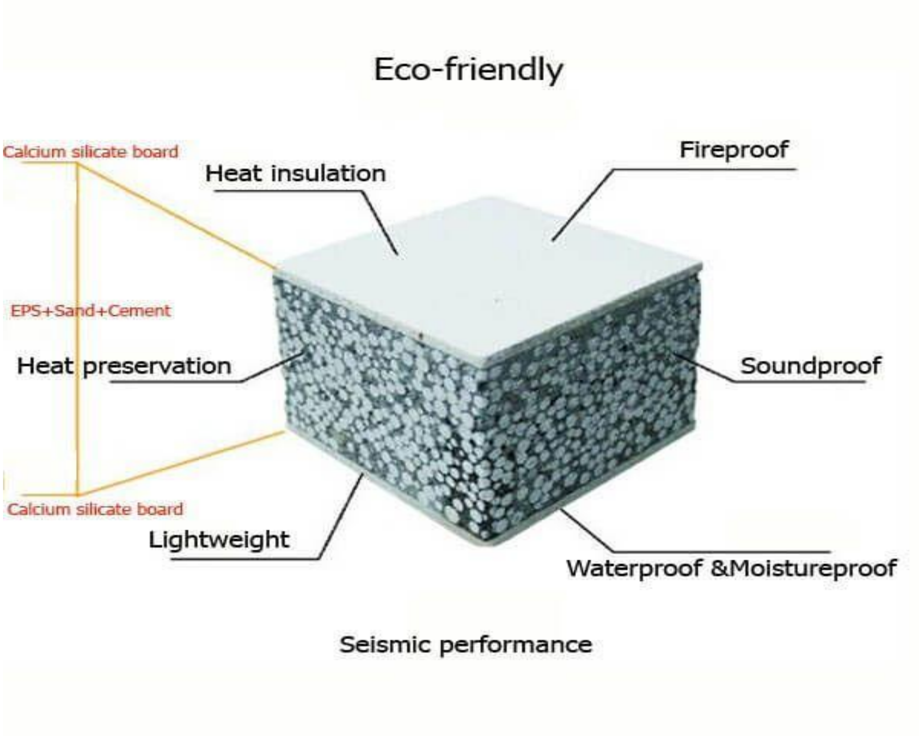
required density is produced.

- Foamed concrete can be produced with dry densities of 400 to 1600 kg/m³, with 7-day strengths

- **Cement for Foam Concrete -** Ordinary Portland cement is commonly used, but rapid hardening cement can also be used if necessary. Foam concrete can incorporate a wide range of cement and other combination, for example, 30 percent of cement, 60 percent of fly ash and limestone in 10 percent. The content of cement range from 300 to 400 kg/m3.

- **Sand for Foam Concrete -** The maximum size of sand used can be 5mm. Use of finer sands up to 2mm with amount passing through 600 micron sieve range from 60 to 95%.

- **Pozzolanas -** The supplementary cementitious materials like fly ash and ground granulated blast furnace slag have been used widely in the manufacture of foam concrete. The amount of fly ash used ranges from 30 to 70 percent. White GGBFS



range from 10 to 50%. This reduces the amount of cement used and economical.

Application of foam concrete are:

bridge approaches / embankments,

pipeline Abandonment / annular fill

trench backfill

cast-in-situ / cast-in-place walls

insulating compensation laying

insulation floor screeds

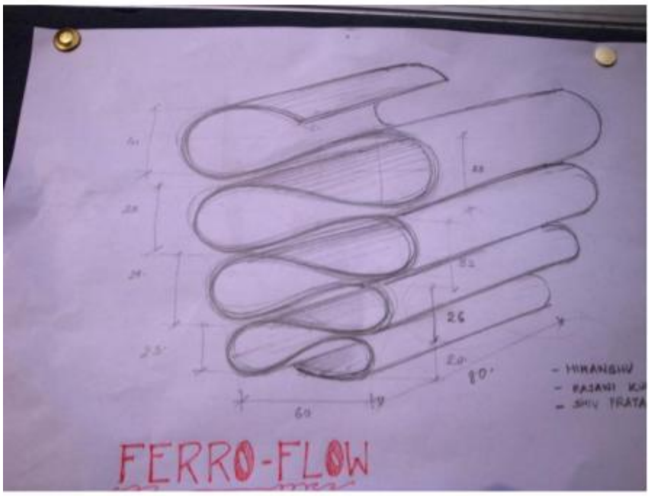
precast blocks

insulation roof screeds

precast wall elements / panels

Advantages of Foam Concrete

- The foam concrete mix does not settle. Hence it does not need any compaction
- The dead weight is reduced as it is light weight concrete
- The foamed concrete under its fresh state has freely flowing consistency. This property will help in completely filling the voids.
- The foam concrete structure has excellent load spreading and distributing capability
- Foamed Concrete Does not impose significant lateral loads
- The Water absorption property
- The foam concrete batches are easy to produce, so quality check and control are easily done
- The foam concrete has higher resistance to freezing and thawing
- Non-hazardous and faster work completion
- Cost effective, less maintenance



Disadvantages of Foam Concrete

- Presence of water in the mixed material make the foam concrete very sensitive
- Difficulty in finishing, Time of mixing longer
- With the increase in density, the compressive strength and flexural strength decreases.

1.5. Ferro-Cement

- Ferro cement is formed with wire meshes and cement mortar. It includes tightly spanned wire meshes which are permeated with strong cement mortar mix.

- The mortar produces the mass, the wire mesh passes on tensile strength and ductility to the material.

- The ferro cement has strong resistance capacity against cracking as well as extreme fatigue resistance, toughness and greater impenetrability.

- **Construction** -The desired shape may be built from a multi-layered construction of wire mesh, and if needed reinforced with steel wire or steel bars. Over this finished framework, an appropriate mixture of cement, sand and water is spread out. During hardening, the ferrocement is kept moist, to ensure the cement is able to set and harden. The wall thickness of ferrocement constructions lies in general between 10 and 30 mm. Like other cement based applications, ferro-cement takes necessary time to fully cure and reach its final strength.

Material needed

- Two material needed for construction of ferro-cement are cememtn mortar and reinforcements

Cement Mortar Mix

- Generally, portland cement and fine aggregate matrix are the main ingredients of ferrocement. The matrix comprises of approx 95% of the ferrocement and controls the behavior of the final product. The cement-sand ratio 1:2 to 1:3 with water cement ratio 0.4 to 0.45 remains in cement mortar.

- The fine aggregate adheres to grading zone II and zone III with particles exceeding 2.36 mm and lesser than um (micro meter) are ideal for ferrocement. The fine sand should not be utilized in ferrocement.

- Plasticizers and other admixtures are included to enhance the functionality, stability and strength as well as decrease permeability. Pozzolanas like fly ash can also be included up to 30% as substitute of cement to improve the stability.

Reinforcement

- Two types of reinforcements alias skeleton steel and wire mesh are applied in ferrocement.

Skeleton steel - It includes considerably large-diameter (approx 3 to 8 mm) bars spanned at 75 mm to 100 mm. It comes as tied-reinforcement or welded wire fabric. The skeleton frame is created with adherence to the geometry and shape of structure and useful for retaining the wire meshes in exact location and shape of the structure.

Wire mesh - The wire mesh comprises of galvanized wire of 0.5 to 1.5 mm diameter and 6 to 20 mm center to center gapping is provided. The wire meshes are created with the help of welding, twisting or weaving. The welded wire mesh may come in the shape of square or hexagonal openings. The mesh having square openings is better as compared to hexagonal wire mesh but it is expensive. Normally, the square woven meshes with 1.0 or 1.5 mm diameter wire spanned at 12 mm are recommended.

- The construction process is divided into the following 4 phases :-
- Fabrication of skeleton frame
- Setting of bars and mesh
- Use of mortar
- Curing
- The necessary number of layer of wire mesh are secured on both sides of the skeleton frame. A gapping of minimum 1 to 3 mm should be provide among two mesh layers. Mortar is used by hand or shotcreting. There is no formwork necessary for ferro-cement construction.

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Advantages of ferro cement

- The construction process is very easy
- It can be transformed into almost any shape for a wide range of uses
- Because of their small thickness, lesser dead weight is created on the element
- Near about 20% savings can be obtained on materials cost.
- Flexibility in cutting, drilling and jointing
- It has high tensile strength, Crack widths are also less with regard to traditional concrete
- It has good resistance capacity against fire

- It has strong waterproof capacity
- Maintenance cost is low

1.6. Fibre-Reinforced Concrete

- **Fiber-reinforced concrete** (FRC) is concrete containing fibrous material which increases its structural integrity. It contains short discrete fibers that are uniformly distributed and randomly oriented. Fibers include steel fibers, glass fibers, synthetic fibers and natural fibers – each of which lend varying properties to the concrete. In addition, the character of fiber-reinforced concrete changes with varying concretes, fiber materials, geometries, distribution, orientation, and densities.

- Fibers are usually used in concrete to control cracking due to plastic shrinkage and to drying shrinkage. They also reduce the permeability of concrete and thus reduce bleeding of water. Some types of fibers produce greater impact–, abrasion–, and shatter–resistance in concrete.
- Generally fibers do not increase the flexural strength of concrete, and so cannot replace moment–resisting or structural steel reinforcement. Indeed, some fibers actually reduce the strength of concrete.

Benefits of FRP

- Steel fibers can Improve structural strength
- Reduce steel reinforcement requirements
- Reduce crack widths and control the crack widths tightly, thus improving durability
- Improve impact– and abrasion–resistance
- Improve freeze-thaw resistance
- Blends of both steel and polymeric fibers are often used in construction projects in order to combine the benefits of both products; structural improvements provided by steel fibers

and the resistance to explosive spalling and plastic shrinkage improvements provided by polymeric fibers.

- In certain specific circumstances, steel fiber or macro synthetic fibers can entirely replace traditional steel reinforcement bar in reinforced concrete. This is most common in industrial flooring but also in some other pre-casting applications. Typically, these are corroborated with laboratory testing to confirm that performance requirements are met. Care should be taken to ensure that local design code requirements are also met, which may impose minimum quantities of steel reinforcement within the concrete. There are increasing numbers of tunnelling projects using precast lining segments reinforced only with steel fibers.

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SCHOOL OF BUILDING AND ENVIRONMENT

DEPARTMENT OF ARCHITECTURE

UNIT – III - Steel in Architectural Design – SAR1613

Innovations in Steel industry

1.1. Innovation in construction industry

1.1.1. Building envelope

- Development of novel, high-performance pre-treatment, primer and topcoat technologies for enhanced coating durability.

- Enhanced functionality for building envelopes. Technologies allowing rapid changes of colour or pattern within the same steel coil; improvements in envelope energy efficiency.

- Novel methods of rapidly identifying or predicting the properties of new metallic coating compositions.

- New and innovative steel-based insulation products or systems that allow thinner composite panels to be produced in a continuous manufacturing process.

1.1.2. Construction Structures

- Sustainable building design from cradle to cradle. Collaboration could focus on: efficient construction methods; reduction of energy consumption in building use; simplified de-mounting and re-use of structural steels.

- Generation of design solutions for extremes of loading (earthquakes, fire) and for highly corrosive environments.

- Creating the residential homes and neighbourhood of the future.

1.1.3. Digital Construction

- The construction industry is changing and is quickly moving to adopt digital tools, interoperable data, and automation as a means to drive efficiencies. Following are the key enablers for digitally capable construction products

  - Structured, accessible, managed, linked and interoperable data – manufacturers must be the Single Source of the Truth for their data.

  - Product marking – linking digital CAD components to physical products to enable Digital twins.

  - Interlinked databases – both internally (for product providence, pricing, etc.) and externally.

  - Digital Platform development – to enable component data to be utilised to drive wider systems.

1.1.4. Smart Products

- Steel manufacturers have started looking at incorporating IoT (e.g. sensors) technology in to or on to their products. These “Smart” products can provide several benefits:

- In-use performance monitoring – for example of the thermal performance of a building envelope panel over time.

- Building and environment monitoring for construction clients – for example monitoring temperature, humidity, water ingress, people movements, etc.

- Building security – CCTV cameras, motion, damage to the building can be monitored.

- By adding this capability, the steel products are enabled to be used in different ways. For example, by knowing how the product is performing over time and whether or not it has been damaged, it makes the concept of leasing products more feasible.

1.2. INSDAG

- INSDAG - Institute for Steel Development And Growth

- Please refer to the attached PDF – INSDAG Parameters

General Info -Steel INstag.pdf

1.3. Recycling Steel

- Why recycle steel? - Metals can be recycled repeatedly without altering their properties. Scrap metal has value, which motivates people to collect it for sale to recycling operations.

- Steel is 100% recyclable - According to the American Iron and Steel Institute (AISI), steel is the most recycled material on the planet. The other highly recycled metals include aluminum, copper, silver, brass, and gold.

- Advantages of Recycling

- The use of scrap steel saves up to 74% of the energy needed to make steel from virigin ore material

- Saves Energy and Reduces Pollution – recycling one tonne of steel cans saves:

– 1.5 tonnes of iron ore
– 0.5 tonnes of coke
– 1.28 tonnes of solid waste
– Reduces air emissions by 86%
– Reduces water pollution by 76%

1.3.1. Steel Recycling Process

.1. **Collection** - because of higher scrap value. As such, it is more likely to be sold to scrap yards

.2. **Sorting** - Sorting involves separating metals from the mixed multi-material waste stream. In automated recycling operations, scrappers may employ a magnet, as well as to observe the material color or weight to help determine the metal type. Scrappers will improve the value of their material by segregating clean metal from the dirty material.

.3. **Processing** - metals are shredded, to promote the melting process as small shredded metals have a large surface to volume ratio, as a result they can be melted using comparatively less energy

.4. **Melting** - Scrap metal is melted in a large furnace. Each metal is taken to a specific furnace designed to melt that particular metal. A considerable amount of energy is used in this step. (IMPORTANT: - the energy required to melt and recycle metals is much less than the energy that is needed to produce metals using virgin raw materials.)

.5. **Purification** - Purification is done to ensure the final product is of high quality and free of contaminants. One of the most common methods used for purification is Electrolysis.

.6. **Solidification** - After purification, melted metals are carried by the conveyor belt to cool and solidify the metals. In this stage, scrap metals are formed into specific shapes such as bars that can be easily used for the production of various metal products.

.7. **Transportation** - Once the metals are cooled and solidified, they are ready to use. They are then transported to various factories where they are used as raw material for the production of brand new products.

– When the products made of these metal bars come to the end of their useful life, the metal recycling process cycles again.

1.3.2. Collection for Recycling

– There are various collection process, few of the successful methods are as below

.1. Via magnetic extraction

.2. Via energy from waste (EFW) plants

.3. Via kerbside collection

.4. Via bring schemes

Magnetic extraction

- Magnetic recovery is the most efficient and cost effective way of extracting steel packaging from non-sorted domestic waste, achieving recovery rates of up to 55%.
- Thanks to its magnetic properties, steel is one of the easiest packaging materials to recover from the waste stream. Steel packaging can be automatically extracted from non-sorted refuse or separated from other recyclable materials using efficient and low cost magnets.
- The magnetic extraction technology can be used to recover steel cans from pulverization, baling and energy-from-waste plants.

Energy from waste (EFW) plants

- EFW plants in the UK handle more than 2 million tonnes of domestic waste each year!
- Conventional magnetic extraction technology at EFW plants recovers steel packaging present in the domestic waste stream after the incineration process.
- The recovery of the ferrous material is generally via a single pass suspended magnet - either an overband magnet or a drum magnet.

Kerbside collection

- Kerbside collection is becoming an increasingly common practice in many Local Authorities. Householders contribute to the scheme by putting their recyclate material into their kerbside boxes / sacks or wheelie bins as issued by the council.
- When the material is collected from the doorstep it can be sorted in two different locations. Some collection schemes sort their recyclate material at the kerbside. This is where the bags or boxes which are taken from the properties and sorted into different compartments onto the vehicle. The advantage of this method is that material is kept 'clean' and free from contaminants. The other method of sorting is for all the recyclate material which is collected at the kerbside to be taken to a MRF (Material Recycling Facility) central depot where operatives would separate the material.

Bring schemes

- Bring schemes are easy to use and provide opportunities to increase recycling levels for all cans.

- With can banks collecting steel cans right across the UK, 'bring' schemes continue to play an important role in the collection of steel drinks and food cans.
- A wide variety of can banks can be included in so-called 'milk-round' collection schemes: Hiab, FEL (front-end loader), REL (rear end loader), mini, modular and wheeled bins.
- The 14 cubic yard skip is a popular choice for bring schemes, as these large capacity banks are taken away to be emptied at a depot. To help minimize costs, an empty bank can be delivered and left on-site at the time of collecting a full skip for servicing, saving time and also reducing operational costs.

1.4. Manufacture and Assembly of Steel

https://www.youtube.com/watch?v=BvpmyOK6mx8

https://www.youtube.com/watch?v=l-0-W2AKPns

http://www.steel-insdag.org/TM_Contents.asp

1.5. Design Considerations

1.5.1. INTRODUCTION – DESIGN CONSIDERATIONS

The precise objectives of structural design vary from one project to another. In all cases, the avoidance of collapse is an important - if not the most important - requirement and an adequate factor of safety must be provided. In this context, the structure must be designed in order to fulfil both strength and stability requirements. These concepts are illustrated in Figure 1 in which a long thin rod is subject to tension (Figure 1a) and compression (Figure 1b). In the case of tension, the load resistance of the rod is governed by strength, that is the ability of the material to carry load without rupturing. The rod can only carry this load in compression if it remains stable, i.e. it does not deform significantly in a direction perpendicular to the line of action of the applied

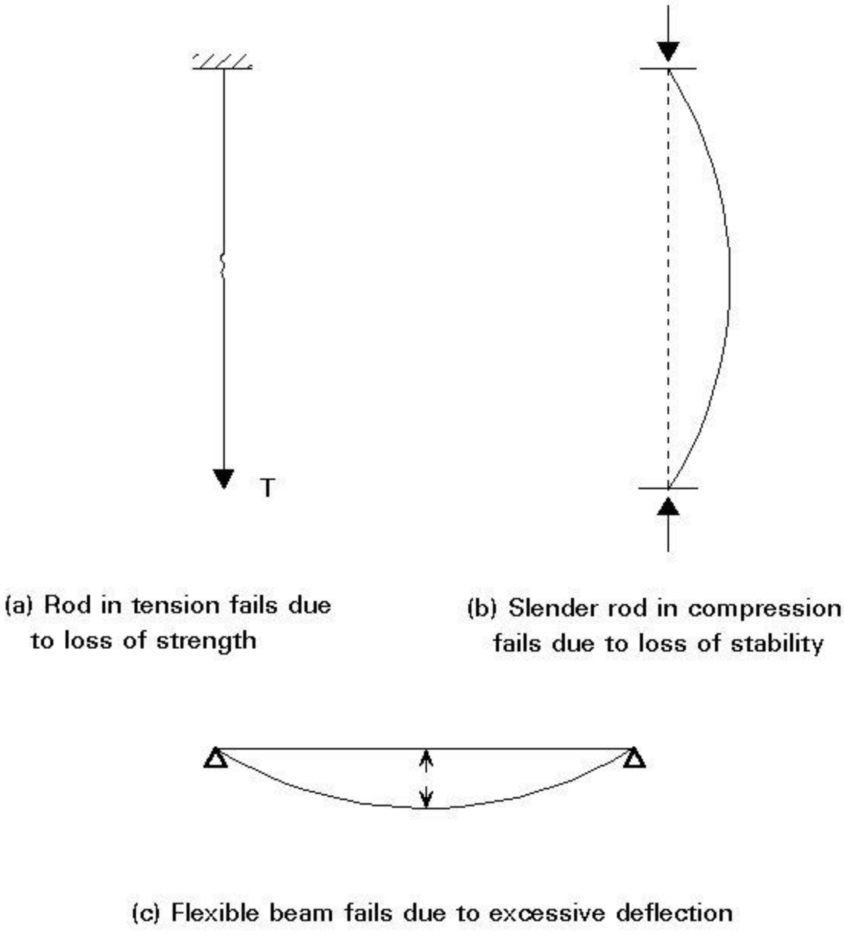


Figure 1 Failure modes

load. The stiffness of the structure is yet another important characteristic, concerned with resistance to deformation rather than collapse. This is particulary important in the case of beams whose deflection under a particular load is related to their stiffness (Figure 1c). Large deformations are not necessarily associated with collapse, and some brittle materials, such as glass, may rupture with little prior deformation. Other considerations may also need to be included in the design process. They include: quantifiable behaviour such as deformation, fatigue, fire resistance and dynamic behaviour; considerations such as corrosion and service accommodation which may influence both detail and overall concept, but in a more qualitative way; and appearance, which is largely a subjective judgement. In addition considerations of economy are likely to be a significant influence on the great majority of structural designs. In this context questions of speed and ease of construction, maintenance and running costs, as well as basic building costs, are all relevant. The relative importance of each of these aspects will vary depending on circumstances.

The approach to structural design is dealt with in Lecture 1B.1, which describes how the designer might begin to accommodate so many different requirements, many of which will exert conflicting pressures. In this lecture the focus is on how a satisfactory structural design can be achieved through a rational analysis of various aspects of the structure's performance. It is worth emphasising that the process of structural design can be considered as two groups of highly interrelated stages. The first group is concerned with defining the overall structural form - the type of structure, e.g. rigid frame or load bearing walls, the arrangement of structural elements (typically in terms of a structural grid), and the type of structural elements and material to be used, e.g. steel beams, columns and composite floor slabs. A high degree of creativity is required. The synthesis of a solution is developed on the basis of a broad understanding of a wide range of topics. The topics include structural and material behaviour, as well as a feel for the detailed implications of design decisions made at this stage - for instance recognising how deep a beam may need to be for a particular purpose. Formalised procedures are of little use at this stage. A satisfactory solution depends more on the creative ability of the designer.

The later stages are concerned with the more detailed sizing of structural components and the connections between them. By now the problem has become clearly defined and the process can become more formalised. In the case of steelwork the process generally involves selecting an appropriate standard section size, although in some circumstances the designer may wish to use a non-standard cross-section which, for execution, would then need to be made up, typically by welding plates or standard sections together into plate girders or trusses.

Design regulations are largely concerned with this stage of detailed element design. Their intention is to help ensure that buildings are designed and constructed to be safe and fit for purpose. Such design legislation can vary considerably in approach. It may be based simply on performance specification, giving the designer great flexibility as to how a satisfactory solution is achieved. An early example of this is the building laws published by King Hummarabi of Babylon in about 2200BC. They are preserved as a cuneiform inscription on a clay tablet and include such provisions as 'If a builder builds a house for a man and does not make its construction firm and if the house which he has built collapses and causes the death of the owner of the house, then that builder shall be put to death. If it causes the death of the son of the owner of the house, then a son of the builder shall be put to death. If it causes the death of a slave of the owner of the house, then the builder shall give the owner a slave of equal value'. The danger, and at the same time the attraction, of such an approach is that it depends heavily on the ability of the designer. Formal constraints, based on current wisdom, are not included and the engineer has the freedom to justify the design in any way.

The other extreme is a highly prescriptive set of design rules providing 'recipes' for satisfactory solutions. Since these can incorporate the results of previous experience gained over many years, supplemented by more recent research work they might appear to be more secure. However, such an approach cannot be applied to the conceptual stages of design and there are many cases where actual circumstances faced by the designer differ somewhat from those envisaged in the rules. There is also a psychological danger that such design rules assume an 'absolute' validity and a blind faith in the results of using the rules may be adopted.

Clearly there is a role for both the above approaches. Perhaps the best approach would be achieved by specifying satisfactory performance criteria to minimise the possibility of collapse or any other type of 'failure'. Engineers should then be given the freedom to achieve the criteria in a variety of ways, but also be provided with the benefit of available data to be used if appropriate. Perhaps the most important aspect is the attitude of the engineer which should be based on simple 'common sense' and include a healthy element of scepticism of the design rules themselves.

1.5.2. UNCERTAINTIES IN STRUCTURAL DESIGN

Simply quantifying the design process, using sophisticated analytical techniques and employing powerful computers does not eliminate the uncertainties associated with structural design, although it may reduce some of them.

These uncertainties include the following:

- loading.
- constitutive laws of the material.
- structural modelling.
- structural imperfections.

Loading is discussed in more detail in Lecture 1B.3. Although it is possible to quantify loads on a structure, it is important to recognise that in most cases these represent little more than an estimate of the likely maximum load intensity to which a structure will be exposed. Some loads, such as the self weight of the structure, may appear to be more easily defined than others, such as wind loads or gravity waves on offshore structures. However, there is a significant degree of uncertainty associated with all loads and this should always be recognised.

Constitutive laws are typically based on the results of tests carried out on small specimens. For convenience, the mathematical representation of the behaviour, for instance in the form of a stress-strain curve, is considered in a simplified form for the purpose of

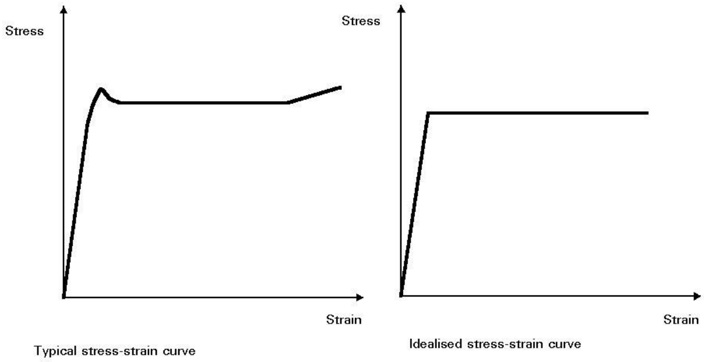


Figure 2 Mechanical properties of steel

structural design. In the case of steel the normal representation is linear elastic behaviour up to the yield point with plastic behaviour at higher strains (Figure 2). Although this representation provides a reasonable measure of the performance of the material, it is clearly not absolutely precise. Furthermore, any material will show a natural variability - two different samples taken from the same batch will typically fail at different stresses when tested. Compared with other materials, steel is remarkably consistent in this respect, but nevertheless variations exist and represent a further source of uncertainty.

Methods of analysing structural behaviour have advanced significantly in recent years, particularly as a result of developments in computing. Despite this, structural analysis is always based on some idealisation of the real behaviour. In some cases, such as isolated beams supported on simple bearings, the idealisation may be quite accurate. In other circumstances, however, the difference between the model and the real structure may be quite significant. One example of this is the truss which is typically assumed to have pinned joints, although the joints may in fact be quite rigid and some members may be continuous. The assumption that loadings are applied only at joint positions may be unrealistic. Whilst these simplifications may be adequate in modelling overall performance the implications, at least with regard to secondary effects, must be recognised.

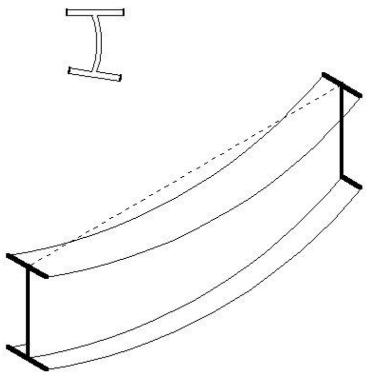


Figure 3 Geometric imperfections in cross-section and along the length of rolled sections (exaggerated)

Yet another source of uncertainty results from structural imperfections which are of two types: geometrical, i.e. out of straightness or lack of fit, and mechanical, i.e. residual stresses due to fabrication procedures or inhomogenities in the material properties. It is not possible to manufacture steel sections to absolute dimensions - wear on machinery and inevitable variations in the manufacturing process will lead to small variations which must be recognised. In the same way, although steel construction is carried out to much tighter tolerances than for most other structural materials, some variations (for instance in the alignment of individual members) will occur (Figure 3).

In adopting a quantified approach to structural design, all these uncertainties must be recognised, and taken into account. They are allowed for by the following means:

- specifying load levels which, based on previous experience, represent the worst conditions which might relate to a particular structural type.
- specifying a sampling procedure, a test plan and limits on material properties.
- specifying limits or tolerances for both manufacture and execution.
- using appropriate methods of analysis, whilst recognising the difference between real and idealised behaviour.

These measures do not eliminate the uncertainties but simply help to control them within defined bounds.

1.5.3. DESIGNING TO AVOID COLLAPSE

Historical Background

Structural design is not something which is new. Ever since man started building - dwellings, places of worship, bridges - some design philosophy has been followed, albeit often unconsciously. For many centuries the basis of design was simply to copy previous "designs". Where "new developments" or modifications were introduced, trial and error techniques were all that was available. As a result many structures were built, or partially built only to collapse or perform inadequately. Yet these failures did have a positive value in that they contributed to the fund of knowledge about what is workable and what is not.

This unscientific approach persisted for many centuries. Indeed it still forms part of the design approach adopted today. Rules of thumb and empirical design recommendations are frequently used, and these are largely based on previous experience. Nor is structural engineering today totally free of failures, despite the apparent sophistication of design methods and the power of computers. The dramatic box girder bridge collapses in the early 1970s were a grim reminder of what can happen if new developments are too far ahead of existing experience.

The emergence of new materials, notably cast and wrought iron, required a new approach and the development of more scientific methods. The new approach included testing, both of samples of the material and proof testing of structural components and assemblies. New concepts too were sometimes justified in this way, for instance in the case of the Forth Rail Bridge.

The first moves to rationalise structural design in a quantitative way came at the beginning of the 19th century with the development of elastic analysis. This type of analysis allowed engineers to determine the effect (on individual structural components) of forces applied to a complete structure.

Testing of materials provided information concerning strength and, in the case of iron and steel, other characteristics such as the elastic limit. Of course there were often great variations in the values measured, as indeed there are even today with some materials. In order to ensure a safe design, a lower bound on the test results - a value below which experimental data did not fall - was normally adopted as the 'strength'. Recognising some of the uncertainties associated with design methods based on calculation, stresses under maximum working load conditions were limited to a value equal to the elastic limit divided by a factor of safety. This factor of safety was specified in an apparently arbitrary fashion with values of 4 or 5 being quite typical.

This approach provided the basis of almost all structural design calculations until quite recently, and for some applications is still used today. As understanding of material behaviour has increased and safety factors have become more rationalised, so design strengths have changed. Changes in construction practice, and the development of new, higher strength materials, have necessitated detailed changes in design rules, particularly with regard to buckling behaviour. However the basic approach remained unchanged until quite recently when certain limitations in classical allowable-stress design became apparent. The limitations can be summarised as follows:

i. there is no recognition of the different levels of uncertainty associated with different types of load.

ii. different types of structure may have significantly different factors of safety in terms of collapse, and these differences do not appear in any quantifiable form.

iii. there is no recognition of the ductility and post-yield reserve of strength characteristic of structural steelwork.

The last of these limitations was overcome by the work of Baker [1] and his colleagues in the 1930s when plastic design was developed. This method was based upon ensuring a global factor of safety against collapse, allowing localised 'failure' with a redistribution of bending stresses. A comparison of elastic and plastic design is given by Beal [2].

In recognition of the disadvantages of the allowable stress design method, an alternative approach, known as limit state design has been adopted. Limit state design procedures have now become well established for most structural types and materials. The approach recognises the inevitable variability and uncertainty in quantifying structural performance, including the uncertainties of material characteristics and loading levels. Ideally, each uncertainty is typically treated in a similar manner using statistical techniques to identify typical or characteristic values and the degree of variation to be expected from this norm [3]. It is then possible to derive partial safety factors, one for each aspect of design uncertainty, which are consistent. Thus different load types, for instance, have different factors applied to them. The structure is then examined for a variety of limit states. In that case the structure is designed to fail under factored loading conditions, giving a clearer picture of the margins of safety than was previously the case with allowable stress design.

Stability

Inadequate strength is not the only cause of collapse. In particular the designer must ensure adequate stability, both of the complete structure (a function of the overall structural form) and of each part of it (dependent on individual member proportions and materials). The latter is generally dealt with by modifying the material strength to account for individual conditions. Overall stability is very much more difficult to quantify and must be carefully considered at the earliest stage of structural design. In this sense structural stability can be defined by the conditions that a structure will neither collapse (completely or partially) due to minor changes, for instance in its form, condition or normal

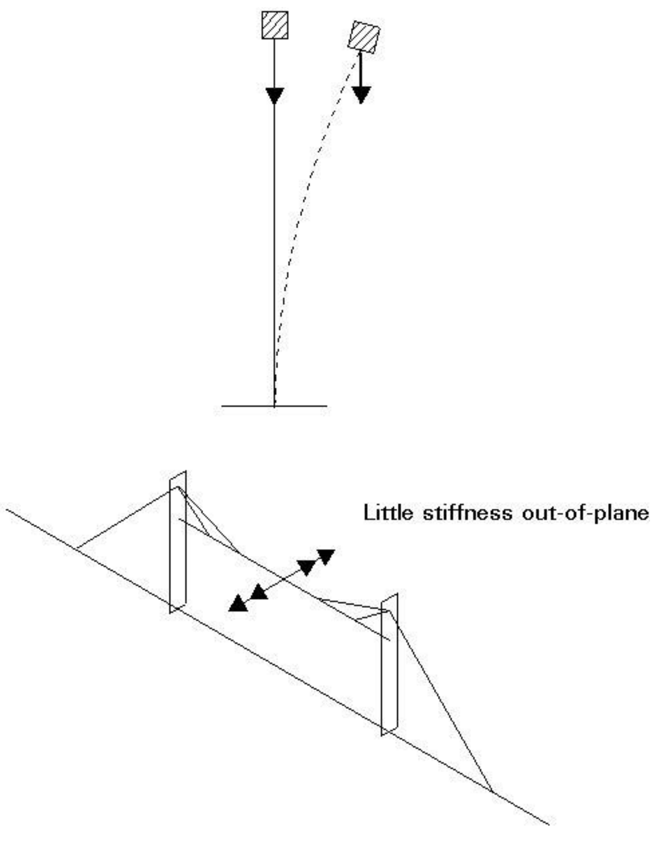


Figure 4 Examples of structural arrangements which are potentially unstable

loading, nor be unduly sensitive to accidental actions. Some examples are shown in Figure 4.

In designing for stability the positioning of the main load-bearing elements should provide a clearly defined path for transmitting loads, including wind and seismic actions to the foundations. In considering wind loads on buildings it is important to provide bracing in two orthogonal vertical planes, distributed in such a way as to avoid undue torsional effects, and to recognise the role of the floor structure in transmitting wind loads to these braced areas (Figure 5). The bracing can be provided in a variety of ways, for instance by cross-bracing elements or rigid frame action.

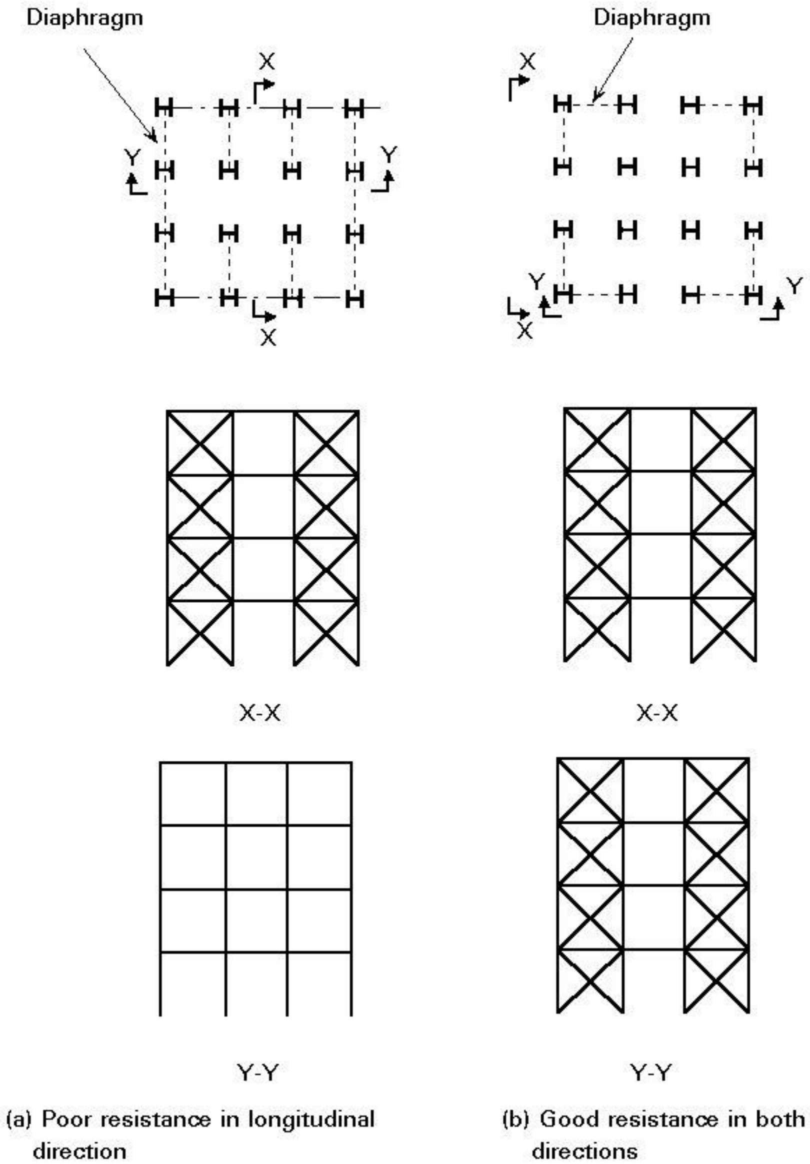


Figure 5 Sway stability

Consideration of accidental actions, such as explosions or impact, is more difficult, but the principle is to limit the extent of any damage caused. Limitation of damage can be achieved by designing for very high loads (not generally appropriate) or providing multiple load paths. Design requires consideration of local damage rendering individual elements of the structure ineffective, and ensuring the remaining structure is able to carry the new distribution of loads, albeit at a lower factor of safety. Alternative strategies are to provide for dissipation of accidental actions, for instance by venting explosions, and to protect the structure, for instance by installing bollards to prevent vehicle impact on columns (Figure 6).

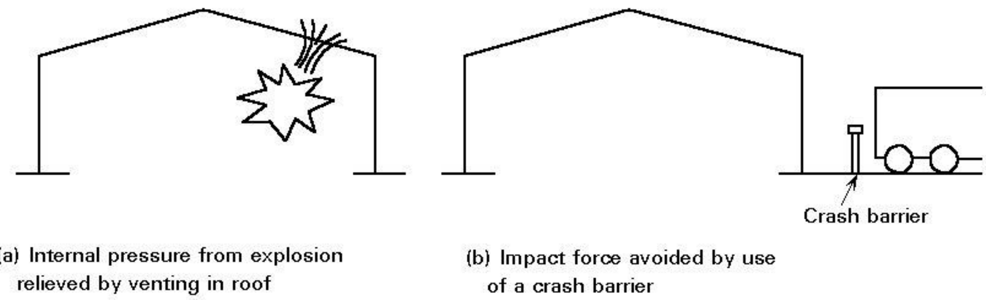


Figure 6 Alternative strategies for dealing with accidental actions

Structural stability must of course be ensured when alterations are to be carried out to existing structures. In all cases stability during execution must be very carefully considered.

Robustness

In many ways robustness is associated with stability. Construction forms which fulfil the primary function of accommodating normal loading conditions - which are highly idealised for design purposes - may not perform a secondary function when the structure is subject to real loading conditions. For instance the floor of a building is normally expected to transmit wind loads in the horizontal plane to the braced positions. Transmission of wind loads can only be achieved if there is adequate connection between the floor and other parts of the structure and building fabric, and the floor itself is of a suitable form of construction.

OTHER DESIGN OBJECTIVES

Although design against collapse is a principal consideration for the structural engineer, there are many other aspects of performance which must be considered. None of these aspects can be quantified and only certain ones will normally apply. However, for a successful solution, the designer must decide which considerations can be ignored, what the most important criteria are in developing the design, and which can be checked simply to ensure satisfactory performance.

4.1 Deformation

The deflection characteristics of a structure are concerned with stiffness rather than strength. Excessive deflections may cause a number of undesirable effects. They include damage to finishes, (particularly where brittle materials such as glass or plaster are used), ponding of water on flat roofs (which can lead to leaks and even collapse in extreme cases), visual alarm to users and, in extreme cases, changes in the structural behaviour which are sufficient to cause collapse. Perhaps the most common example of deflection effects occurs in columns, which are designed for largely compressive loads but may become subject to significant bending effects when the column deforms in a horizontal plane - the so called P-delta effect.

The normal approach in design is to check that calculated deflections do not exceed allowable levels, which are dependent upon structural type and finishes used. For instance, deflection limits for roof structures are not normally as severe as those for floor structures. In performing these checks it is important to recognise that the total deflection δ_{max} consists of various components, as shown in
Figure 7, namely:

$\delta_{max} = \delta_1 + \delta_2 - \delta_0$

where δ_1 is the deflection due to permanent loads

δ_2 is the deflection due to variable loads

δ_0 is the precamber (if any) of the beam in the unloaded state.

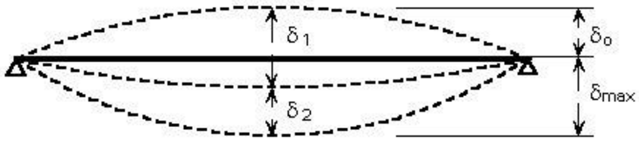


Figure 7 Components of deflection to be considered

In controlling deflections it is often necessary to consider both δ_{max} and δ_2, with more severe limits applying in the latter case.

Although the calculated deflections do not necessarily provide an accurate prediction of likely values, they do give a measure of the stiffness of the structure. They are therefore a reasonable guide to structural performance in this respect. With the trend towards longer spans and higher strength materials, design for deflection has become more important in recent years. In many cases this consideration dictates the size of structural elements rather than their resistance. In the case of certain structures, deflection control is of paramount importance. Examples include structures supporting overhead cranes and those housing sensitive equipment. Design for deflection is likely to be the critical condition in such cases.

4.2 Vibration

The vibration characteristics of a structure are, like deflection behaviour, dependent upon stiffness rather than strength. The design principle is to adopt a solution for which the natural frequency of vibration is sufficiently different from any source of excitation, such as machines, to avoid resonance. Longer spans, lighter structures and a reduction in the mass and stiffness of partitions and cladding have all contributed to a general lowering of the natural frequencies for building structures. Cases of human discomfort have been recorded and Eurocode 3 [4] now requires a minimum natural frequency of 3 cycles per second for floors in normal use and 5 cycles per second for dance floors.

Wind excited oscillations may also need to be considered for unusually flexible structures such as very slender, tall buildings, long-span bridges, large roofs, and unusually flexible elements such as light tie rods. These flexible structures should be investigated under dynamic wind loads for vibrations both in-plane and normal to the wind direction, and be examined for gust and vortex induced vibrations. The dynamic characteristics of the structure may be the principal design criterion in such cases.

4.3 Fire Resistance

The provision for safety in the event of fire is dealt with in Group 4B. It is a common requirement that structural integrity is maintained for a specified period to allow building occupants to escape and fire-fighting to be carried out without the danger of structural collapse. For steel structures alternative design strategies can be adopted to achieve this requirement. The traditional approach has been to complete the structural design 'cold' and to provide some form of insulation to the steelwork. This approach can give an expensive solution and alternative methods have now been developed, allowing reductions, and in some cases complete elimination, of fire protection. In order to implement these alternatives in an effective manner, it is important that, at an early stage in the design process, the structural design considers how the fire resistance of the steelwork is to be achieved. Adopting a design solution which may be relatively inefficient in terms of the weight of steel for normal conditions may be more than offset by savings in fire protection (Figure 8).

Buildings close to a site boundary may require special consideration to prevent an outbreak of fire spreading to adjacent sites due to structural collapse. Again quantitative design procedures have been developed for such circumstances [5].

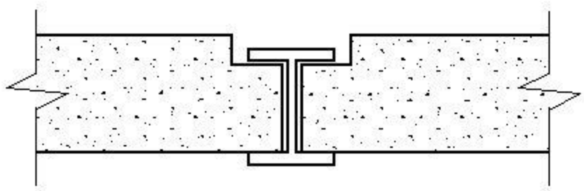


Figure 8 'Slimfloor' beams provide effective fire resistance to unprotected steel beams

4.4 Fatigue

Where structures, or individual structural elements, are subject to significant fluctuations in stress, fatigue failure can occur after a number of loading cycles at stress levels well below the normal static resistance. The principal factors affecting fatigue behaviour are the range of stresses experienced, the number of cycles of loading and the environment. Structures which need particular consideration in this respect are crane gantry girders, road and rail bridges, and structures subject to repeated cycles from vibrating machinery or wind-induced oscillations. Design guidance is included in Eurocode 3 [4].

4.5 Execution

One of the principal advantages of steelwork is the speed with which execution can proceed. In order to maximise this advantage it may be necessary to adopt a structurally less efficient solution, for instance by using the same profile for all members in a floor construction, even though some floor beams are less highly loaded than others (Figure 9). Temporary propping

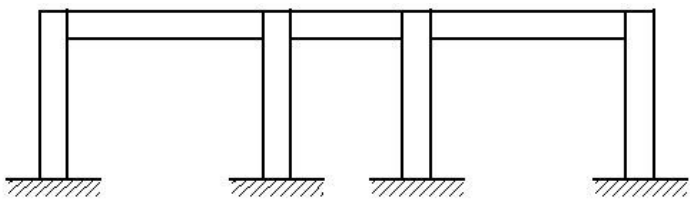


Figure 9 Adopting the same profile for all the members in a floor may be inefficient in material usage, but results in economy of construction

should be avoided as must late changes in detail which might affect fabrication.

It is important that the structure is not considered in isolation, but rather treated as one part of the complete construction, along with services, cladding and finishes. By adopting a co-ordinated approach to the design, integrating the parts and eliminating or reducing wet trades, speed of execution of the project as a whole can be maximised. A good example of this is the two-way continuous grillage system used for the BMW Headquarters at Bracknell and other projects [6].

The installation of services can have significant implications for speed, cost and detail of construction. In buildings with major service requirements, the cost of the services can be considerably greater than the cost of the structure. In such circumstances it may well be better to sacrifice structural efficiency for ease of accommodating the services. The design of the total floor zone including finishes, structure, fire protection and services also has implications for other aspects of the building construction. The greater the depth of floor construction, the greater the overall height of the building and hence the quantity of external cladding required. In many commercial developments very sophisticated and expensive cladding systems are used. Savings in cladding systems may more than offset the use of shallower, but less efficient, floor construction. Where there is strict planning control of overall building height, it may even be possible to accommodate additional storeys in this way.

4.6 Maintenance

All structures should be inspected and maintained on a regular basis, although some conditions are likely to be more demanding in this respect. For instance, steelwork within a dry, heated interior environment should not suffer from corrosion, whilst a bridge structure in a coastal area will need rigorous maintenance schedules. Some structural forms are easier to maintain than others, and where exposure conditions are severe, ease of inspection and maintenance should be an important criterion. Principal objectives in this context are the avoidance of inaccessible parts, dirt and moisture traps, and the use of rolled or tubular individual sections in preference to truss-like assemblies composed of smaller sections.

DESIGN RESPONSIBILITIES

One engineer should be responsible for ensuring that the design and details of all components are compatible and comply with the overall design requirements. This responsibility is most important when different designers or organisations are responsible for individual parts of the structure, such as foundations, superstructure and cladding. It should include an appraisal of the working drawings and other documents to establish, inter alia, that requirements for stability have been incorporated in all elements, and that they can be met during the execution stage.

Effective communication both within the design team and between the designer and constructor before and during execution is essential. Good communication will help to avoid potential design conflicts, for instance when services have to penetrate the structure, and also to promote safe completion of the structure in accordance with the drawings and specification. The constructor may also require information concerning results of site surveys and soil investigations, design loadings, load resistance of members, limits on positions of construction joints, and lifting positions on members to be erected as single pieces. A statement accompanied by sketches detailing any special requirements should be prepared when necessary, e.g. for any unusual design or for any particularly sensitive aspects of the structure or construction. This statement should be made available to the contractor for appropriate action regarding temporary works and execution procedures.

The designer should be made aware of the proposed construction methods, erection procedures, use of plant, and temporary works. The execution programme and sequence of erection should be agreed between the designer and constructor.

Full and effective communication between all parties involved will help not only to promote safe and efficient execution but may also improve design concepts and details. Design should not be seen as an end in itself, but rather as an important part of any construction project.

CONCLUDING SUMMARY

- There are very many uncertainties associated with structural design. However powerful the tools available, the engineer should always recognise that the design model is no more than an idealisation and simplification of the real condition.
- A quantified approach to structural design can take different forms with a view to providing a framework for satisfactory solutions. The application of design rules should be tempered with common sense and understanding.
- Structural design must consider many aspects of both performance and cost. The most efficient structural solution may not result in the most efficient solution overall if other interdependent aspects of the construction are not considered in a co-ordinated fashion.

1.6. FABRICATION & ASSEMBLY

The fabricator's role is to convert rolled steel into finished goods with added value. This is achieved by selling workmanship and machine utilisation on a competitive basis where costs are directly related to time.

Fabricators rely increasingly upon production engineering techniques. Their continued success in this direction depends upon better standardisation. Time and therefore labour costs can be cut significantly by the repetition of dimensions and geometry, member sizes and shapes, centres and diameters of bolts, etc. All of these are amenable to rationalisation. Further economy is derived by reducing the number of detailed components, which tend to be labour intensive to produce, even when this results in heavier parent members. The cardinal rule is that, relatively, labour is expensive but material is cheap (Figure 1).

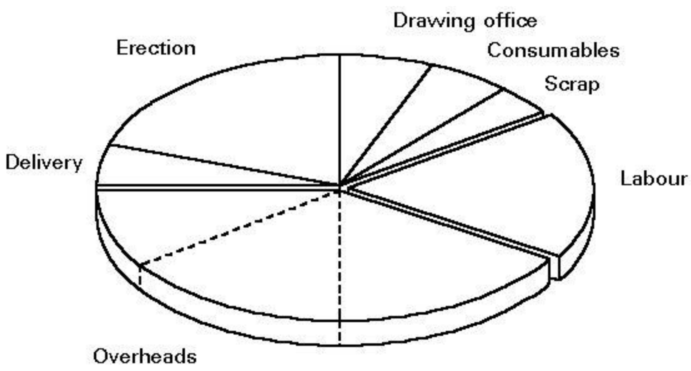


Figure 1 Fabricator's costs for steelwork for light / medium buildings.

COST STRUCTURE

Fabrication costs are estimated by separating the various activities into categories such as cutting, drilling and welding which enables man hours to be allocated and valued to arrive at a total price.

Relying upon a combination of historical data and practical experience, the cost build-up bears little relationship to the weight of steel involved, although cost references in ECU/tonne can be a useful index for rapid comparison of different classes of work.

A typical breakdown in costs, in the light to medium category, shows that over 50% of the fabricator's cost is absorbed by labour charges and overhead expenses (Figure 1).

It is customary to recover such expenses as a contributory factor to labour. If the ratio between labour and overheads is 1: 2½, it is significant that for every 100 ECU of labour cost incurred, the amount chargeable would be 100+250=350ECU.

PRODUCTION NETWORK

Fabricating companies differ widely in layout, capacity and scope. Whilst the extent and nature of the services available is influenced by policy and resources, the basic flow of activities tends to follow a similar pattern. This can be visualised as a tunnel for the main flow or Primary Operations, supported by branches or Secondary Operations (Figure 2).

This network forms the basis for production control, which is time related to cost standards. Output must be geared to the sequence of the construction programme. This rarely coincides with the most effective use of all resources. The system has to be extremely flexible to respond to changes in demand whilst minimising disruption or costly delays.

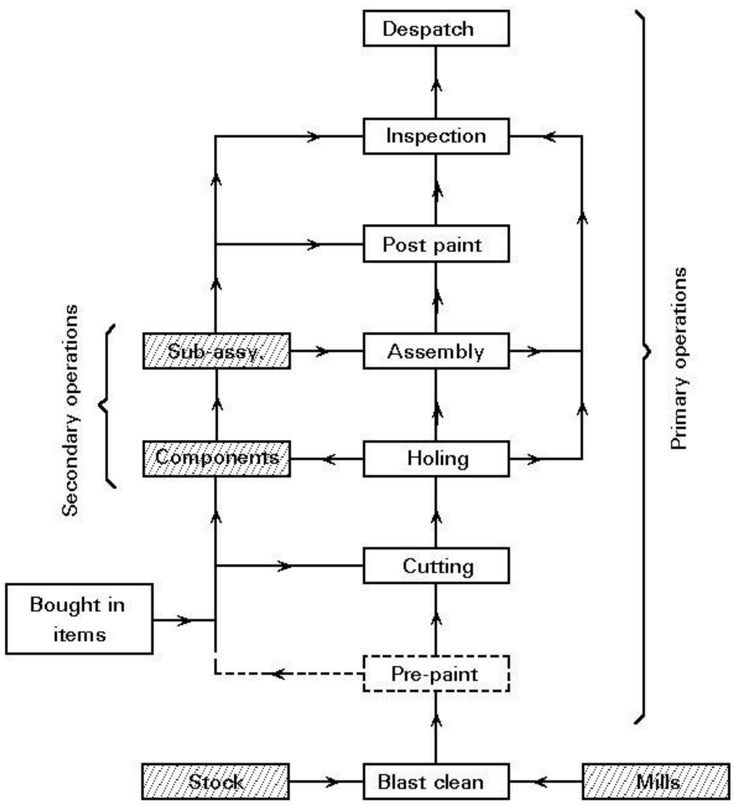


Figure 2 Production network

Primary / Secondary Production

The planning objective is to schedule production so that raw material is transformed into a finished state within an allocated time.

Since most of the important machine tools, such as saws, are sited at the start of the primary production line, the flow of material has to be sustained by an independent supply of essential components such as brackets, cleats and plates in the correct quantities and in the correct order.

This is the task of secondary production together with sub-assembly of detailed fabrications in suitable cases. Bought-in (BI) items or services of a specialised nature such as forgings, pressings or even non-destructive testing have to be available at the correct time.

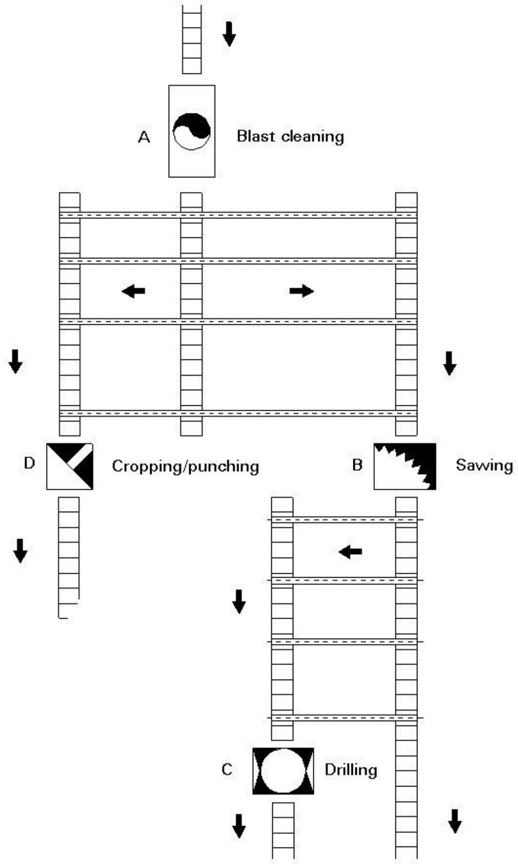


Figure 3 Typical workshop layout

Workshop Layout - Material Preparation

Steel framed buildings are mainly constructed as a series of linear elements using standard sections. The preparation area for these is typified by a group of fixed work sections consisting of (Figure 3):

A. Blast cleaning

B. Sawing

C. Drilling

D. Cropping/Punching

The initial step is to pass the steel through a blast cleaning cabinet at "A" to remove any surface rust and mill scale. Various levels of surface treatment are available, but for most buildings, a standard of SA 2½ to the Swedish specification SIS 055900 is adequate. This requires at least 95% of the surface to be clean.

The next stage is to transfer the material to the sawing station at "B" for cutting to length followed by drilling of holes at "C". In a number of workshops, sawing and simultaneous 3 axis drilling may be combined as one activity. Alternatively, angle sections and flats of suitable thickness for cropping and punching would be routed directly to "D".

For speed and ease of handling, sections are transported increasingly by a system of powered conveyors fed by cross transfers. The latest automation now allows all operations and material flow to be conducted from a central numerically controlled console.

Because plates are less stiff, these tend to be more awkward to handle. Lifting and handling is usually carried out by an overhead magnetic crane for subsequent cutting by flame or guillotine in a separate plate working area.

Workshop Layout – Assembly / Finishing

At this stage the main elements on the primary flow are joined by secondary components, end plates, stiffeners, etc. for fitting and assembly, mostly by welding. Depending upon the nature and purpose of the structure, some bolting may be used, if only for trial alignment. However, as a general rule, shop connections are welded and site connections bolted.

Due to variations in the size and nature of the work carried out in any period, the assembly area has to be extremely flexible and well serviced by cranes. Output must be geared to the sequence of the construction programme. As a result designated areas may have to be switched rapidly from beams and columns to bulky lattice girders.

Further planning complications arise because the most cost effective use of workshop labour and equipment rarely coincides with site requirements. It is for this reason that seemingly simple modifications are costly to execute once production has commenced.

Where priming paint is required, elaborate specifications, which are not necessary for steelwork contained within a normal building environment, can easily add 20% to fabrication costs. The function and future maintenance requirements should be considered in each case, rather than adopting a blanket philosophy.

Paint coatings for structural steelwork should "flash off" fairly rapidly to allow further handling and to minimise congestion. Whilst brushing is suitable for touching up minor damage, large surfaces can only be covered economically by spraying. Spraying can be carried out manually or automatically where the work is conveyed through an enclosed cabinet containing the spray nozzles. The process may also be supplemented by a drying kiln.

After assembly, inspection concentrates mainly upon overall dimensions, position of cleats, holes and so on, to ensure proper alignment during site erection. Framed elements, such as latticed girders, are self checking to a certain extent by virtue of the fit of members during assembly. This principle is often used to prove complex structures by trial erection prior to despatch.

Where in-depth weld examination is required, it should be conducted at the appropriate stage determined by the nature of the work, and to the level specified by the Engineer. In the interests of economy however, it should be noted that radiographic and allied techniques are, not only expensive operations, but attract additional costs due to their disruptive influence upon production. Judgement should be exercised to confine the programme of examination to those areas critical to structural performance.

The aim of inspection is to ensure that the steelwork complies with the contract documents. For the majority of building structures the inspection pattern outlined is practical and economic. Where more precise tolerances or accuracy are required, the frequency and intensity of inspection may need to be higher. For this reason inspection procedures need to be clearly identified in the tender documents so that appropriate provisions may be made by the fabricator.

Following an itemised numerical check together with application of identification marks, the steelwork is transferred to the finished stockyard unless it is due for immediate transport. There it is stacked ready for consignment, together with any loose fittings wired together and attached to the parent member.

Transport operating costs are not based upon load factor. A vehicle loaded to a fraction of its rated capacity will cost exactly the same as one which is fully laden. Framed elements occupy considerable space but it may be possible to mitigate the consequences by the number and disposition of splices.

In addition to the site programme, due regard must be given to limitations of off-loading and handling facilities, to access restricted to particular timings, to clearance under low bridges, and to police authority requirements concerning the transport of wide loads.

GENERAL - ERECTION

Whilst steelwork erection may be regarded as the final stage of fabrication, it differs from the latter in two principal ways: firstly, there is the added dimension of height and the time occupied by vertical movement of materials, equipment and labour; secondly, the fact that work has to be carried out in the open means that progress may be hampered by adverse weather.

By its nature, work done on site can become unduly expensive. The primary aim of the programme should be to minimise costs by condensing the time scale realistically. Options and alternatives need to be carefully examined at the preliminary design stage otherwise the scope for reducing the time scale may be unduly restricted.

Clearly the significance of the various issues will vary according to the type of building and any limitations which the site and its environment may impose. Even when structures possess marked similarities, different erection methods and procedures may need to be adopted. For this reason, only the broad principles concerning erection can be stated.

5.1 Site Planning

Invariably, erection of structural steelwork has to be closely integrated with other major trades such as flooring, cladding and services. Operations on site where there may be competition for limited resources, are potentially difficult to control. A far-sighted strategy has to be developed and maintained.

Key objectives and, most importantly, starting and finishing dates must be clearly established and progress reviewed on a regular basis. Failure to meet commitments can result in substantial cost penalties. Further complications may easily arise which are totally disproportionate to the cause.

5.2 Site Organisation

The maximum size and weight of the various steel members which can be delivered may be restricted on a site with limited and restricted access.

Narrow streets in a busy town centre may cause difficulties with space to manoeuvre. Waiting time to off-load may also be restricted to specific periods. Matters of this kind must be investigated well in advance and decisions made accordingly.

Within site, movement may often be hampered by a variety of obstructions such as scaffolding, shoring, pile caps, excavation, and so on. Service roads and off-loading areas need to be hard cored and adequately drained to support heavy vehicles during the severest winter conditions. The steelwork has to be erected in the general sequence determined by the construction programme. Each consignment of steel has to be strictly regulated to this timetable. Whilst in some instances, a few key components can be lifted directly from the vehicle into position, most of the material will need to be off-loaded and stacked temporarily until needed.

The area of the site allocated for this purpose has to be orderly and well managed, particularly where space is limited. To compensate for minor interruptions in delivery, for example due to traffic delays, a small buffer stock is usually held in reserve.

Space is also required for laying material out and for assembly of frames or girders prior to hoisting into position.

5.3 Setting Out

Before commencement of erection, the plan position and level of the column bases should be verified by the erection contractor. This needs to be carried out as soon as possible to ensure that any errors can be corrected in good time or, at least, alternative measures approved and introduced.

Checks should include not only the centres of the foundation bolts relative to the reference grid lines, but also the projection of the bolts above the base level.

To compensate for minor discrepancies, a limited amount of deviation of the column from its true vertical and horizontal position is provided for by the grout space under the baseplate and by leaving a movement pocket around each bolt during pouring of the concrete. Normally this will allow latitude of about ±25mm in any direction.

5.4 Operations

Steel erection may appear to be a series of distinct operations when in reality they overlap and merge. Nevertheless, each complete stage of the work has to follow a methodical routine which consists of:

- Hoisting
- Temporary Connections
- Plumbing, lining and levelling
- Permanent connections.

Because minor dimensional inaccuracies can accumulate during fabrication and setting out, it would be impractical to complete the entire structure before compensating for these by adjustment. The work is therefore sub-divided into a number of phases which may be controlled by shape or simply by an appropriate number of bays or storeys. For stability, each phase relies upon some form of restraint to create a local box effect. This effect may be achieved in various ways, such as employment of temporary or permanent diagonal bracing.

Initially, end connections and base anchorages are only secured temporarily. After completion of plumbing, lining and levelling, all connections are then made permanent by tightening up all nuts or inserting any bolts initially omitted to assist adjustment. This process allows substantial areas to be released quickly for grouting and following trades are able to proceed much earlier than would otherwise be possible.

5.5 Single-Storey Buildings

Under normal circumstances, single-storey buildings are quickly and easily erected. A high proportion of industrial buildings are rigid jointed. It is common practice to bolt, assemble or weld these joints on the ground and then lift the complete frame upright using a mobile crane.

Lattice girders and trusses are also erected in a similar manner but temporary stiffening may be required to prevent lateral buckling. Care should also be taken, by provision of lifting eyes or similar at specific positions, to ensure that slender members are not subjected to undue compressive stresses.

Ideally, erection should commence at an end which is permanently braced. When this is not possible, temporary bracings should be provided at regular intervals as a safeguard against collapse or deformation (Figure 7).

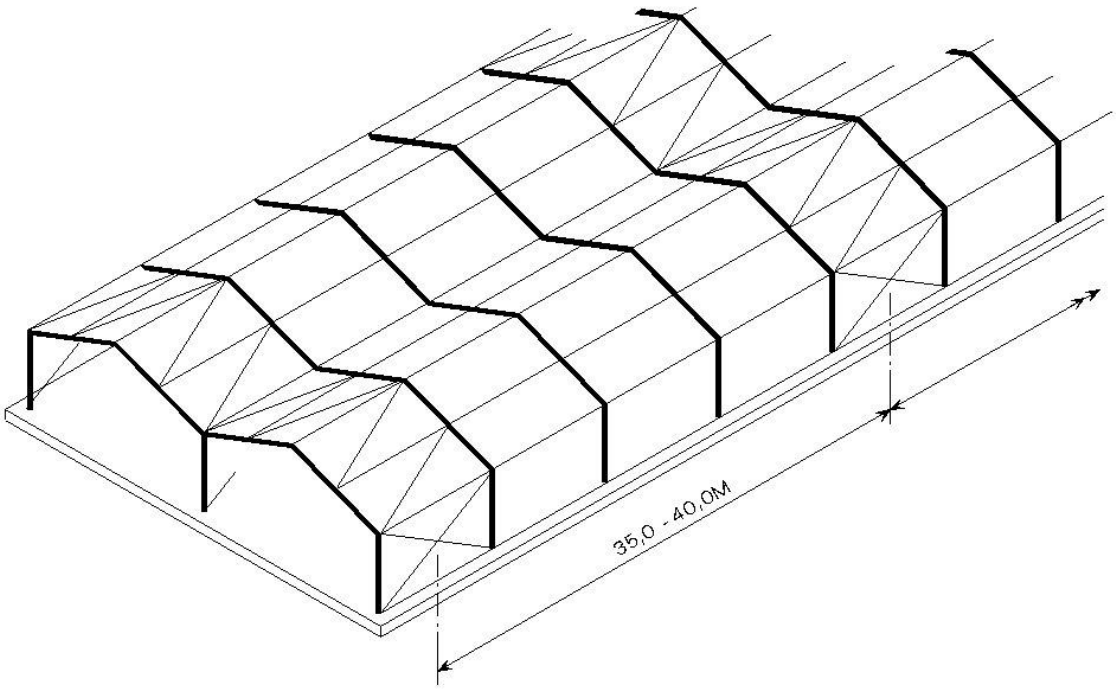


Figure 7 Single storey building

Space frames are designed to span in two directions. Because of the number of connections required, it is much more economical to assemble the modules at ground level where the joints are readily accessible and then hoist the complete framework. Two or possibly four cranes may be needed depending on the size of the building. Meticulous co-ordination is essential.

5.6 Multi-storey Buildings

In most cases, multi-storey buildings are erected storey by storey enabling the lower floors to be completed earlier, offering access, overhead safety and weather protection. Depending upon the site, a single tower crane may be the sole lifting facility. In this case use of the crane has to be shared between a number of sub-contractors, thereby limiting available "hook" time for any given trade.

Since the position of a tower crane is fixed (Figure 8), it is completely independent of any obstructions, such as basements or ground slabs, which could deny access to a mobile crane. This independence allows useful freedom in overall planning. However, the fixed location also means a fixed arc of lifting capacity where the load will be minimum at the greatest reach. As a result the steelwork may have to be provided with site splices simply to keep the weight of the components within such limits.

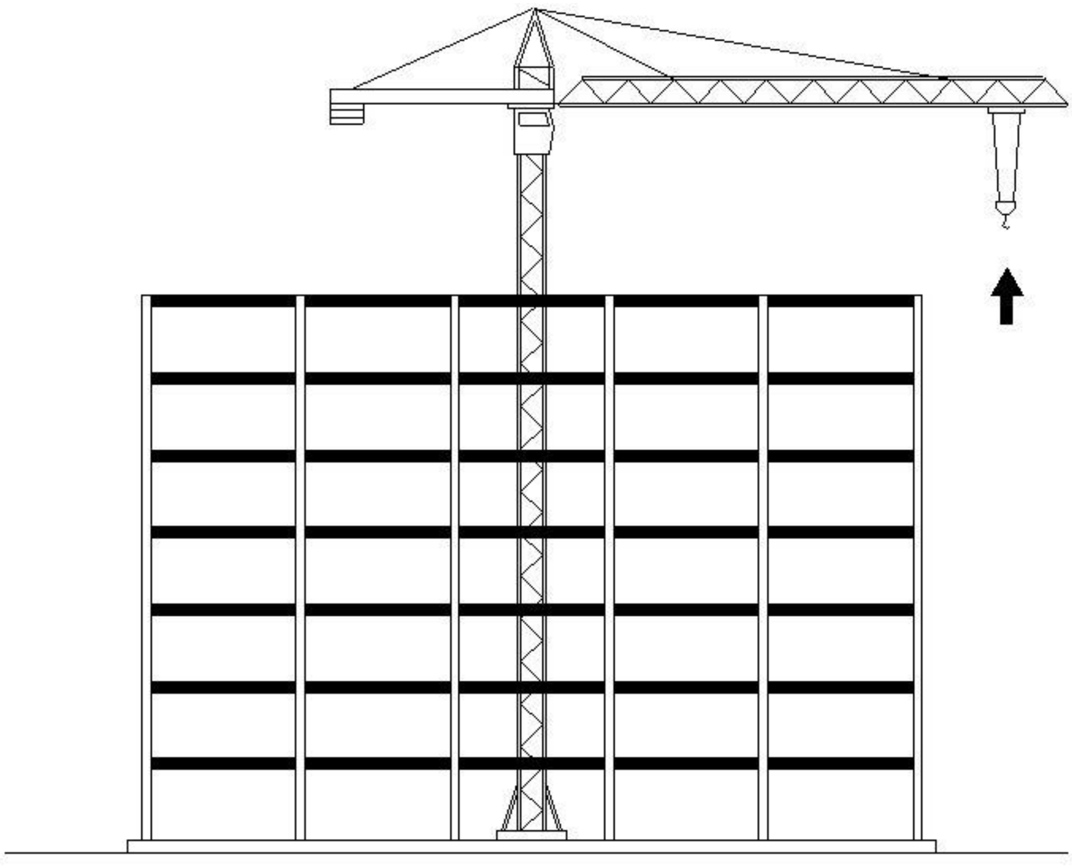


Figure 8 Multi-storey building erected by tower crane

One of the major virtues of a mobile crane (Figure 9) is its flexibility and independence which enables it to keep moving with the flow of the work. These cranes are generally fitted with telescopic jibs which allow then to become operational very quickly. The vehicles are stabilised during lifting by extended outriggers equipped with levelling jacks.

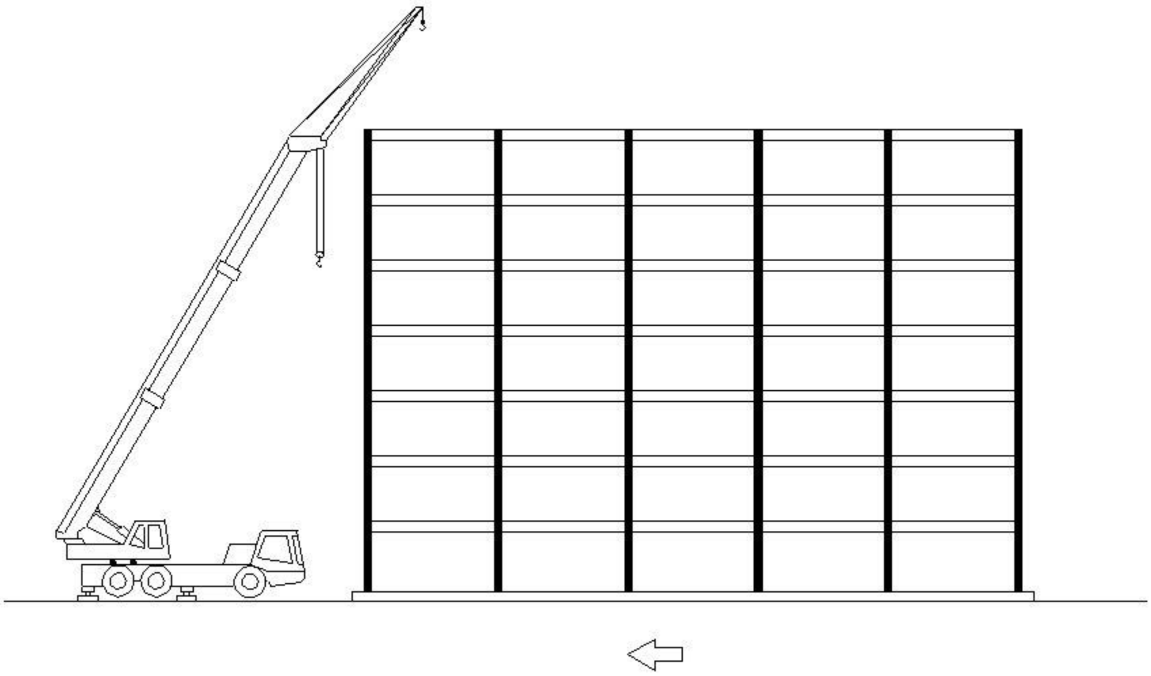


Figure 9 Multi-storey building erected by mobile crane

Whilst permanent stability in the completed building may be introduced, in a number of ways, including braced bays, rigid joints and stiff service cores (Figure 10) and via diaphragm action of the floors, stability must also be ensured throughout the entire construction programme. It may therefore be necessary to install temporary bracings solely for this purpose, which must not be removed until the permanent system has been provided and has become effective.

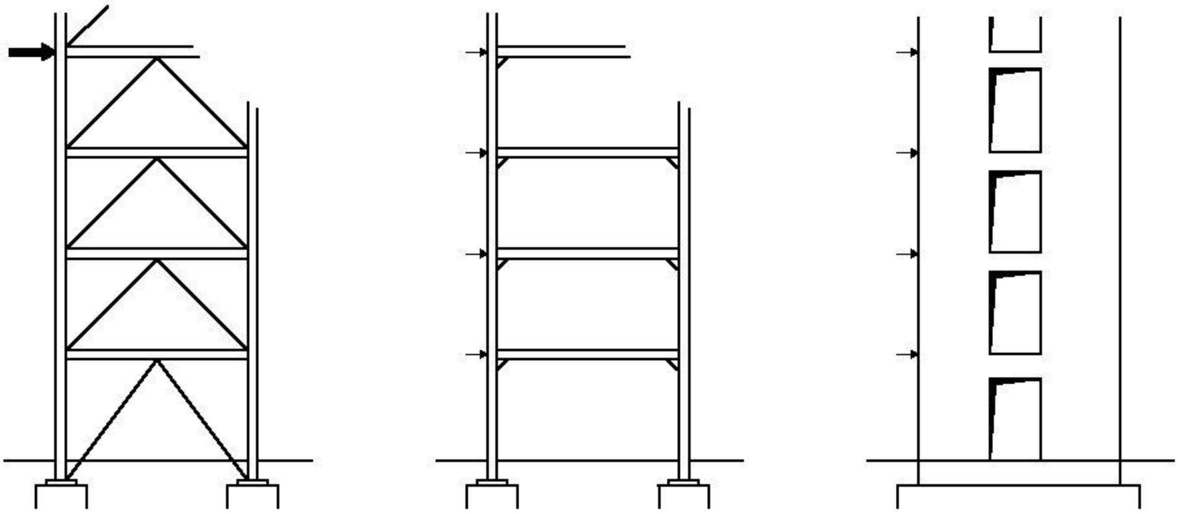


Figure 10 Bracing systems

5.7 Timing

The rate of steelwork erection is governed by a wide range of factors some of which are beyond the influence of the design engineer. The factors which he can control include:

- type of end connections.
- extent/type of bolting or welding.
- number of separate pieces.

Simple connections for shear force are straightforward and employ Grade 4.6 or 8.8 bolts. The bolt diameter should be selected with a degree of care. For example, whilst a single M30 bolt has more than twice the shear capacity of two M20's, the effort required to tighten an M30 bolt is some 3½ times greater. An M20 bolt can be tightened without difficulty using ordinary hand tools, a considerable advantage when working at height.

Joints which are required to transmit bending moments are inherently more robust and may require stiffening ribs and haunches; if this is the case careful attention is required to ensure access for the bolts. For such applications pre-tensioned bolts are often used. They are normally tightened to a minimum torque using a power operated wrench.

Compared to bolting, the site welding of joints is time-consuming and expensive for conventional structures. There may be occasions, however, when site welding is the only realistic way to form a joint, as, for example, in alterations or remedial work. In this case, joint preparation, fitting, inspection and the provision of purpose made enclosures (for access and weather protection) are additional cost factors that must be taken into account.

As a rough guide, about 50% of erection man hours are occupied with lining, levelling, plumbing and final bolting and the remainder of the time is spent hoisting members into position. However, in suitable cases, beam and column elements may be pre-assembled at ground level and lifted directly on to their foundations.

5.8 Safety

The erection of a building framework is potentially hazardous. Many serious and fatal accidents occur each year on construction sites and most of these are caused by falling from, or whilst gaining access to, heights; handling, lifting and moving materials, however, are also hazardous.

Risks can be minimised considerably by measures such as adequate provision for stability throughout construction, accessibility of splices and connections, guard rails and attachments for safety harnesses and so on.

In addition, safety, need not be compromised on grounds of cost. For example, it will prove cheaper to assemble frames at ground level (Figure 11) rather than bolt them together in mid-air. Metal decked floor systems are not only economical but offer rapid access for all trades whilst providing overhead protection. Safer access is also promoted by the immediate provision of steel stair flights at each floor level as steelwork erection proceeds.

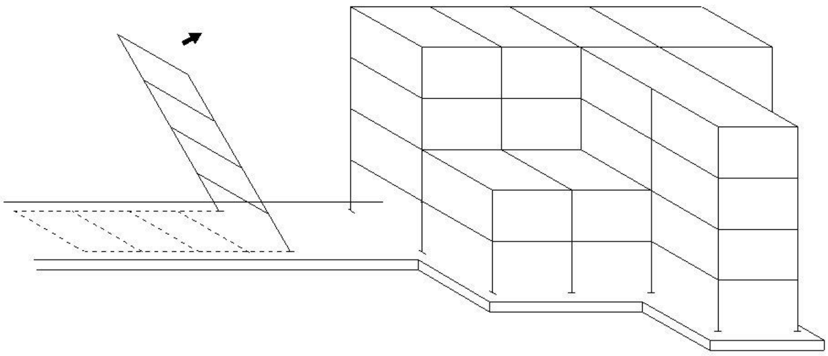


Figure 11 Erection of assembled frames

Current and future legislation may place greater responsibilities upon the design engineer because of the influence of design and details on the method and sequence of erection.

CONCLUDING SUMMARY

- Steelwork erection normally occupies a relatively short period in the construction programme, but considerable activity occurs during this time which is vital to the performance of the contract as a whole.
- The steel framework should not be seen in isolation but as a key link in the construction chain where the time saved can have considerable impact in lowering overall costs.
- Early consideration should be given to erection during design and detailing so that the full benefits of steel construction may be realised and, the need for late changes and subsequent compromise can be substantially reduced.

1.7. INDUSTRIAL / FACTORY BUILDINGS

The reasons for the wide use of steel for industrial buildings are discussed. The advantages of steel include its high strength-to-weight ratio, speed of erection and ease of extension. Steel is used not only for members but also for cladding.

Common types of structure are described. These types include portal frame, lattice girder and truss construction. It is shown that overall stability is easily achieved. The wide variety of sections used in industrial buildings is presented. Possible approaches to global analysis are identified.

1. TYPES OF INDUSTRIAL BUILDING

A wide variety of building types exists, ranging from major structures, such as power stations and process plants, to small manufacturing units for high quality goods.

The most common type is the simple rectangular structure (Figure 1), typically single-storey, which provides a weatherproof and environmentally comfortable space for carrying out manufacturing or for storage. First cost is always an overriding consideration, but within a reasonable budget a building of good appearance with moderate maintenance requirements can be achieved. While ease of extension and flexibility are desirable, first cost usually limits the provisions which can be usefully included in the design for these potential requirements. Although savings in the cost of specific future modifications can be achieved by suitable provisions, for example by avoiding the use of special gable frames (Figure 2), changes in manufacturing processes or building use may vary the modifications required.

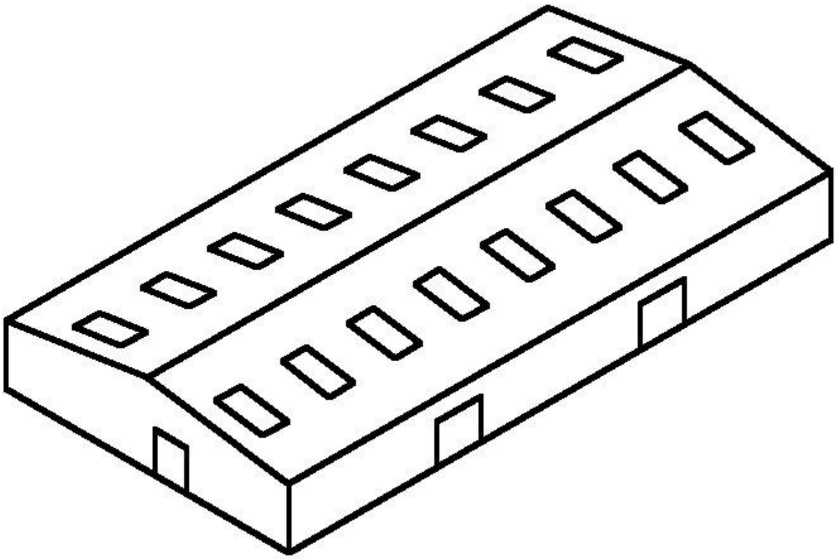
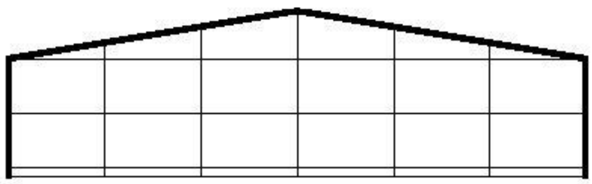
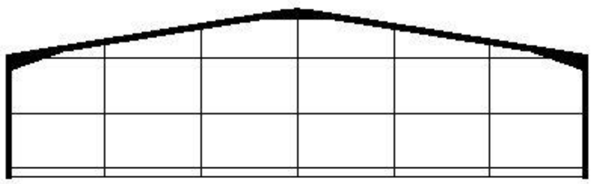


Figure 1 Typical industrial building



Gable frame (does not permit future extension)



End portal frame (permits future extension)

Figure 2 Gable ends

When, for reasons of prestige, the budget is more liberal, a complex plan shape or unusual structural arrangement may provide a building of architectural significance.

While many features are common to all industrial buildings, this lecture deals mainly with single-storey buildings of straightforward construction and shape.

2. STRUCTURAL STEEL FOR INDUSTRIAL BUILDINGS

Compared to other materials, particularly reinforced or prestressed concrete, steel has major advantages. Its high strength-to-weight ratio and its high tensile and compressive strength enable steel buildings to be of relatively light construction. Steel is therefore the most suitable material for long-span roofs, where self-weight is of prime importance. Steel buildings can also be modified for extension or change of use due to the ease with which steel sections can be connected to existing work.

Not only is steel a versatile material for the structure of a building, but a wide variety of cladding has been devised utilising the strength developed by folding thin sheets into profiled form (Figure 3). Insulated cladding systems with special coatings are now widely used for roofing and sidewall cladding. They have good appearance and durability, and are capable of being speedily fixed into position.

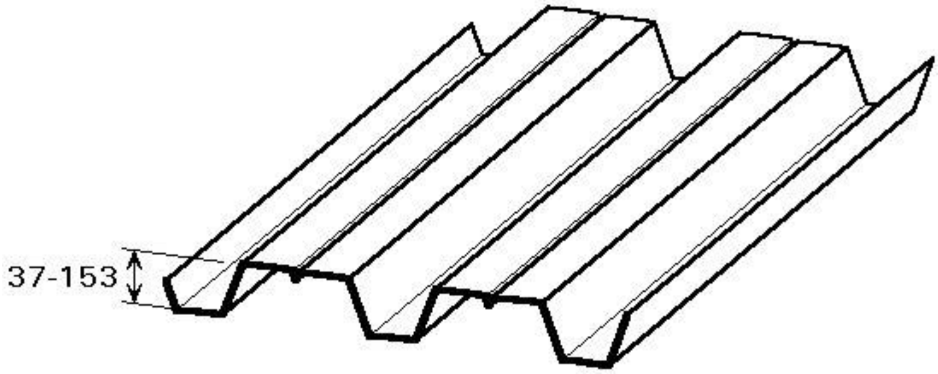


Figure 3 Cladding

The structure of a steel building, especially of an industrial building, is quickly erected and clad, providing a weatherproof envelope which enables the floor and installation of services and internal finishes to proceed at an early stage. Since the construction schedule is always tied to the earliest handover date fixed by production planning, time saved in construction is usually very valuable.

In a dry closed environment steel does not rust, and protection against corrosion is needed only for the erection period. For other environments protection systems are available, which, depending on cost and suitable maintenance, prevent corrosion adequately.

Single storey industrial buildings are usually exempt from structural fire protection requirements. Spread of fire beyond the boundary of the building must not occur as a result of collapse of the structure. This requirement can be met by the provision of fire walls and through the restraint which arises in practice between the bases and the columns which they support.

3. CHOICE OF INDUSTRIAL BUILDING

A prospective owner may have a fully detailed design brief derived from the construction of industrial plants elsewhere. More usually the owner is assisted in the choice of a suitable building by the completion of a detailed list of requirements so that a design brief can be prepared. Initial options in respect of preferred location, site acquisition and environmental needs must first be decided. Then main dimensions, process operation, plant layout, foundation needs, handling systems, daylighting, environmental control, service routes, staffing level and access all require definition.

The preliminary selection must be made between a building specially designed for the owner, a new factory largely built of standard structural components, or the adaptation of an existing building. The latter may be either an advance unit built as a speculative development, or a unit which has been vacated.

The location of internal columns and the internal headroom are always important, and consideration of these requirements alone may determine the choice. The advantage of freedom to plan the building to suit requirements closely and allow for future development is very valuable. However, unless there are exceptional reasons such as permanence of specific use, it is unwise to design an industrial building exclusively for a single process, since special features appropriate to the process may make redevelopment difficult.

4. SHAPES OF INDUSTRIAL BUILDINGS

Because of its economy, the most widely used building shape is the pin-based single or multi-bay pitched roof portal frame, typically of 20-30m span at 6m centres (Figure 4). Hot-rolled I, welded or cold-formed sections are usually used for the members.

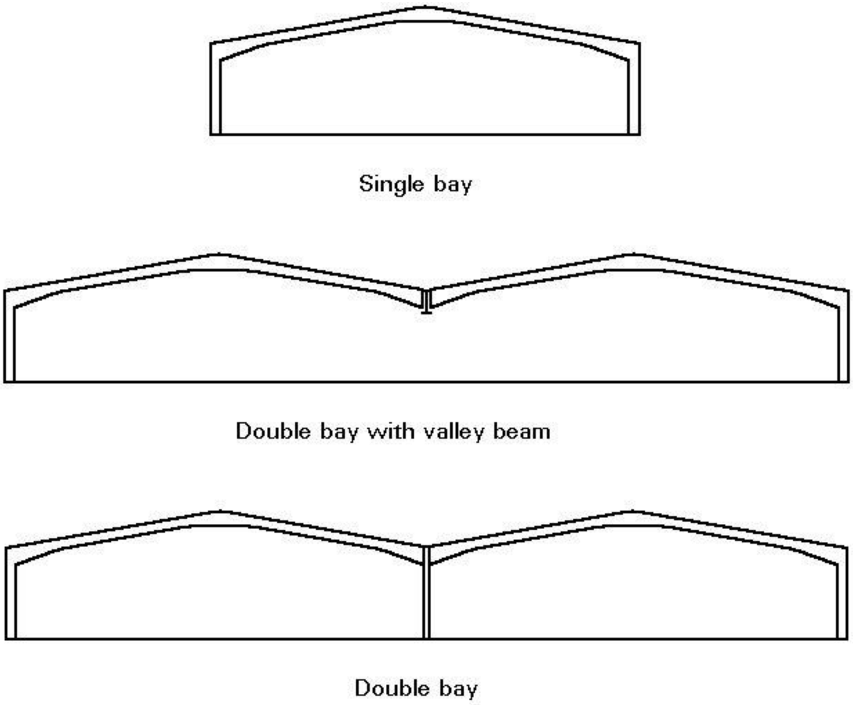
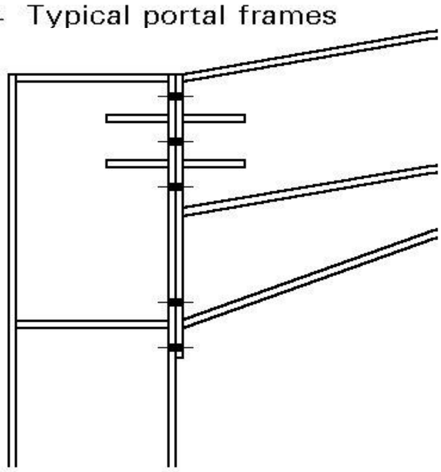


Figure 4 Typical portal frames

During recent years an increasing use of welded sections has occurred. This increase is the result of progress achieved in making welding automatic and the ability to adapt the cross-section to the internal forces.

Since internal columns sterilise an appreciable space around them, their spacing may be increased by using spine I-beams to support the portal rafters. For this type of roof the cladding is usually insulated metal decking, which may also be used for the upper sidewalls. Daylight is provided by profiled translucent sheeting in the roof.

When hot-rolled sections are used, haunches (Figure 5) are usually provided at the eaves and the ridge. These haunches deepen the overall section, thereby reducing bolt forces. By extending the haunched regions along the rafter the frame is also strengthened and stiffened.



Lattice girders (Figure 6) are lighter than portal frame rafters for wider spans, but the additional workmanship increases fabrication costs. Based on structural requirements alone, lattice systems are likely to be cost-

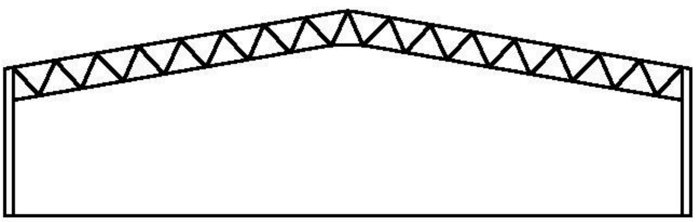


Figure 6 Lattice girder structure

effective for spans above 20m. Roof trusses may also be used for structures which support heavy cranes (Figure 7).

A wide variety of structural sections may be used for lattice girders and roof trusses, including single angles, angles back- to-back, tees, H-sections or hollow sections (Figure 8). For light loading, cold-formed sections may be used as booms, with reinforcing bars as the web members (Figure 9).

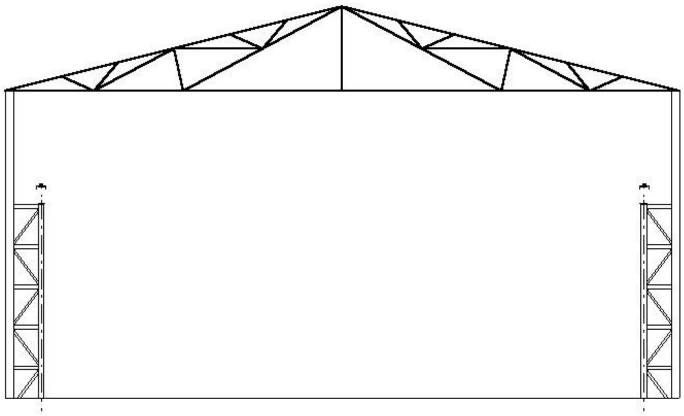


Figure 7 Lattice column and roof truss construction

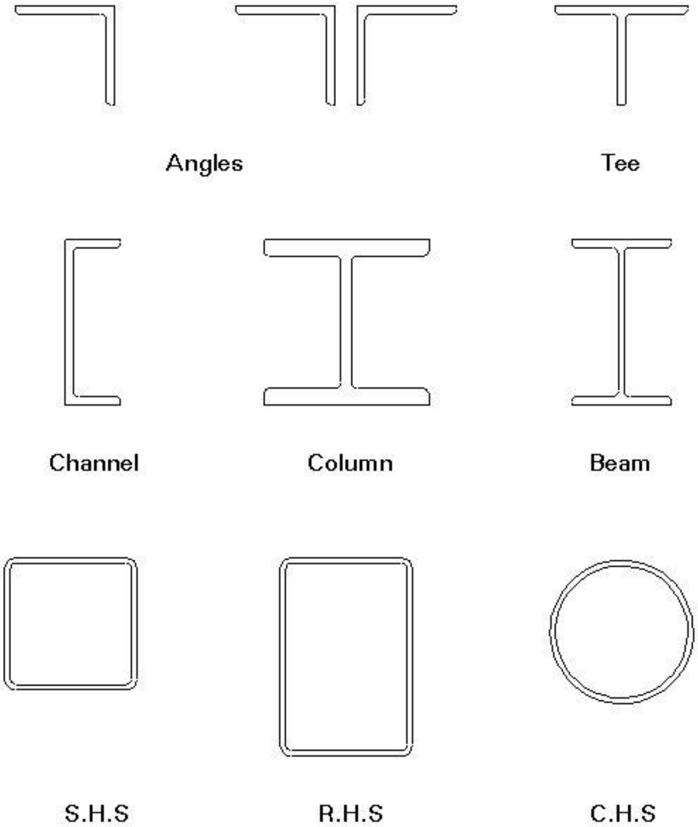


Figure 8 Structural sections

The disadvantages of multi-bay pitched roofs are that internal gutters and rainwater disposal are required, which are a possible source of leaks, and access to plant mounted externally on the roof is difficult.

The most versatile roof shape is the nominally flat roof, covered with an insulated membrane on metal decking (Figure 10). This shape allows wide freedom in plan form, and eliminates the need for internal gutters, although some internal rainwater disposal may be necessary if the extent of the roof is large. The mounting and weather protection of external plant on the roof is simply achieved, and access can readily be provided.

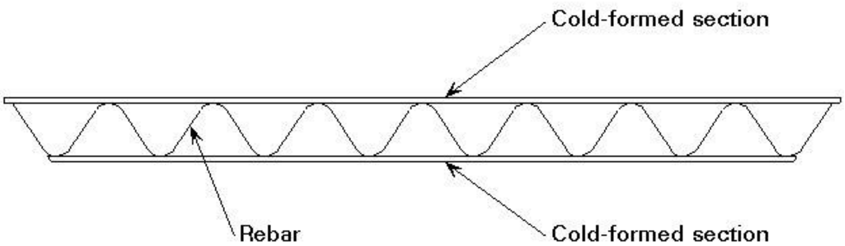
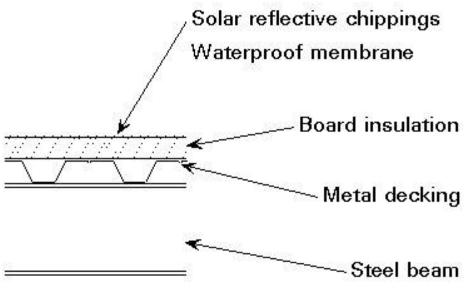


Figure 9 Light lattice beam



Typical section through roof

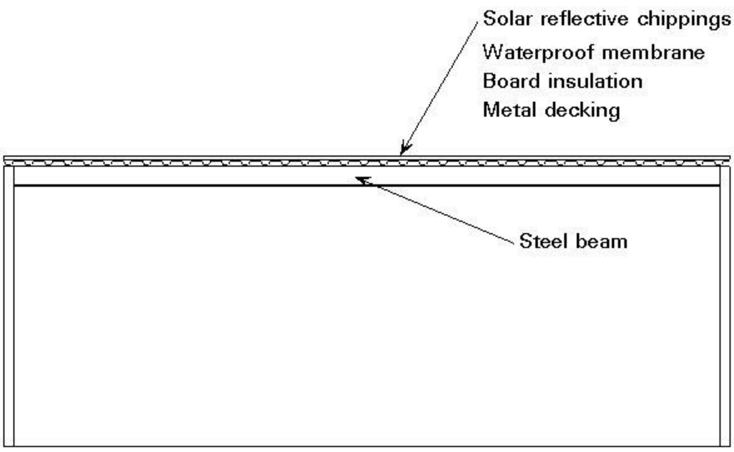


Figure 10 Steel decking on flat roof

Flat roofs can be supported by rolled or cold-formed purlins on main I-beams or lattice girders. For smaller structures the deck may span directly from one frame to another, without the need for purlins.

When services are extensive and there are many external plant units on the roof, castellated beams or double-layer grid space frames (Figures 11 and 12) can be very suitable for flat roofs. The two-way grid distributes local loads better than any other structural form. The support for the roof deck is provided directly by the top layer and support for the services by the bottom layer of the grid. Castellated beams have a much higher moment of resistance than I-beams.

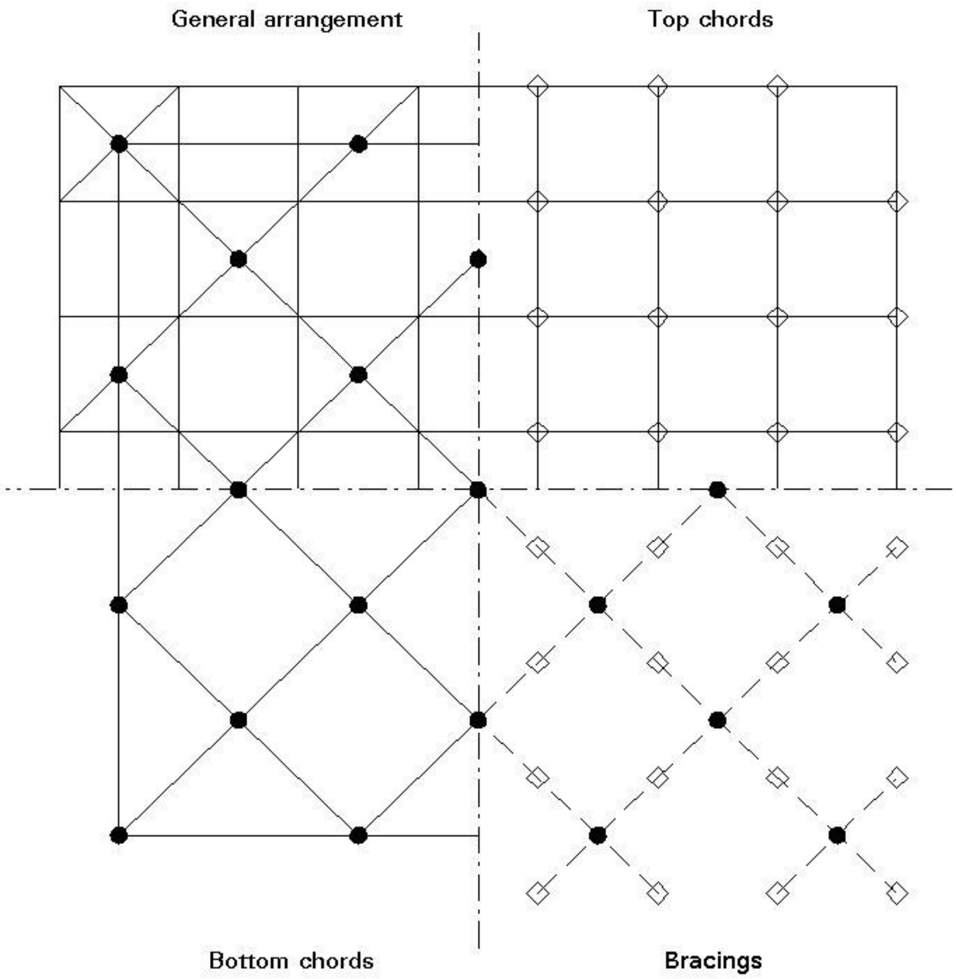


Figure 11 Double layer grid space frame

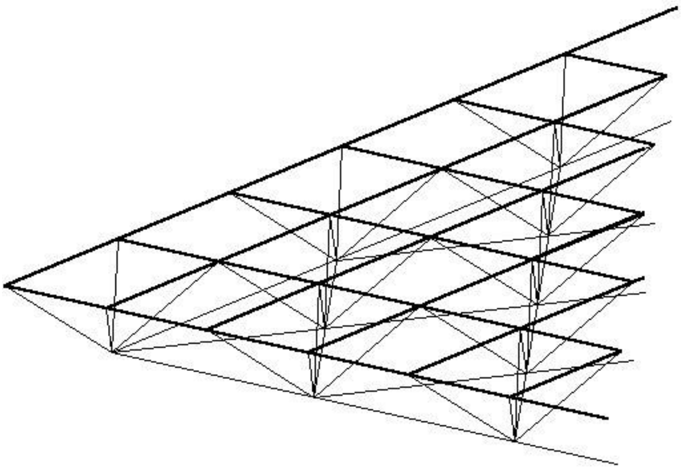


Figure 12 Double layer grid space frame

The provision of daylighting in flat roofs is expensive, since either dome or monitor lights must be used. Flat roofs are most common for industries where daylighting requirements are minimal.

5. STABILITY OF INDUSTRIAL BUILDINGS

It is essential to ascertain the loads applied to the structure and to determine the load paths from the cladding to the purlins and side rails, through the main frames to the foundations. The loads may arise from dead load, wind load and snow load, and sometimes from cranes or impact caused by fork-lift trucks.

The overall resistance of simple single-storey industrial buildings to horizontal loading is usually easy to achieve. One of the attractions of portal frame buildings is that in-plane stability follows from the rigidity of the frame connections. Stabilising bracing between the portals is therefore only required in line with corresponding rafter bracing in the roof plane.

For short buildings, bracing in one end bay may be sufficient. For longer buildings, bracing of two or more bays may be necessary.

The rafter bracing itself provides restraint to the heads of the gable stanchions. The braced end bays provide anchor points to which the longitudinal rafter stabilising ties, which are usually the purlins, are attached. During erection, bracing facilitates plumbing and squaring of the building, as well as providing essential stability.

For frames with lattice girders (Figure 6), in-plane stability can be provided by connecting both top and bottom booms to the column.

If the building has roof trusses (Figure 7), or if only the top booms of the lattice girders are connected to the column (Figure 13), the frame is effectively pinned at eaves level. To provide in-plane stability, either the column bases should be fixed or longitudinal girders should be provided in the plane of the roof (Figure 14). These girders span between the gable ends, which must be braced appropriately. If the building is long, or is divided by expansion joints, longitudinal bracing may not be practicable and the columns must have fixed bases.

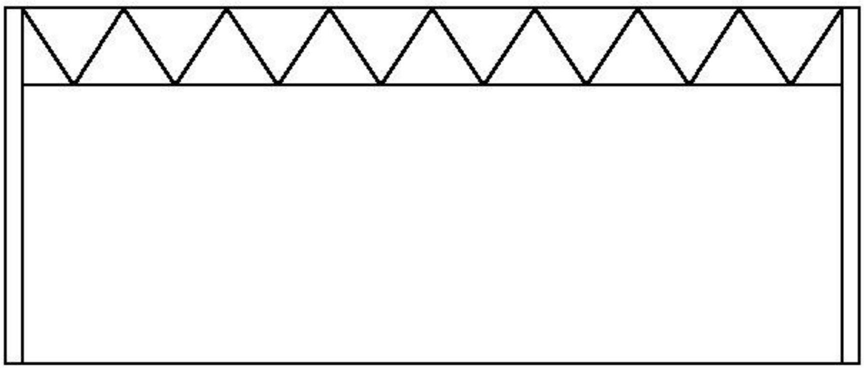


Figure 13 Lattice beam and columns

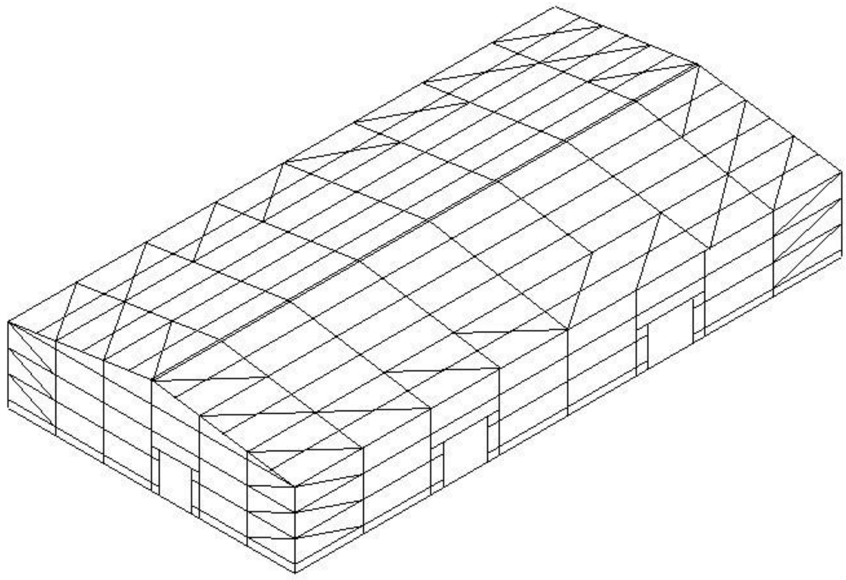


Figure 14 Bracing systems

Buildings using lattice girders or truss roofs also need bracing to provide longitudinal stability.

Bracing members for industrial buildings commonly use circular hollow sections, rods or angles.

When cranage is provided the stability requirements need further examination, since longitudinal and transverse surge from the crane increases the forces in the bracing systems.

6. GLOBAL ANALYSIS

The structure may be treated either as a 2-D or 3-D system.

Bracing systems are analysed as if pin-jointed. When cross-bracing is used, for example in vertical bracing, only the members in tension are assumed to be effective (compression members are assumed ineffective because of buckling).

The choice of the method of global analysis, either plastic or elastic, of portal frames at the ultimate limit states depends on the class of the cross-section.

An example of the plastic collapse mechanism of a frame with haunches is given in Figure 15. Buildings with cranes should always be analyzed elastically. Elastic analysis should always be used to determine deflections under service loading.

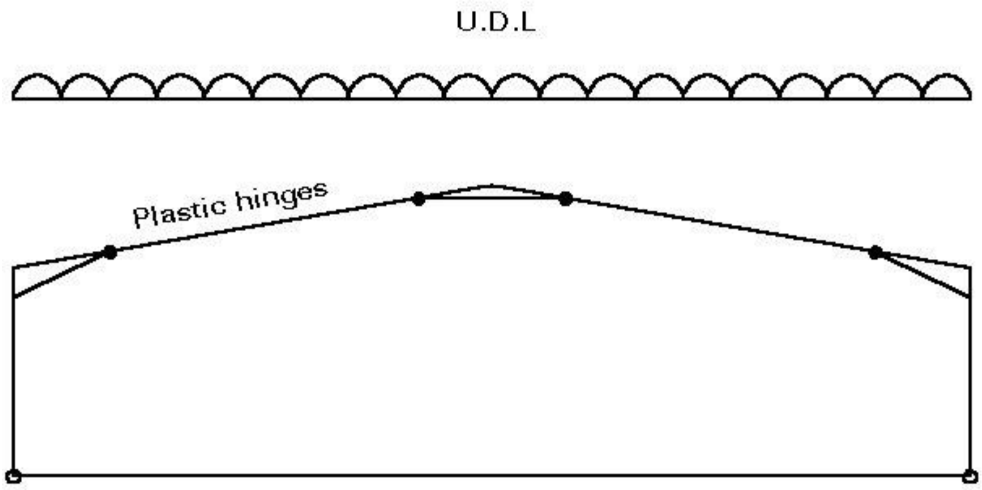


Figure 15 Plastic collapse mechanism

7. CONCLUDING SUMMARY

- Steel construction is widely used for industrial buildings, including structural members (like frames, purlins, side rails) and cladding systems.
- Overall stability is obtained from the rigidity of connections and the use of bracing systems.
- The buildings may be analyzed using 2-D or 3-D modelling and elastic or plastic analysis, depending on their cross-sections.
- A wide variety of hot-rolled shapes are available for structural members. More flexibility can be obtained using welded sections. Purlins and side rails may be formed from cold-rolled sections

1.8. MULTI-STORY BUILDINGS

The notes gives a brief description of the fundamental components of a building frame. It presents different structural arrangements to resist horizontal and vertical loadings. Finally, consideration is given to the question of fire protection.

1. INTRODUCTION

A multi-storey building must resist the combined effects of horizontal and vertical loads; it is composed of foundations, frameworks and floor slabs.

The framework comprises columns and beams together with horizontal and vertical bracings, which stabilise the building by resisting horizontal actions (wind and seismic loads).

Floor slabs are supported by beams so that their vertical loads are transmitted to the columns. They are made of reinforced concrete or composite slabs using profiled steel sheets. Columns are commonly made of H or hollow hot-rolled steel sections. The use of hollow sections filled with concrete can improve their fire resistance. Beams are commonly made of I and H profiles. Nevertheless, the use of welded built-up sections can offer more rational solutions in some cases.

The usual structural systems belong essentially to two categories: moment resisting frame systems and braced-frame systems, the second being the simplest and, therefore, the most economic solution.

In braced frames, vertical bracings are formed by diagonal members within the steel frame. These bracings may be of different form (cross-braced X shaped; V or inverted V shaped; symmetrical or unsymmetrical portal). Alternatives to steel bracings are the reinforced concrete shear walls or cores.

These main components of multi-storey buildings and their design are described in the following section:

2. THE STRUCTURAL SCHEME

A multi-storey building includes the following structural components (Figure 1):

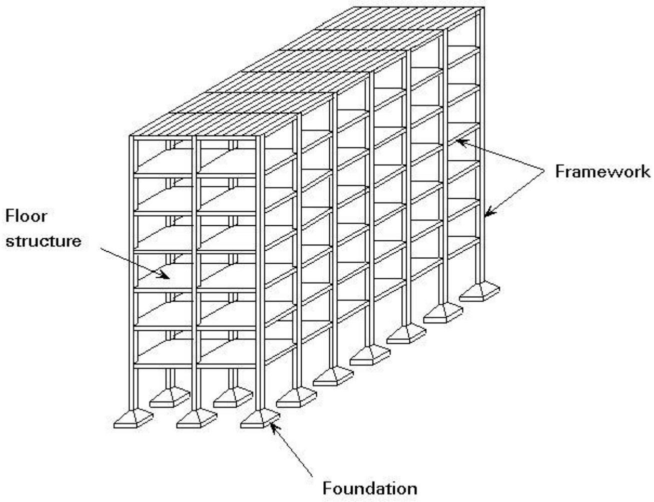


Figure 1 Main structural components of a multi-storey building

a. foundations

b. framework

c. floor structures.

Foundations are made of reinforced concrete. The type of foundation is selected according to the features of the ground and the ground conditions.

The framework is the steel skeleton which provides the load-bearing resistance of the structure and supports the secondary elements such as the floor slab and cladding.

All external loads, both vertical and horizontal, are transmitted to the foundations by means of the steel framework. It is mainly composed of vertical elements (columns) and horizontal elements (beams), which may be connected together in different ways. According to the degree of restraint at the beam-to-column connections, the framework can be considered as 'rigid', 'semi-rigid' or 'pin-ended'. For the pin-ended case, the framework must incorporate bracing elements which are located in the rectangular panels bounded by columns and beams.

The floor slabs are required to resist the vertical loads directly acting on them and to transmit these loads to the supporting floor beams. They also transfer the horizontal loads to the points on the framework where the bracing members are located.

The structural arrangement of multi-storey buildings is often inspired by the shape of the building plan, resulting in different solutions (Figure 2). The plan can be rectangular (Figure 2a), L-shaped (Figure 2b), curved (Figure 2c), polygonal (Figure 2d) or perhaps composed of rectangular and triangular elements (Figure 2e).

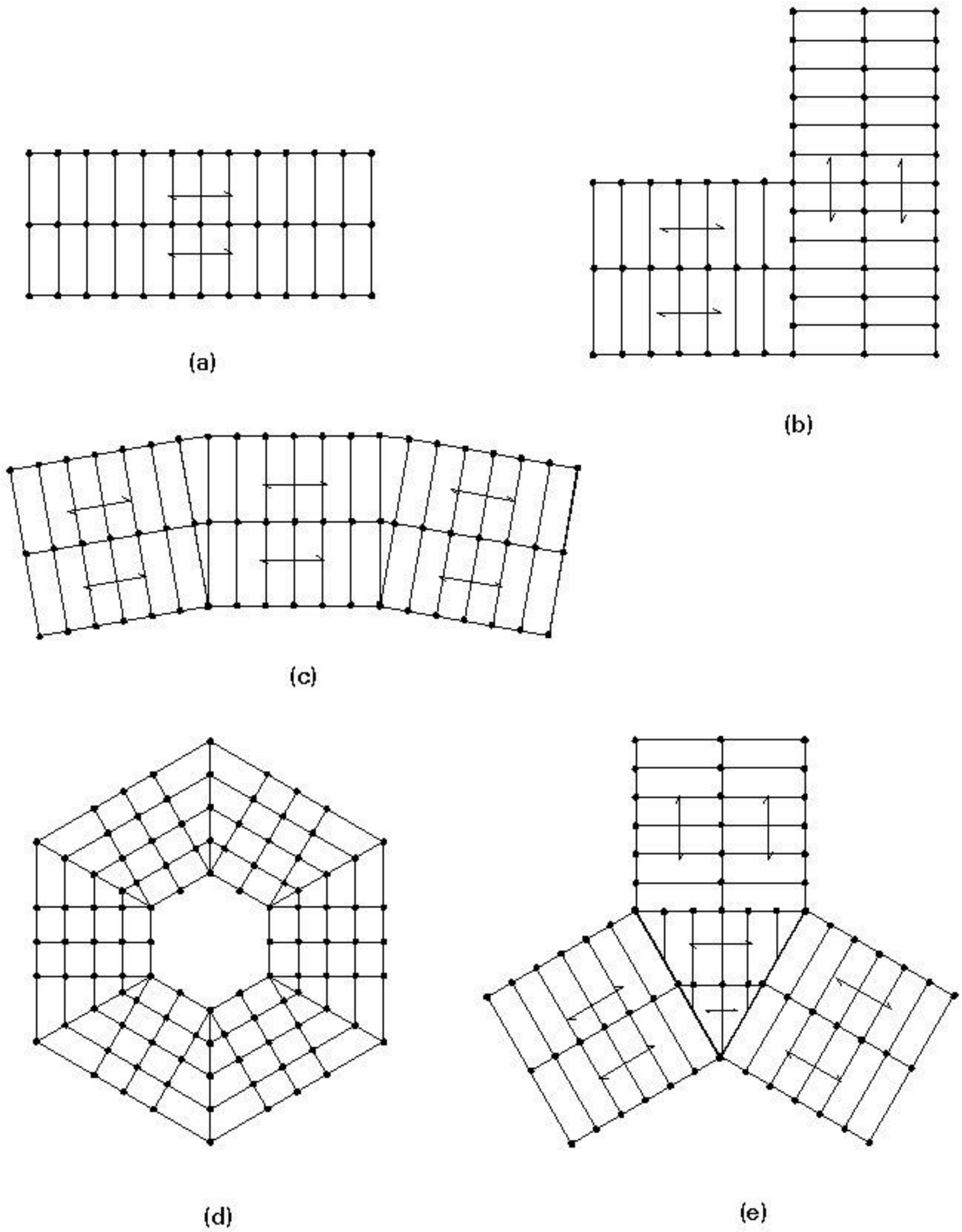
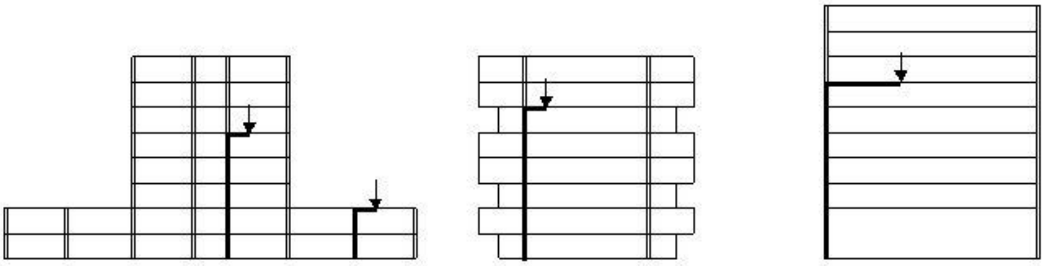


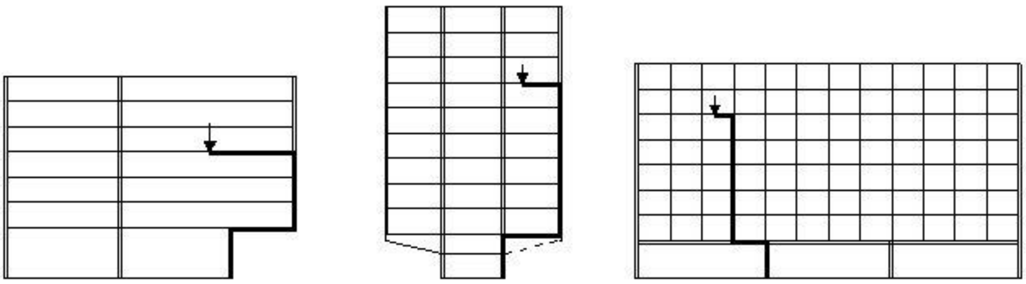
Figure 2 Structural arrangements according to the shape of the building plan

3. COLUMNS

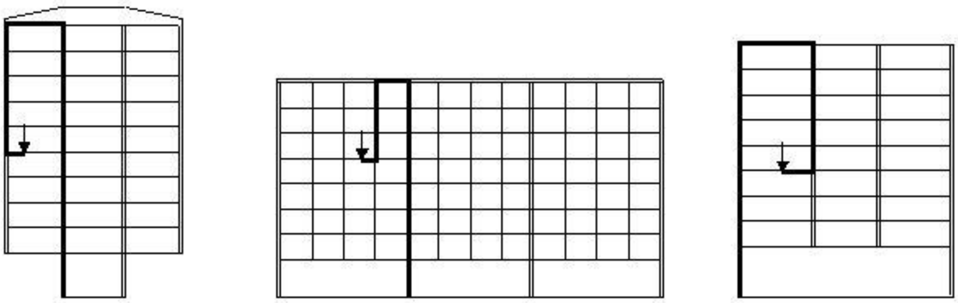
Columns are the structural components which transmit all vertical loads from the floors to the foundations. The means of transmission of vertical load is related to the particular structural system used for the framework (Figure 4).



(a)



(b)



(c)

Figure 4 Different methods of vertical load transmission

The location of columns in plan is governed by the structural lay-out. The most common grid arrangements are square, rectangular, or occasionally triangular, according to the choice of the global structural system (Figure 3). The spacing of columns depends upon the load-bearing resistance of the beams and floor structures. It can vary from 3 to 20m, but is typically in the range of 6 to 10m.

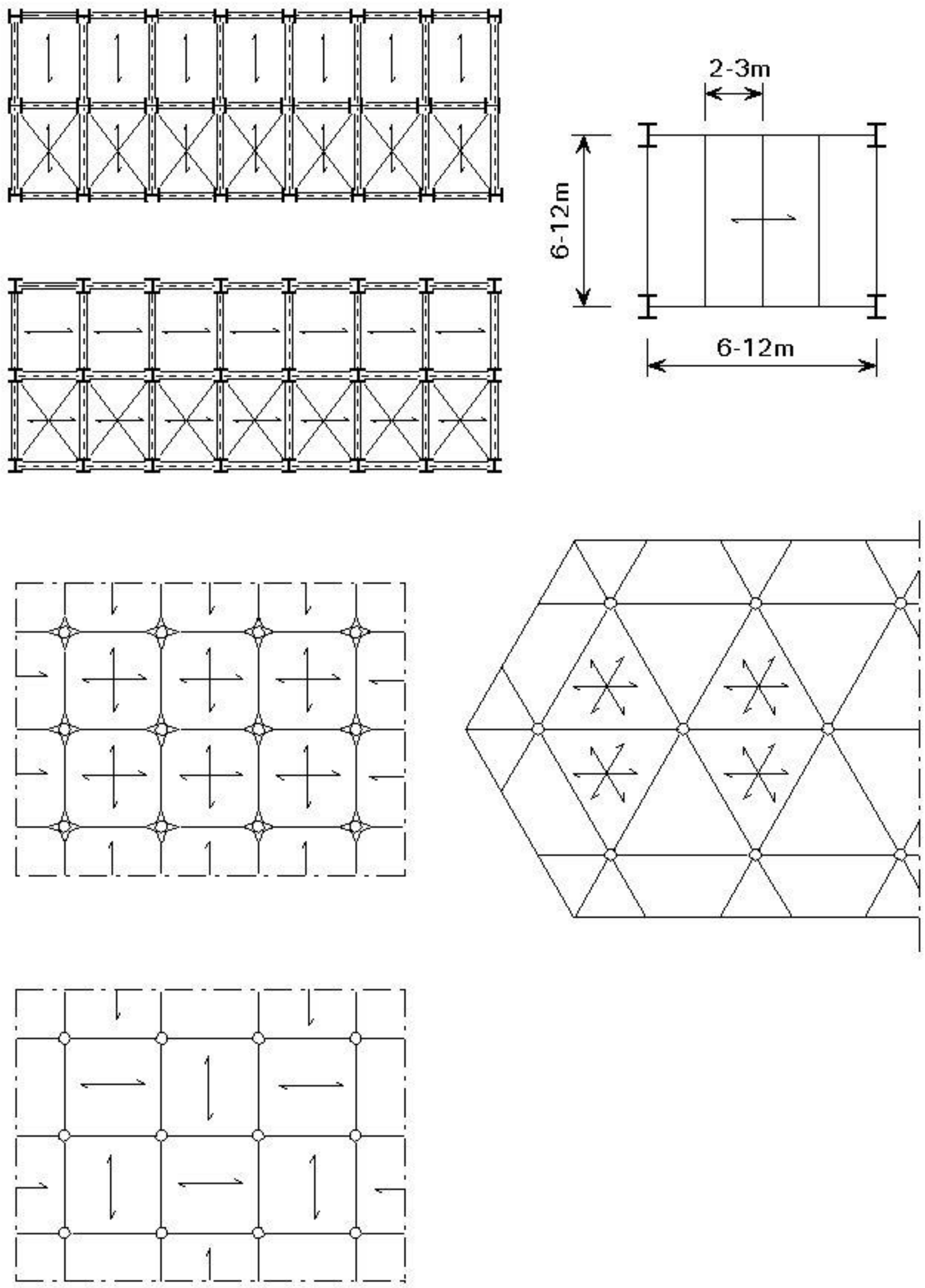


Figure 3 Different locations of columns

Load transmission from floors to columns may occur directly from the floor beams to the column (Figure 4a), or it can be indirect. Indirect transmission involves the use of major 'transfer' beams (Figure 4b), which resist all the loads transmitted by the columns above.

In suspended systems (Figure 4c), the transmission of vertical loads is much more complicated. It is directly provided by tensile members (ties), hung from the top beam elements which support the total vertical load of all floors. A limited number of large columns provide the transmission of the total load to the foundations.

The choice of location and spacing of columns depends on the structural system which has to harmonize functional and economical requirements.

The shapes of cross-section commonly used for columns can be subdivided into (Figure 5):

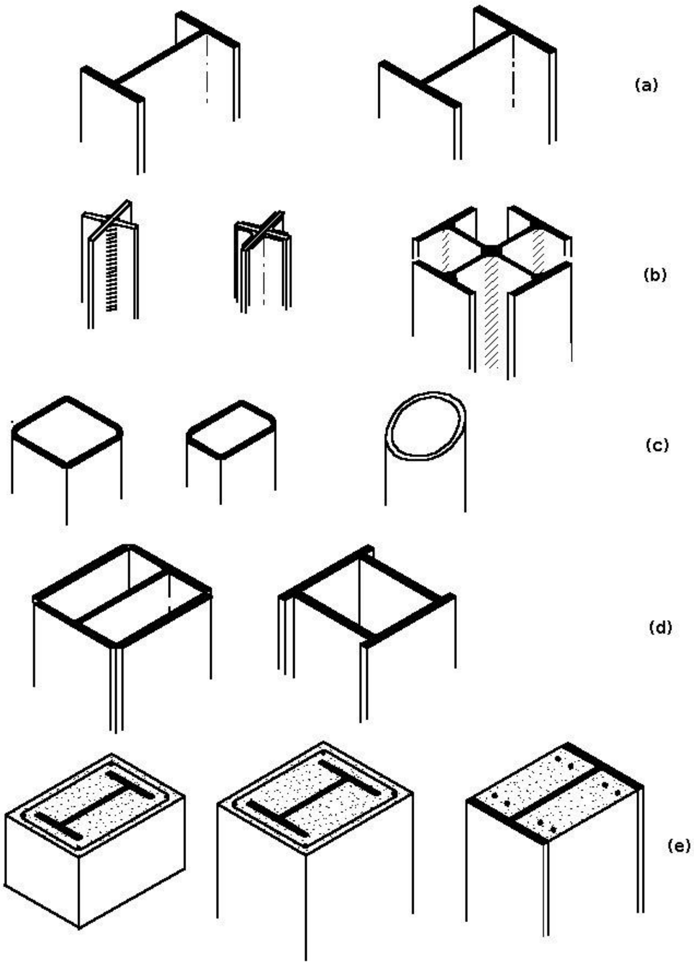


Figure 5 Different sections of columns

- open sections.
- hollow sections.

Open sections are basically standard hot-rolled I and H profiles (Figure 5a). Double-T sections can be also built up by welding. Cross-shaped sections can be obtained by welding L profiles, plates or double-T profiles (Figure 5b).

Hollow sections are tubes of circular, square or rectangular cross-section (Figure 5c). They can also be made from plates or double-T profiles by welding (Figure 5d). Circular and square hollow sections have the advantage that they have the same resistance in the two principal directions, enabling the minimum section dimensions to be obtained. Sometimes hollow sections are filled with concrete, giving an increase in strength and, at the same time, achieving significant fire resistance (> 60 minutes) (Figure 5e). However the beam-to-column connections are more complicated than between I-sections.

4. BEAMS

Beams support the floor elements and transmit their vertical loads to the columns. In a typical rectangular building frame the beams comprise the horizontal members which span between adjacent columns; secondary beams may also be used to transmit the floor loading to the main (or primary) beams.

In multi-storey buildings the most common section shapes for beams are the hot rolled I (Figure 6a) or H shapes (Figure 6c) with depth ranging from 80 to 600mm. In some cases channels, (either single or double) can also be used (Figure 6b).

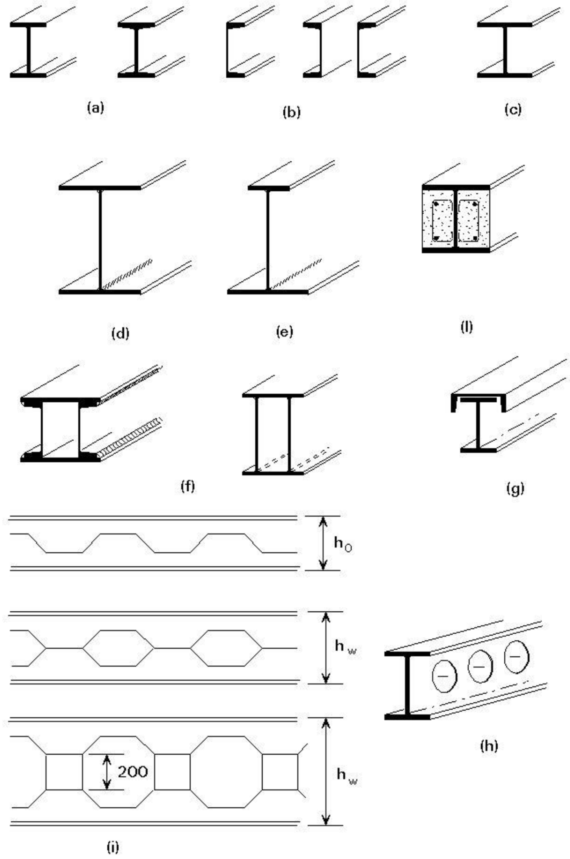


Figure 6 Different sections of beams

Where a greater depth is necessary, built-up sections can be used. Sections fabricated by welding can have double-symmetrical (Figure 6d) or non-symmetrical (Figure 6e) shape, the latter being advantageous for composite steel-concrete sections. By combining plates and/or profiles, box-sections (Figure 6f) or open sections (Figure 6g) can be fabricated.

Sometimes openings in the webs of beams are required in order to permit the passage of horizontal services, such as pipes (for water and gas), cables (for electricity and telephone), ducts (for air conditioning), etc. The openings may be circular (Figure 6h) or square with suitable stiffeners in the web. Another solution to this problem is given by using castellated beams (Figure 6i), which are composed by welding together the two parts of a double-T profile, whose web has been previously cut along a trapezoidal line.

For buildings, the common range for the span to depth ratio is 15 to 30 in order to achieve most efficient design.

In addition to the strength, beams must provide enough stiffness to avoid large deflections which could be incompatible with non-structural components (such as partition walls). For this purpose the maximum mid-span deflection of a beam is usually limited to a fraction of the span equal to 1/400 - 1/500. Where this limitation is too severe, an appropriate initial deformation (camber) equal and opposite to that due to the permanent loads can be pre-formed into the beam.

Steel sections can be partly encased in concrete by filling between the flanges of the section. Partly encased sections are fire resisting without conventional fire protection (Figure 5e). For longer periods of fire resistance, additional reinforcing bars are required.

5. FLOOR STRUCTURES

Floor are required to resist vertical loads directly acting on them. They usually consist of slabs which are supported by the secondary steel beams. The spacing of supporting beams must be compatible with the resistance of the floor slabs. Floor slabs may be made from pre-cast concrete, in-situ concrete or composite slabs using steel decking. A number of options are available:

- conventional in-situ concrete on temporary shuttering (Figure 7a).
- thin precast elements (40 - 50mm thick) with an in-situ structural concrete topping (Figure 7b).
- thicker precast concrete elements which require no structural topping (Figure 7c).
- steel decking acting as permanent shuttering only (Figure 8b).
- steel decking with suitable embossments/indentations so that it also acts compositely with the concrete slab (Figure 8c).

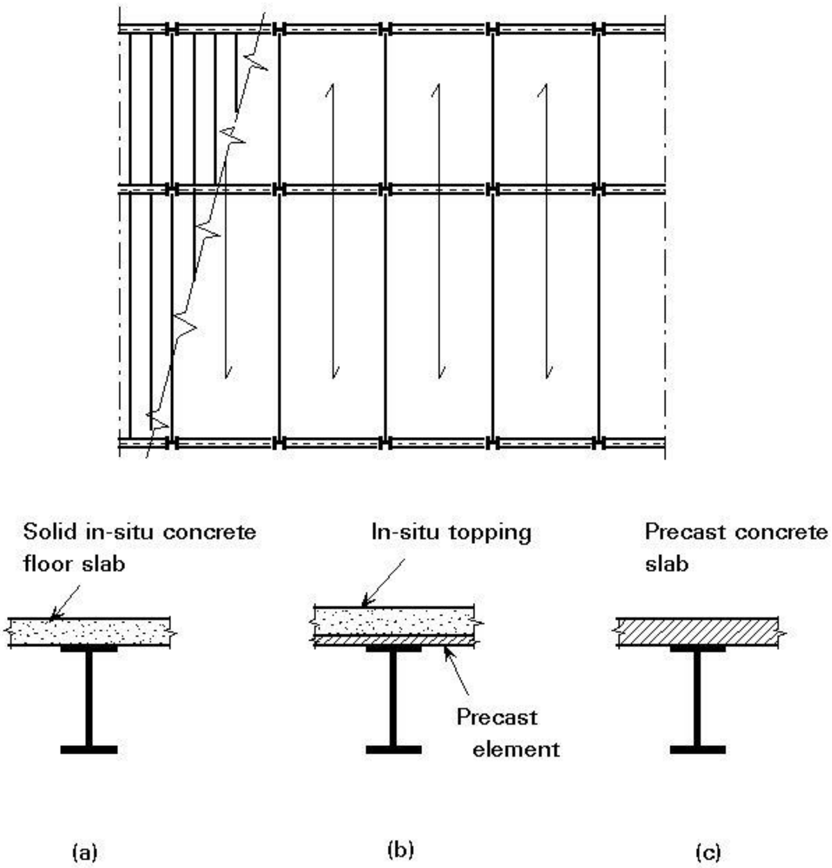


Figure 7 Floor structure comprising reinforced concrete slabs

Typical spans for concrete slabs are 4m to 7m, thus avoiding the need for secondary beams. For composite slabs, various cross-section shapes of steel decking are available (Figure 8a). They are classified in three categories according to their load-carrying resistance:

- profiles with a plain trapezoidal shape without stiffeners with a depth up to 80mm (Figure 8c);
- profiles with a trapezoidal shape with longitudinal stiffeners both in web and flange with a depth up to 100mm (Figure 8d);
- profiles with both longitudinal and transverse stiffeners with a depth up to 220mm (Figure 8c).

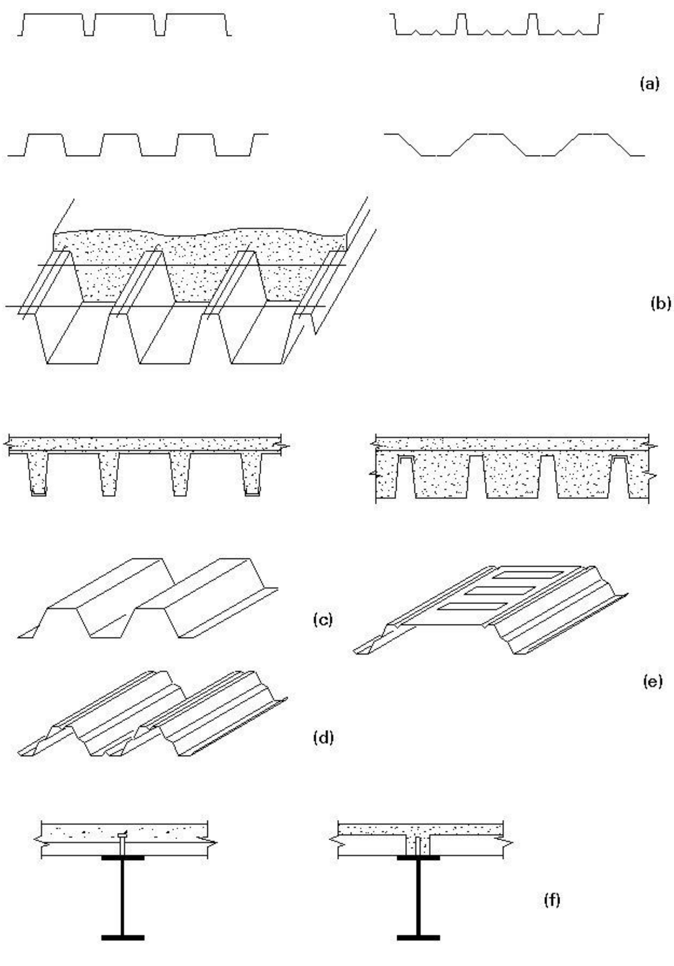


Figure 8 Different types of profiled steel sheets

Deck spans range in length from 2 to 4m for the first category, from 3 to 5m for the second category, and from 5 to 7m for the third category. Secondary floor beams can be avoided in the last case.

Permissible spans for steel decking are influenced by conditions of execution, in particular whether temporary propping is used. Such propping is best avoided since the principal advantage of using steel decking, i.e. speed, is otherwise diminished.

To increase the strength and stiffness of the floor beams, a composite steel-concrete system can be obtained by means of appropriate studs welded on the top of the flange (Figure 8f). In this case the slab and beam may be designed compositely using conventional theory.

6. BRACING

Bracing systems are used to resist horizontal forces (wind load, seismic action) and to transmit them to the foundations.

When a horizontal load F (Figure 9a) is concentrated at any point of the facade of the building, it is transmitted to two adjacent floors by means of the cladding elements (Figure 9b).

The effects of loads H acting in the floor slab are distributed to the vertical supporting elements which are located in strategic positions of the structural layout (dotted lines in Figure 8c) by means of an appropriate horizontal resisting element in the floor.

The vertical supporting elements are called vertical bracings; the horizontal resisting element is the horizontal bracing which is located at each floor.

Where horizontal bracings are necessary, they are in the form of diagonal members in the plan of each floor, as shown in Figure 9c).

If steel decking is used, the diagonal bracing can be replaced by diaphragm action of the steel sheeting if it is fixed adequately.

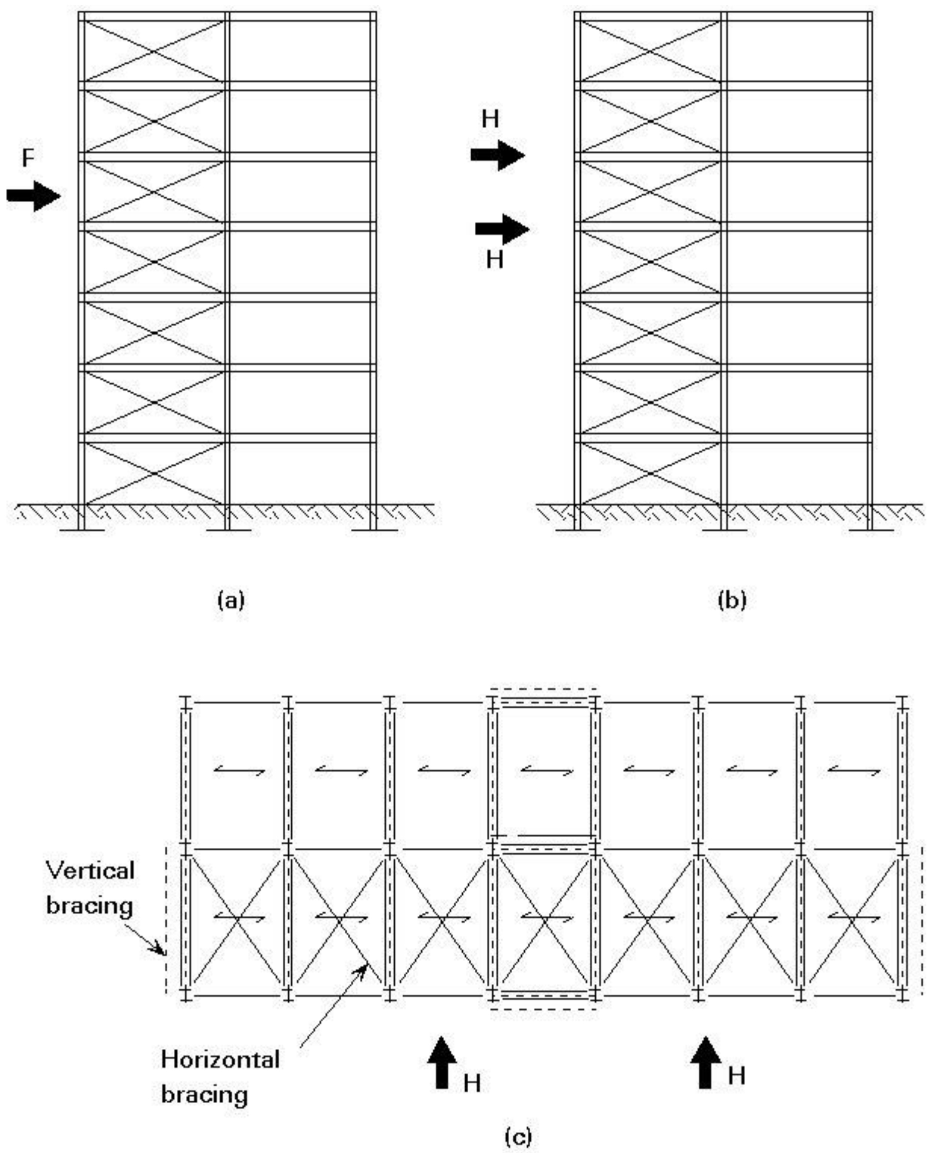


Figure 9 The function of bracing systems

Both horizontal and vertical bracings represent together the global bracing system, which provides the transfer of all horizontal forces to the foundations.

Vertical bracings are characterised by different arrangements of the diagonal members in the steel frame. They are (Figure 10):

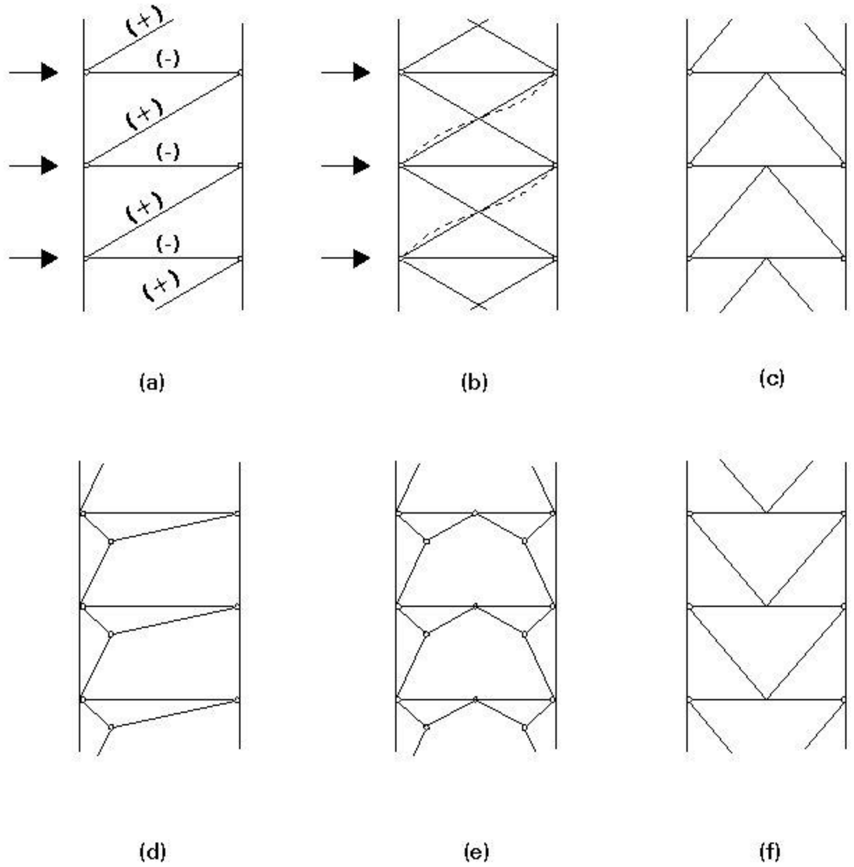


Figure 10 Different types of arrangements for bracings

a. Single diagonal

b. Cross-braced (X-shaped bracing)

c. Inverted V-shaped bracing

d. Unsymmetrical portal

e. Symmetrical portal

f. V-shaped bracing.

An alternative to steel bracings is provided by reinforced concrete walls or cores which are designed to resist the horizontal forces (Figure 11). In these systems, so-called dual systems, the steel skeleton is subjected to vertical forces only. Reinforced concrete cores are usually located around the stairway and elevator zones.

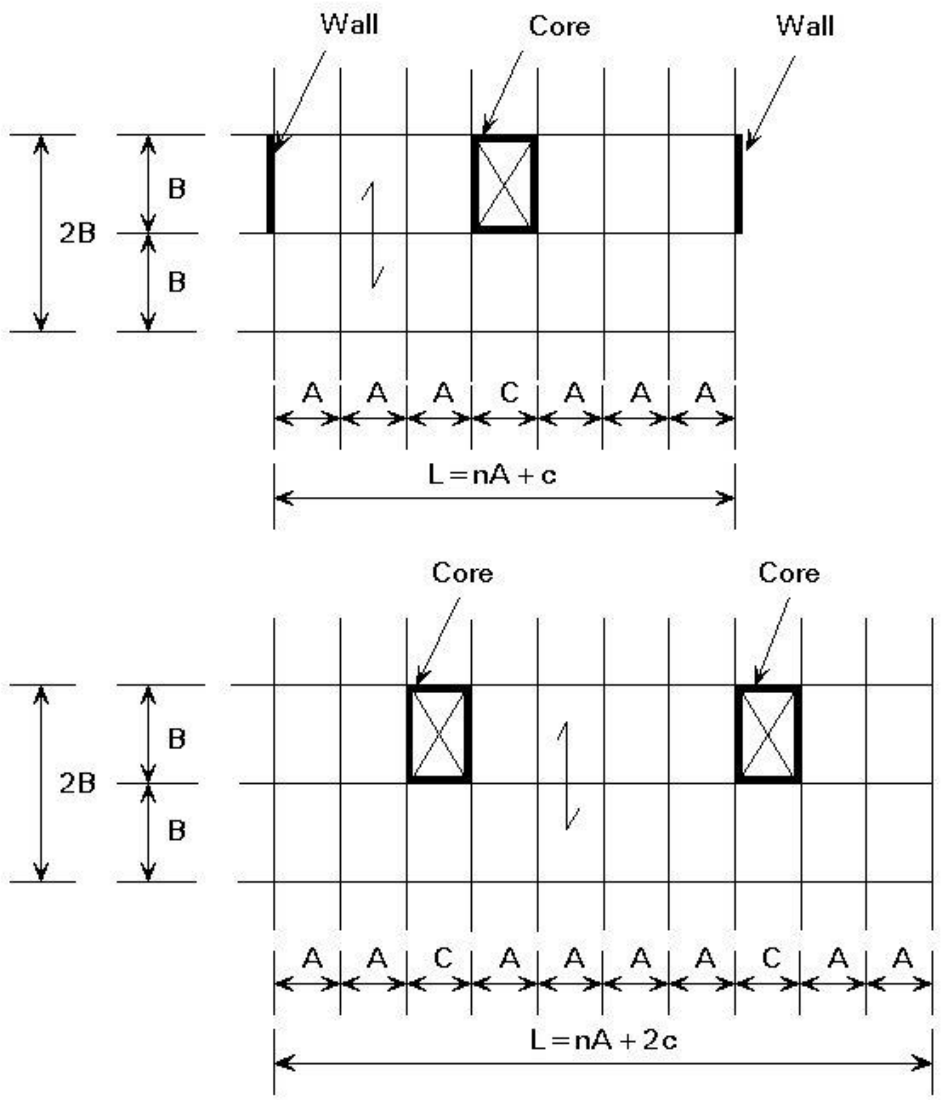


Figure 11 Reinforced concrete walls and cores

Normally, the floor slab can be designed to resist in-plane forces to avoid the use of horizontal diagonals. This is the case for in-situ reinforced concrete slabs, or composite slabs with appropriate shear connectors.

7. STRUCTURAL SYSTEMS

To provide resistance to the combined effects of horizontal and vertical loads in a multistorey building, two alternative concepts are possible for the structural system.

The first, so-called 'moment resisting frame system', is a combination of horizontal (beams) and vertical (columns) members which are able to resist axial, bending and shear actions. In this system no bracing elements are necessary. The moment resisting frame behaviour is obtained only if the beam-to-column connections are rigid, leading to a framed structure with a high degree of redundancy. As a consequence of this choice:

- the connections or joints between members are complicated.

- 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.

Typical details of beam-to-column joints for rigid framed systems are shown in Figure 12. They are called 'rigid joints' and their task is to transfer bending moment from the beam to the column. Type (a) can transfer limited bending moments only because the column web can buckle due to local concentration of effects. The presence of horizontal stiffeners in the column web (Type (b)) recreates the cross-section of the beam and the column web panel has to resist the shear force only.

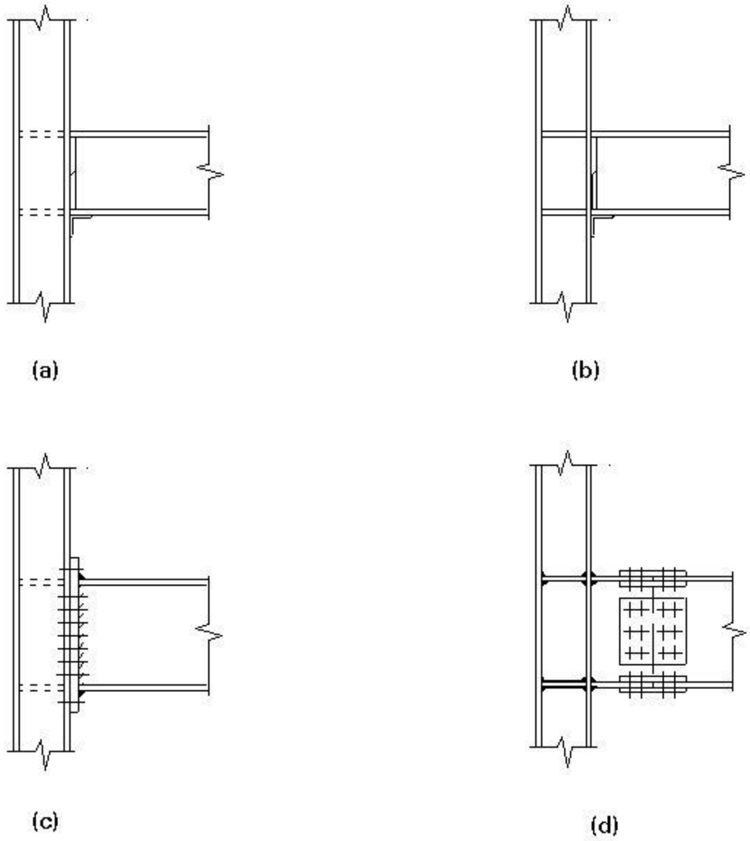


Figure 12 Beam-to-column joints for rigid frames

Types (a) and (b) require the execution of welding operations on site. Such operations are not completely reliable and they are also expensive and can cause delay in erection.

A better alternative is to use bolted connections which allow rigid joints to be made without the disadvantages of site welds. Two typical solutions for rigid frame structures, shown in Figures 12c and 12d, are:

- Type (c) is the extended end plate joint.
- Type (d) is the cover plate joint.

These solutions allow the most suitable use of connecting methods, i.e. welding in the shop to build up prefabricated elements and bolting in site for connecting them together. This type of joint can be, therefore, called 'shop-welded field-bolted'.

To avoid the practical problems of rigid frame construction, a more convenient solution can be obtained by conceiving the structural behaviour in a different way. The functions of resistance to vertical and horizontal loads are separated in the different 'families' of members, which are grouped in two sub-structures (Figure 13):

a. a simple frame composed by beams pinned together, which is capable of transferring the vertical loads to the foundation (Figure 13a).

b. a cantilever fixed to the ground which resists horizontal forces and transfers their effects to the foundation (Figure 13b).

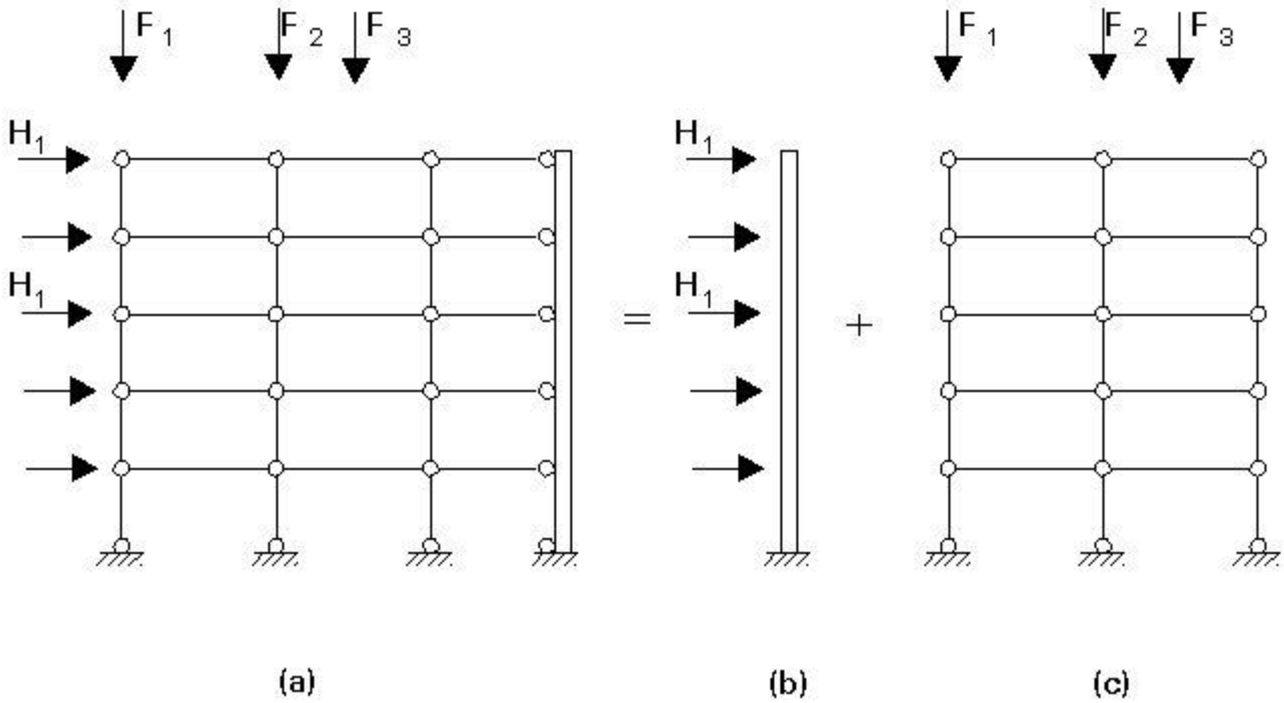


Figure 13 Calculation model for braced frame

Sub-structure a. is hyperstatic; beams are bent in the vertical plane, columns are simply compressed, the hinged joints between beams and columns absorb shear forces only.

Sub-structure b. is isostatic; its bracing function can be obtained by means of steel trusses or by reinforced concrete walls. These bracing structures are mainly loaded in shear and bending and their deformability must be checked under serviceability conditions in order to limit sway.

The combination of both sub-structures a. and b. provides the complete structure (Figure 13c), which is able to resist both vertical and horizontal loads.

The main advantages of this solution, the so-called 'braced-frame system', are:

- construction details of joints are very simple, because they act as hinges.
- sway deformability of the structure is limited by the bracing system (sub-structure b).
- interaction between axial forces and bending moments in the column is virtually absent.

In contrast, some complications arise in the foundation of bracings which must resist the overall horizontal forces with a very small amount of axial compression. High values of eccentricity occur which require large dimensions of the contact area under the foundation.

In these structural systems beam-to-column joints must resist only axial and shear forces. Some typical solutions of joints for pin-ended structures are shown in Figure 14; they are 'shop-welded field-bolted' joints. The most commonly used is the bolted connection between the beam web and the column flange (or web) by means of double angles (Figure 14e, f). They are more economic than the fully welded solutions (Figure 12a, b) for rigid structures and allow simple erection.

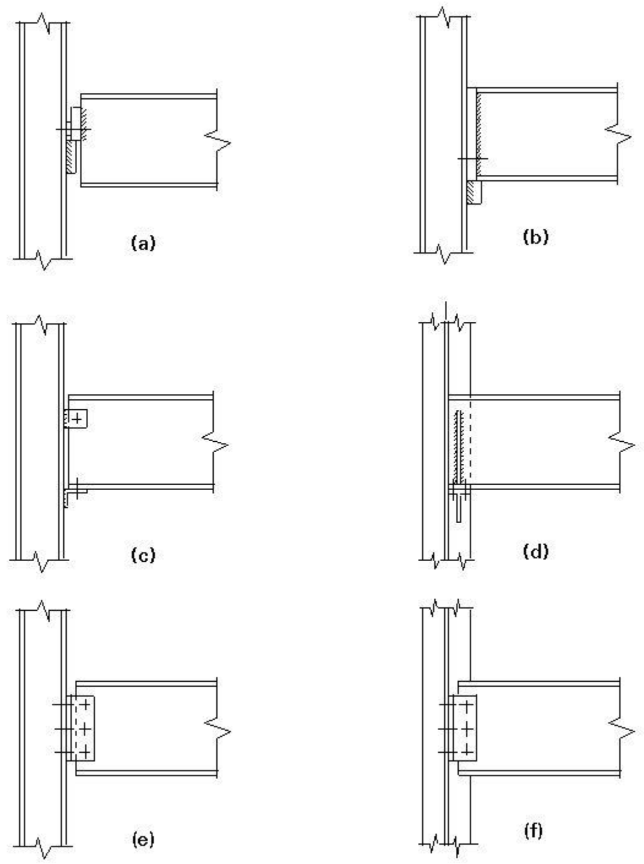


Figure 14 Beam-to-column joints for pin-ended frames

8. DESIGN REQUIREMENTS

The design of a structural system for a multi-storey building must to take into account its spatial behaviour.

For the 'braced frame system', which seems to be most convenient for economy and reliability, it is necessary to locate a sufficient number of bracings to allow any horizontal loads however directed to be resisted. For this purpose, the requirements are:

(1) it must be possible to consider any floor system as a plane structure, restrained by the vertical bracings.

(2) bracings, as external restraints of the floor system, must provide a system of at least three degrees of restraint.

(3) the floor system must be capable of resisting the internal forces due to the applied horizontal loads.

To fulfil requirement (1), diagonal bracings must be introduced in the plane of the floor, thus transforming the floor system itself into a horizontal truss.

As an alternative, the slab of prefabricated concrete elements in the floor system can be assumed to resist directly the horizontal forces as a plane plate structure, because its deformability is normally negligible.

Where concrete slabs are used, the erection of the steel skeleton requires particular care, because it is unstable until the floor elements are placed. Temporary bracing is therefore necessary during this phase of execution.

To fulfil requirement (2) the steel truss bracings are active only in their own plane and therefore represent a simple restraint for the floor system. When reinforced concrete bracings are used, they can have one, two or three degrees of restraint, depending upon their resistance to one plane bending (wall), bi-axial bending or bi-axial bending and torsion (core), respectively.

Finally, requirement (3) is fulfilled by evaluating internal forces in the floor elements due to the horizontal loads by considering the location of the vertical bracings.

Figure 15 shows a three-dimensional structure for a multi-storey building with steel bracings. Every point of the floor system is fixed in two directions. In particular, the diagonals connecting points A and B restrain all the points in line '1' in the 'x' direction. The floor bracing is able to receive external forces from both direction 'x' and 'y' and to transmit them to the vertical bracings.

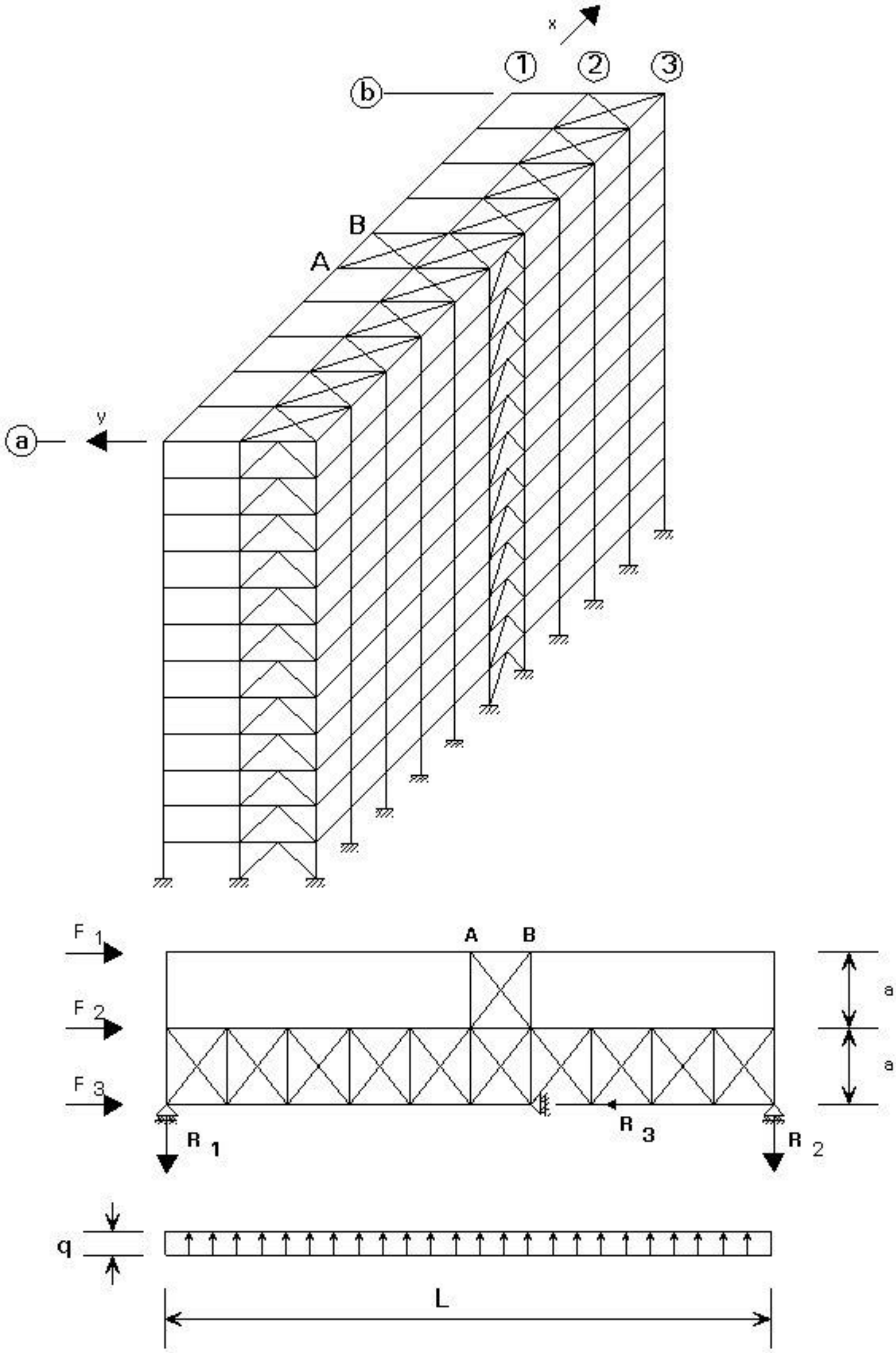
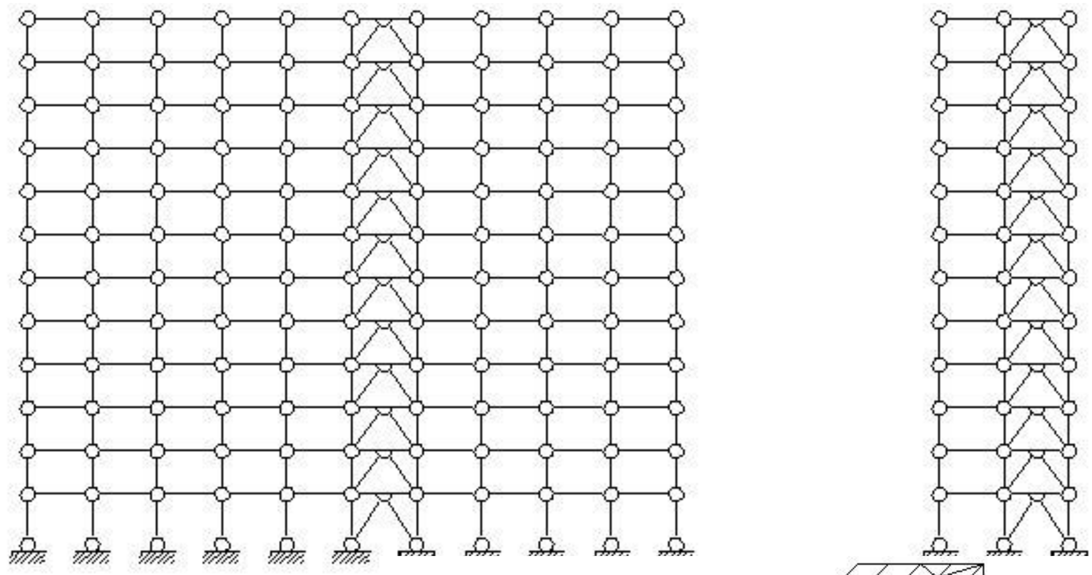
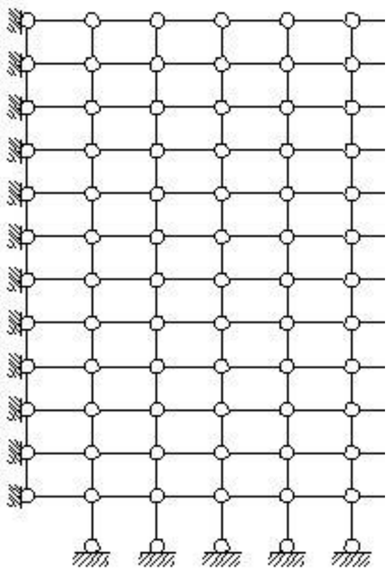


Figure 15 Multi-storey building with horizontal steel bracings

The spatial structure can be reduced to plane sub-structures whose static schemes are shown in Figure 16. The longitudinal facade along row '3' is directly braced in its plane as well as the lateral facades by the transverse bracings of axes 'a' and 'b'.



Row (



Rows (

Figure 16 Longitudin

The pinned joints of the intermediate transverse frames and of the

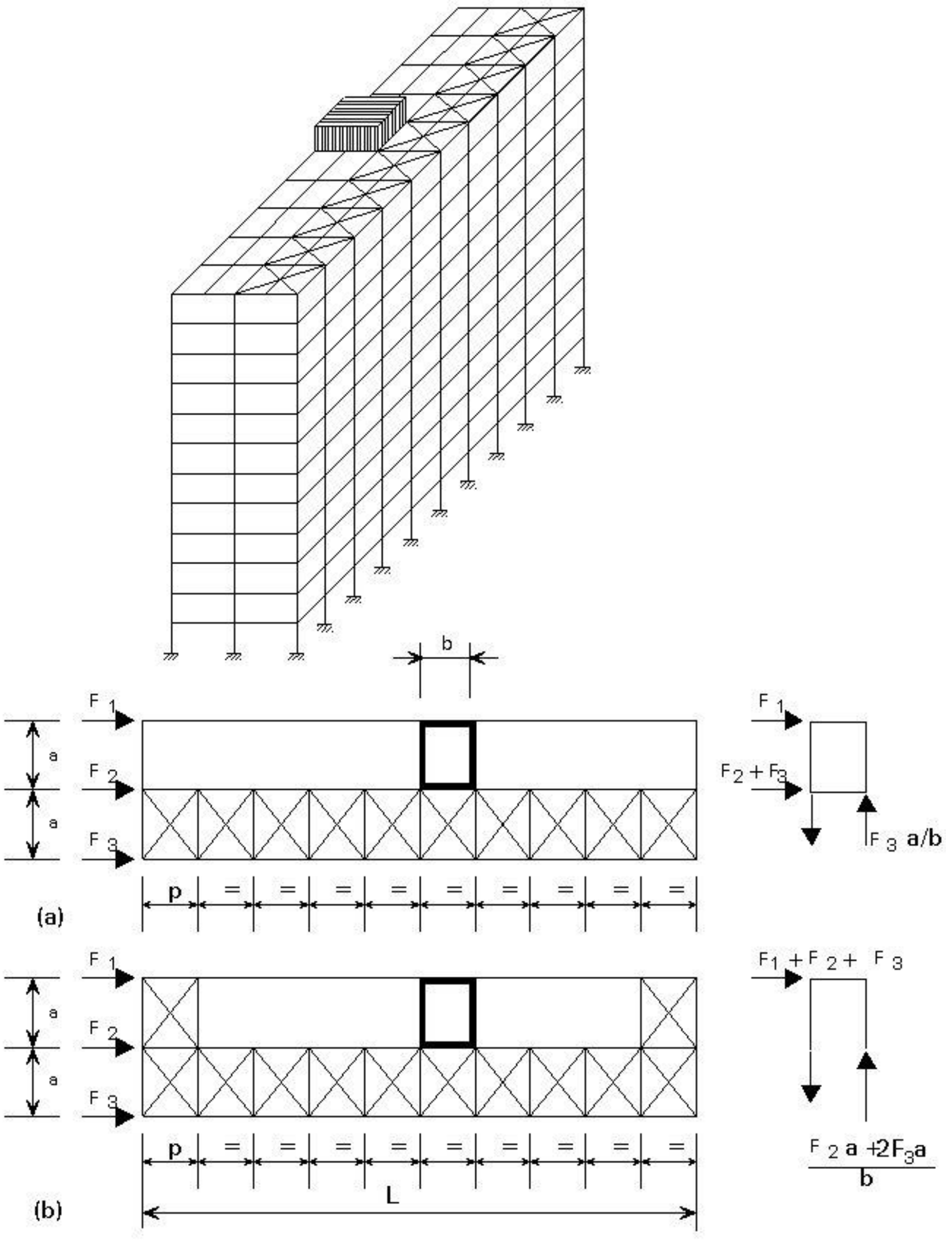


Figure 17 Multi-storey building with a concrete core

longitudinal frames of axes '1' and '2' are prevented from any horizontal displacement because they are all connected to the vertical bracings by means of the floor bracings. Thus they can be considered as non-sway frames.

Figure 17 represents the spatial structural scheme of a multi-storey building with a reinforced concrete bracing core. It can be considered as an alternative solution of the previous example for the same building, in which the concrete core substitutes both longitudinal and transverse steel bracings.

Two floor bracing systems can be considered:

If all the four walls of the staircase core are structurally effective, the solution of Figure 17a is correct. If only three sides of the staircase core are structurally effective, the transmission of the horizontal forces acting in the longitudinal direction to the longitudinal wall requires the use of additional floor diagonals, as shown in Figure 17b.

MULTI-STOREY STEEL FRAMED STRUCTURES...

Structural behaviour of structural steel construction for high-rise building
Ta1l and slim buildings like many of the sky-scrapers find in Hong Kong may not be a kind of structure that are favourable in the using of structural steel construction. The main problem is that tall buildings may bend significantly under normal wind load and produce undesirable movements and deflection. Rigidity in the connection of the steel members is of no doubt required to improve such situation, but of course, this incurs certain technical difficulties especially when site connection is concerned.

To overcome such drawback, one of the common methods is to build a strong reinforced concrete core which usually locates in the centre of a building (refer also to figure 1 & 4). This core acts as a stiffening structure and help to take up most of the bending movement created by wind load. The core is usually rectangular or square in section with the perimeter wall sometimes more than 450mm thick and accommodating part of the essential utilities such as the staircases, lift shafts, toilets or services ducts etc. Sometimes, suitably located shear wails can act similarly to a rigid core.

The second method is by the introduction of more bracing or truss members between the main structural steel members (refer also to figure 6 & 7). The bracing members can produce stiff diagonal supports and help to resist wind pressure by transmitting the load from the external faces of the building through the floors which act as rigid diaphragms also. However, this may make the layout of the building becomes complicated, lower the space efficiency of the building or produce additional technical difficulties to internal or external finishes.
To increase the overall performance, most of the modern floor systems for this kind of structure are using composite floor design (Figure 12 & 13), that is, the steel floor joists are topped with a RC slab that form a very strong and rigid composite floor membrane as part of the stiffening provision for the entire building system.

1.9. CAR PARKS

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SCHOOL OF BUILDING AND ENVIRONMENT

DEPARTMENT OF ARCHITECTURE

UNIT – III - Steel in Architectural Design – SAR1613

Innovations in Steel industry

1.1. Innovation in construction industry

1.1.1. Building envelope

- Development of novel, high-performance pre-treatment, primer and topcoat technologies for enhanced coating durability.
- Enhanced functionality for building envelopes. Technologies allowing rapid changes of colour or pattern within the same steel coil; improvements in envelope energy efficiency.
- Novel methods of rapidly identifying or predicting the properties of new metallic coating compositions.
- New and innovative steel-based insulation products or systems that allow thinner composite panels to be produced in a continuous manufacturing process.

1.1.2. Construction Structures

- Sustainable building design from cradle to cradle. Collaboration could focus on: efficient construction methods; reduction of energy consumption in building use; simplified de-mounting and re-use of structural steels.
- Generation of design solutions for extremes of loading (earthquakes, fire) and for highly corrosive environments.
- Creating the residential homes and neighbourhood of the future.

1.1.3. Digital Construction

- The construction industry is changing and is quickly moving to adopt digital tools, interoperable data, and automation as a means to drive efficiencies. Following are the key enablers for digitally capable construction products
  - Structured, accessible, managed, linked and interoperable data – manufacturers must be the Single Source of the Truth for their data.
  - Product marking – linking digital CAD components to physical products to enable Digital twins.
  - Interlinked databases – both internally (for product providence, pricing, etc.) and externally.
  - Digital Platform development – to enable component data to be utilised to drive wider systems.

1.1.4. Smart Products

- Steel manufacturers have started looking at incorporating IoT (e.g. sensors) technology in to or on to their products. These “Smart” products can provide several benefits:

- In-use performance monitoring – for example of the thermal performance of a building envelope panel over time.

- Building and environment monitoring for construction clients – for example monitoring temperature, humidity, water ingress, people movements, etc.

- Building security – CCTV cameras, motion, damage to the building can be monitored.

- By adding this capability, the steel products are enabled to be used in different ways. For example, by knowing how the product is performing over time and whether or not it has been damaged, it makes the concept of leasing products more feasible.

1.2. INSDAG

- INSDAG - Institute for Steel Development And Growth

- Please refer to the attached PDF – INSDAG Parameters

General Info -Steel INstag.pdf

1.3. Recycling Steel

- Why recycle steel? - Metals can be recycled repeatedly without altering their properties. Scrap metal has value, which motivates people to collect it for sale to recycling operations.

- Steel is 100% recyclable - According to the American Iron and Steel Institute (AISI), steel is the most recycled material on the planet. The other highly recycled metals include aluminum, copper, silver, brass, and gold.

- Advantages of Recycling

- The use of scrap steel saves up to 74% of the energy needed to make steel from virigin ore material

- Saves Energy and Reduces Pollution – recycling one tonne of steel cans saves:

– 1.5 tonnes of iron ore
– 0.5 tonnes of coke
– 1.28 tonnes of solid waste
– Reduces air emissions by 86%
– Reduces water pollution by 76%

1.3.1. Steel Recycling Process

.1. **Collection** - because of higher scrap value. As such, it is more likely to be sold to scrap yards

.2. **Sorting** - Sorting involves separating metals from the mixed multi-material waste stream. In automated recycling operations, scrappers may employ a magnet, as well as to observe the material color or weight to help determine the metal type. Scrappers will improve the value of their material by segregating clean metal from the dirty material.

.3. **Processing** - metals are shredded, to promote the melting process as small shredded metals have a large surface to volume ratio, as a result they can be melted using comparatively less energy

.4. **Melting** - Scrap metal is melted in a large furnace. Each metal is taken to a specific furnace designed to melt that particular metal. A considerable amount of energy is used in this step. (IMPORTANT: - the energy required to melt and recycle metals is much less than the energy that is needed to produce metals using virgin raw materials.)

.5. **Purification** - Purification is done to ensure the final product is of high quality and free of contaminants. One of the most common methods used for purification is Electrolysis.

.6. **Solidification** - After purification, melted metals are carried by the conveyor belt to cool and solidify the metals. In this stage, scrap metals are formed into specific shapes such as bars that can be easily used for the production of various metal products.

.7. **Transportation** - Once the metals are cooled and solidified, they are ready to use. They are then transported to various factories where they are used as raw material for the production of brand new products.

- When the products made of these metal bars come to the end of their useful life, the metal recycling process cycles again.

1.3.2. Collection for Recycling

- There are various collection process, few of the successful methods are as below

.1. Via magnetic extraction

.2. Via energy from waste (EFW) plants

.3. Via kerbside collection

.4. Via bring schemes

Magnetic extraction

- Magnetic recovery is the most efficient and cost effective way of extracting steel packaging from non-sorted domestic waste, achieving recovery rates of up to 55%.
- Thanks to its magnetic properties, steel is one of the easiest packaging materials to recover from the waste stream. Steel packaging can be automatically extracted from non-sorted refuse or separated from other recyclable materials using efficient and low cost magnets.
- The magnetic extraction technology can be used to recover steel cans from pulverization, baling and energy-from-waste plants.

Energy from waste (EFW) plants

- EFW plants in the UK handle more than 2 million tonnes of domestic waste each year!
- Conventional magnetic extraction technology at EFW plants recovers steel packaging present in the domestic waste stream after the incineration process.
- The recovery of the ferrous material is generally via a single pass suspended magnet - either an overband magnet or a drum magnet.

Kerbside collection

- Kerbside collection is becoming an increasingly common practice in many Local Authorities. Householders contribute to the scheme by putting their recyclate material into their kerbside boxes / sacks or wheelie bins as issued by the council.
- When the material is collected from the doorstep it can be sorted in two different locations. Some collection schemes sort their recyclate material at the kerbside. This is where the bags or boxes which are taken from the properties and sorted into different compartments onto the vehicle. The advantage of this method is that material is kept 'clean' and free from contaminants. The other method of sorting is for all the recyclate material which is collected at the kerbside to be taken to a MRF (Material Recycling Facility) central depot where operatives would separate the material.

Bring schemes

- Bring schemes are easy to use and provide opportunities to increase recycling levels for all cans.

- With can banks collecting steel cans right across the UK, 'bring' schemes continue to play an important role in the collection of steel drinks and food cans.
- A wide variety of can banks can be included in so-called 'milk-round' collection schemes: Hiab, FEL (front-end loader), REL (rear end loader), mini, modular and wheeled bins.
- The 14 cubic yard skip is a popular choice for bring schemes, as these large capacity banks are taken away to be emptied at a depot. To help minimize costs, an empty bank can be delivered and left on-site at the time of collecting a full skip for servicing, saving time and also reducing operational costs.

1.4. Manufacture and Assembly of Steel

https://www.youtube.com/watch?v=BvpmyOK6mx8

https://www.youtube.com/watch?v=l-0-W2AKPns

http://www.steel-insdag.org/TM_Contents.asp

1.5. Design Considerations

1.5.1. INTRODUCTION – DESIGN CONSIDERATIONS

The precise objectives of structural design vary from one project to another. In all cases, the avoidance of collapse is an important - if not the most important - requirement and an adequate factor of safety must be provided. In this context, the structure must be designed in order to fulfil both strength and stability requirements. These concepts are illustrated in Figure 1 in which a long thin rod is subject to tension (Figure 1a) and compression (Figure 1b). In the case of tension, the load resistance of the rod is governed by strength, that is the ability of the material to carry load without rupturing. The rod can only carry this load in compression if it remains stable, i.e. it does not deform significantly in a direction perpendicular to the line of action of the applied

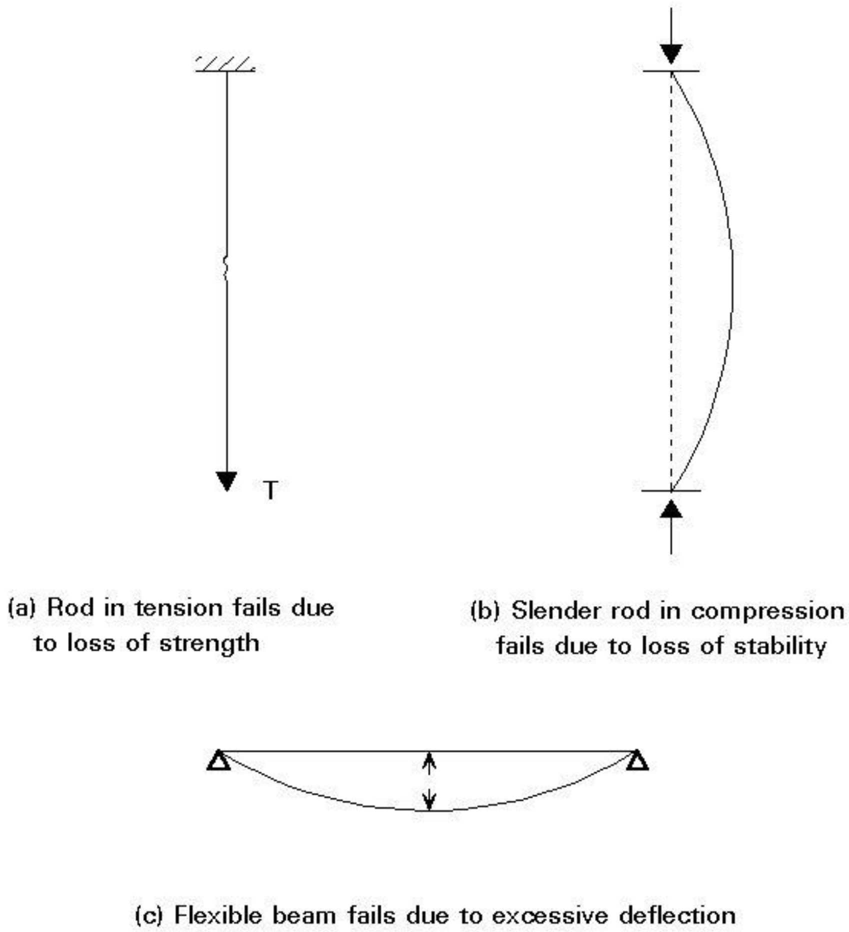


Figure 1 Failure modes

load. The stiffness of the structure is yet another important characteristic, concerned with resistance to deformation rather than collapse. This is particulary important in the case of beams whose deflection under a particular load is related to their stiffness (Figure 1c). Large deformations are not necessarily associated with collapse, and some brittle materials, such as glass, may rupture with little prior deformation. Other considerations may also need to be included in the design process. They include: quantifiable behaviour such as deformation, fatigue, fire resistance and dynamic behaviour; considerations such as corrosion and service accommodation which may influence both detail and overall concept, but in a more qualitative way; and appearance, which is largely a subjective judgement. In addition considerations of economy are likely to be a significant influence on the great majority of structural designs. In this context questions of speed and ease of construction, maintenance and running costs, as well as basic building costs, are all relevant. The relative importance of each of these aspects will vary depending on circumstances.

The approach to structural design is dealt with in Lecture 1B.1, which describes how the designer might begin to accommodate so many different requirements, many of which will exert conflicting pressures. In this lecture the focus is on how a satisfactory structural design can be achieved through a rational analysis of various aspects of the structure's performance. It is worth emphasising that the process of structural design can be considered as two groups of highly interrelated stages. The first group is concerned with defining the overall structural form - the type of structure, e.g. rigid frame or load bearing walls, the arrangement of structural elements (typically in terms of a structural grid), and the type of structural elements and material to be used, e.g. steel beams, columns and composite floor slabs. A high degree of creativity is required. The synthesis of a solution is developed on the basis of a broad understanding of a wide range of topics. The topics include structural and material behaviour, as well as a feel for the detailed implications of design decisions made at this stage - for instance recognising how deep a beam may need to be for a particular purpose. Formalised procedures are of little use at this stage. A satisfactory solution depends more on the creative ability of the designer.

The later stages are concerned with the more detailed sizing of structural components and the connections between them. By now the problem has become clearly defined and the process can become more formalised. In the case of steelwork the process generally involves selecting an appropriate standard section size, although in some circumstances the designer may wish to use a non-standard cross-section which, for execution, would then need to be made up, typically by welding plates or standard sections together into plate girders or trusses.

Design regulations are largely concerned with this stage of detailed element design. Their intention is to help ensure that buildings are designed and constructed to be safe and fit for purpose. Such design legislation can vary considerably in approach. It may be based simply on performance specification, giving the designer great flexibility as to how a satisfactory solution is achieved. An early example of this is the building laws published by King Hummarabi of Babylon in about 2200BC. They are preserved as a cuneiform inscription on a clay tablet and include such provisions as 'If a builder builds a house for a man and does not make its construction firm and if the house which he has built collapses and causes the death of the owner of the house, then that builder shall be put to death. If it causes the death of the son of the owner of the house, then a son of the builder shall be put to death. If it causes the death of a slave of the owner of the house, then the builder shall give the owner a slave of equal value'. The danger, and at the same time the attraction, of such an approach is that it depends heavily on the ability of the designer. Formal constraints, based on current wisdom, are not included and the engineer has the freedom to justify the design in any way.

The other extreme is a highly prescriptive set of design rules providing 'recipes' for satisfactory solutions. Since these can incorporate the results of previous experience gained over many years, supplemented by more recent research work they might appear to be more secure. However, such an approach cannot be applied to the conceptual stages of design and there are many cases where actual circumstances faced by the designer differ somewhat from those envisaged in the rules. There is also a psychological danger that such design rules assume an 'absolute' validity and a blind faith in the results of using the rules may be adopted.

Clearly there is a role for both the above approaches. Perhaps the best approach would be achieved by specifying satisfactory performance criteria to minimise the possibility of collapse or any other type of 'failure'. Engineers should then be given the freedom to achieve the criteria in a variety of ways, but also be provided with the benefit of available data to be used if appropriate. Perhaps the most important aspect is the attitude of the engineer which should be based on simple 'common sense' and include a healthy element of scepticism of the design rules themselves.

1.5.2. UNCERTAINTIES IN STRUCTURAL DESIGN

Simply quantifying the design process, using sophisticated analytical techniques and employing powerful computers does not eliminate the uncertainties associated with structural design, although it may reduce some of them.

These uncertainties include the following:

- loading.
- constitutive laws of the material.
- structural modelling.
- structural imperfections.

Loading is discussed in more detail in Lecture 1B.3. Although it is possible to quantify loads on a structure, it is important to recognise that in most cases these represent little more than an estimate of the likely maximum load intensity to which a structure will be exposed. Some loads, such as the self weight of the structure, may appear to be more easily defined than others, such as wind loads or gravity waves on offshore structures. However, there is a significant degree of uncertainty associated with all loads and this should always be recognised.

Constitutive laws are typically based on the results of tests carried out on small specimens. For convenience, the mathematical representation of the behaviour, for instance in the form of a stress-strain curve, is considered in a simplified form for the purpose of

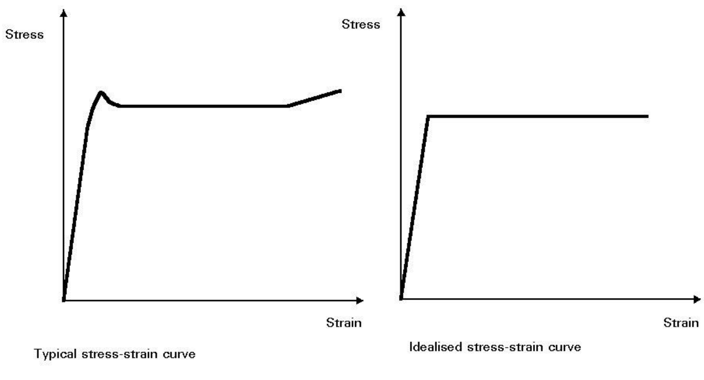


Figure 2 Mechanical properties of steel

structural design. In the case of steel the normal representation is linear elastic behaviour up to the yield point with plastic behaviour at higher strains (Figure 2). Although this representation provides a reasonable measure of the performance of the material, it is clearly not absolutely precise. Furthermore, any material will show a natural variability - two different samples taken from the same batch will typically fail at different stresses when tested. Compared with other materials, steel is remarkably consistent in this respect, but nevertheless variations exist and represent a further source of uncertainty.

Methods of analysing structural behaviour have advanced significantly in recent years, particularly as a result of developments in computing. Despite this, structural analysis is always based on some idealisation of the real behaviour. In some cases, such as isolated beams supported on simple bearings, the idealisation may be quite accurate. In other circumstances, however, the difference between the model and the real structure may be quite significant. One example of this is the truss which is typically assumed to have pinned joints, although the joints may in fact be quite rigid and some members may be continuous. The assumption that loadings are applied only at joint positions may be unrealistic. Whilst these simplifications may be adequate in modelling overall performance the implications, at least with regard to secondary effects, must be recognised.

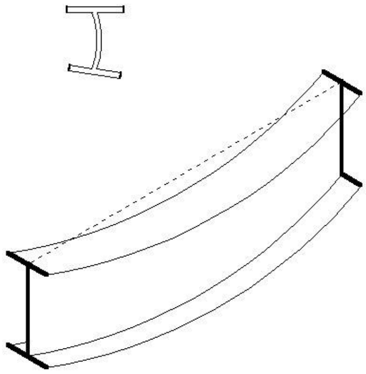


Figure 3 Geometric imperfections in cross-section and along the length of rolled sections (exaggerated)

Yet another source of uncertainty results from structural imperfections which are of two types: geometrical, i.e. out of straightness or lack of fit, and mechanical, i.e. residual stresses due to fabrication procedures or inhomogenities in the material properties. It is not possible to manufacture steel sections to absolute dimensions - wear on machinery and inevitable variations in the manufacturing process will lead to small variations which must be recognised. In the same way, although steel construction is carried out to much tighter tolerances than for most other structural materials, some variations (for instance in the alignment of individual members) will occur (Figure 3).

In adopting a quantified approach to structural design, all these uncertainties must be recognised, and taken into account. They are allowed for by the following means:

- specifying load levels which, based on previous experience, represent the worst conditions which might relate to a particular structural type.
- specifying a sampling procedure, a test plan and limits on material properties.
- specifying limits or tolerances for both manufacture and execution.
- using appropriate methods of analysis, whilst recognising the difference between real and idealised behaviour.

These measures do not eliminate the uncertainties but simply help to control them within defined bounds.

1.5.3. DESIGNING TO AVOID COLLAPSE

Historical Background

Structural design is not something which is new. Ever since man started building - dwellings, places of worship, bridges - some design philosophy has been followed, albeit often unconsciously. For many centuries the basis of design was simply to copy previous "designs". Where "new developments" or modifications were introduced, trial and error techniques were all that was available. As a result many structures were built, or partially built only to collapse or perform inadequately. Yet these failures did have a positive value in that they contributed to the fund of knowledge about what is workable and what is not.

This unscientific approach persisted for many centuries. Indeed it still forms part of the design approach adopted today. Rules of thumb and empirical design recommendations are frequently used, and these are largely based on previous experience. Nor is structural engineering today totally free of failures, despite the apparent sophistication of design methods and the power of computers. The dramatic box girder bridge collapses in the early 1970s were a grim reminder of what can happen if new developments are too far ahead of existing experience.

The emergence of new materials, notably cast and wrought iron, required a new approach and the development of more scientific methods. The new approach included testing, both of samples of the material and proof testing of structural components and assemblies. New concepts too were sometimes justified in this way, for instance in the case of the Forth Rail Bridge.

The first moves to rationalise structural design in a quantitative way came at the beginning of the 19th century with the development of elastic analysis. This type of analysis allowed engineers to determine the effect (on individual structural components) of forces applied to a complete structure.

Testing of materials provided information concerning strength and, in the case of iron and steel, other characteristics such as the elastic limit. Of course there were often great variations in the values measured, as indeed there are even today with some materials. In order to ensure a safe design, a lower bound on the test results - a value below which experimental data did not fall - was normally adopted as the 'strength'. Recognising some of the uncertainties associated with design methods based on calculation, stresses under maximum working load conditions were limited to a value equal to the elastic limit divided by a factor of safety. This factor of safety was specified in an apparently arbitrary fashion with values of 4 or 5 being quite typical.

This approach provided the basis of almost all structural design calculations until quite recently, and for some applications is still used today. As understanding of material behaviour has increased and safety factors have become more rationalised, so design strengths have changed. Changes in construction practice, and the development of new, higher strength materials, have necessitated detailed changes in design rules, particularly with regard to buckling behaviour. However the basic approach remained unchanged until quite recently when certain limitations in classical allowable-stress design became apparent. The limitations can be summarised as follows:

i. there is no recognition of the different levels of uncertainty associated with different types of load.

ii. different types of structure may have significantly different factors of safety in terms of collapse, and these differences do not appear in any quantifiable form.

iii. there is no recognition of the ductility and post-yield reserve of strength characteristic of structural steelwork.

The last of these limitations was overcome by the work of Baker [1] and his colleagues in the 1930s when plastic design was developed. This method was based upon ensuring a global factor of safety against collapse, allowing localised 'failure' with a redistribution of bending stresses. A comparison of elastic and plastic design is given by Beal [2].

In recognition of the disadvantages of the allowable stress design method, an alternative approach, known as limit state design has been adopted. Limit state design procedures have now become well established for most structural types and materials. The approach recognises the inevitable variability and uncertainty in quantifying structural performance, including the uncertainties of material characteristics and loading levels. Ideally, each uncertainty is typically treated in a similar manner using statistical techniques to identify typical or characteristic values and the degree of variation to be expected from this norm [3]. It is then possible to derive partial safety factors, one for each aspect of design uncertainty, which are consistent. Thus different load types, for instance, have different factors applied to them. The structure is then examined for a variety of limit states. In that case the structure is designed to fail under factored loading conditions, giving a clearer picture of the margins of safety than was previously the case with allowable stress design.

Stability

Inadequate strength is not the only cause of collapse. In particular the designer must ensure adequate stability, both of the complete structure (a function of the overall structural form) and of each part of it (dependent on individual member proportions and materials). The latter is generally dealt with by modifying the material strength to account for individual conditions. Overall stability is very much more difficult to quantify and must be carefully considered at the earliest stage of structural design. In this sense structural stability can be defined by the conditions that a structure will neither collapse (completely or partially) due to minor changes, for instance in its form, condition or normal

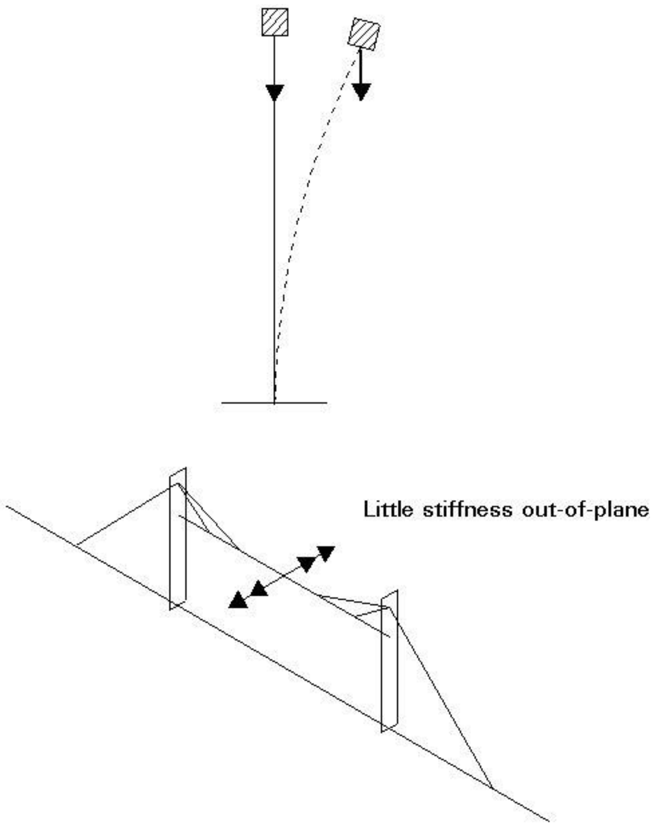


Figure 4 Examples of structural arrangements which are potentially unstable

loading, nor be unduly sensitive to accidental actions. Some examples are shown in Figure 4.

In designing for stability the positioning of the main load-bearing elements should provide a clearly defined path for transmitting loads, including wind and seismic actions to the foundations. In considering wind loads on buildings it is important to provide bracing in two orthogonal vertical planes, distributed in such a way as to avoid undue torsional effects, and to recognise the role of the floor structure in transmitting wind loads to these braced areas (Figure 5). The bracing can be provided in a variety of ways, for instance by cross-bracing elements or rigid frame action.

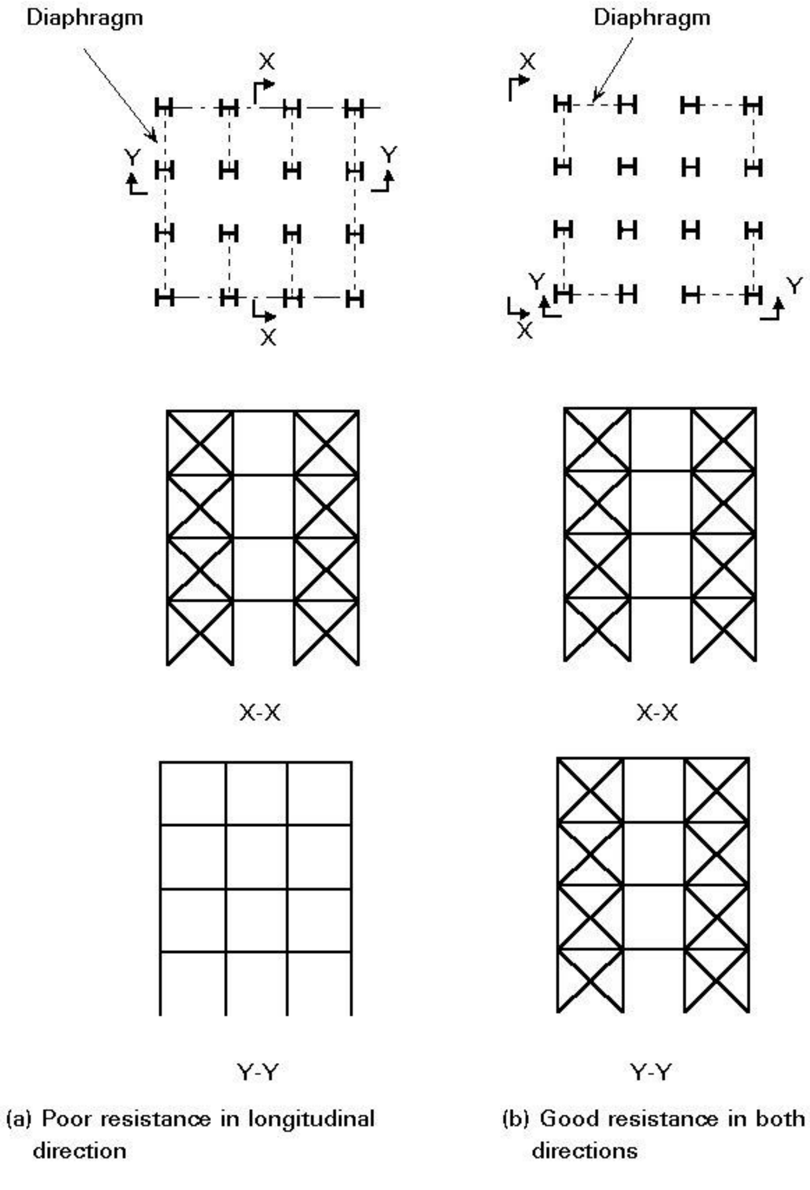


Figure 5 Sway stability

Consideration of accidental actions, such as explosions or impact, is more difficult, but the principle is to limit the extent of any damage caused. Limitation of damage can be achieved by designing for very high loads (not generally appropriate) or providing multiple load paths. Design requires consideration of local damage rendering individual elements of the structure ineffective, and ensuring the remaining structure is able to carry the new distribution of loads, albeit at a lower factor of safety. Alternative strategies are to provide for dissipation of accidental actions, for instance by venting explosions, and to protect the structure, for instance by installing bollards to prevent vehicle impact on columns (Figure 6).

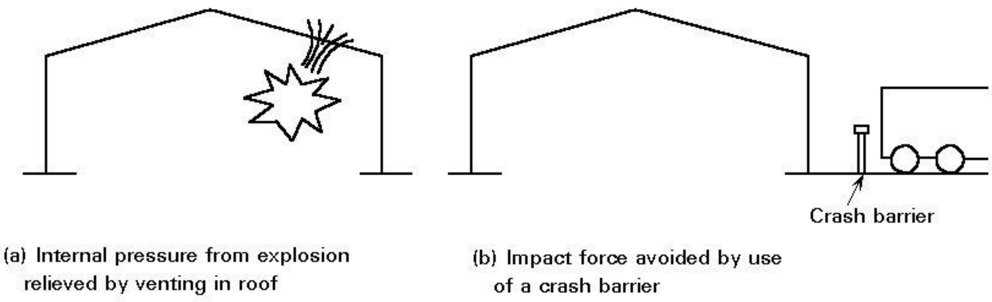


Figure 6 Alternative strategies for dealing with accidental actions

Structural stability must of course be ensured when alterations are to be carried out to existing structures. In all cases stability during execution must be very carefully considered.

Robustness

In many ways robustness is associated with stability. Construction forms which fulfil the primary function of accommodating normal loading conditions - which are highly idealised for design purposes - may not perform a secondary function when the structure is subject to real loading conditions. For instance the floor of a building is normally expected to transmit wind loads in the horizontal plane to the braced positions. Transmission of wind loads can only be achieved if there is adequate connection between the floor and other parts of the structure and building fabric, and the floor itself is of a suitable form of construction.

OTHER DESIGN OBJECTIVES

Although design against collapse is a principal consideration for the structural engineer, there are many other aspects of performance which must be considered. None of these aspects can be quantified and only certain ones will normally apply. However, for a successful solution, the designer must decide which considerations can be ignored, what the most important criteria are in developing the design, and which can be checked simply to ensure satisfactory performance.

4.1 Deformation

The deflection characteristics of a structure are concerned with stiffness rather than strength. Excessive deflections may cause a number of undesirable effects. They include damage to finishes, (particularly where brittle materials such as glass or plaster are used), ponding of water on flat roofs (which can lead to leaks and even collapse in extreme cases), visual alarm to users and, in extreme cases, changes in the structural behaviour which are sufficient to cause collapse. Perhaps the most common example of deflection effects occurs in columns, which are designed for largely compressive loads but may become subject to significant bending effects when the column deforms in a horizontal plane - the so called P-delta effect.

The normal approach in design is to check that calculated deflections do not exceed allowable levels, which are dependent upon structural type and finishes used. For instance, deflection limits for roof structures are not normally as severe as those for floor structures. In performing these checks it is important to recognise that the total deflection δ_{max} consists of various components, as shown in
Figure 7, namely:

$$\delta_{max} = \delta_1 + \delta_2 - \delta_0$$

where δ_1 is the deflection due to permanent loads

δ_2 is the deflection due to variable loads

δ_0 is the precamber (if any) of the beam in the unloaded state.

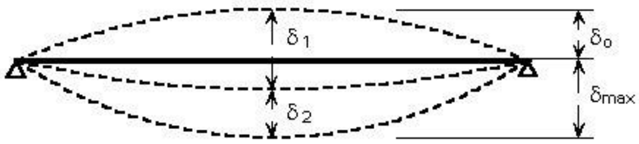


Figure 7 Components of deflection to be considered

In controlling deflections it is often necessary to consider both δ_{max} and δ_2, with more severe limits applying in the latter case.

Although the calculated deflections do not necessarily provide an accurate prediction of likely values, they do give a measure of the stiffness of the structure. They are therefore a reasonable guide to structural performance in this respect. With the trend towards longer spans and higher strength materials, design for deflection has become more important in recent years. In many cases this consideration dictates the size of structural elements rather than their resistance. In the case of certain structures, deflection control is of paramount importance. Examples include structures supporting overhead cranes and those housing sensitive equipment. Design for deflection is likely to be the critical condition in such cases.

4.2 Vibration

The vibration characteristics of a structure are, like deflection behaviour, dependent upon stiffness rather than strength. The design principle is to adopt a solution for which the natural frequency of vibration is sufficiently different from any source of excitation, such as machines, to avoid resonance. Longer spans, lighter structures and a reduction in the mass and stiffness of partitions and cladding have all contributed to a general lowering of the natural frequencies for building structures. Cases of human discomfort have been recorded and Eurocode 3 [4] now requires a minimum natural frequency of 3 cycles per second for floors in normal use and 5 cycles per second for dance floors.

Wind excited oscillations may also need to be considered for unusually flexible structures such as very slender, tall buildings, long-span bridges, large roofs, and unusually flexible elements such as light tie rods. These flexible structures should be investigated under dynamic wind loads for vibrations both in-plane and normal to the wind direction, and be examined for gust and vortex induced vibrations. The dynamic characteristics of the structure may be the principal design criterion in such cases.

4.3 Fire Resistance

The provision for safety in the event of fire is dealt with in Group 4B. It is a common requirement that structural integrity is maintained for a specified period to allow building occupants to escape and fire-fighting to be carried out without the danger of structural collapse. For steel structures alternative design strategies can be adopted to achieve this requirement. The traditional approach has been to complete the structural design 'cold' and to provide some form of insulation to the steelwork. This approach can give an expensive solution and alternative methods have now been developed, allowing reductions, and in some cases complete elimination, of fire protection. In order to implement these alternatives in an effective manner, it is important that, at an early stage in the design process, the structural design considers how the fire resistance of the steelwork is to be achieved. Adopting a design solution which may be relatively inefficient in terms of the weight of steel for normal conditions may be more than offset by savings in fire protection (Figure 8).

Buildings close to a site boundary may require special consideration to prevent an outbreak of fire spreading to adjacent sites due to structural collapse. Again quantitative design procedures have been developed for such circumstances [5].

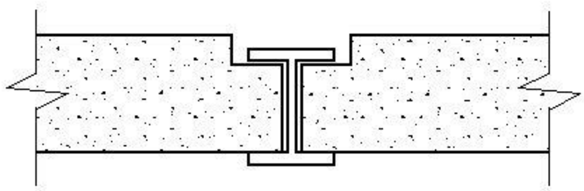


Figure 8 'Slimfloor' beams provide effective fire resistance to unprotected steel beams

4.4 Fatigue

Where structures, or individual structural elements, are subject to significant fluctuations in stress, fatigue failure can occur after a number of loading cycles at stress levels well below the normal static resistance. The principal factors affecting fatigue behaviour are the range of stresses experienced, the number of cycles of loading and the environment. Structures which need particular consideration in this respect are crane gantry girders, road and rail bridges, and structures subject to repeated cycles from vibrating machinery or wind-induced oscillations. Design guidance is included in Eurocode 3 [4].

4.5 Execution

One of the principal advantages of steelwork is the speed with which execution can proceed. In order to maximise this advantage it may be necessary to adopt a structurally less efficient solution, for instance by using the same profile for all members in a floor construction, even though some floor beams are less highly loaded than others (Figure 9). Temporary propping

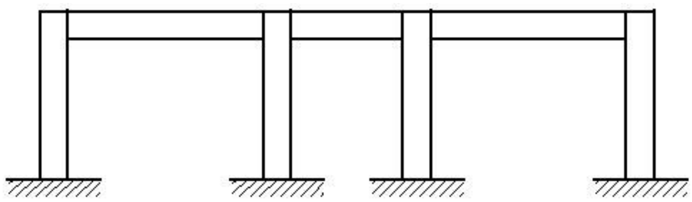


Figure 9 Adopting the same profile for all the members in a floor may be inefficient in material usage, but results in economy of construction

should be avoided as must late changes in detail which might affect fabrication.

It is important that the structure is not considered in isolation, but rather treated as one part of the complete construction, along with services, cladding and finishes. By adopting a co-ordinated approach to the design, integrating the parts and eliminating or reducing wet trades, speed of execution of the project as a whole can be maximised. A good example of this is the two-way continuous grillage system used for the BMW Headquarters at Bracknell and other projects [6].

The installation of services can have significant implications for speed, cost and detail of construction. In buildings with major service requirements, the cost of the services can be considerably greater than the cost of the structure. In such circumstances it may well be better to sacrifice structural efficiency for ease of accommodating the services. The design of the total floor zone including finishes, structure, fire protection and services also has implications for other aspects of the building construction. The greater the depth of floor construction, the greater the overall height of the building and hence the quantity of external cladding required. In many commercial developments very sophisticated and expensive cladding systems are used. Savings in cladding systems may more than offset the use of shallower, but less efficient, floor construction. Where there is strict planning control of overall building height, it may even be possible to accommodate additional storeys in this way.

4.6 Maintenance

All structures should be inspected and maintained on a regular basis, although some conditions are likely to be more demanding in this respect. For instance, steelwork within a dry, heated interior environment should not suffer from corrosion, whilst a bridge structure in a coastal area will need rigorous maintenance schedules. Some structural forms are easier to maintain than others, and where exposure conditions are severe, ease of inspection and maintenance should be an important criterion. Principal objectives in this context are the avoidance of inaccessible parts, dirt and moisture traps, and the use of rolled or tubular individual sections in preference to truss-like assemblies composed of smaller sections.

DESIGN RESPONSIBILITIES

One engineer should be responsible for ensuring that the design and details of all components are compatible and comply with the overall design requirements. This responsibility is most important when different designers or organisations are responsible for individual parts of the structure, such as foundations, superstructure and cladding. It should include an appraisal of the working drawings and other documents to establish, inter alia, that requirements for stability have been incorporated in all elements, and that they can be met during the execution stage.

Effective communication both within the design team and between the designer and constructor before and during execution is essential. Good communication will help to avoid potential design conflicts, for instance when services have to penetrate the structure, and also to promote safe completion of the structure in accordance with the drawings and specification. The constructor may also require information concerning results of site surveys and soil investigations, design loadings, load resistance of members, limits on positions of construction joints, and lifting positions on members to be erected as single pieces. A statement accompanied by sketches detailing any special requirements should be prepared when necessary, e.g. for any unusual design or for any particularly sensitive aspects of the structure or construction. This statement should be made available to the contractor for appropriate action regarding temporary works and execution procedures.

The designer should be made aware of the proposed construction methods, erection procedures, use of plant, and temporary works. The execution programme and sequence of erection should be agreed between the designer and constructor.

Full and effective communication between all parties involved will help not only to promote safe and efficient execution but may also improve design concepts and details. Design should not be seen as an end in itself, but rather as an important part of any construction project.

CONCLUDING SUMMARY

- There are very many uncertainties associated with structural design. However powerful the tools available, the engineer should always recognise that the design model is no more than an idealisation and simplification of the real condition.
- A quantified approach to structural design can take different forms with a view to providing a framework for satisfactory solutions. The application of design rules should be tempered with common sense and understanding.
- Structural design must consider many aspects of both performance and cost. The most efficient structural solution may not result in the most efficient solution overall if other interdependent aspects of the construction are not considered in a co-ordinated fashion.

1.6. FABRICATION & ASSEMBLY

The fabricator's role is to convert rolled steel into finished goods with added value. This is achieved by selling workmanship and machine utilisation on a competitive basis where costs are directly related to time.

Fabricators rely increasingly upon production engineering techniques. Their continued success in this direction depends upon better standardisation. Time and therefore labour costs can be cut significantly by the repetition of dimensions and geometry, member sizes and shapes, centres and diameters of bolts, etc. All of these are amenable to rationalisation. Further economy is derived by reducing the number of detailed components, which tend to be labour intensive to produce, even when this results in heavier parent members. The cardinal rule is that, relatively, labour is expensive but material is cheap (Figure 1).

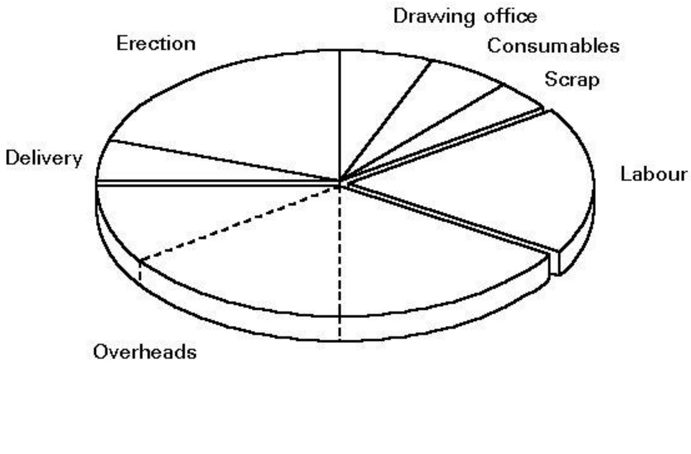


Figure 1 Fabricator's costs for steelwork for light / medium buildings.

COST STRUCTURE

Fabrication costs are estimated by separating the various activities into categories such as cutting, drilling and welding which enables man hours to be allocated and valued to arrive at a total price.

Relying upon a combination of historical data and practical experience, the cost build-up bears little relationship to the weight of steel involved, although cost references in ECU/tonne can be a useful index for rapid comparison of different classes of work.

A typical breakdown in costs, in the light to medium category, shows that over 50% of the fabricator's cost is absorbed by labour charges and overhead expenses (Figure 1).

It is customary to recover such expenses as a contributory factor to labour. If the ratio between labour and overheads is 1: 2½, it is significant that for every 100 ECU of labour cost incurred, the amount chargeable would be 100+250=350ECU.

PRODUCTION NETWORK

Fabricating companies differ widely in layout, capacity and scope. Whilst the extent and nature of the services available is influenced by policy and resources, the basic flow of activities tends to follow a similar pattern. This can be visualised as a tunnel for the main flow or Primary Operations, supported by branches or Secondary Operations (Figure 2).

This network forms the basis for production control, which is time related to cost standards. Output must be geared to the sequence of the construction programme. This rarely coincides with the most effective use of all resources. The system has to be extremely flexible to respond to changes in demand whilst minimising disruption or costly delays.

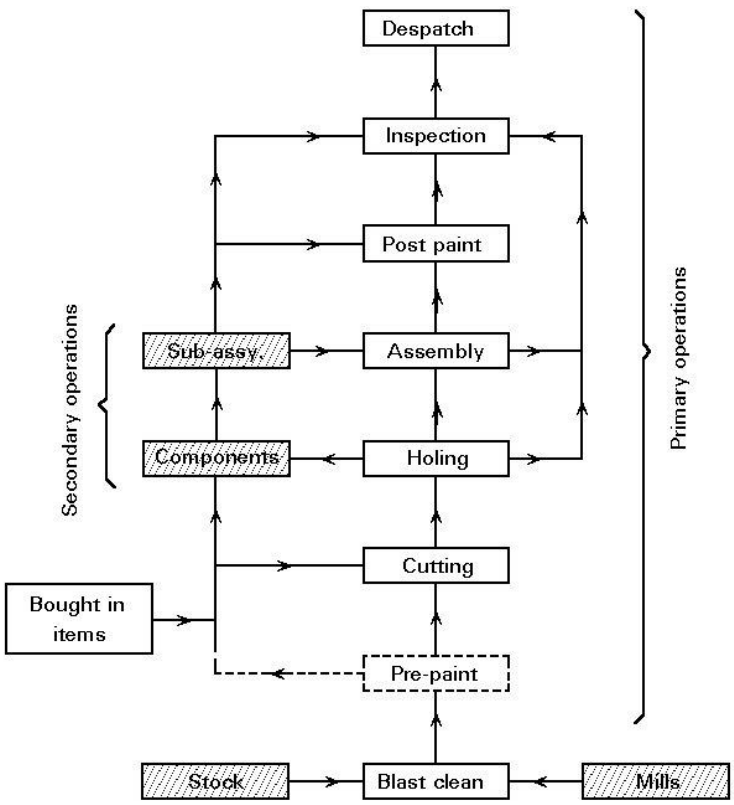


Figure 2 Production network

Primary / Secondary Production

The planning objective is to schedule production so that raw material is transformed into a finished state within an allocated time.

Since most of the important machine tools, such as saws, are sited at the start of the primary production line, the flow of material has to be sustained by an independent supply of essential components such as brackets, cleats and plates in the correct quantities and in the correct order.

This is the task of secondary production together with sub-assembly of detailed fabrications in suitable cases. Bought-in (BI) items or services of a specialised nature such as forgings, pressings or even non-destructive testing have to be available at the correct time.

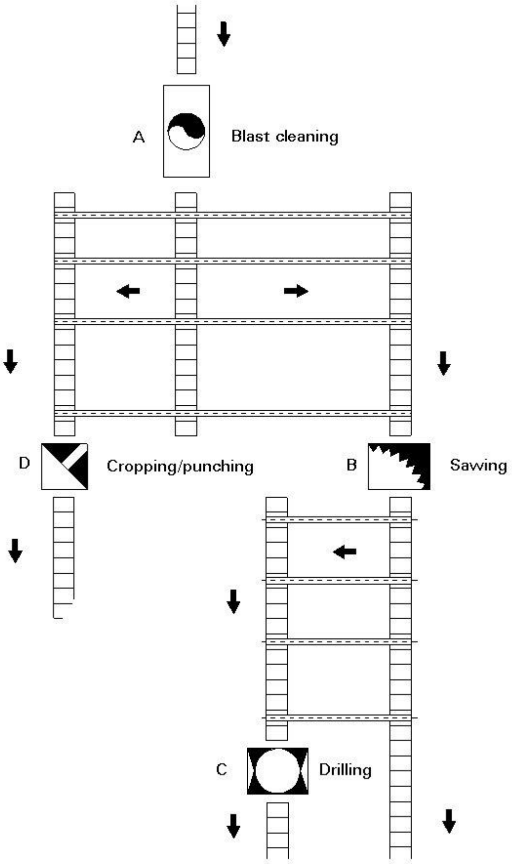


Figure 3 Typical workshop layout

Workshop Layout - Material Preparation

Steel framed buildings are mainly constructed as a series of linear elements using standard sections. The preparation area for these is typified by a group of fixed work sections consisting of (Figure 3):

A. Blast cleaning

B. Sawing

C. Drilling

D. Cropping/Punching

The initial step is to pass the steel through a blast cleaning cabinet at "A" to remove any surface rust and mill scale. Various levels of surface treatment are available, but for most buildings, a standard of SA 2½ to the Swedish specification SIS 055900 is adequate. This requires at least 95% of the surface to be clean.

The next stage is to transfer the material to the sawing station at "B" for cutting to length followed by drilling of holes at "C". In a number of workshops, sawing and simultaneous 3 axis drilling may be combined as one activity. Alternatively, angle sections and flats of suitable thickness for cropping and punching would be routed directly to "D".

For speed and ease of handling, sections are transported increasingly by a system of powered conveyors fed by cross transfers. The latest automation now allows all operations and material flow to be conducted from a central numerically controlled console.

Because plates are less stiff, these tend to be more awkward to handle. Lifting and handling is usually carried out by an overhead magnetic crane for subsequent cutting by flame or guillotine in a separate plate working area.

Workshop Layout – Assembly / Finishing

At this stage the main elements on the primary flow are joined by secondary components, end plates, stiffeners, etc. for fitting and assembly, mostly by welding. Depending upon the nature and purpose of the structure, some bolting may be used, if only for trial alignment. However, as a general rule, shop connections are welded and site connections bolted.

Due to variations in the size and nature of the work carried out in any period, the assembly area has to be extremely flexible and well serviced by cranes. Output must be geared to the sequence of the construction programme. As a result designated areas may have to be switched rapidly from beams and columns to bulky lattice girders.

Further planning complications arise because the most cost effective use of workshop labour and equipment rarely coincides with site requirements. It is for this reason that seemingly simple modifications are costly to execute once production has commenced.

Where priming paint is required, elaborate specifications, which are not necessary for steelwork contained within a normal building environment, can easily add 20% to fabrication costs. The function and future maintenance requirements should be considered in each case, rather than adopting a blanket philosophy.

Paint coatings for structural steelwork should "flash off" fairly rapidly to allow further handling and to minimise congestion. Whilst brushing is suitable for touching up minor damage, large surfaces can only be covered economically by spraying. Spraying can be carried out manually or automatically where the work is conveyed through an enclosed cabinet containing the spray nozzles. The process may also be supplemented by a drying kiln.

After assembly, inspection concentrates mainly upon overall dimensions, position of cleats, holes and so on, to ensure proper alignment during site erection. Framed elements, such as latticed girders, are self checking to a certain extent by virtue of the fit of members during assembly. This principle is often used to prove complex structures by trial erection prior to despatch.

Where in-depth weld examination is required, it should be conducted at the appropriate stage determined by the nature of the work, and to the level specified by the Engineer. In the interests of economy however, it should be noted that radiographic and allied techniques are, not only expensive operations, but attract additional costs due to their disruptive influence upon production. Judgement should be exercised to confine the programme of examination to those areas critical to structural performance.

The aim of inspection is to ensure that the steelwork complies with the contract documents. For the majority of building structures the inspection pattern outlined is practical and economic. Where more precise tolerances or accuracy are required, the frequency and intensity of inspection may need to be higher. For this reason inspection procedures need to be clearly identified in the tender documents so that appropriate provisions may be made by the fabricator.

Following an itemised numerical check together with application of identification marks, the steelwork is transferred to the finished stockyard unless it is due for immediate transport. There it is stacked ready for consignment, together with any loose fittings wired together and attached to the parent member.

Transport operating costs are not based upon load factor. A vehicle loaded to a fraction of its rated capacity will cost exactly the same as one which is fully laden. Framed elements occupy considerable space but it may be possible to mitigate the consequences by the number and disposition of splices.

In addition to the site programme, due regard must be given to limitations of off-loading and handling facilities, to access restricted to particular timings, to clearance under low bridges, and to police authority requirements concerning the transport of wide loads.

GENERAL - ERECTION

Whilst steelwork erection may be regarded as the final stage of fabrication, it differs from the latter in two principal ways: firstly, there is the added dimension of height and the time occupied by vertical movement of materials, equipment and labour; secondly, the fact that work has to be carried out in the open means that progress may be hampered by adverse weather.

By its nature, work done on site can become unduly expensive. The primary aim of the programme should be to minimise costs by condensing the time scale realistically. Options and alternatives need to be carefully examined at the preliminary design stage otherwise the scope for reducing the time scale may be unduly restricted.

Clearly the significance of the various issues will vary according to the type of building and any limitations which the site and its environment may impose. Even when structures possess marked similarities, different erection methods and procedures may need to be adopted. For this reason, only the broad principles concerning erection can be stated.

5.1 Site Planning

Invariably, erection of structural steelwork has to be closely integrated with other major trades such as flooring, cladding and services. Operations on site where there may be competition for limited resources, are potentially difficult to control. A far-sighted strategy has to be developed and maintained.

Key objectives and, most importantly, starting and finishing dates must be clearly established and progress reviewed on a regular basis. Failure to meet commitments can result in substantial cost penalties. Further complications may easily arise which are totally disproportionate to the cause.

5.2 Site Organisation

The maximum size and weight of the various steel members which can be delivered may be restricted on a site with limited and restricted access.

Narrow streets in a busy town centre may cause difficulties with space to manoeuvre. Waiting time to off-load may also be restricted to specific periods. Matters of this kind must be investigated well in advance and decisions made accordingly.

Within site, movement may often be hampered by a variety of obstructions such as scaffolding, shoring, pile caps, excavation, and so on. Service roads and off-loading areas need to be hard cored and adequately drained to support heavy vehicles during the severest winter conditions. The steelwork has to be erected in the general sequence determined by the construction programme. Each consignment of steel has to be strictly regulated to this timetable. Whilst in some instances, a few key components can be lifted directly from the vehicle into position, most of the material will need to be off-loaded and stacked temporarily until needed.

The area of the site allocated for this purpose has to be orderly and well managed, particularly where space is limited. To compensate for minor interruptions in delivery, for example due to traffic delays, a small buffer stock is usually held in reserve.

Space is also required for laying material out and for assembly of frames or girders prior to hoisting into position.

5.3 Setting Out

Before commencement of erection, the plan position and level of the column bases should be verified by the erection contractor. This needs to be carried out as soon as possible to ensure that any errors can be corrected in good time or, at least, alternative measures approved and introduced.

Checks should include not only the centres of the foundation bolts relative to the reference grid lines, but also the projection of the bolts above the base level.

To compensate for minor discrepancies, a limited amount of deviation of the column from its true vertical and horizontal position is provided for by the grout space under the baseplate and by leaving a movement pocket around each bolt during pouring of the concrete. Normally this will allow latitude of about ±25mm in any direction.

5.4 Operations

Steel erection may appear to be a series of distinct operations when in reality they overlap and merge. Nevertheless, each complete stage of the work has to follow a methodical routine which consists of:

- Hoisting
- Temporary Connections
- Plumbing, lining and levelling
- Permanent connections.

Because minor dimensional inaccuracies can accumulate during fabrication and setting out, it would be impractical to complete the entire structure before compensating for these by adjustment. The work is therefore sub-divided into a number of phases which may be controlled by shape or simply by an appropriate number of bays or storeys. For stability, each phase relies upon some form of restraint to create a local box effect. This effect may be achieved in various ways, such as employment of temporary or permanent diagonal bracing.

Initially, end connections and base anchorages are only secured temporarily. After completion of plumbing, lining and levelling, all connections are then made permanent by tightening up all nuts or inserting any bolts initially omitted to assist adjustment. This process allows substantial areas to be released quickly for grouting and following trades are able to proceed much earlier than would otherwise be possible.

5.5 Single-Storey Buildings

Under normal circumstances, single-storey buildings are quickly and easily erected. A high proportion of industrial buildings are rigid jointed. It is common practice to bolt, assemble or weld these joints on the ground and then lift the complete frame upright using a mobile crane.

Lattice girders and trusses are also erected in a similar manner but temporary stiffening may be required to prevent lateral buckling. Care should also be taken, by provision of lifting eyes or similar at specific positions, to ensure that slender members are not subjected to undue compressive stresses.

Ideally, erection should commence at an end which is permanently braced. When this is not possible, temporary bracings should be provided at regular intervals as a safeguard against collapse or deformation (Figure 7).

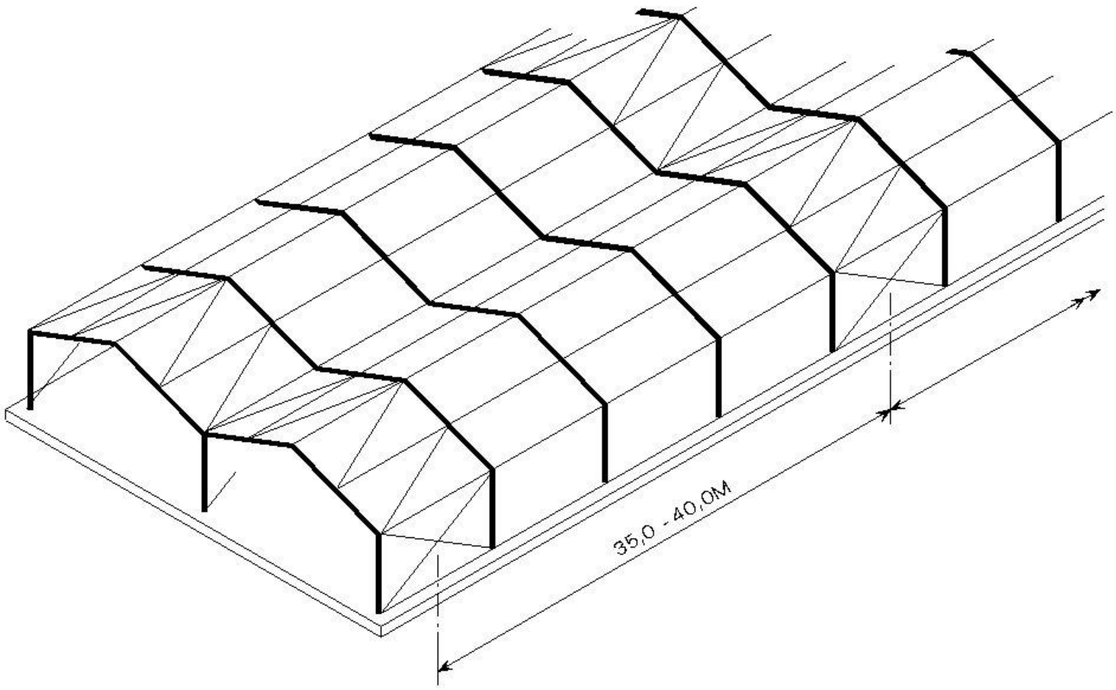


Figure 7 Single storey building

Space frames are designed to span in two directions. Because of the number of connections required, it is much more economical to assemble the modules at ground level where the joints are readily accessible and then hoist the complete framework. Two or possibly four cranes may be needed depending on the size of the building. Meticulous co-ordination is essential.

5.6 Multi-storey Buildings

In most cases, multi-storey buildings are erected storey by storey enabling the lower floors to be completed earlier, offering access, overhead safety and weather protection. Depending upon the site, a single tower crane may be the sole lifting facility. In this case use of the crane has to be shared between a number of sub-contractors, thereby limiting available "hook" time for any given trade.

Since the position of a tower crane is fixed (Figure 8), it is completely independent of any obstructions, such as basements or ground slabs, which could deny access to a mobile crane. This independence allows useful freedom in overall planning. However, the fixed location also means a fixed arc of lifting capacity where the load will be minimum at the greatest reach. As a result the steelwork may have to be provided with site splices simply to keep the weight of the components within such limits.

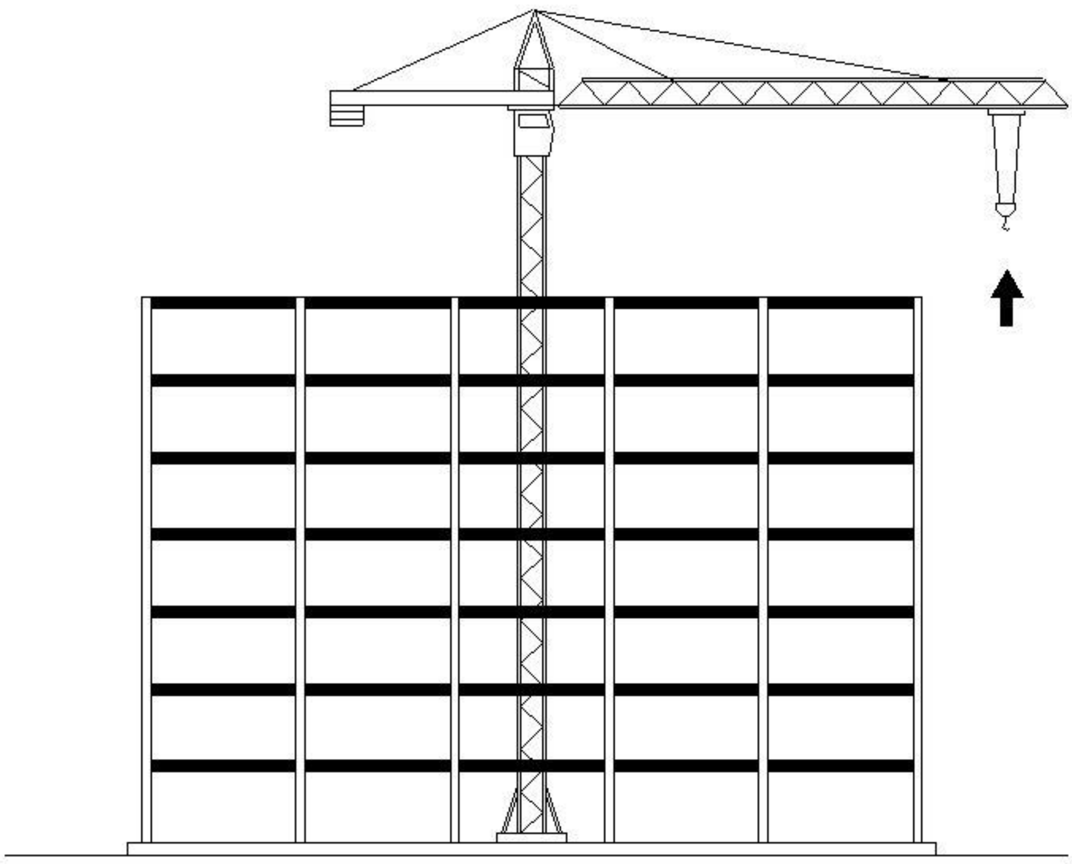


Figure 8 Multi-storey building erected by tower crane

One of the major virtues of a mobile crane (Figure 9) is its flexibility and independence which enables it to keep moving with the flow of the work. These cranes are generally fitted with telescopic jibs which allow then to become operational very quickly. The vehicles are stabilised during lifting by extended outriggers equipped with levelling jacks.

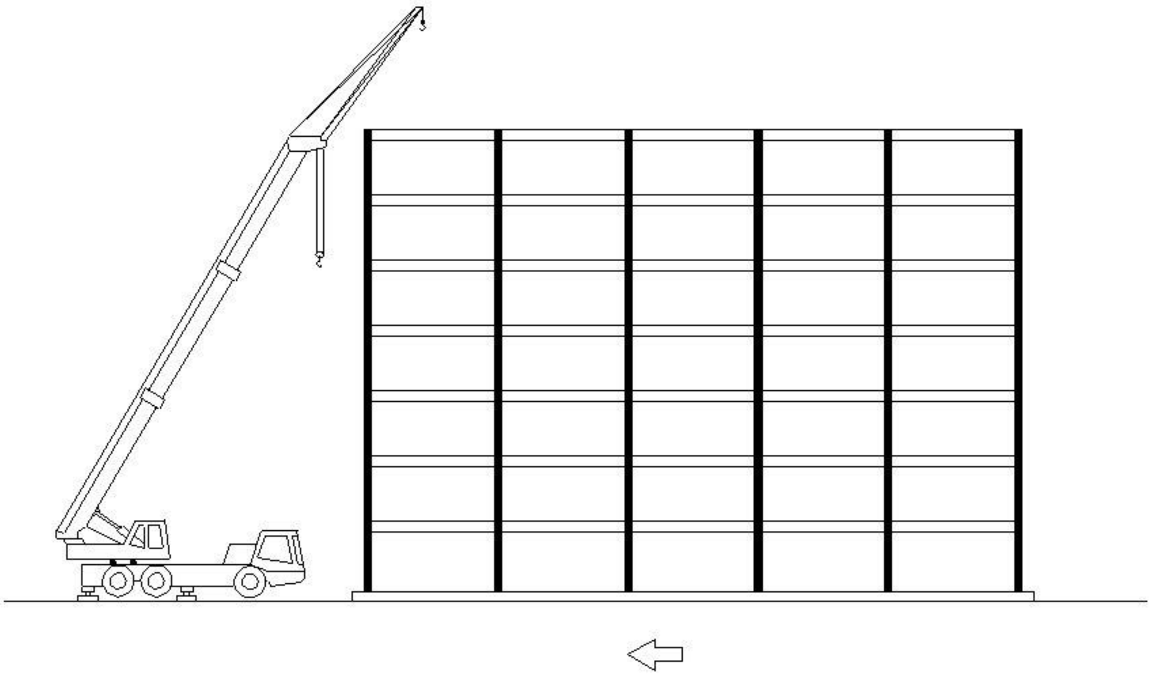


Figure 9 Multi-storey building erected by mobile crane

Whilst permanent stability in the completed building may be introduced, in a number of ways, including braced bays, rigid joints and stiff service cores (Figure 10) and via diaphragm action of the floors, stability must also be ensured throughout the entire construction programme. It may therefore be necessary to install temporary bracings solely for this purpose, which must not be removed until the permanent system has been provided and has become effective.

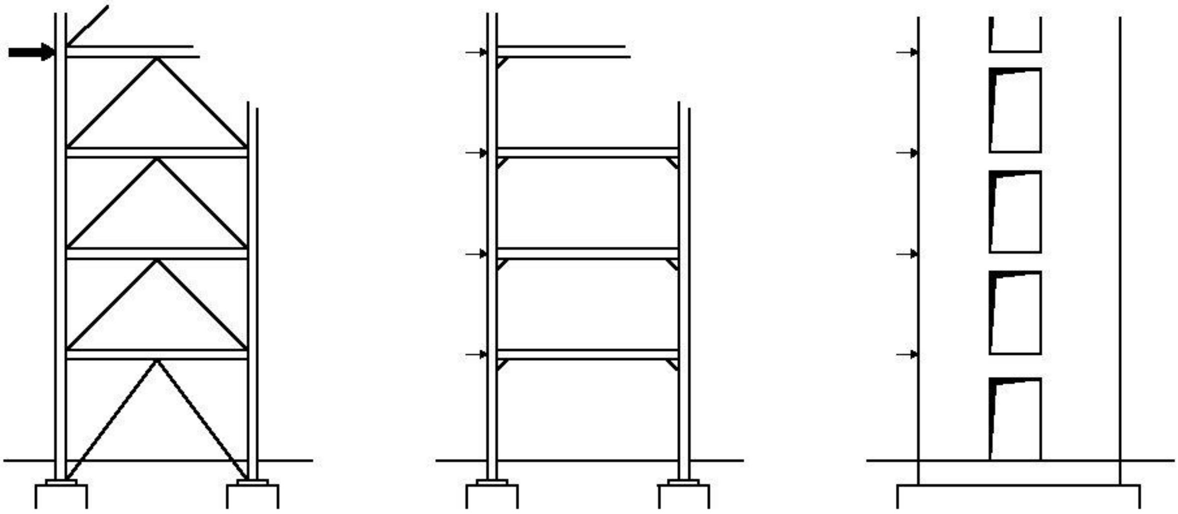


Figure 10 Bracing systems

5.7 Timing

The rate of steelwork erection is governed by a wide range of factors some of which are beyond the influence of the design engineer. The factors which he can control include:

- type of end connections.
- extent/type of bolting or welding.
- number of separate pieces.

Simple connections for shear force are straightforward and employ Grade 4.6 or 8.8 bolts. The bolt diameter should be selected with a degree of care. For example, whilst a single M30 bolt has more than twice the shear capacity of two M20's, the effort required to tighten an M30 bolt is some 3½ times greater. An M20 bolt can be tightened without difficulty using ordinary hand tools, a considerable advantage when working at height.

Joints which are required to transmit bending moments are inherently more robust and may require stiffening ribs and haunches; if this is the case careful attention is required to ensure access for the bolts. For such applications pre-tensioned bolts are often used. They are normally tightened to a minimum torque using a power operated wrench.

Compared to bolting, the site welding of joints is time-consuming and expensive for conventional structures. There may be occasions, however, when site welding is the only realistic way to form a joint, as, for example, in alterations or remedial work. In this case, joint preparation, fitting, inspection and the provision of purpose made enclosures (for access and weather protection) are additional cost factors that must be taken into account.

As a rough guide, about 50% of erection man hours are occupied with lining, levelling, plumbing and final bolting and the remainder of the time is spent hoisting members into position. However, in suitable cases, beam and column elements may be pre-assembled at ground level and lifted directly on to their foundations.

5.8 Safety

The erection of a building framework is potentially hazardous. Many serious and fatal accidents occur each year on construction sites and most of these are caused by falling from, or whilst gaining access to, heights; handling, lifting and moving materials, however, are also hazardous.

Risks can be minimised considerably by measures such as adequate provision for stability throughout construction, accessibility of splices and connections, guard rails and attachments for safety harnesses and so on.

In addition, safety, need not be compromised on grounds of cost. For example, it will prove cheaper to assemble frames at ground level (Figure 11) rather than bolt them together in mid-air. Metal decked floor systems are not only economical but offer rapid access for all trades whilst providing overhead protection. Safer access is also promoted by the immediate provision of steel stair flights at each floor level as steelwork erection proceeds.

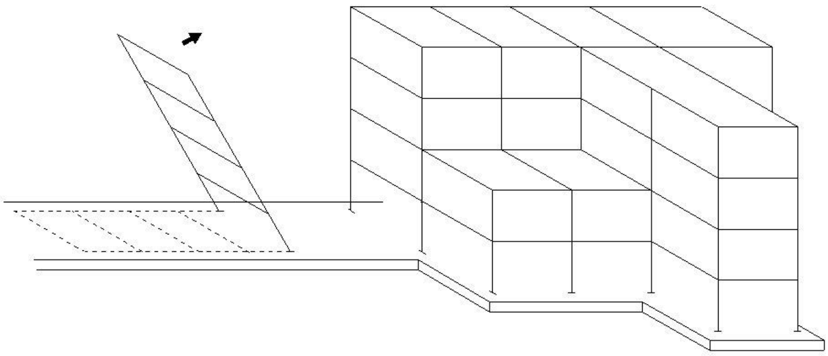


Figure 11 Erection of assembled frames

Current and future legislation may place greater responsibilities upon the design engineer because of the influence of design and details on the method and sequence of erection.

CONCLUDING SUMMARY

- Steelwork erection normally occupies a relatively short period in the construction programme, but considerable activity occurs during this time which is vital to the performance of the contract as a whole.
- The steel framework should not be seen in isolation but as a key link in the construction chain where the time saved can have considerable impact in lowering overall costs.
- Early consideration should be given to erection during design and detailing so that the full benefits of steel construction may be realised and, the need for late changes and subsequent compromise can be substantially reduced.

1.7. INDUSTRIAL / FACTORY BUILDINGS

The reasons for the wide use of steel for industrial buildings are discussed. The advantages of steel include its high strength-to-weight ratio, speed of erection and ease of extension. Steel is used not only for members but also for cladding.

Common types of structure are described. These types include portal frame, lattice girder and truss construction. It is shown that overall stability is easily achieved. The wide variety of sections used in industrial buildings is presented. Possible approaches to global analysis are identified.

1. TYPES OF INDUSTRIAL BUILDING

A wide variety of building types exists, ranging from major structures, such as power stations and process plants, to small manufacturing units for high quality goods.

The most common type is the simple rectangular structure (Figure 1), typically single-storey, which provides a weatherproof and environmentally comfortable space for carrying out manufacturing or for storage. First cost is always an overriding consideration, but within a reasonable budget a building of good appearance with moderate maintenance requirements can be achieved. While ease of extension and flexibility are desirable, first cost usually limits the provisions which can be usefully included in the design for these potential requirements. Although savings in the cost of specific future modifications can be achieved by suitable provisions, for example by avoiding the use of special gable frames (Figure 2), changes in manufacturing processes or building use may vary the modifications required.

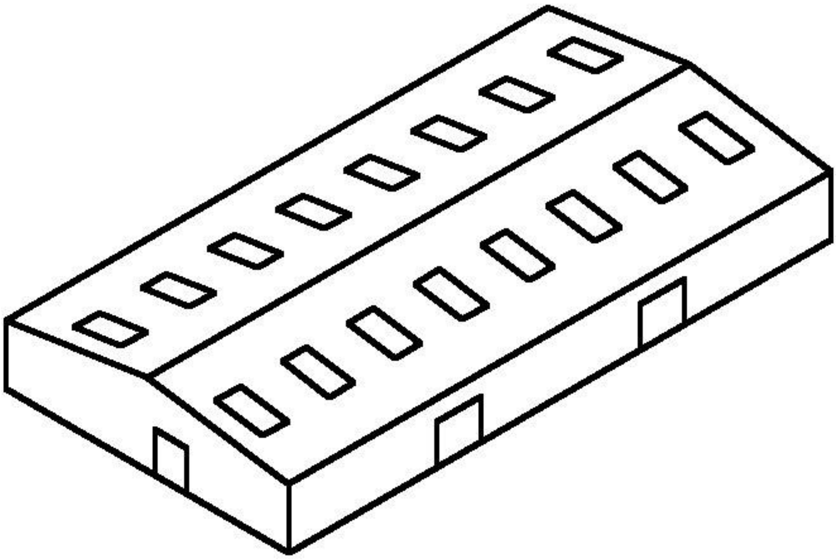
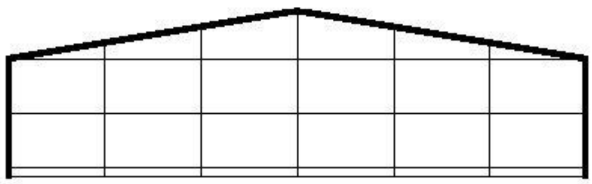
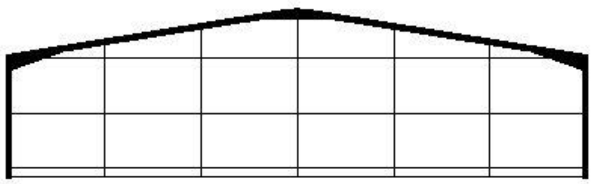


Figure 1 Typical industrial building

When, for reasons of prestige, the budget is more liberal, a complex plan shape or unusual structural arrangement may provide a building of architectural significance.



Gable frame (does not permit future extension)



End portal frame (permits future extension)

Figure 2 Gable ends

While many features are common to all industrial buildings, this lecture deals mainly with single-storey buildings of straightforward construction and shape.

2. STRUCTURAL STEEL FOR INDUSTRIAL BUILDINGS

Compared to other materials, particularly reinforced or prestressed concrete, steel has major advantages. Its high strength-to-weight ratio and its high tensile and compressive strength enable steel buildings to be of relatively light construction. Steel is therefore the most suitable material for long-span roofs, where self-weight is of prime importance. Steel buildings can also be modified for extension or change of use due to the ease with which steel sections can be connected to existing work.

Not only is steel a versatile material for the structure of a building, but a wide variety of cladding has been devised utilising the strength developed by folding thin sheets into profiled form (Figure 3). Insulated cladding systems with special coatings are now widely used for roofing and sidewall cladding. They have good appearance and durability, and are capable of being speedily fixed into position.

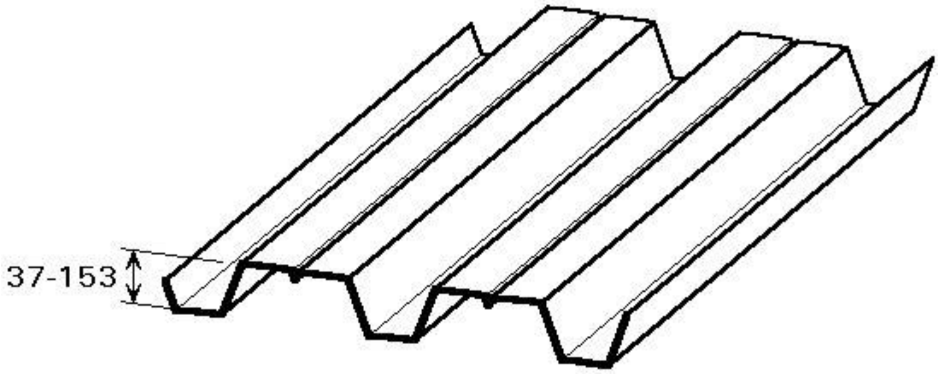


Figure 3 Cladding

The structure of a steel building, especially of an industrial building, is quickly erected and clad, providing a weatherproof envelope which enables the floor and installation of services and internal finishes to proceed at an early stage. Since the construction schedule is always tied to the earliest handover date fixed by production planning, time saved in construction is usually very valuable.

In a dry closed environment steel does not rust, and protection against corrosion is needed only for the erection period. For other environments protection systems are available, which, depending on cost and suitable maintenance, prevent corrosion adequately.

Single storey industrial buildings are usually exempt from structural fire protection requirements. Spread of fire beyond the boundary of the building must not occur as a result of collapse of the structure. This requirement can be met by the provision of fire walls and through the restraint which arises in practice between the bases and the columns which they support.

3. CHOICE OF INDUSTRIAL BUILDING

A prospective owner may have a fully detailed design brief derived from the construction of industrial plants elsewhere. More usually the owner is assisted in the choice of a suitable building by the completion of a detailed list of requirements so that a design brief can be prepared. Initial options in respect of preferred location, site acquisition and environmental needs must first be decided. Then main dimensions, process operation, plant layout, foundation needs, handling systems, daylighting, environmental control, service routes, staffing level and access all require definition.

The preliminary selection must be made between a building specially designed for the owner, a new factory largely built of standard structural components, or the adaptation of an existing building. The latter may be either an advance unit built as a speculative development, or a unit which has been vacated.

The location of internal columns and the internal headroom are always important, and consideration of these requirements alone may determine the choice. The advantage of freedom to plan the building to suit requirements closely and allow for future development is very valuable. However, unless there are exceptional reasons such as permanence of specific use, it is unwise to design an industrial building exclusively for a single process, since special features appropriate to the process may make redevelopment difficult.

4. SHAPES OF INDUSTRIAL BUILDINGS

Because of its economy, the most widely used building shape is the pin-based single or multi-bay pitched roof portal frame, typically of 20-30m span at 6m centres (Figure 4). Hot-rolled I, welded or cold-formed sections are usually used for the members.

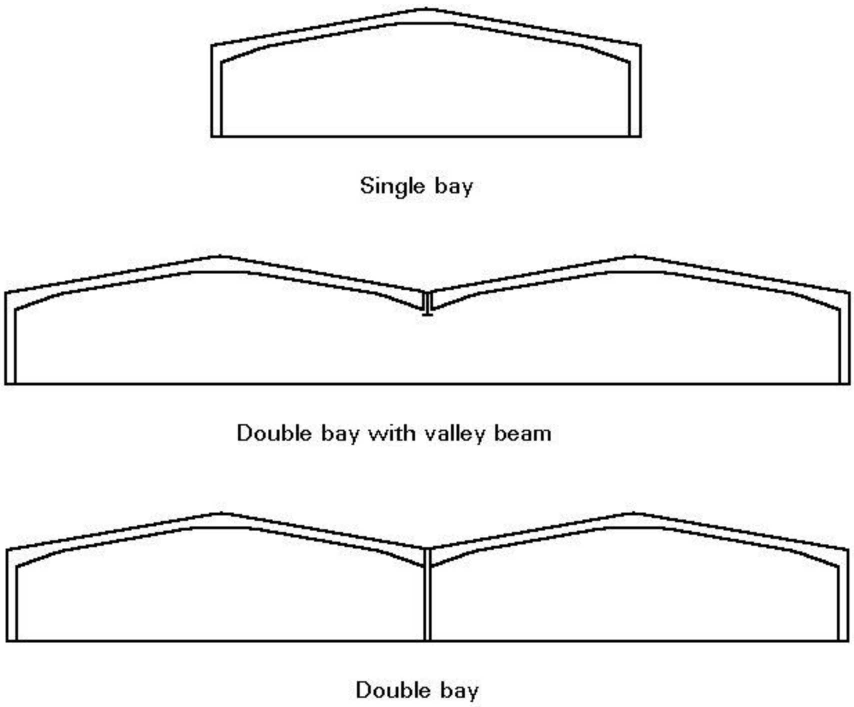
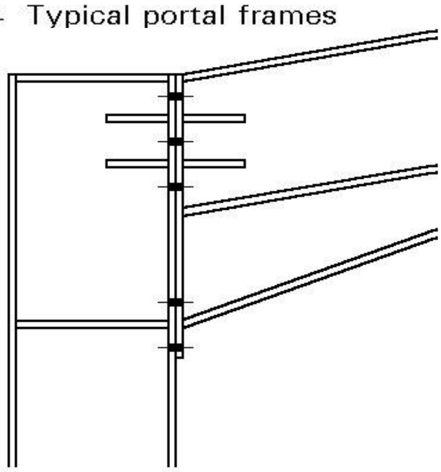


Figure 4 Typical portal frames

During recent years an increasing use of welded sections has occurred. This increase is the result of progress achieved in making welding automatic and the ability to adapt the cross-section to the internal forces.

Since internal columns sterilise an appreciable space around them, their spacing may be increased by using spine I-beams to support the portal rafters. For this type of roof the cladding is usually insulated metal decking, which may also be used for the upper sidewalls. Daylight is provided by profiled translucent sheeting in the roof.

When hot-rolled sections are used, haunches (Figure 5) are usually provided at the eaves and the ridge. These haunches deepen the overall section, thereby reducing bolt forces. By extending the haunched regions along the rafter the frame is also strengthened and stiffened.



Lattice girders (Figure 6) are lighter than portal frame rafters for wider spans, but the additional workmanship increases fabrication costs. Based on structural requirements alone, lattice systems are likely to be cost-

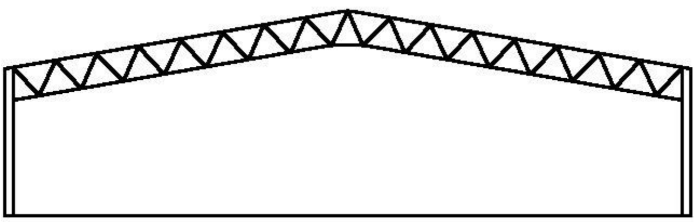


Figure 6 Lattice girder structure

effective for spans above 20m. Roof trusses may also be used for structures which support heavy cranes (Figure 7).

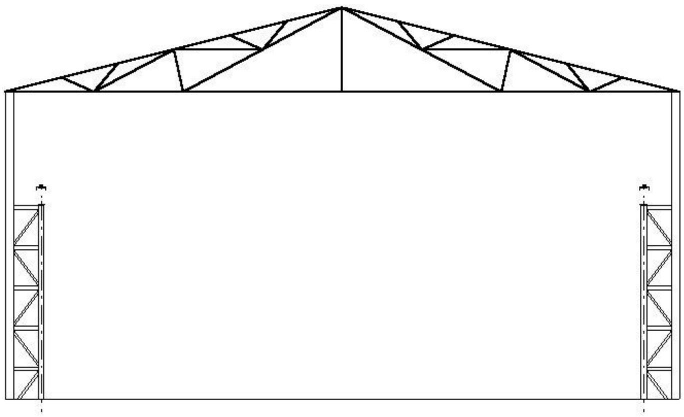


Figure 7 Lattice column and roof truss construction

A wide variety of structural sections may be used for lattice girders and roof trusses, including single angles, angles back- to-back, tees, H-sections or hollow sections (Figure 8). For light loading, cold-formed sections may be used as booms, with reinforcing bars as the web members (Figure 9).

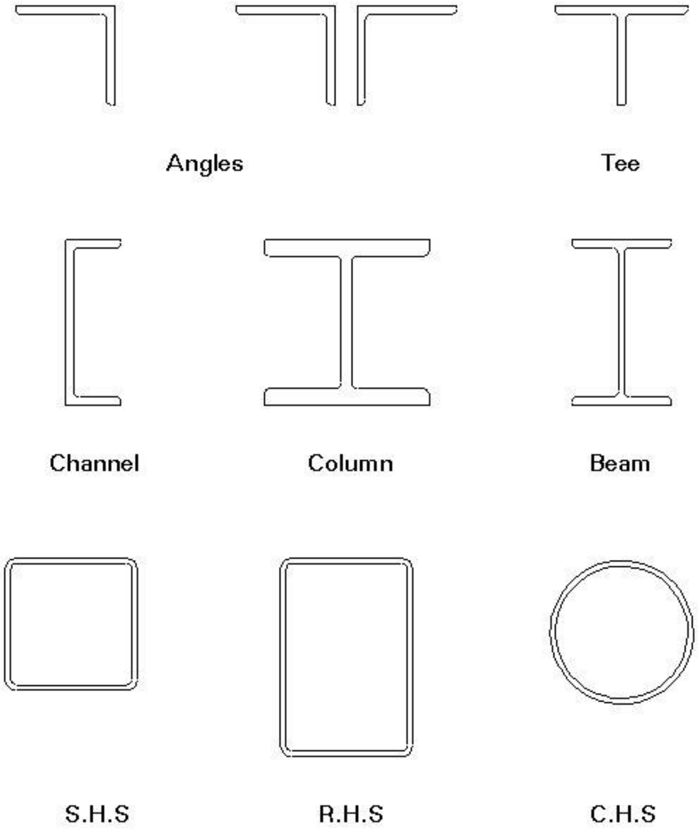


Figure 8 Structural sections

The disadvantages of multi-bay pitched roofs are that internal gutters and rainwater disposal are required, which are a possible source of leaks, and access to plant mounted externally on the roof is difficult.

The most versatile roof shape is the nominally flat roof, covered with an insulated membrane on metal decking (Figure 10). This shape allows wide freedom in plan form, and eliminates the need for internal gutters, although some internal rainwater disposal may be necessary if the extent of the roof is large. The mounting and weather protection of external plant on the roof is simply achieved, and access can readily be provided.

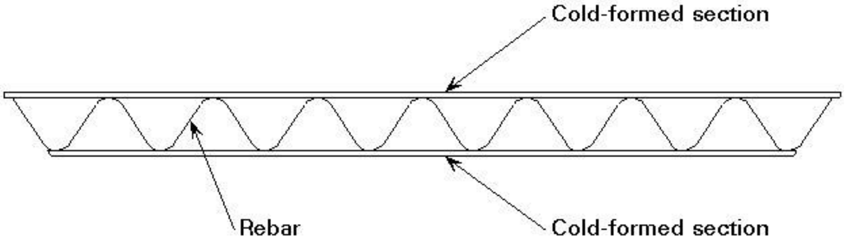


Figure 9 Light lattice beam

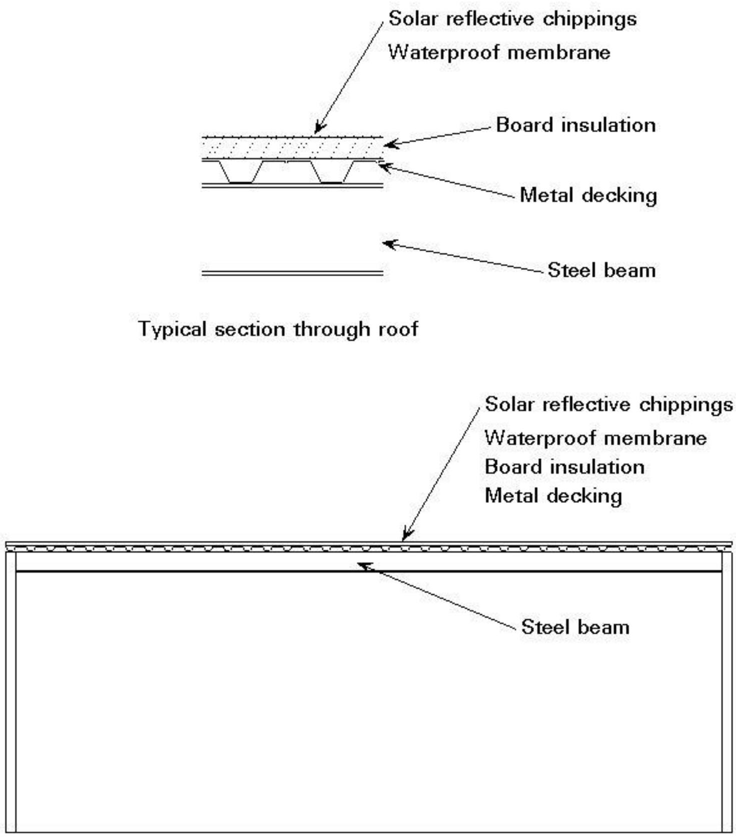


Figure 10 Steel decking on flat roof

Flat roofs can be supported by rolled or cold-formed purlins on main I-beams or lattice girders. For smaller structures the deck may span directly from one frame to another, without the need for purlins.

When services are extensive and there are many external plant units on the roof, castellated beams or double-layer grid space frames (Figures 11 and 12) can be very suitable for flat roofs. The two-way grid distributes local loads better than any other structural form. The support for the roof deck is provided directly by the top layer and support for the services by the bottom layer of the grid. Castellated beams have a much higher moment of resistance than I-beams.

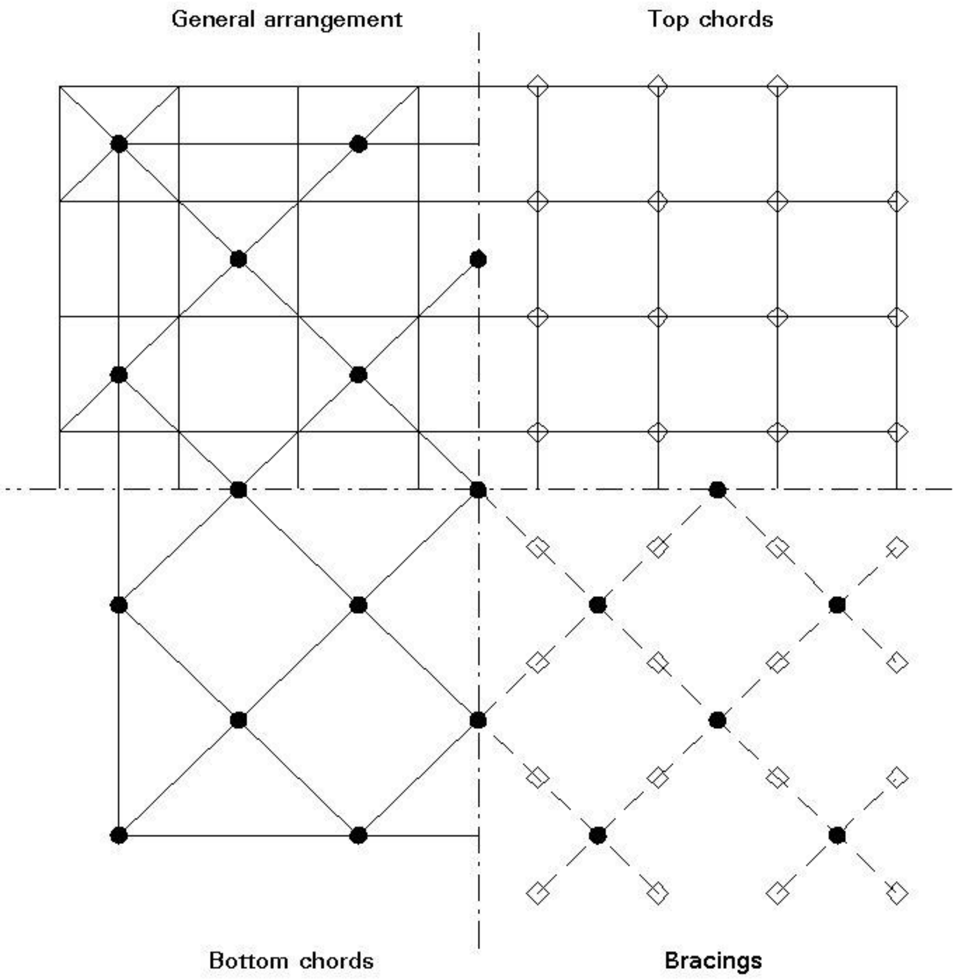


Figure 11 Double layer grid space frame

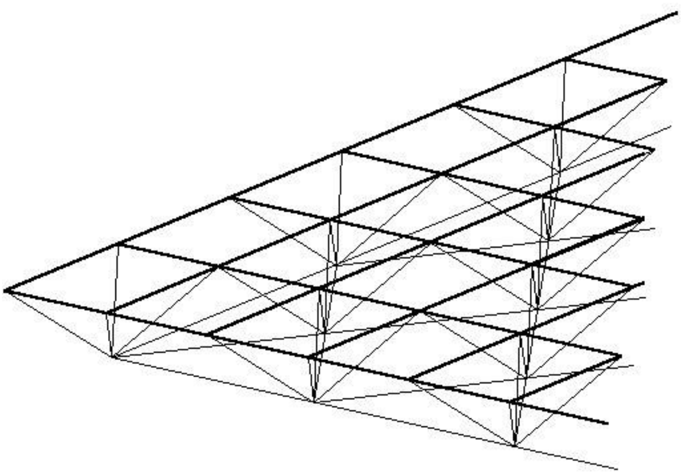


Figure 12 Double layer grid space frame

The provision of daylighting in flat roofs is expensive, since either dome or monitor lights must be used. Flat roofs are most common for industries where daylighting requirements are minimal.

5. STABILITY OF INDUSTRIAL BUILDINGS

It is essential to ascertain the loads applied to the structure and to determine the load paths from the cladding to the purlins and side rails, through the main frames to the foundations. The loads may arise from dead load, wind load and snow load, and sometimes from cranes or impact caused by fork-lift trucks.

The overall resistance of simple single-storey industrial buildings to horizontal loading is usually easy to achieve. One of the attractions of portal frame buildings is that in-plane stability follows from the rigidity of the frame connections. Stabilising bracing between the portals is therefore only required in line with corresponding rafter bracing in the roof plane.

For short buildings, bracing in one end bay may be sufficient. For longer buildings, bracing of two or more bays may be necessary.

The rafter bracing itself provides restraint to the heads of the gable stanchions. The braced end bays provide anchor points to which the longitudinal rafter stabilising ties, which are usually the purlins, are attached. During erection, bracing facilitates plumbing and squaring of the building, as well as providing essential stability.

For frames with lattice girders (Figure 6), in-plane stability can be provided by connecting both top and bottom booms to the column.

If the building has roof trusses (Figure 7), or if only the top booms of the lattice girders are connected to the column (Figure 13), the frame is effectively pinned at eaves level. To provide in-plane stability, either the column bases should be fixed or longitudinal girders should be provided in the plane of the roof (Figure 14). These girders span between the gable ends, which must be braced appropriately. If the building is long, or is divided by expansion joints, longitudinal bracing may not be practicable and the columns must have fixed bases.

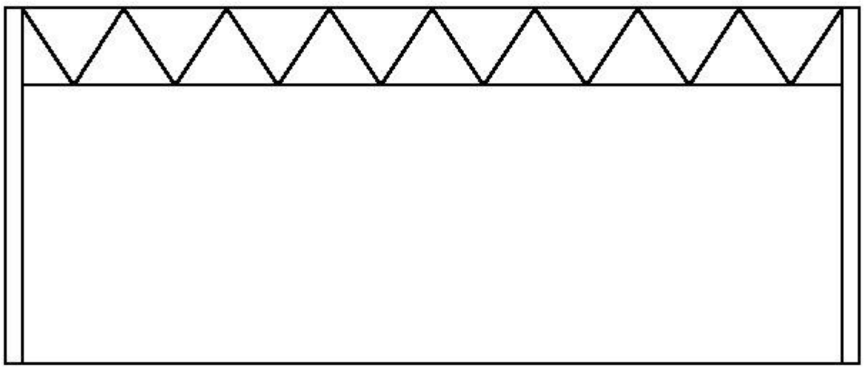


Figure 13 Lattice beam and columns

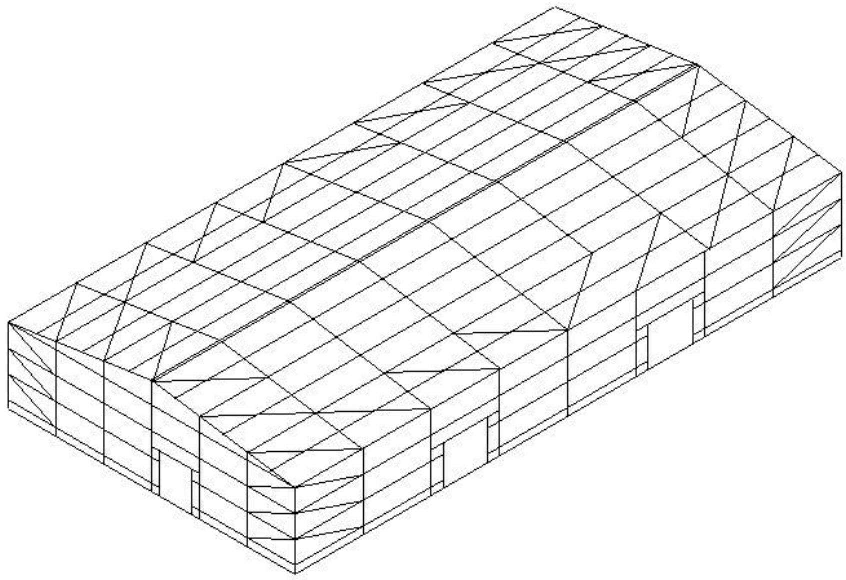


Figure 14 Bracing systems

Buildings using lattice girders or truss roofs also need bracing to provide longitudinal stability.

Bracing members for industrial buildings commonly use circular hollow sections, rods or angles.

When cranage is provided the stability requirements need further examination, since longitudinal and transverse surge from the crane increases the forces in the bracing systems.

6. GLOBAL ANALYSIS

The structure may be treated either as a 2-D or 3-D system.

Bracing systems are analysed as if pin-jointed. When cross-bracing is used, for example in vertical bracing, only the members in tension are assumed to be effective (compression members are assumed ineffective because of buckling).

The choice of the method of global analysis, either plastic or elastic, of portal frames at the ultimate limit states depends on the class of the cross-section.

An example of the plastic collapse mechanism of a frame with haunches is given in Figure 15. Buildings with cranes should always be analyzed elastically. Elastic analysis should always be used to determine deflections under service loading.

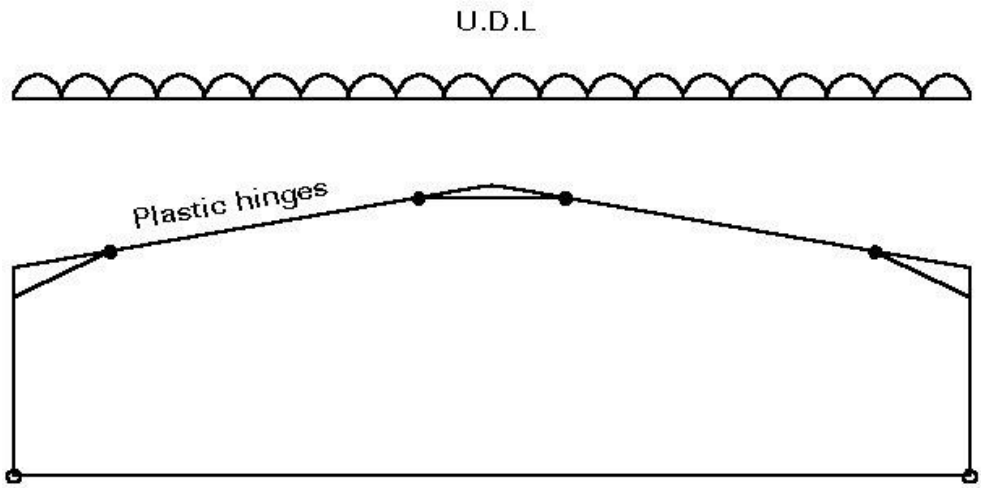


Figure 15 Plastic collapse mechanism

7. CONCLUDING SUMMARY

- Steel construction is widely used for industrial buildings, including structural members (like frames, purlins, side rails) and cladding systems.
- Overall stability is obtained from the rigidity of connections and the use of bracing systems.
- The buildings may be analyzed using 2-D or 3-D modelling and elastic or plastic analysis, depending on their cross-sections.
- A wide variety of hot-rolled shapes are available for structural members. More flexibility can be obtained using welded sections. Purlins and side rails may be formed from cold-rolled sections

1.8. MULTI-STORY BUILDINGS

The notes gives a brief description of the fundamental components of a building frame. It presents different structural arrangements to resist horizontal and vertical loadings. Finally, consideration is given to the question of fire protection.

1. INTRODUCTION

A multi-storey building must resist the combined effects of horizontal and vertical loads; it is composed of foundations, frameworks and floor slabs.

The framework comprises columns and beams together with horizontal and vertical bracings, which stabilise the building by resisting horizontal actions (wind and seismic loads).

Floor slabs are supported by beams so that their vertical loads are transmitted to the columns. They are made of reinforced concrete or composite slabs using profiled steel sheets. Columns are commonly made of H or hollow hot-rolled steel sections. The use of hollow sections filled with concrete can improve their fire resistance. Beams are commonly made of I and H profiles. Nevertheless, the use of welded built-up sections can offer more rational solutions in some cases.

The usual structural systems belong essentially to two categories: moment resisting frame systems and braced-frame systems, the second being the simplest and, therefore, the most economic solution.

In braced frames, vertical bracings are formed by diagonal members within the steel frame. These bracings may be of different form (cross-braced X shaped; V or inverted V shaped; symmetrical or unsymmetrical portal). Alternatives to steel bracings are the reinforced concrete shear walls or cores.

These main components of multi-storey buildings and their design are described in the following section:

2. THE STRUCTURAL SCHEME

A multi-storey building includes the following structural components (Figure 1):

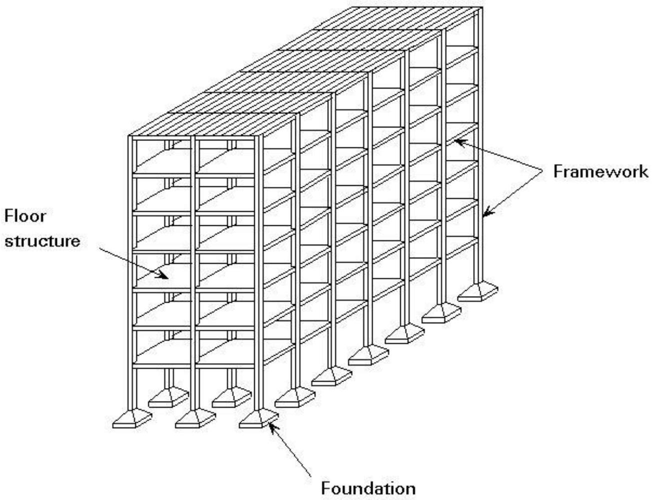


Figure 1 Main structural components of a multi-storey building

a. foundations

b. framework

c. floor structures.

Foundations are made of reinforced concrete. The type of foundation is selected according to the features of the ground and the ground conditions.

The framework is the steel skeleton which provides the load-bearing resistance of the structure and supports the secondary elements such as the floor slab and cladding.

All external loads, both vertical and horizontal, are transmitted to the foundations by means of the steel framework. It is mainly composed of vertical elements (columns) and horizontal elements (beams), which may be connected together in different ways. According to the degree of restraint at the beam-to-column connections, the framework can be considered as 'rigid', 'semi-rigid' or 'pin-ended'. For the pin-ended case, the framework must incorporate bracing elements which are located in the rectangular panels bounded by columns and beams.

The floor slabs are required to resist the vertical loads directly acting on them and to transmit these loads to the supporting floor beams. They also transfer the horizontal loads to the points on the framework where the bracing members are located.

The structural arrangement of multi-storey buildings is often inspired by the shape of the building plan, resulting in different solutions (Figure 2). The plan can be rectangular (Figure 2a), L-shaped (Figure 2b), curved (Figure 2c), polygonal (Figure 2d) or perhaps composed of rectangular and triangular elements (Figure 2e).

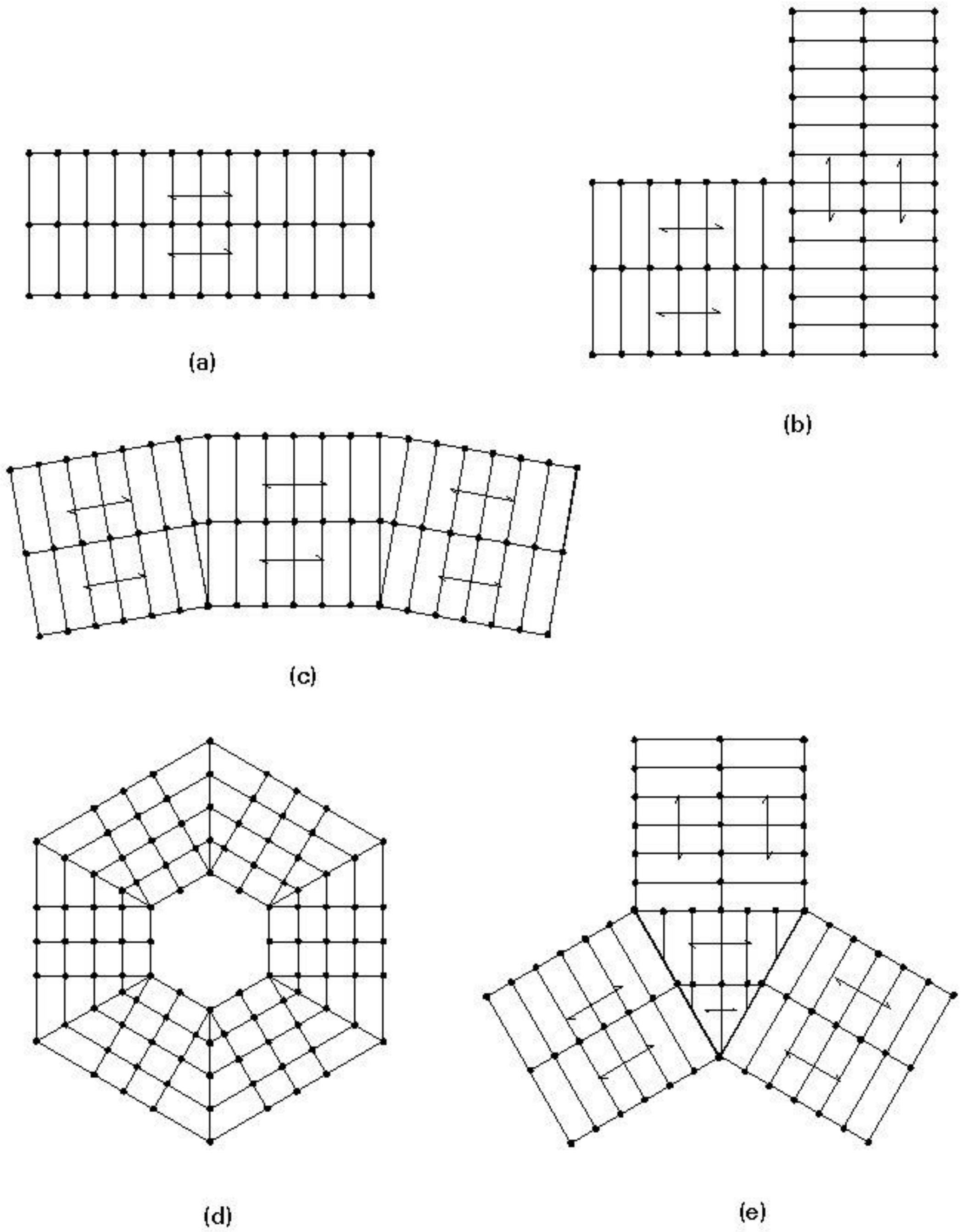


Figure 2 Structural arrangements according to the shape of the building plan

3. COLUMNS

Columns are the structural components which transmit all vertical loads from the floors to the foundations. The means of transmission of vertical load is related to the particular structural system used for the framework (Figure 4).

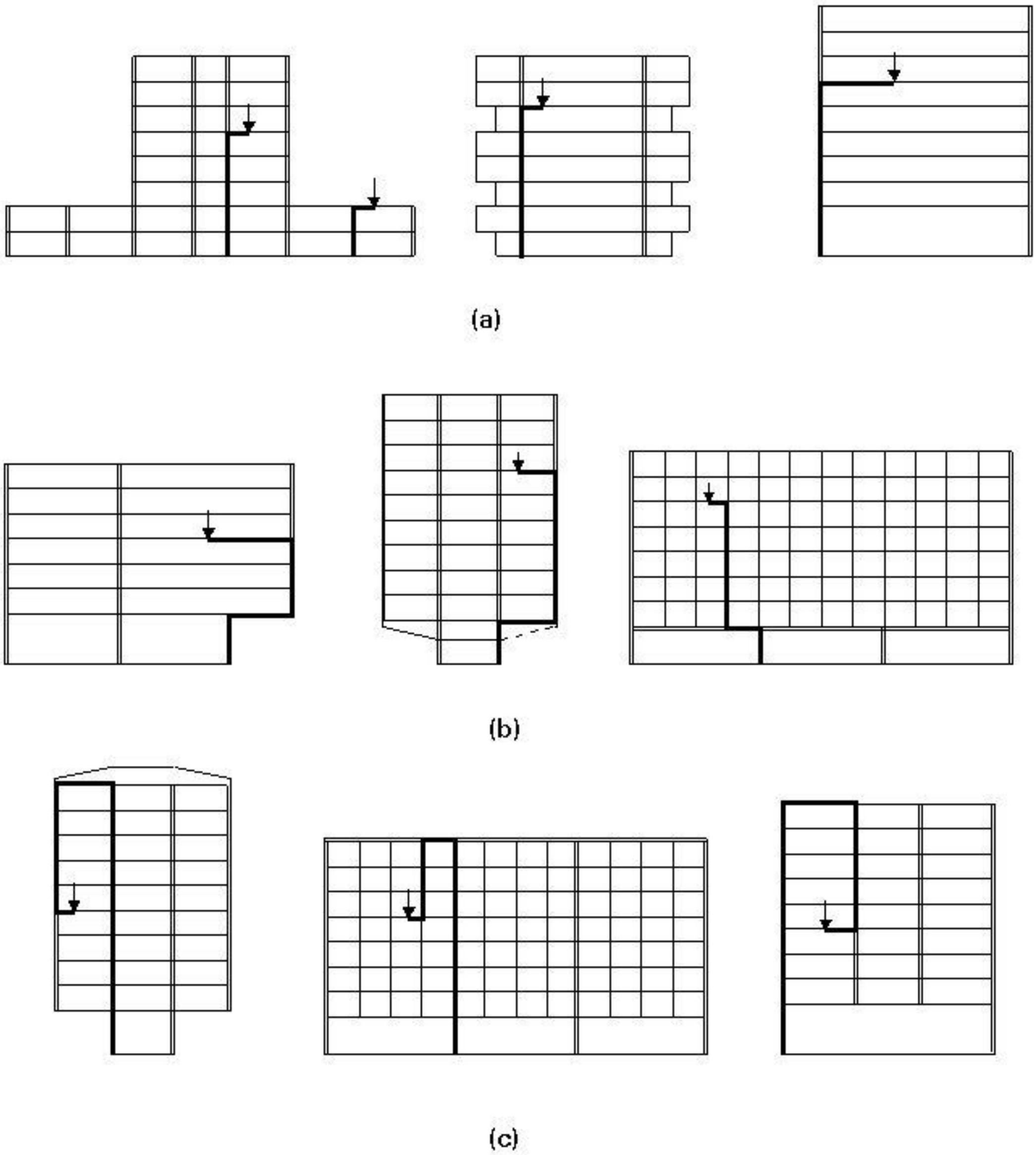


Figure 4 Different methods of vertical load transmission

The location of columns in plan is governed by the structural lay-out. The most common grid arrangements are square, rectangular, or occasionally triangular, according to the choice of the global structural system (Figure 3). The spacing of columns depends upon the load-bearing resistance of the beams and floor structures. It can vary from 3 to 20m, but is typically in the range of 6 to 10m.

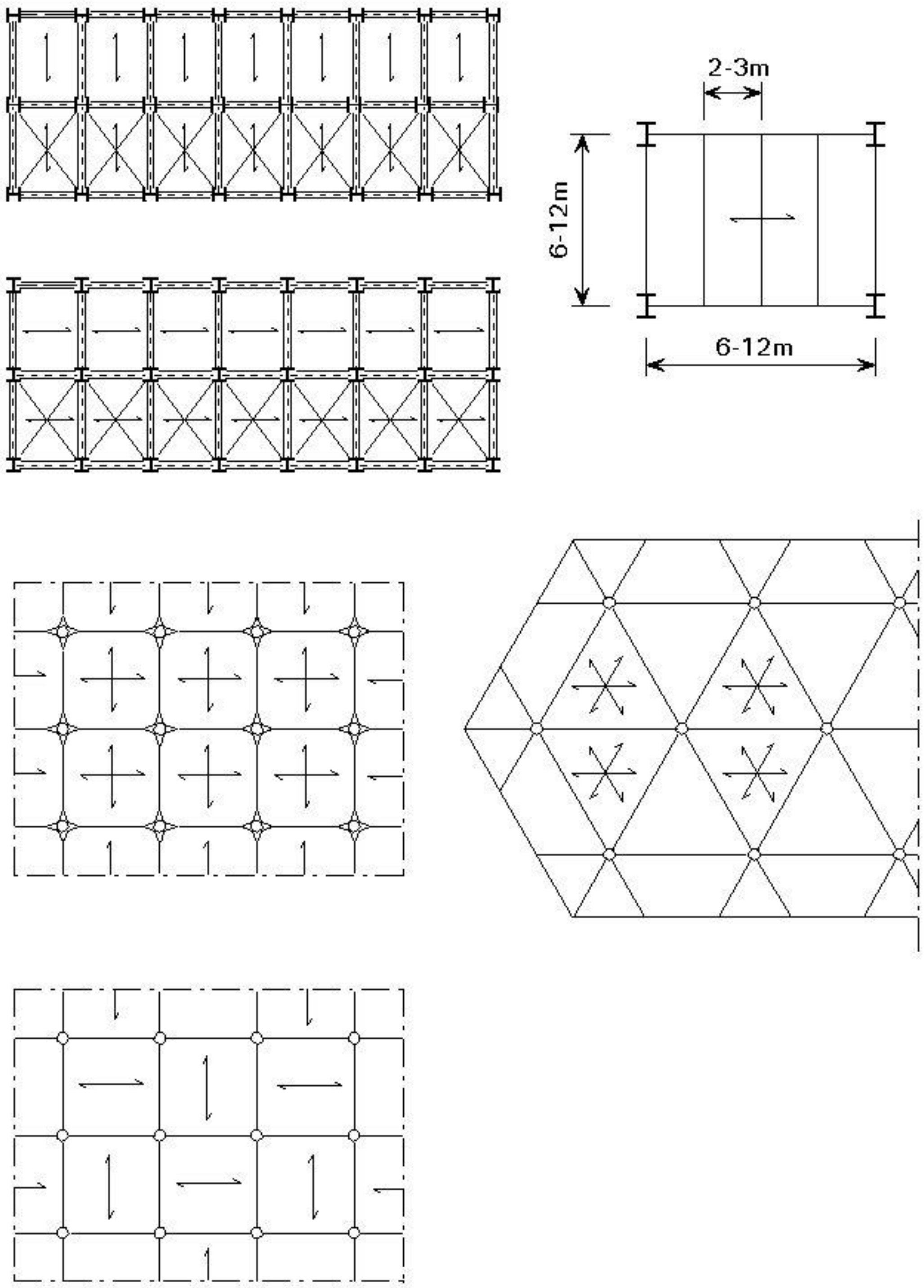


Figure 3 Different locations of columns

Load transmission from floors to columns may occur directly from the floor beams to the column (Figure 4a), or it can be indirect. Indirect transmission involves the use of major 'transfer' beams (Figure 4b), which resist all the loads transmitted by the columns above.

In suspended systems (Figure 4c), the transmission of vertical loads is much more complicated. It is directly provided by tensile members (ties), hung from the top beam elements which support the total vertical load of all floors. A limited number of large columns provide the transmission of the total load to the foundations.

The choice of location and spacing of columns depends on the structural system which has to harmonize functional and economical requirements.

The shapes of cross-section commonly used for columns can be subdivided into (Figure 5):

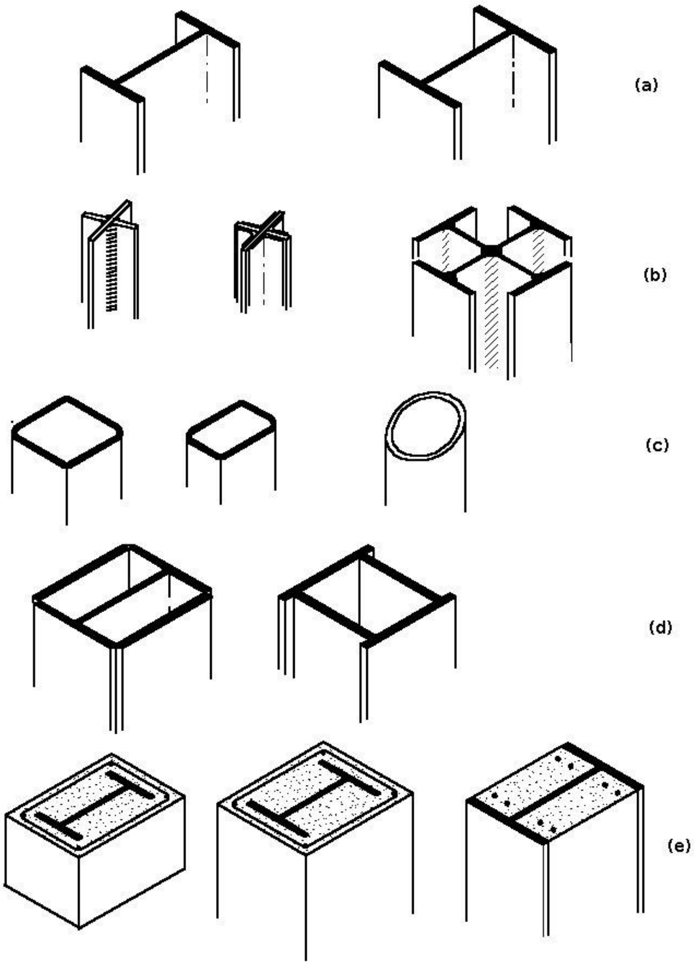


Figure 5 Different sections of columns

- open sections.
- hollow sections.

Open sections are basically standard hot-rolled I and H profiles (Figure 5a). Double-T sections can be also built up by welding. Cross-shaped sections can be obtained by welding L profiles, plates or double-T profiles (Figure 5b).

Hollow sections are tubes of circular, square or rectangular cross-section (Figure 5c). They can also be made from plates or double-T profiles by welding (Figure 5d). Circular and square hollow sections have the advantage that they have the same resistance in the two principal directions, enabling the minimum section dimensions to be obtained. Sometimes hollow sections are filled with concrete, giving an increase in strength and, at the same time, achieving significant fire resistance (> 60 minutes) (Figure 5e). However the beam-to-column connections are more complicated than between I-sections.

4. BEAMS

Beams support the floor elements and transmit their vertical loads to the columns. In a typical rectangular building frame the beams comprise the horizontal members which span between adjacent columns; secondary beams may also be used to transmit the floor loading to the main (or primary) beams.

In multi-storey buildings the most common section shapes for beams are the hot rolled I (Figure 6a) or H shapes (Figure 6c) with depth ranging from 80 to 600mm. In some cases channels, (either single or double) can also be used (Figure 6b).

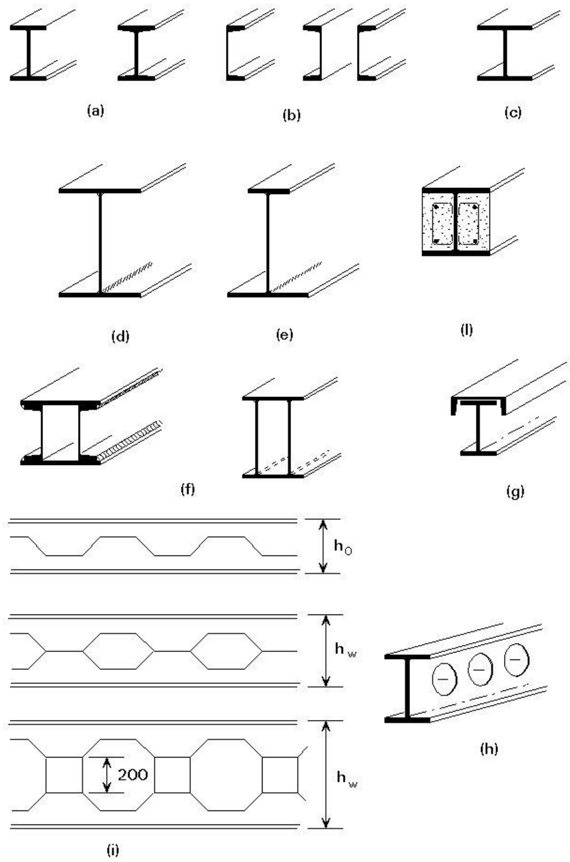


Figure 6 Different sections of beams

Where a greater depth is necessary, built-up sections can be used. Sections fabricated by welding can have double-symmetrical (Figure 6d) or non-symmetrical (Figure 6e) shape, the latter being advantageous for composite steel-concrete sections. By combining plates and/or profiles, box-sections (Figure 6f) or open sections (Figure 6g) can be fabricated.

Sometimes openings in the webs of beams are required in order to permit the passage of horizontal services, such as pipes (for water and gas), cables (for electricity and telephone), ducts (for air conditioning), etc. The openings may be circular (Figure 6h) or square with suitable stiffeners in the web. Another solution to this problem is given by using castellated beams (Figure 6i), which are composed by welding together the two parts of a double-T profile, whose web has been previously cut along a trapezoidal line.

For buildings, the common range for the span to depth ratio is 15 to 30 in order to achieve most efficient design.

In addition to the strength, beams must provide enough stiffness to avoid large deflections which could be incompatible with non-structural components (such as partition walls). For this purpose the maximum mid-span deflection of a beam is usually limited to a fraction of the span equal to 1/400 - 1/500. Where this limitation is too severe, an appropriate initial deformation (camber) equal and opposite to that due to the permanent loads can be pre-formed into the beam.

Steel sections can be partly encased in concrete by filling between the flanges of the section. Partly encased sections are fire resisting without conventional fire protection (Figure 5e). For longer periods of fire resistance, additional reinforcing bars are required.

5. FLOOR STRUCTURES

Floor are required to resist vertical loads directly acting on them. They usually consist of slabs which are supported by the secondary steel beams. The spacing of supporting beams must be compatible with the resistance of the floor slabs. Floor slabs may be made from pre-cast concrete, in-situ concrete or composite slabs using steel decking. A number of options are available:

- conventional in-situ concrete on temporary shuttering (Figure 7a).
- thin precast elements (40 - 50mm thick) with an in-situ structural concrete topping (Figure 7b).
- thicker precast concrete elements which require no structural topping (Figure 7c).
- steel decking acting as permanent shuttering only (Figure 8b).
- steel decking with suitable embossments/indentations so that it also acts compositely with the concrete slab (Figure 8c).

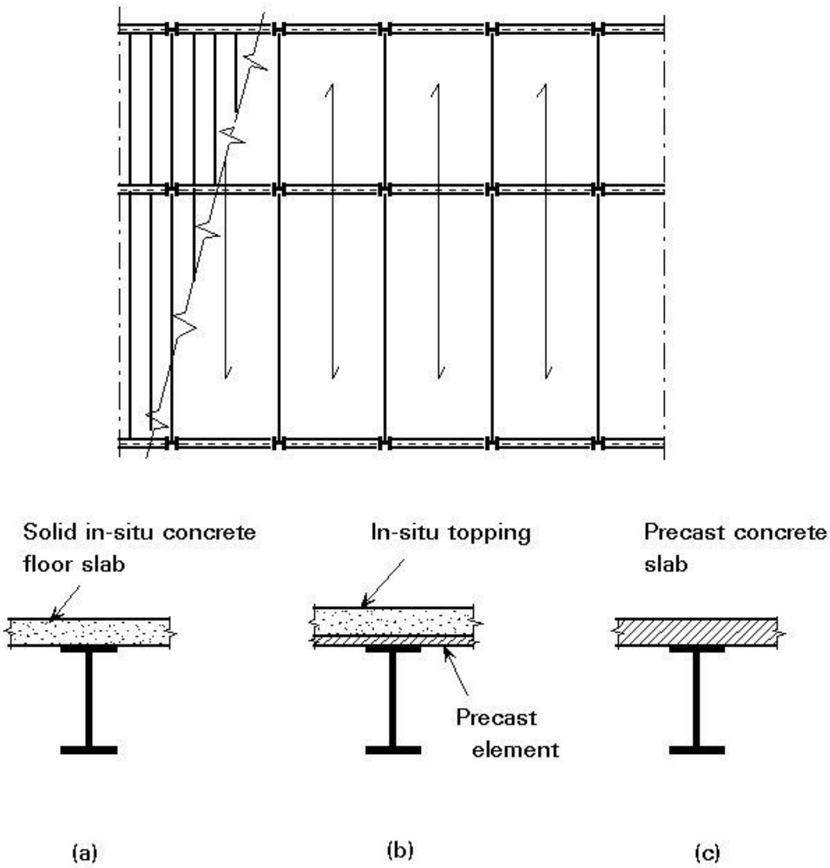


Figure 7 Floor structure comprising reinforced concrete slabs

Typical spans for concrete slabs are 4m to 7m, thus avoiding the need for secondary beams. For composite slabs, various cross-section shapes of steel decking are available (Figure 8a). They are classified in three categories according to their load-carrying resistance:

- profiles with a plain trapezoidal shape without stiffeners with a depth up to 80mm (Figure 8c);
- profiles with a trapezoidal shape with longitudinal stiffeners both in web and flange with a depth up to 100mm (Figure 8d);
- profiles with both longitudinal and transverse stiffeners with a depth up to 220mm (Figure 8c).

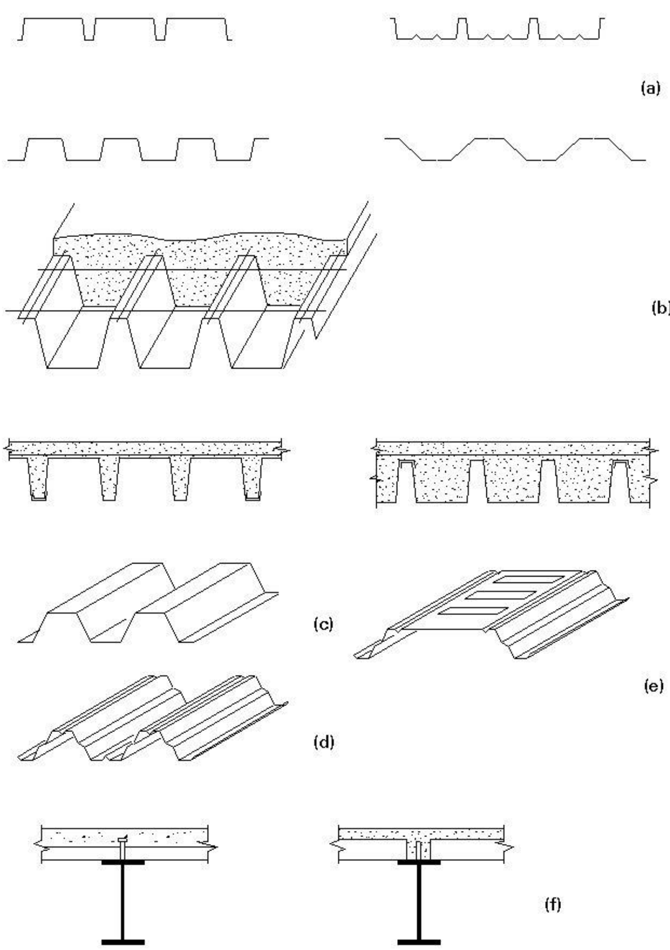


Figure 8 Different types of profiled steel sheets

Deck spans range in length from 2 to 4m for the first category, from 3 to 5m for the second category, and from 5 to 7m for the third category. Secondary floor beams can be avoided in the last case.

Permissible spans for steel decking are influenced by conditions of execution, in particular whether temporary propping is used. Such propping is best avoided since the principal advantage of using steel decking, i.e. speed, is otherwise diminished.

To increase the strength and stiffness of the floor beams, a composite steel-concrete system can be obtained by means of appropriate studs welded on the top of the flange (Figure 8f). In this case the slab and beam may be designed compositely using conventional theory.

6. BRACING

Bracing systems are used to resist horizontal forces (wind load, seismic action) and to transmit them to the foundations.

When a horizontal load F (Figure 9a) is concentrated at any point of the facade of the building, it is transmitted to two adjacent floors by means of the cladding elements (Figure 9b).

The effects of loads H acting in the floor slab are distributed to the vertical supporting elements which are located in strategic positions of the structural layout (dotted lines in Figure 8c) by means of an appropriate horizontal resisting element in the floor.

The vertical supporting elements are called vertical bracings; the horizontal resisting element is the horizontal bracing which is located at each floor.

Where horizontal bracings are necessary, they are in the form of diagonal members in the plan of each floor, as shown in Figure 9c).

If steel decking is used, the diagonal bracing can be replaced by diaphragm action of the steel sheeting if it is fixed adequately.

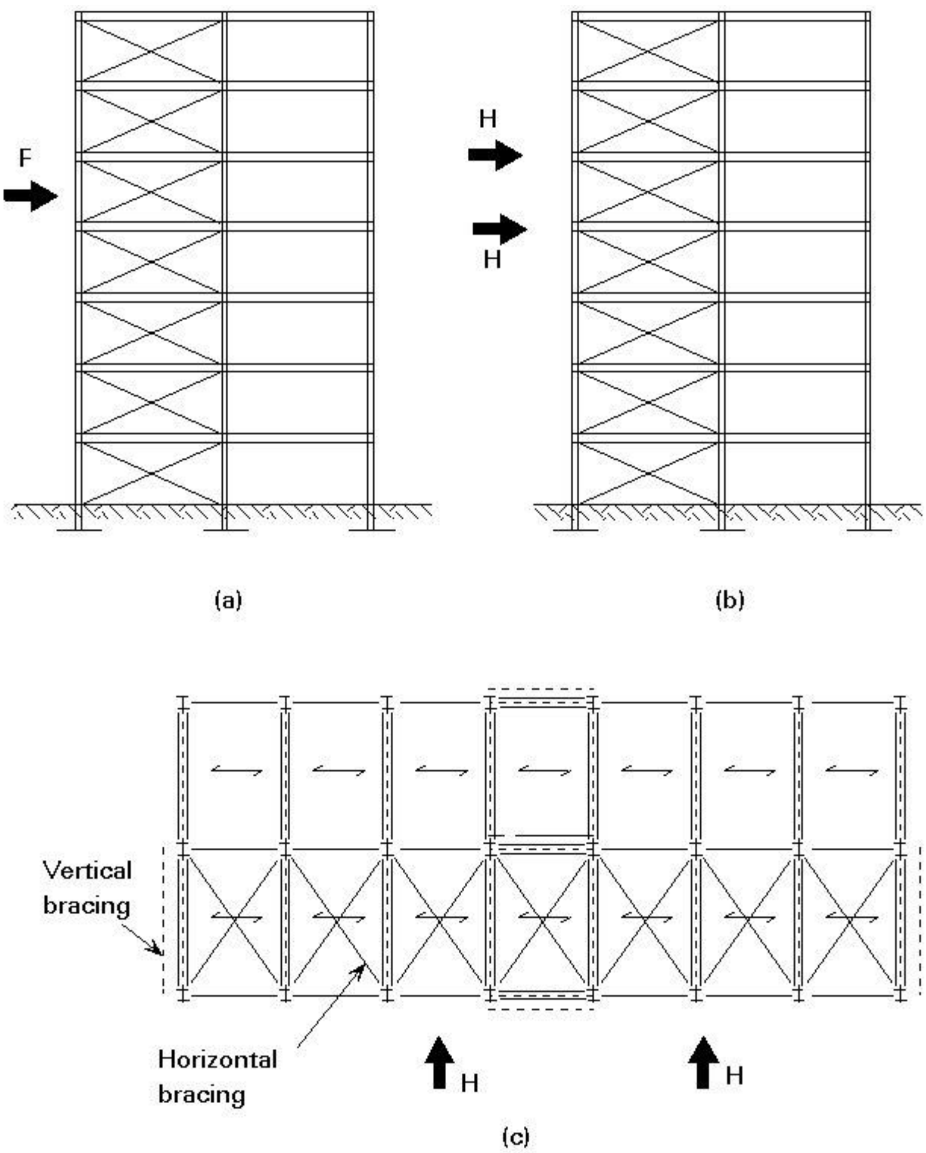


Figure 9 The function of bracing systems

Both horizontal and vertical bracings represent together the global bracing system, which provides the transfer of all horizontal forces to the foundations.

Vertical bracings are characterised by different arrangements of the diagonal members in the steel frame. They are (Figure 10):

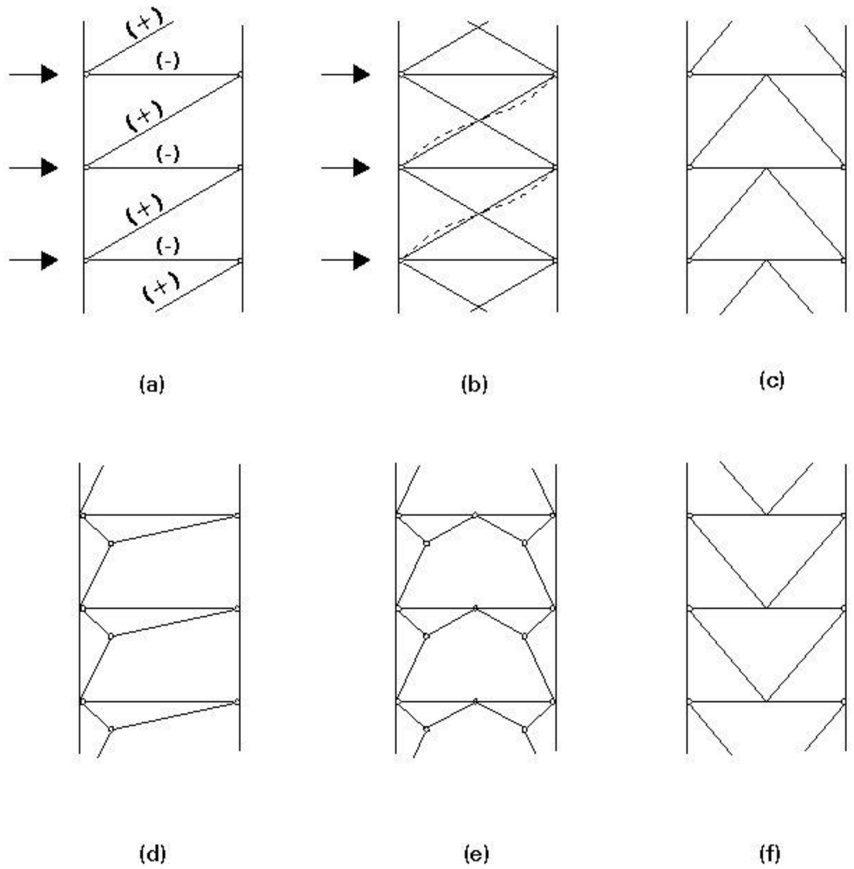


Figure 10 Different types of arrangements for bracings

a. Single diagonal

b. Cross-braced (X-shaped bracing)

c. Inverted V-shaped bracing

d. Unsymmetrical portal

e. Symmetrical portal

f. V-shaped bracing.

An alternative to steel bracings is provided by reinforced concrete walls or cores which are designed to resist the horizontal forces (Figure 11). In these systems, so-called dual systems, the steel skeleton is subjected to vertical forces only. Reinforced concrete cores are usually located around the stairway and elevator zones.

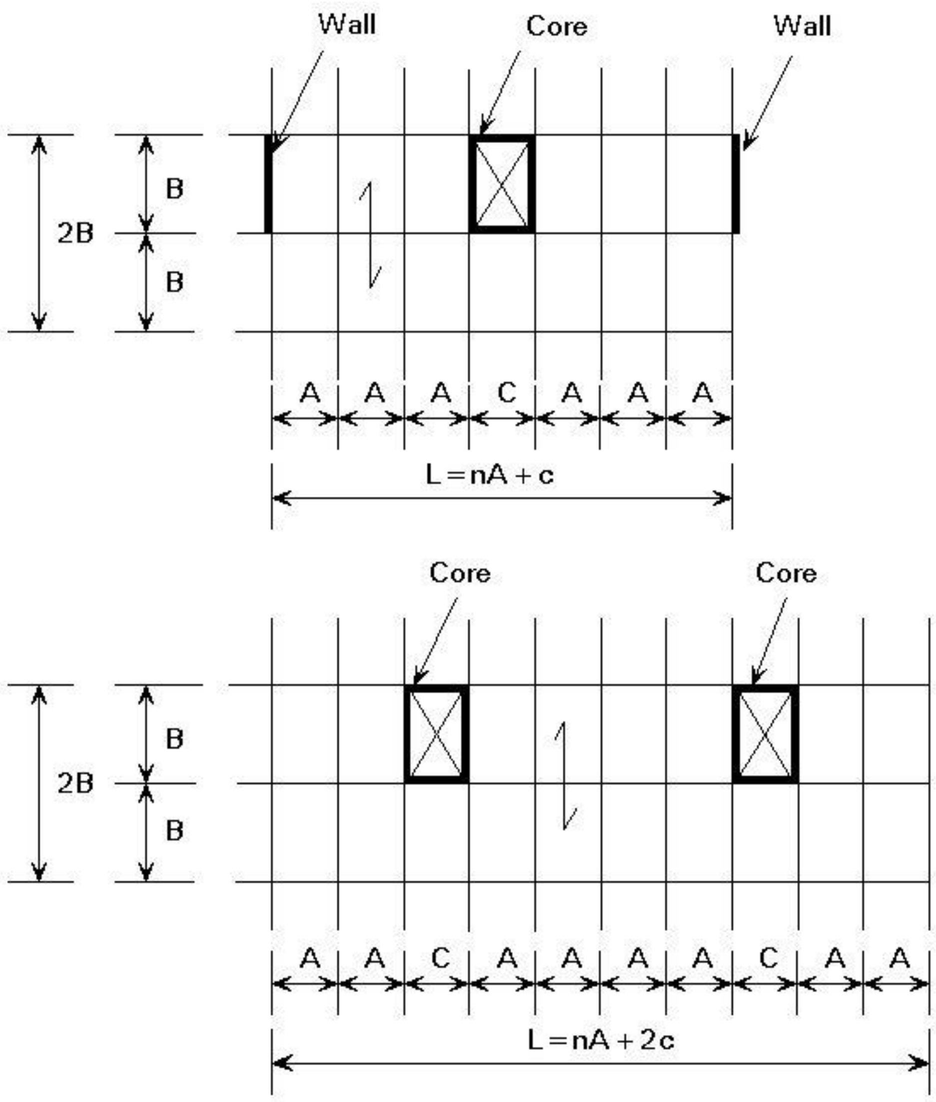


Figure 11 Reinforced concrete walls and cores

Normally, the floor slab can be designed to resist in-plane forces to avoid the use of horizontal diagonals. This is the case for in-situ reinforced concrete slabs, or composite slabs with appropriate shear connectors.

7. STRUCTURAL SYSTEMS

To provide resistance to the combined effects of horizontal and vertical loads in a multistorey building, two alternative concepts are possible for the structural system.

The first, so-called 'moment resisting frame system', is a combination of horizontal (beams) and vertical (columns) members which are able to resist axial, bending and shear actions. In this system no bracing elements are necessary. The moment resisting frame behaviour is obtained only if the beam-to-column connections are rigid, leading to a framed structure with a high degree of redundancy. As a consequence of this choice:

- the connections or joints between members are complicated.

- 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.

Typical details of beam-to-column joints for rigid framed systems are shown in Figure 12. They are called 'rigid joints' and their task is to transfer bending moment from the beam to the column. Type (a) can transfer limited bending moments only because the column web can buckle due to local concentration of effects. The presence of horizontal stiffeners in the column web (Type (b)) recreates the cross-section of the beam and the column web panel has to resist the shear force only.

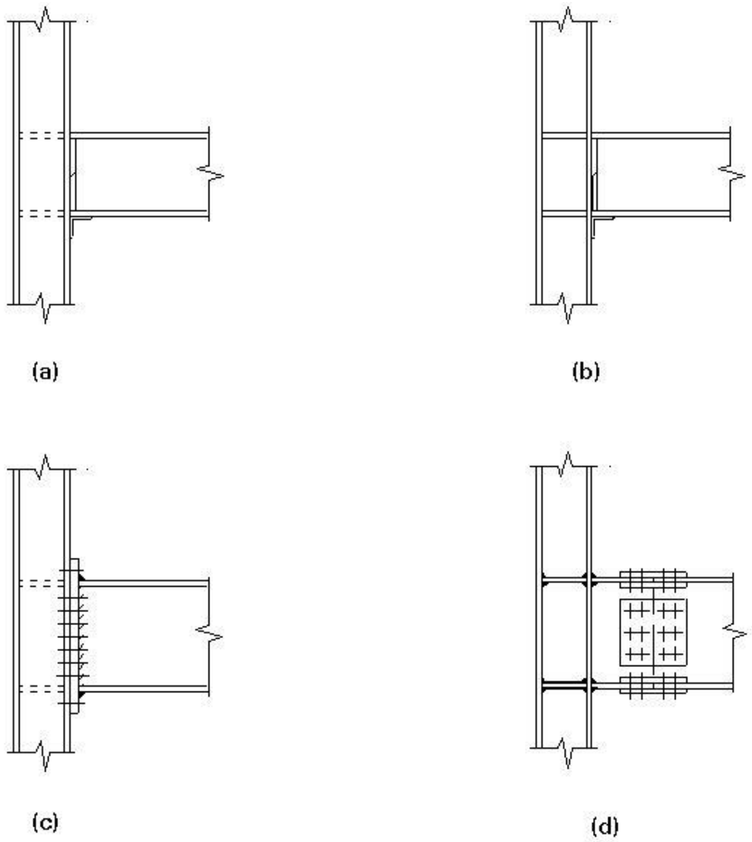


Figure 12 Beam-to-column joints for rigid frames

Types (a) and (b) require the execution of welding operations on site. Such operations are not completely reliable and they are also expensive and can cause delay in erection.

A better alternative is to use bolted connections which allow rigid joints to be made without the disadvantages of site welds. Two typical solutions for rigid frame structures, shown in Figures 12c and 12d, are:

- Type (c) is the extended end plate joint.
- Type (d) is the cover plate joint.

These solutions allow the most suitable use of connecting methods, i.e. welding in the shop to build up prefabricated elements and bolting in site for connecting them together. This type of joint can be, therefore, called 'shop-welded field-bolted'.

To avoid the practical problems of rigid frame construction, a more convenient solution can be obtained by conceiving the structural behaviour in a different way. The functions of resistance to vertical and horizontal loads are separated in the different 'families' of members, which are grouped in two sub-structures (Figure 13):

a. a simple frame composed by beams pinned together, which is capable of transferring the vertical loads to the foundation (Figure 13a).

b. a cantilever fixed to the ground which resists horizontal forces and transfers their effects to the foundation (Figure 13b).

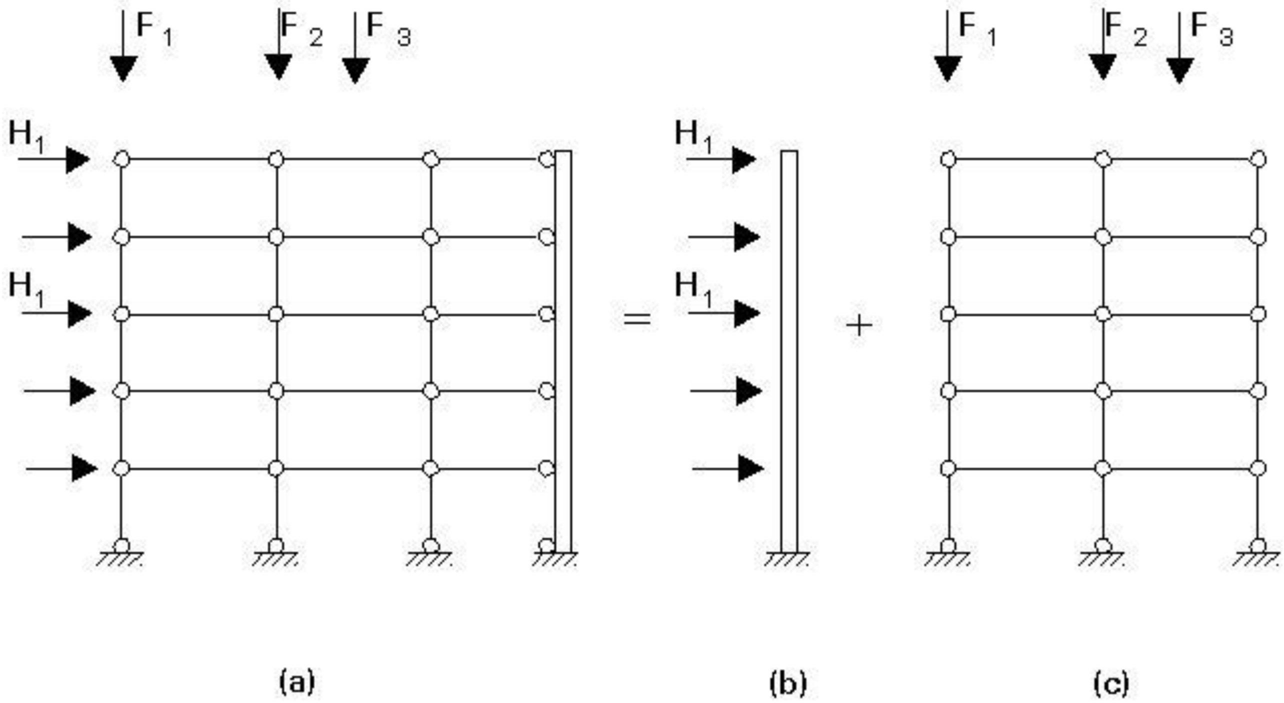


Figure 13 Calculation model for braced frame

Sub-structure a. is hyperstatic; beams are bent in the vertical plane, columns are simply compressed, the hinged joints between beams and columns absorb shear forces only.

Sub-structure b. is isostatic; its bracing function can be obtained by means of steel trusses or by reinforced concrete walls. These bracing structures are mainly loaded in shear and bending and their deformability must be checked under serviceability conditions in order to limit sway.

The combination of both sub-structures a. and b. provides the complete structure (Figure 13c), which is able to resist both vertical and horizontal loads.

The main advantages of this solution, the so-called 'braced-frame system', are:

- construction details of joints are very simple, because they act as hinges.
- sway deformability of the structure is limited by the bracing system (sub-structure b).
- interaction between axial forces and bending moments in the column is virtually absent.

In contrast, some complications arise in the foundation of bracings which must resist the overall horizontal forces with a very small amount of axial compression. High values of eccentricity occur which require large dimensions of the contact area under the foundation.

In these structural systems beam-to-column joints must resist only axial and shear forces. Some typical solutions of joints for pin-ended structures are shown in Figure 14; they are 'shop-welded field-bolted' joints. The most commonly used is the bolted connection between the beam web and the column flange (or web) by means of double angles (Figure 14e, f). They are more economic than the fully welded solutions (Figure 12a, b) for rigid structures and allow simple erection.

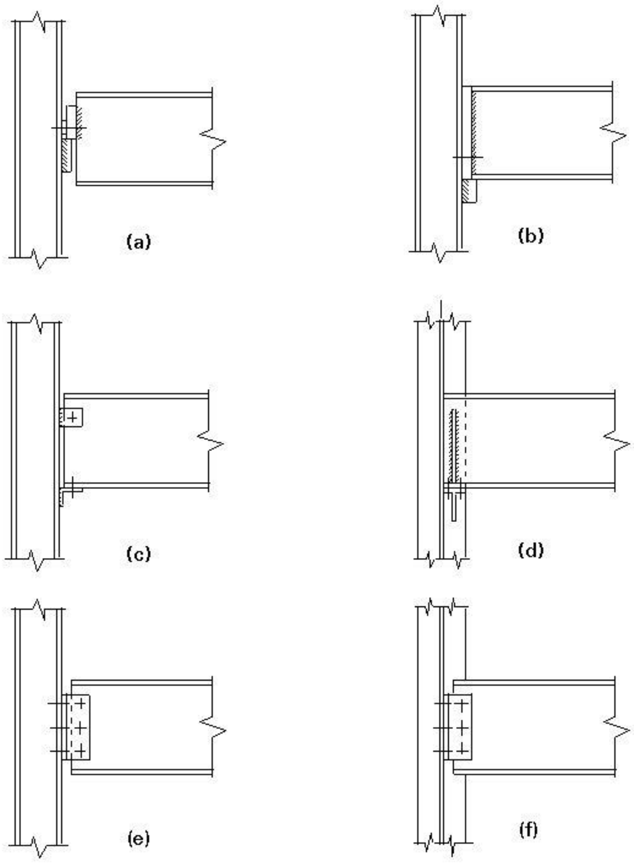


Figure 14 Beam-to-column joints for pin-ended frames

8. DESIGN REQUIREMENTS

The design of a structural system for a multi-storey building must to take into account its spatial behaviour.

For the 'braced frame system', which seems to be most convenient for economy and reliability, it is necessary to locate a sufficient number of bracings to allow any horizontal loads however directed to be resisted. For this purpose, the requirements are:

(1) it must be possible to consider any floor system as a plane structure, restrained by the vertical bracings.

(2) bracings, as external restraints of the floor system, must provide a system of at least three degrees of restraint.

(3) the floor system must be capable of resisting the internal forces due to the applied horizontal loads.

To fulfil requirement (1), diagonal bracings must be introduced in the plane of the floor, thus transforming the floor system itself into a horizontal truss.

As an alternative, the slab of prefabricated concrete elements in the floor system can be assumed to resist directly the horizontal forces as a plane plate structure, because its deformability is normally negligible.

Where concrete slabs are used, the erection of the steel skeleton requires particular care, because it is unstable until the floor elements are placed. Temporary bracing is therefore necessary during this phase of execution.

To fulfil requirement (2) the steel truss bracings are active only in their own plane and therefore represent a simple restraint for the floor system. When reinforced concrete bracings are used, they can have one, two or three degrees of restraint, depending upon their resistance to one plane bending (wall), bi-axial bending or bi-axial bending and torsion (core), respectively.

Finally, requirement (3) is fulfilled by evaluating internal forces in the floor elements due to the horizontal loads by considering the location of the vertical bracings.

Figure 15 shows a three-dimensional structure for a multi-storey building with steel bracings. Every point of the floor system is fixed in two directions. In particular, the diagonals connecting points A and B restrain all the points in line '1' in the 'x' direction. The floor bracing is able to receive external forces from both direction 'x' and 'y' and to transmit them to the vertical bracings.

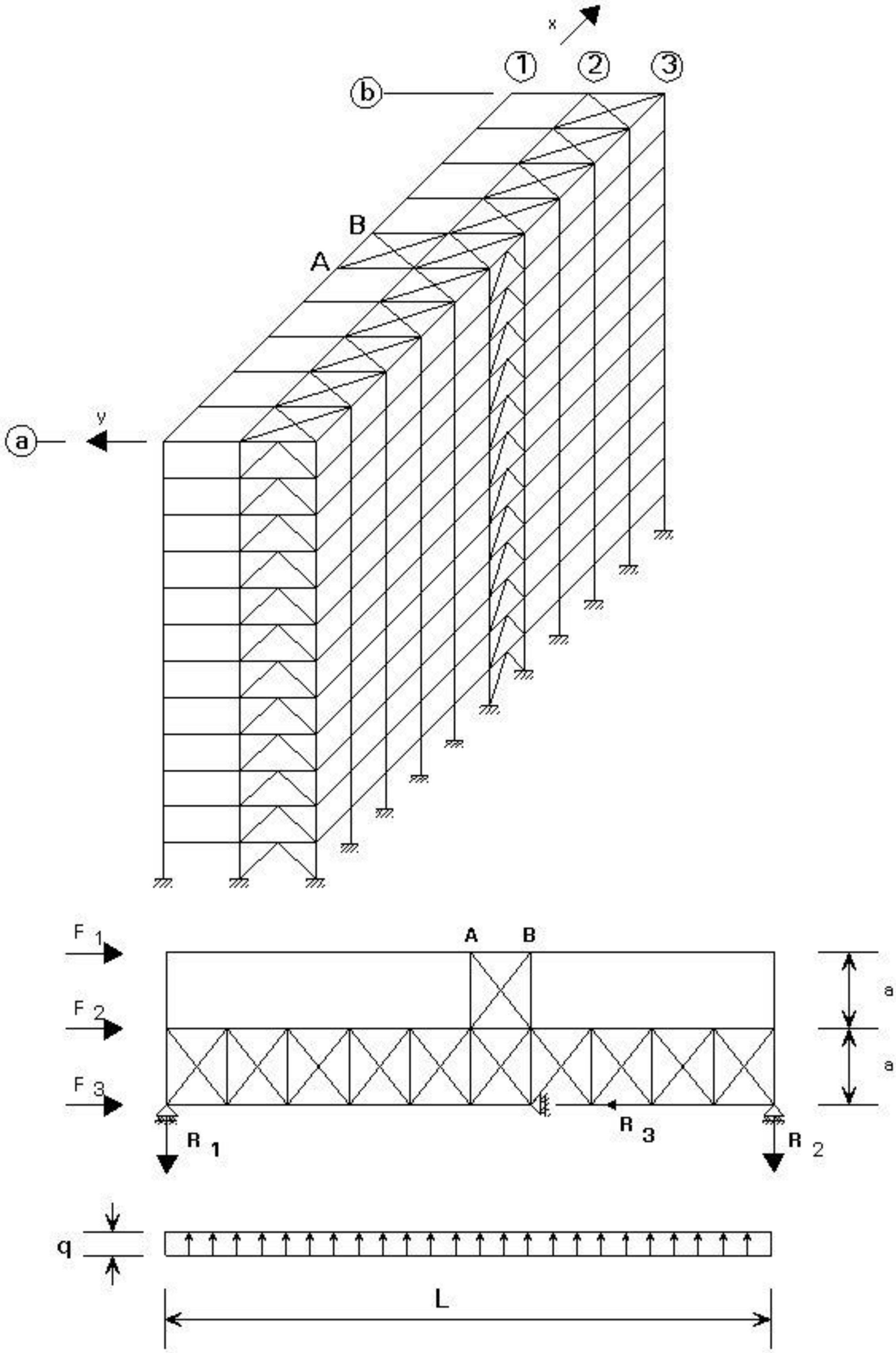
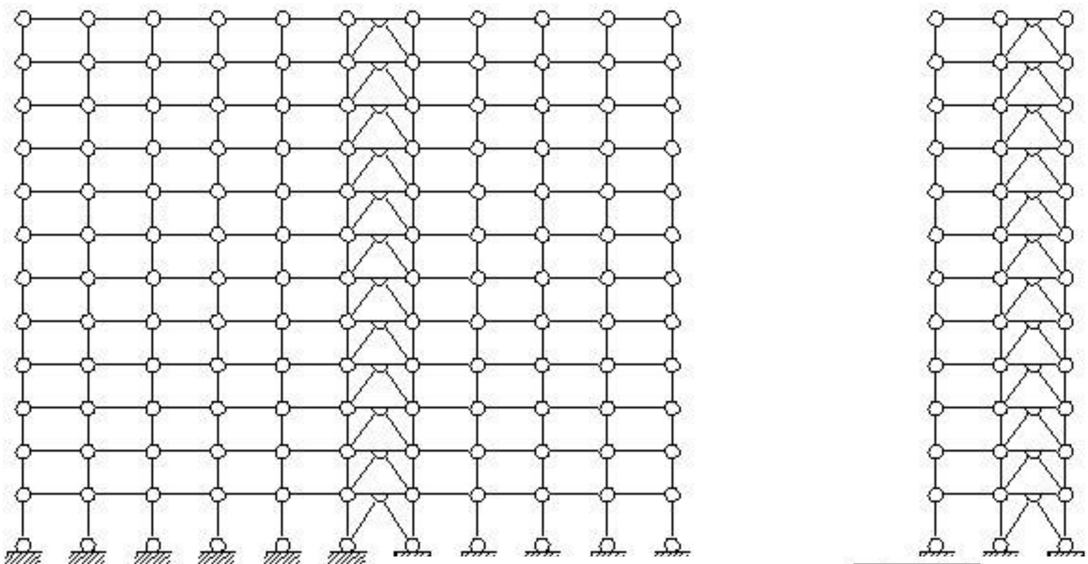


Figure 15 Multi-storey building with horizontal steel bracings

The spatial structure can be reduced to plane sub-structures whose static schemes are shown in Figure 16. The longitudinal facade along row '3' is directly braced in its plane as well as the lateral facades by the transverse bracings of axes 'a' and 'b'.



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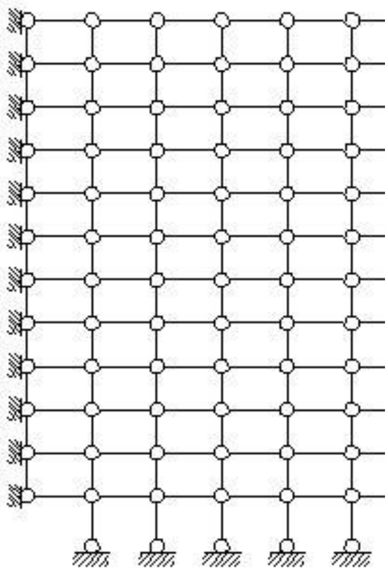

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Figure 16 Longitudin

The pinned joints of the intermediate transverse frames and of the

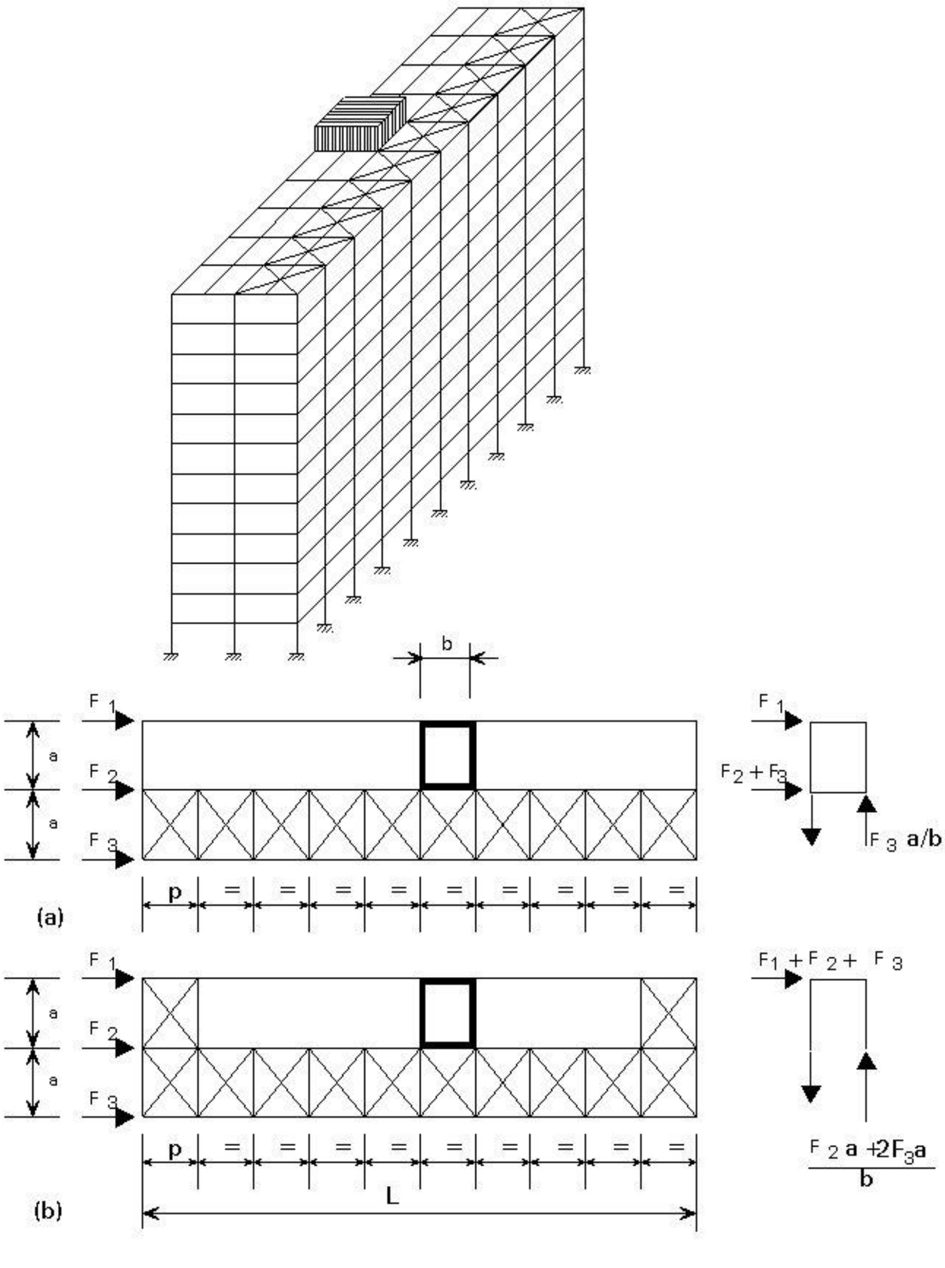

Figure 17 Multi-storey building with a concrete core

longitudinal frames of axes '1' and '2' are prevented from any horizontal displacement because they are all connected to the vertical bracings by means of the floor bracings. Thus they can be considered as non-sway frames.

Figure 17 represents the spatial structural scheme of a multi-storey building with a reinforced concrete bracing core. It can be considered as an alternative solution of the previous example for the same building, in which the concrete core substitutes both longitudinal and transverse steel bracings.

Two floor bracing systems can be considered:

If all the four walls of the staircase core are structurally effective, the solution of Figure 17a is correct. If only three sides of the staircase core are structurally effective, the transmission of the horizontal forces acting in the longitudinal direction to the longitudinal wall requires the use of additional floor diagonals, as shown in Figure 17b.

MULTI-STOREY STEEL FRAMED STRUCTURES...

Structural behaviour of structural steel construction for high-rise building
Ta1l and slim buildings like many of the sky-scrapers find in Hong Kong may not be a kind of structure that are favourable in the using of structural steel construction. The main problem is that tall buildings may bend significantly under normal wind load and produce undesirable movements and deflection. Rigidity in the connection of the steel members is of no doubt required to improve such situation, but of course, this incurs certain technical difficulties especially when site connection is concerned.

To overcome such drawback, one of the common methods is to build a strong reinforced concrete core which usually locates in the centre of a building (refer also to figure 1 & 4). This core acts as a stiffening structure and help to take up most of the bending movement created by wind load. The core is usually rectangular or square in section with the perimeter wall sometimes more than 450mm thick and accommodating part of the essential utilities such as the staircases, lift shafts, toilets or services ducts etc. Sometimes, suitably located shear wails can act similarly to a rigid core.

The second method is by the introduction of more bracing or truss members between the main structural steel members (refer also to figure 6 & 7). The bracing members can produce stiff diagonal supports and help to resist wind pressure by transmitting the load from the external faces of the building through the floors which act as rigid diaphragms also. However, this may make the layout of the building becomes complicated, lower the space efficiency of the building or produce additional technical difficulties to internal or external finishes.
To increase the overall performance, most of the modern floor systems for this kind of structure are using composite floor design (Figure 12 & 13), that is, the steel floor joists are topped with a RC slab that form a very strong and rigid composite floor membrane as part of the stiffening provision for the entire building system.

1.9. CAR PARKS