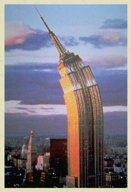
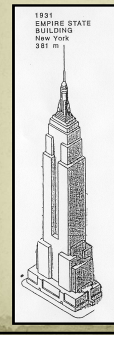
High Rise Construction

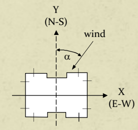


Dr. Karamjit Singh Chahal
Associate Professor
Dept of architecture

Tall buildings

❖ Empire State Building - full-scale and wind-tunnel studies in 1930's

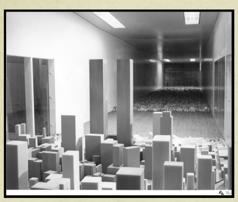




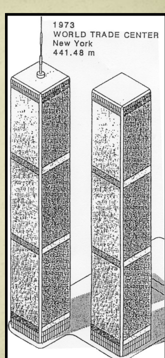
Δ - Mean deflection (inches)
U_h - Mean wind speed at 1250 feet in MPH (uncorrected)

Tall buildings

- World Trade Center – New York 1973-2001

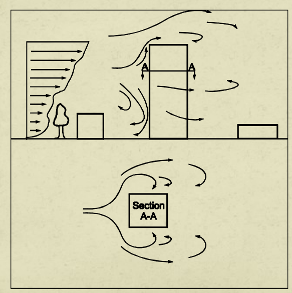


- First buildings to be tested in a turbulent boundary-layer flow wind tunnel (mid 1960's)



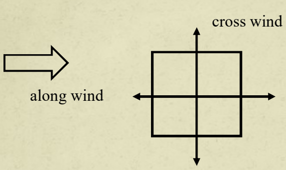
Tall buildings

- Flow around a tall building :



Tall buildings

- Overall loading and dynamic response

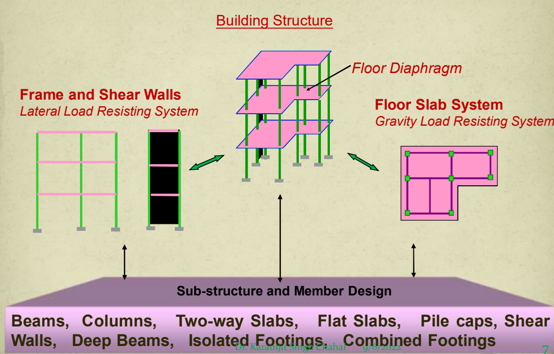


Cross-wind vibrations are usually greater than along-wind vibrations for buildings of heights greater than 100m (330 feet)

Building Systems

- Building is an assemblage of various Systems
  - Basic Functional System
  - Structural System
  - HVAC System
  - Plumbing and Drainage System
  - Electrical, Electronic and Communication System
  - Security System
  - Other specialized systems

The Building Structural System - Physical



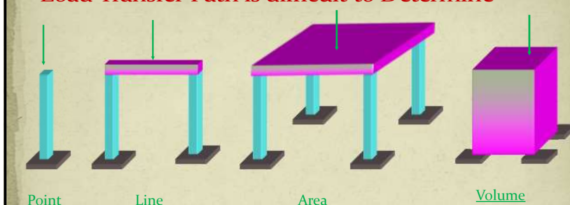
The Building Structural System: Conceptual

- The Gravity Load Resisting System
  - The structural system (beams, slab, girders, columns, etc) that act primarily to support the gravity or vertical loads
- The Lateral Load Resisting System
  - The structural system (columns, shear walls, bracing, etc) that primarily acts to resist the lateral loads
- The Floor Diaphragm
  - The structural system that transfers lateral loads to the lateral load resisting system and provides in-plane floor stiffness

Building Response

- How Gravity Loads are Distributed
  - Analysis of Gravity Load Resisting System for:
    - Dead Load, Live Load, Pattern Loads, temperature, shrinkage
  - Important Elements: Floor slabs, beams, openings, Joists, etc.
- How Lateral Loads are Distributed
  - Analysis of Lateral Load Resisting System for:
    - Wind Loads, Seismic Loads, Structural Un-symmetry
  - Important elements: Columns, shear walls, bracing , beams

Load Transfer Path is difficult to Determine



Transfer of a Point Load to Point Supports Through Various Mediums

Technological Innovations and the Skyscraper

- Iron and Steel Skeleton (1850s-1860s).
  - Before that supporting walls were stone and brick. Too expensive to build high, needed thicker and thicker base walls.
  - 1855: Bessemer Steel process
- The Elevator
  - Elisha Otis of Yonkers, NY developed safety break in 1851 (demonstrated at New York's Crystal Palace exhibition).
  - 1871: Hydraulic elevator replaces steam.

Skyscraper Technology cont.

- Heating and Cooling technology
  - Steam and hot water systems were developed in 19th c.
- Wind-bracing technology.
- Artificial Light
  - Edison laid electric lights in downtown NYC in 1871.
  - 1938s fluorescent light bulbs on market.
- Steam powered construction tools
  - cranes, shovels, etc.

How High to Build?

- Key difference between *engineering height* and *economic height.*
- There is virtually no engineering limit to height.
- Economic height reflects the maximum height (and square footage) that generates the highest net return on the investment.
- Economic height reflects various costs to purchasing land, building and operating the structure.

Economic Costs

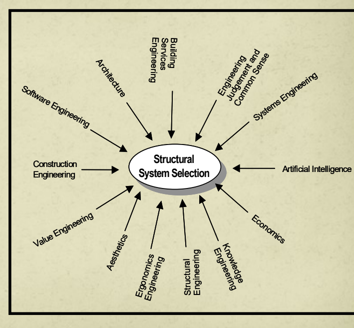
- At some point (for floor height) the law of marginal diminishing returns starts to kick in (i.e., additional market rents do not cover additional costs):
- Taller buildings need:
  - Heavier foundations.
  - Extra wind bracing.
  - More space for elevators.
  - More and larger mechanical systems for ventilation and heating.

Selection Of Structural Systems

Basic Concepts and Considerations

Knowledge Model for System Selection

- Architecture
- Building Services
- Construction Eng.
- Value Eng.
- Aesthetics
- Structural Eng.
- Economics
- Artificial Intelligence
- System Eng.
- Common Sense



Selection of Structural System

Function has considerable effect on the selection of structural system

- Based on Function/Occupancy of Tall Buildings:
- Residential Buildings
  - Apartments
  - Hotels
  - Dormitories
- Office and Commercial Buildings
- Mixed Occupancy – Commercial + Residential
- Industrial Buildings and Parking Garages

Typical Characteristics of Residential Bldg

- Known location of partitions and their load
- Column lines generally matches architectural layout
- Typical spans 15-22 ft
- Tall buildings economy in achieved using the thinnest slab
- One way pre-cast or flat slab – popular
- Lateral load resistance provided by frame or shear walls
- More or less fixed M/E system layouts

Typical Characteristics of Office and Commercial Bldg

- Unknown location of partitions and their load
- Typical spans 20-35 ft
- Need for flexible layouts
- Post-tension or ribbed and flat slab with drop panel popular
- Ideal balance between vertical and lateral load resisting systems: sufficient shear walls to limit the resultant tension under gravity plus wind
- Lateral load resistance varies significantly

Gravity /Vertical Load Resisting Systems

1. Slabs supported on Long Rigid Supports
   - Supported on stiff Beams or Walls
   - One-way and Two-way Slabs
   - Main consideration is flexural reinforcement
2. Slab-System supported on Small Rigid Supports
   - Supported on Columns directly
   - Flat Slab Floor systems
   - Main consideration is shear transfer, moment distribution in various parts, lateral load resistance
3. Slabs supported on soil
   - Slabs on Grade: Light, uniformly distributed loads
   - Footings, Mat etc. Heavy concentrated loads

Vertical Load Behavior and Response

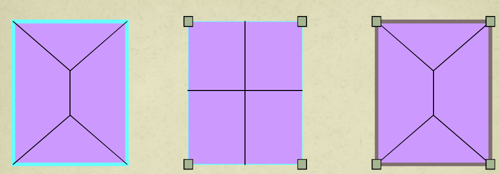
Popular Gravity Load Resting Systems

- Direct Load Transfer Systems *(Single load transfer path)*
  - Flat Slab and Flat Plate
  - Beam-Slab
  - Waffle Slab
  - Wall Joist
- Indirect Load Transfer System *(Multi step load transfer path)*
  - Beam, Slab
  - Girder, Beam, Slab
  - Girder, Joist

Conventional Approach

- For Wall Supported Slabs
  - Assume load transfer in One-Way or Two-Way manner
  - Uniform, Triangular or Trapezoidal Load on Walls
- For Beam Supported Slabs
  - Assume beams to support the slabs in similar ways as walls
  - Design slabs as edge supported on beams
  - Transfer load to beams and design beams for slab load
- For Flat-Slabs or Columns Supported Slabs
  - Assume load transfer in strips directly to columns

Gravity Load Transfer Paths

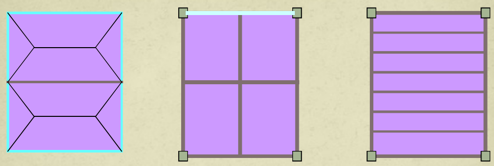


Single Path
Slab On Walls

Single Path
Slab on Columns

Dual Path
Slab On Beams,
Beams on Columns

Gravity Load Transfer Paths

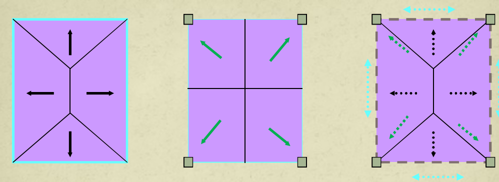


Mixed Path
Slab On Walls
Slab On Beams
Beams on Walls

Complex Path
Slab on Beams
Slab on Walls
Beams on Beams
Beams on Columns

Three Step Path
Slab On Ribs
Ribs On Beams
Beams on Columns

Simplified Load Transfer



To Lines

To Points

To Lines and Points

Transfer of Area Load

Factors in selection of Structural systems

1. Soil conditions
2. The program and concept
3. Applicable codes
4. Potential code changes
5. Flexibility
6. Impact on finished-ceiling and building height
7. Material delivery and construction timing
8. Local construction capabilities and preferences
9. Ease of construction and schedule
10. Cost of the selected system
11. Cost impact on other systems
12. Appearance and aesthetic potential

Lateral Load Resisting Systems

Lateral forces due to wind or seismic loading must be considered for tall buildings along with gravity forces. Very often the design of tall buildings is governed by lateral load resistance requirement in conjunction with gravity load. High wind pressures on the sides of tall buildings produce base shear and overturning moments. These forces cause horizontal deflection in a multi-storey building. This horizontal deflection at the top of a building is called *drift*. The drift is measured by *drift index*, Δ/h, where, Δ is the horizontal deflection at top of the building and h is the height of the building. Lateral drift of a typical moment resisting frame is shown in Fig. 8.

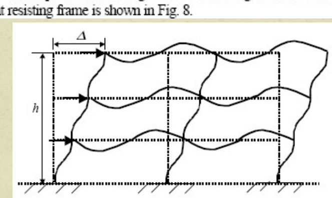
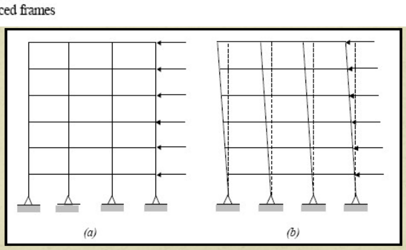


Fig. 8 Lateral drift

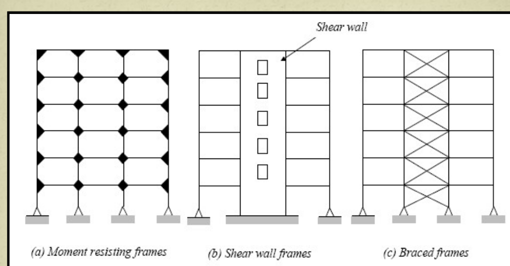
Lateral Load Resisting Systems

One of the following three types structural systems is used to resist the lateral loads and limit the drift within acceptable range mentioned above:

- Rigid Frames
- Shear walls.
- Braced frames



Lateral Load Resisting Systems



Lateral load resisting systems

The innovative structural system of the John Hancock Center consists of a bearing structure around the perimeter which behaves as a framed and diagonal tube.

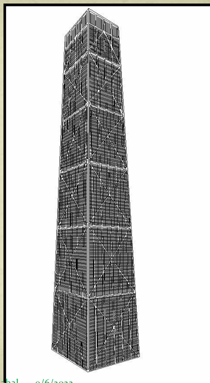


Figure 2 John Hancock Centre, Chicago

STRUCTURAL SYSTEMS FOR HIGH-RISE BUILDINGS

- ❖ The structural system of a high-rise building must resist both gravity and lateral loads.
- ❖ As the height of the building increases, the lateral loads gradually dominate the structural design.
- ❖ Lateral loads due to wind and earthquake produce lateral accelerations.
- ❖ As people normally perceive these accelerations during service conditions, stiffness rather than strength tends to become the dominant factor in buildings of great height.

Structure System

For high-rise buildings, different structural systems are used according to the height range:

Up to 30 stories, concrete wall or core systems.
From 30 to 60 stories, frame systems.
Above 60 stories, tube systems.

For 'braced' steel frames, different types of bracing can be used according to the structural and functional requirements.

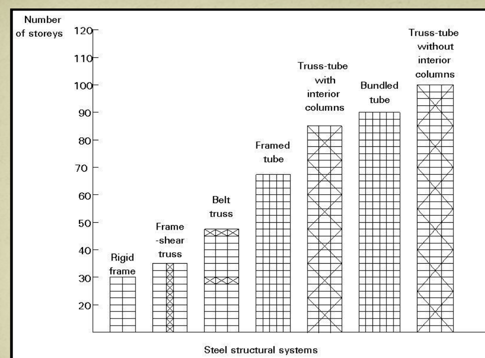
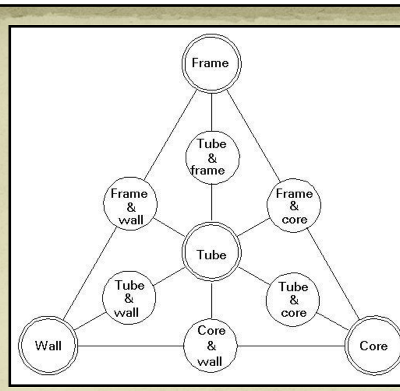


Figure 7 Steel structural systems and the number of storeys

Structure System

Four overall groupings of structural systems may be identified. They are:

- ❖Bearing wall system
- ❖Core system
- ❖Frame system
- ❖Tube system



Classification of Structural Systems of Multi storey buildings (Drosdov, Lishak- 1978

Braced Frames

- ❖ Pure rigid frame systems are not sufficient for buildings higher than about 30 stories
- ❖ Because the shear racking component of deflection produced by the bending of columns and girders causes the building drift to be too large.
- ❖ The efficiency is improved by adding truss members such as diagonals between the floor systems.

Braced Frames

- ❖ Bracing types available for incorporation into the structural system range from a concentric simple K or X brace between two columns to knee bracing and eccentric bracing.
- ❖ In an eccentric bracing system the connection of the diagonal brace is deliberately offset from the connection between the beam and the vertical column.

Figure 4.16 Inverted K bracing with double-angle connections.

Braced Frames

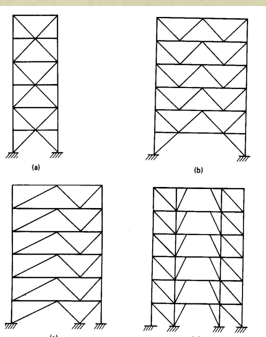
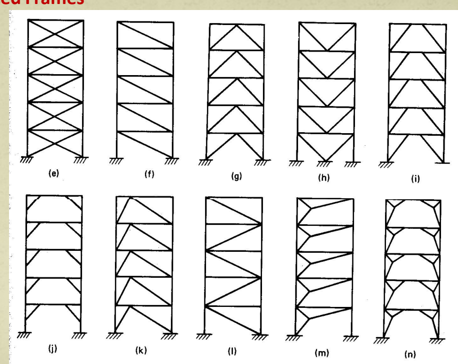


Figure 4.17 Common types of braced frames.

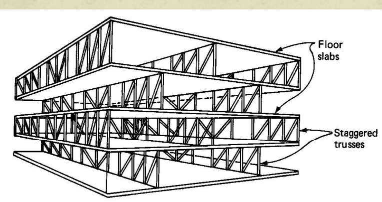
Braced Frames



Staggered Truss System

- ❖ Using staggered trusses, as shown in the next slide, the required flexibility in unit layouts is achieved by arranging the trusses in a staggered plan at alternate floors.
- ❖ The floor system acts as a diaphragm transferring lateral loads in the short direction to the trusses.
- ❖ Lateral loads are resisted by truss diagonals and are transferred into only the direct/axial loads in the columns (without moments).

Staggered Truss System

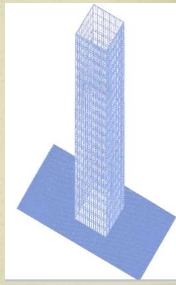


(c)

Figure 4.18 Staggered truss system.
c) perspective view of truss arrangement.

Rigid Frame Structure

- Resist Shear+ bending moment
- Height efficiency Steel = 30 floors Concrete = 20 floors
- Column size increases towards the base of the building.
- become cost-prohibit for use in buildings exceeding 35 stories.



Rigid Frame Structure

Shear Frame Systems

- Shear frames or Vierendeel frames, in which beams and columns are rigidly connected to provide moment resistance at joints, are placed in two orthogonal directions to resist wind forces in each direction.
- The efficiency of development of lateral stiffness is dependent on bay span, number of bays in the frame, number of frames and the available depth in the floors for the frame girders.
- Bay dimensions in the range of 6m to 9m are commonly used.

Shear Frame Systems

- In these shear frames; the predominant contribution to sway deflection under wind load comes from the bending of beams and columns due to the wind shear and to a smaller extent, from column shortening or the cantilever component (Figure 2).
- The design of these frames is controlled therefore by the bending stiffness of individual members.
- The deeper the member, the more efficiently the bending stiffness can be developed

Shear Frame Systems

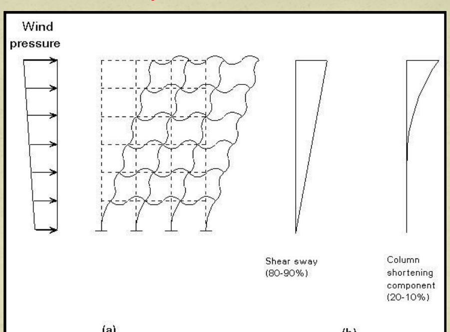


Figure 2. Frame sway

Shear Frame Systems

In current practice, buildings with pure shear frames are generally restricted to only a few stories in height, since other more efficient forms are available.

- However, the uncluttered rectilinear Vierendeel form may still be preferred in cases where other forms involving diagonals or trusses may interfere with architecture and space planning.
- The basic inefficiency in shear frame buildings arises from the need for moment-connected rigid joints which are expensive to fabricate, in addition to the steel quantities involved.

Shear Wall Core Rigid Frame Structure

- ❖ Shear trusses can be provided in the vertical direction, if the organization of the core permits such an arrangement.
- ❖ In general, building core elements including elevator banks are centralized and will permit core trusses connecting columns in at least one direction.
- ❖ These trusses combined with perimeter shear frames produce a Shear Truss and Frame System (Figure 3).

Shear Wall Core Rigid Frame Structure

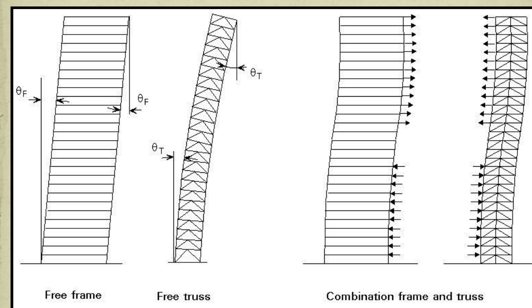


Figure 3 Frame-shear truss interaction

Shear Wall Core Rigid Frame Structure

- ❖ There may be other interior frames which participate as well.
- ❖ This type of interacting system has a wide range of application in structures from 10 to 40 stories.
- ❖ Particular coordination with respect to providing access into the core needs then to be considered.
- ❖ The combination of the Shear Frame and vertical braces produces interaction of two modes of behavior, that of a Shear Frame and a Cantilever (Figure 3).
- ❖ This combination produces desirable results in the stiffness efficiency of the overall system.

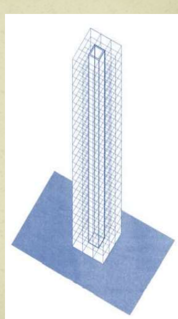
Shear Wall Core Rigid Frame Structure

Vertical trusses resist wind forces as a cantilever and therefore provide lateral stiffness more efficiently than shear frames.

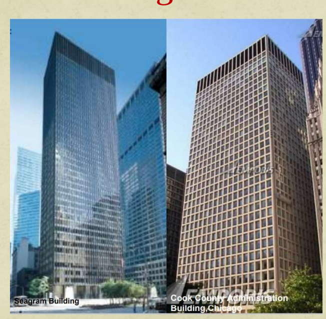
- ❖ However, the depth available to the truss (dependent on the planning of the core area) determines the overall effectiveness of the system.
- ❖ For the truss bracing K-forms, X-forms or single brace forms can be used.
- ❖ The K-form is common since the bracings do not participate extensively in carrying gravity load, and can be designed for axial forces due to wind
- ❖ without gravity axial forces. In the X and single brace forms, gravity axial forces may dominate in the design of braces.
- ❖ In general, Shear Truss and Frame Systems produce the most economical steel structural system for buildings up to 30 stories in height.

Shear Wall Core Rigid Frame Structure

- Shear walls and rigid moment resisting frames.
- Greater lateral rigidity for building
- Capacity to rise unto 60 floors.

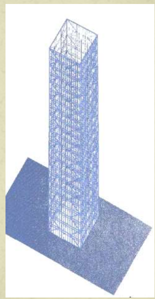


Shear Wall Core Rigid Frame Structure



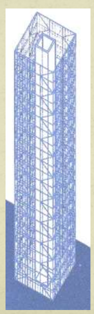
Braced Frame Structure

- Vertical truss: resist lateral loads
- K,V,X members eliminating bending under lateral loading.
- Column girder and diagonal bracing are connected by pin joints.
- Fabrication is more economical than other moment resisting connection in rigid framed structure



John Hancock building, chicago

- Shear walls: To resist the lateral load caused by wind & earthquake
- Relatively thin: height/width
- The assembly of shear walls is known as "coupled shear wall"
- Belt trusses distribute the tensile and compressive force to the large no. of exterior trusses



Empire State Building (NewYork)

Shanghai Financial Centre, Chaina

Frames, Vertical Trusses

Belt and Outrigger Trusses

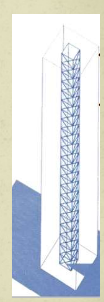
- ❖ The exterior fascia shear frames and the vertical trusses in the core can be tied together by a system of outrigger and belt trusses which are provided at room levels, where the trusses will not interfere with the interior space planning.
- ❖ The primary result of the outrigger trusses is the development of axial forces in the exterior columns due to wind action.

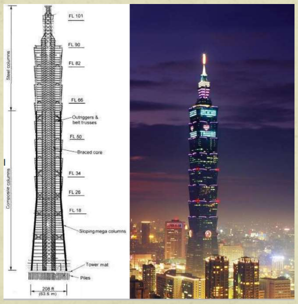
Braced Core Structure:

- Shear Resisting core
- Minimized possibility of torsion due to lateral load
- It May contain one or more cores Connected by outriggers to provide column-free space

BRACED CORE STRUCTURE:

- Outrigger generally form of steel trusses or reinforced concrete
- connect the core to the peripheral columns, reduce the overturning moment and lateral drift in the building.





Belt and Outrigger Trusses

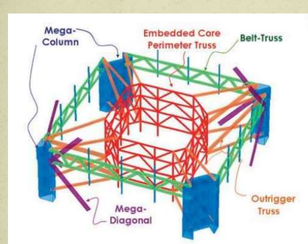
- Outrigger trusses run parallel to the direction of lateral force.
- Belt trusses run perpendicular to the direction of the lateral force, along the perimeter of the building.
- This behavior significantly improves the lateral stiffness under wind forces.
- The use of belt trusses on the facades, at the same level and perpendicular to the outrigger trusses, further enhances participation of exterior frames in the cantilever behavior.

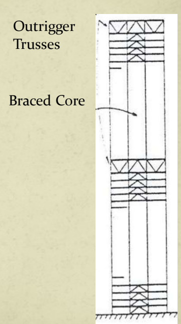
Belt and Outrigger Trusses

- The belt trusses transform the two-dimensional frame system into a three-dimensional frame system which resists wind action.
- The building sway under wind is significantly reduced by the introduction of these trusses.
- A review of the deflection curve indicates two stiffening effects: one related to the participation of the external columns in a total-building-width cantilever mode;
- the other related to the stiffening of the facade frame by the belt trusses.
- Improvements in overall stiffness of up to 25% can result as compared to the Shear Truss and Frame System without such outrigger-belt trusses.

BELT TRUSS SYSTEM

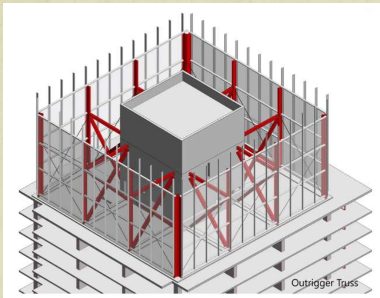
- Placed on exterior wall panels
- Strong and stiff subsystem
- Reduce the shear lag
- Entire story depth can be used to construct mechanical floor
- It distributes loads equally on exterior columns





OUTRIGGER SYSTEM

- Generally in form of a steel truss or reinforced concrete or composite.
- Tied to the core and combined with exterior columns
- Reduce overturning moment and lateral shift
- Under load, shear core tend to bend and the outrigger act as a lever arm
- Use at different levels: create mechanical floors



Belt and Outrigger Trusses

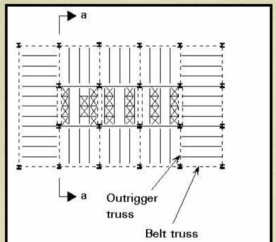
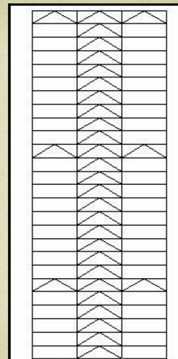


Figure 4 Belt-outrigger truss system



Belt and Outrigger Trusses

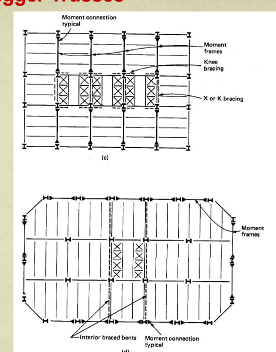


Figure 4.24 (*Continued*) (*c*) Braced core and interior frames; (*d*) full-width interior bracing and exterior frames.

Belt and Outrigger Trusses

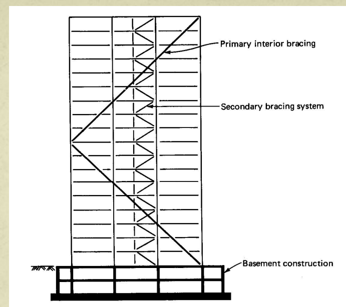


Figure 4.24 (*Continued*) (*e*) Transverse cross section showing primary interior bracing, secondary bracing, and basement construction.

Belt and Outrigger Trusses

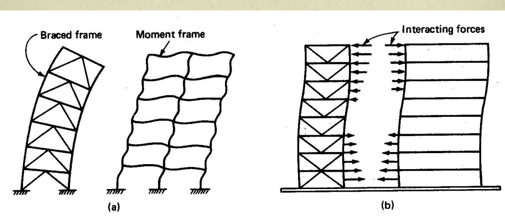


Figure 4.25 Interaction between braced and unbraced frames. (*a*) Characteristic deformation shapes; (*b*) variation of shear forces resulting from interaction.

Belt and Outrigger Trusses

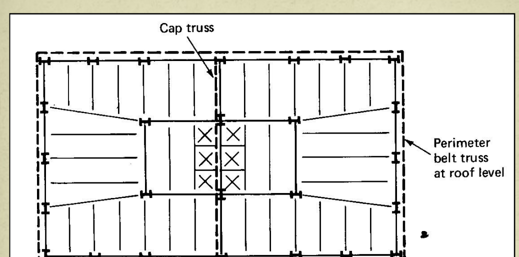


Figure 4.26 Building floor plan showing cap and belt trusses.

Belt and Outrigger Trusses

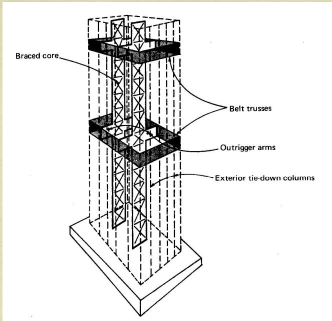
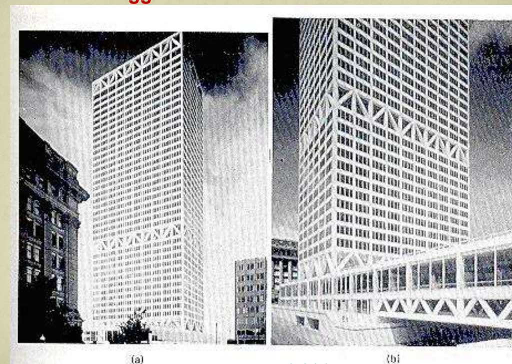


Figure 4.31 Schematic elevation of two outrigger and belt truss system.

Belt and Outrigger Trusses



First Wisconsin Center, Milwaukee

Belt and Outrigger Trusses

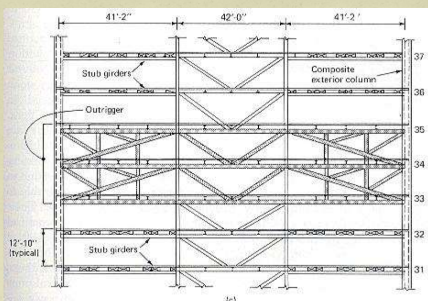
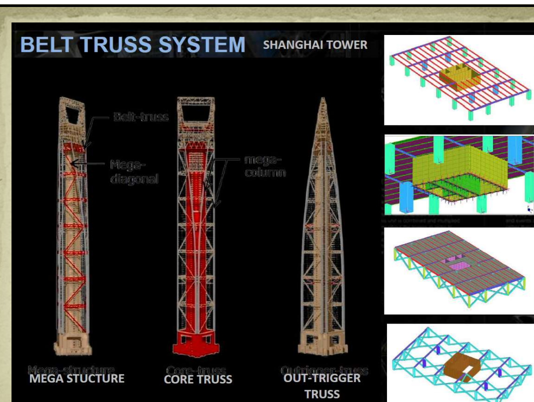


Figure 4.35 (*a* and *b*) Photographs of First Wisconsin Center, Milwaukee. A system of outriggers and belt trusses interacting with moment frames constitutes the lateral bracing system (Architect/Engineer, Skidmore, Owings & Merrill, Chicago); (*c*) schematic framing elevation of outrigger truss for One Houston Center project (Structural engineers, Walter P. Moore and Associates).

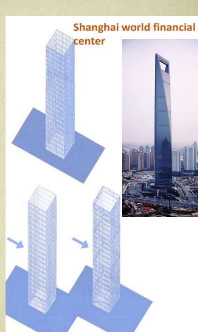


Tube Structure

- Utilize entire building to resist lateral loads.
- Outer frame: closely spaced columns rigidly connected to deep spandrel beams.
- Loads are transferred by external frame

Exterior column spacing 5ft to 15 ft (1.5 m-4.5 m) Spandrel beam depth 24 in-48 inch (600-1200mm)

- Shear lag reduced by use of belt truss placed on exterior wall panels. Belt truss used to equalize tension and compression forces due to shear lag.



The Framed Tube

- ❖ If the facade shear frame is made stronger by closer spacing of columns and larger member proportions and if such frames are continuous at corners, the overall frame is transformed into a cantilever Framed Tube fixed at the ground.
- ❖ When such frames are provided on all four faces of a tower, one obtains a hollow tubular configuration.
- ❖ This 'silo' form containing small window perforations is most efficient in resisting wind forces.

The Framed Tube

- The more the distribution is similar to that of a fully rigid box with uniform axial stress on the flanges and triangular distribution on the webs, the more efficient the system will be as a cantilever.
- The Framed Tube system was first introduced in the mid-1960's in reinforced concrete.
- The dense grid exterior structure was readily formed, creating the appearance of a punched tube.
- This system was adopted later for steel buildings.

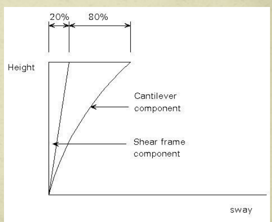


Figure 6a Framed tube : lateral sway

The Framed Tube

- In structural steel, the joints need to be welded for rigidity and the members built-up for larger widths.
- The use of a prefabricated Framed Tube "Tree“ element (Figure 7) where all welding can be done in the shop in a horizontal position has made the steel Framed Tube more practical and efficient.
- The "Trees" are then erected by bolting at mid-span of the beams. Considerable speed of construction of the order of 3 to 4 stories per week can result if "Trees" are used.

The Framed Tube

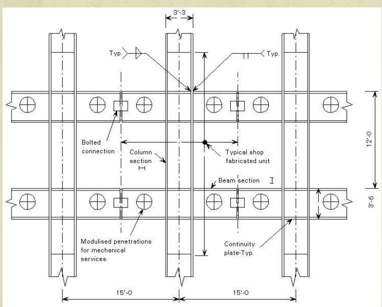


Figure 7 Tree fabrication unit

The Framed Tube

- Steel Framed Tube buildings involve column spacing of 3m to 5m on the exterior which can be transferred or transitioned into wider spacing, if required, at the lower stories to integrate street level activities.
- Such tubular systems have been used extensively for structures of 30 to 110 stories in height.
- An outstanding example was the World Trade Centre in New York.
- Tubular systems are generally adaptable to prismatic vertical profiles.

The Framed Tube

- For varying vertical profiles and buildings involving significant fascia offsets, the discontinuity required in the tubular frame to achieve the shape introduces serious disadvantages.
- The system can however, be readily adapted to a variety of non-rectilinear plan forms.
- Figure 8 shows a particular plan configuration that has been used as a Framed Tube.
- Provided the proportionality of the elements of the tubes is maintained, any closed overall form can be used as a Tubular system.

Braced Tube Structure

- Framed tube + Diagonals = braced tube
- Diagonal braces and spandrel beams give wall like rigidity against lateral loads
- Stiffening the parameter frames overcomes the shear lag problem faced by framed tube.

The Diagonalized Tube

- ❖ The most efficient structure acting as a cantilever is the exterior Diagonalized system.
- ❖ This system was first introduced in the John Hancock Centre in Chicago, a multi-use, 100-storey structure (Figure 9a).
- ❖ The system is essentially a Trussed Tube with the fascia diagonals not only acting as a truss in the plane, but also interacting with the trusses on the perpendicular facades to develop the tube action.

The Diagonalized Tube

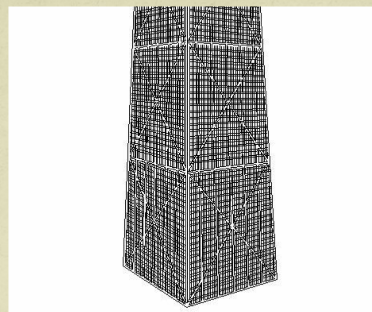


Figure 9a John Hancock Centre, Chicago

The Diagonalized Tube

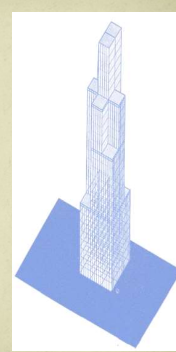
- ❖ A principal advantage of the Trussed Tube is that it eliminates the need for the closely spaced columns of a framed tube.
- ❖ In the John Hancock Centre, the column spacing on the broad face is 12.2m and on the short face, 7.62m.
- ❖ Another advantage of this Tube is that the interior is free from structure for resisting wind action.
- ❖ The design of most members is controlled by gravity forces rather than wind forces.

Bundled Tube Structure

- Cluster of individual tubes tied together to act as a single unit
- framed tubes are bundled at the base and terminates at different levels, without loss of structural integrity
- Single tube : height restriction – slenderness ratio
- Height efficiency : 110 story
- Advantage: flexibility of organizing floor areas
- Individual tube can be of any shape rectangular, triangular, hexagonal

110 story sears tower designed by SOM

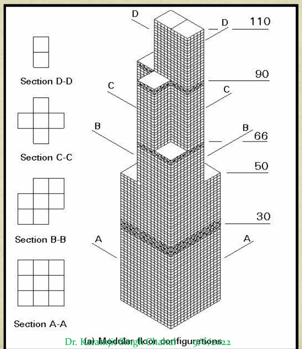
- Framed steel tubes- each with structural integrity
- Individual tubes bundled together in varying configuration and terminated at various levels breaking the wind sway by breaking flow of the wind.



Bundled Tube or Modular Tube System

- ❖ The need for vertical modulation in a logical fashion has created a variation of the tubular structure based on clustering or bundling of smaller sized tubes, each of which rises to a different height.
- ❖ This variation is clarified by the bundled tube system of the Sears Tower in Chicago, Figure 10.
- ❖ In the Sears Tower, the Bundled Tube is composed of 22.86 m square modules, and nine modules are lumped together to form the total system.

Modular Tube System

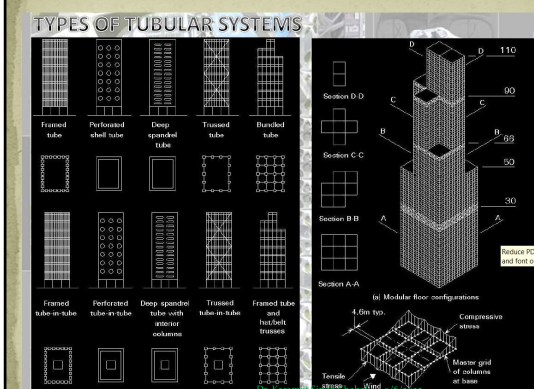


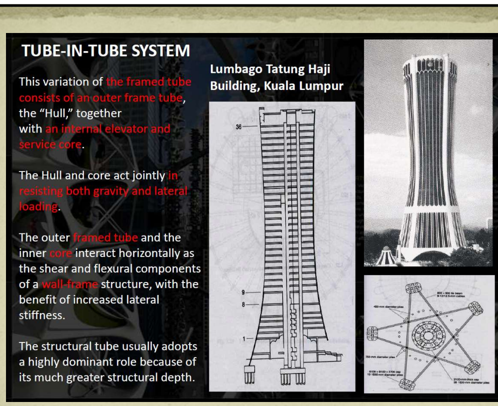
Modular Tube System

- The walls of the tube are formed by columns at 4.57m centers and deep frame beams at each floor.
- The introduction of Framed Tube lines on the interior greatly reduced the influence of the "shear lag" effect that is present in exterior tubes of large side dimensions.
- The modularity and the conceptual basis of the Bundled Tube have a broad application.
- The cells or tubes can be arranged in a variety of ways to create different massing. It can be applied to 30 stories as well as to ultra-tall structures.

Modular Tube System

- The shape of each tube itself can be changed to any other closed clustered shape.
- Triangular and hexagonal units have been used in some existing applications.
- A significant advantage of the Bundled Tube system is the enormous torsional resistance which is helpful in absorbing torsional lateral forces due to asymmetry.
- The torsional loads may be generated both by wind and seismic forces.





Mixed Steel-Concrete Systems

- Mixed Steel-Concrete systems are now a well established new system that can be used as readily as either steel or concrete systems for high-rise buildings.
- Such mixed systems which involve reinforced concrete and structural steel components in forms that are generally applicable, such as the Composite Tubular system, and Concrete Core Braced systems, have been widely used.
- Shear wall elements and/or punched wall or framed-tube elements with monolithically cast beam-column joints are of higher strength concrete.

Mixed Steel-Concrete Systems

- Concrete has extended the application to structures of 50 to 80 stories in height.
- Concrete strengths of 40 MPa to 55 MPa are commonly used, but in some cases, strengths up to 95 MPa have been used.
- The floor framing is of steel in mixed systems, which is advantageous because of the ability to span longer distances with lighter members. Thus larger column-free spaces are possible.

Composite tube systems

- Structural steel floor framing and other interior steel columns complete the system of the first Canadian Centre in Calgary, Canada, as shown in Figure 12.
- The Tube system on the exterior is a combination of Framed Tube of beams and columns with solid walls at the corners.
- The structural concept is based on a tube-in-tube concept involving an exterior reinforced concrete framed-tube and an interior shear wall core tube.

Composite tube systems

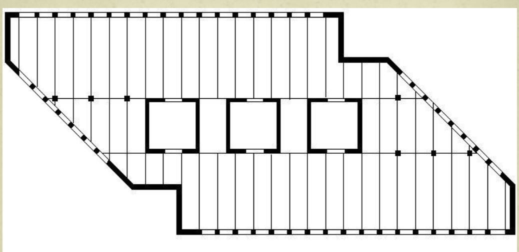


Figure 12 Composite tube

Core braced systems

- In contrast to exterior Tubular systems, Core Braced Systems resist wind forces by shear walls in the core.
- Core walls for wind resistance have been utilized quite extensively in concrete buildings.
- The closed tube shape is then in the interior with access penetrations into the core.
- This type of core element can be used in a steel frame to form the Core Braced Steel system

Core braced systems

- Since all wind forces are resisted by the concrete core, the steel components need only be connected non-rigidly to resist gravity forces.
- Figures 13a and 13b show an arrangement of cores for a 75-storey structure which required considerable flexibility in exterior shaping with offsets and setbacks.
- A lighter, non-rigid structure in steel on the exterior allowed this flexibility.

Core braced systems

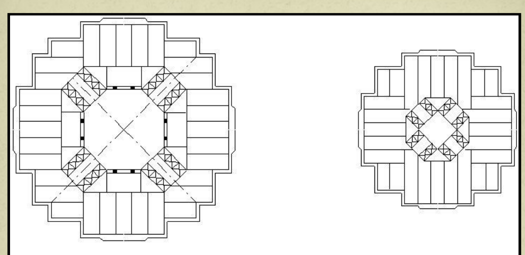


Figure 13 Arrangement of cores for the scheme design of a 75-storey building

Core braced systems

- ❖ The Core Wall Tube system was planned with four inter-connected pods encasing an atrium in the lower part and an octagonal shaped core in the upper parts.
- ❖ This simple arrangement of walls and cores allowed maximum efficiency of the wall system for the structure and maximum flexibility for exterior architecture.

ULTRA HIGH-RISE STRUCTURES

Superframe or Megaframe

❖Superframes or Megaframes assume the form of a portal which is provided on the exterior of a building.

❖The frames resist all wind forces as an exterior tubular structure.

❖The portal frame of the Superframe is composed of vertical legs in each corner of the building which are linked by horizontal elements at about every 12 to 14 floors.

Megaframe Structure

- Building rise above 60 stories
- Utilizes mega columns comprise the chords of oversized braced frames at building corners.
- Linked by multi story trusses at every 15-20 story intervals.
- Often at mechanical floor levels
- Mechanical floors can be used to construct stiff horizontal sub system.

Hotel de las Artes, madrid

Superframe or Megaframe

- ❖ Since the vertical elements are concentrated in the corner areas of the building, maximum efficiency is obtained for resisting wind forces.
- ❖ The vertical legs and the horizontal links are themselves frames with large dimensions in the plane of the frame.
- ❖ Inherent in the concept of a Superframe is the ability of the system to accommodate varieties of spaces suitable for multiple functions.
- ❖ Ultra high-rise Megastructures will need to improve the idea of flexible space or modular spaces, where each space can be planned efficiently for its own use and inserted into a Megaframe.

Superframe or Megaframe

- ❖ Superframes allow this modularization of space to occur with maximum freedom from structural encumbrance.
- ❖ Portal apertures on the exterior wall allow freedom of expression for each unit and also provide access for daylight.
- ❖ Figure 14b indicates an arrangement of interior spaces with an atrium in each space module.

Superframe or Megaframe

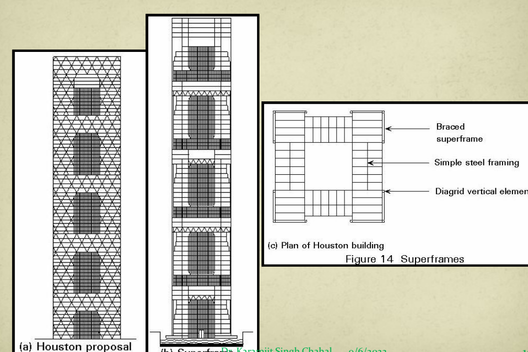


Figure 14 Superframes

Superframe or Megaframe

- The net effect of this combination would be to produce an equivalent cantilever structure as effective as a Tubular system.
- An appropriate diagonalization of structure is represented by an overall modularized diagrid frame, in which the structural members within the portals are removed (Figure 14a).
- Figure 14a also shows the adoption of the Superframe concept to an 80-storey structure in its simplest rectilinear form.
- Figure 15 shows a study of a Superframe concept applied to a 170-storey, 655m tall tower involving 706.000 sq. meters of floor space.

Superframe or Megaframe

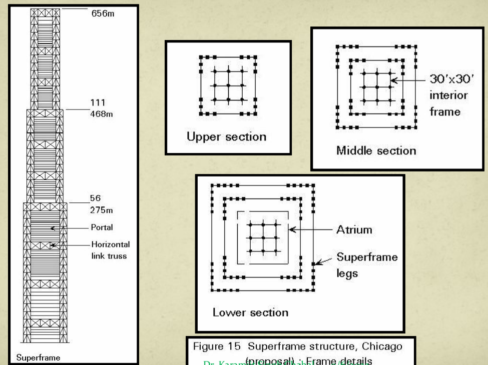


Figure 15 Superframe structure, Chicago (proposal) : Frame details

Superframe or Megaframe

- The structural efficiency is obtained from the concentration of material close to the corners.
- Each of these vertical legs is required to be stiff in its own plane.
- The legs then take the form of a diagonalized truss chord.
- The corner truss legs need strong horizontal connections at frequent modular intervals to make them function together like an equivalent cantilever.

Superframe or Megaframe

- The horizontal members, therefore, will need to be equally stiff, and are diagonalized as well.
- The multiple functions involved are indicated in Figure 16a.
- The tower form, step-tapered from 88m x 88m at the base to 44m x 44m at the top denotes the functional needs of space.
- The effectiveness was confirmed by wind tunnel testing.

Superframe or Megaframe

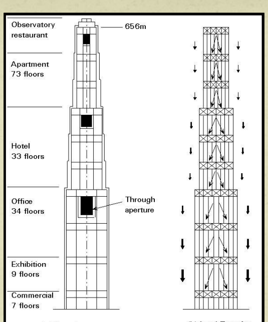


Figure 16 Superframe structure, Chicago, (proposal) : details

Superframe or Megaframe

- The equivalent dampening effect of this aerodynamic shaping illustrates the need for such design coordination in super tall structures.
- The significant aspects of this structural design were:
  - Telescoping of the Super frames allowed an orderly transition of the structure and the needed lateral stiffness.

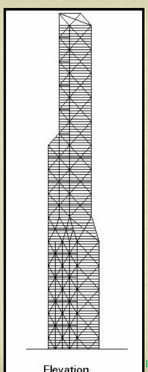
Superframe or Megaframe

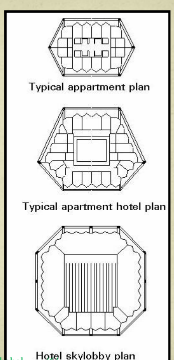
- The aerodynamic behavior was greatly assisted by the apertures which reduced the cross-wind accelerations and forces due to vortex shedding by as much as 25%.
- The overall tapered form assisted as well in reducing the wind 'sail' area gradually toward the top.
- The structural system efficiency was enhanced by the sequential load transfer from the interior to the exterior, as shown in Figure 16, so that all gravity loads were carried by the Superframes.

Super-Trussed Tubes

- The general concept of the exterior Trussed Tube can be extended to ultra high-rise structures involving multiple functions.
- Figure 17 shows a 135-storey exterior Trussed Tube, which was submitted for a project competition in New York.
- This slender form, having an aspect ratio of 10 to 1, involved approximately 185.908 sq. meters of floor space.

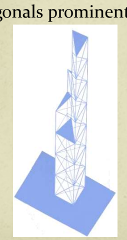
Superframe or Megaframe

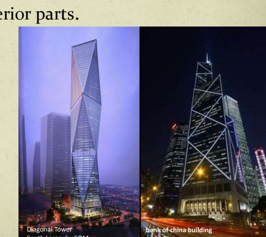

Elevation



Space Truss Structure

- IDEA of stacking triangulated prisms which contain diagonal bracing the exterior and interior frame.
- Resist both lateral + vertical loads
- Diagonals prominent part of interior parts.

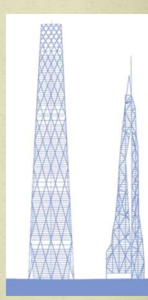




Diagrid Structure

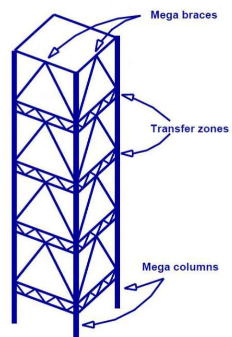
Proposed by Sir Norman Foster Height efficiency: Concrete: 60 Steel : 100

- Lattice work on exterior
- Resist both lateral & gravity loads
- Vertical columns eliminated
- Triangulation (gravity and lateral loads) - uniformly distributed
- Shear deformation minimized
- Resist shear through axial action rather than by bending vertical columns & spandrel
- Both shear & bending rigidity to resist the effects of drift & overturning moment.
- Highly redundant – can transfer loads through multiple paths in case of a localized structural failure.



High-Efficiency Mega-Braced Frame System

- Very large columns and bracing
- Small number of columns
- Bracing extends over multiple floors
- Stiff transfer floors allow for internal flexiblity



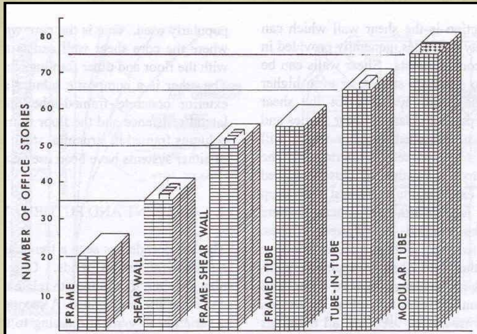


Figure 2 Comparison of Concrete Systems

Category	Material / Configuration	Efficient Height Limit	Advantages	Disadvantages	Building Examples
Rigid Frames	Steel	30	Provide in floor planning. Fast construction flexibility.	Expensive moment connections. Expensive fire proofing	Lake Shore Drive Apartments (Chicago, USA) Assurance Tower (Kansas City)
	Concrete	20	Provide flexibility in the floor planning. Easily mouldable.	Expensive formwork. Slow construction.	Ingalls Building (Cincinnati, USA)
Braced Hinged Frames	Steel Shear Trusses + Steel Hinged Frames	10	Efficiently resist lateral loads by axial forces in the shear truss members. Allows shallower beams compared with the rigid frames without diagonals.	Interior planning limitations due to diagonals in the shear trusses. Expensive diagonal connections.	Low-rise buildings

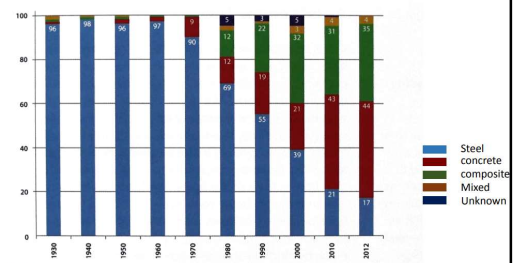
Category	Material / Configuration	Height Limit	Advantages	Disadvantages	Building Examples
Shear Wall / Hinged Frames	Concrete Shear Wall + Steel Hinged Frame	35	Effectively resists lateral shear by concrete shear walls.	Interior planning limitations due to shear walls.	77 West Wacker Drive (Chicago, USA), Casselden Place (Melbourne, Australia)
Outrigger Structures	Shear Cores(Steel Trusses or Concrete Shear Walls) + Outriggers (Steel Trusses or Concrete Walls) + (BeltTrusses) + Steel or Concrete Composite (Super) Columns	150	Effectively resists bending by exterior columns connected to outriggers extended from the core.	Outrigger structure does not add shear resistance.	Taipei 101 (Taipei, Taiwan), Jin Mao Building (Shanghai, China)

Category	Sub Category	Material / Configuration	Efficient Height Limit	Advantages	Disadvantages	Building Examples
Shear Wall (or Shear Truss) - Frame Interaction System	Braced Rigid Frames	Steel Shear Trusses + Steel Rigid Frames	40	Effectively resists lateral loads by producing shear truss - frame interacting system.	Interior planning limitations due to shear trusses.	Empire State Building (New York, USA), Seagram Building
	Shear Wall / Rigid Frames	Concrete Shear Wall + Steel Rigid Frame	60	Effectively resists lateral loads by producing shear wall - frame interacting system.	Interior planning limitations due to shear walls.	Seagram Building, (New York, USA)
		Concrete Shear Wall + Concrete Frame	70			

Category	Sub Category	Material / Configuration	Efficient Height Limit	Advantages	Disadvantages	Building Examples
Tube	Framed tube	steel	80	Efficiently resist lateral loads by locating lateral system at the building perimeter.	Shear lag hinders true tubular behaviour Narrow column spacing obstruct the view	AON Centre (Chicago, USA)
		concrete	60			Water tower place (Chicago, USA)
	Braced tube	steel	100(+ interior) / 150(- interior)	Efficiently resist lateral shear by axial forces in the diagonal members. Wider column spacing possible compared with framed tubes. Reduced shear lag.	Bracing obstruct the view.	John Hancock Centre (Chicago , USA) Ontario Centre (Chicago)
		concrete	100			
	Bundled tube	steel	110	Reduced shear lag.	Interior planning limitations	Sears Tower (Chicago)
	Tube in tube	Ext. Framed Tube (Steel or Concrete) + Int. Core Tube (Steel or Concrete)	80	Effectively resists lateral loads by producing interior shear core - exterior framed tube interacting system.	Interior planning limitations due to shear core.	181 West Madison Street (Chicago, USA)

Category	Material / Configuration	Efficient Height Limit	Advantages	Disadvantages	Building Examples
Diagrid	Steel	100	Efficiently resists lateral shear by axial forces in the diagonal members.	Complicated joints.	Hearst Building (New York,USA), 30 St Mary Axe, also known as Swiss Re Building (London, UK)
	Concrete	60	same	Expensive formwork. Slow construction.	O-14 Building (Dubai)
Space Truss Structures	Steel	150	Efficiently resists lateral shear by axial forces in the space truss members.	Obstruct the view. May obstruct the view.	Bank of China (Hong Kong, China)
Super frames	steel	160	Could produce super tall buildings.	Building form depends to a great degree on the structural system.	Chicago World Trade Center (Chicago, USA)
	Concrete	100			Parque Central Tower (Caracas, Venezuela)

100 Tallest Buildings by structural material



Ref. : The Tall Building Reference Book by Dave Parker & Antony Wood (Data as of January 2013) CTBUH (Council on Tall Buildings & Urban Habitat)

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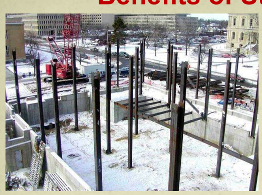
Benefits of Structural Steel




Some benefits associated with use of structural steel for owners are:

- Steel allows for reduced frame construction time and the ability to construct in all seasons
- Steel makes large spans and bay sizes possible, providing more flexibility for owners
- Steel is easier to modify and reinforce if architectural changes are made to a facility over its life
- Steel is lightweight and can reduce foundation costs
- Steel is durable, long-lasting and recyclable

(AISC 1999) 129

Unique Aspects of Steel Construction


Procurement and management of structural steel is similar to other materials, but there are some unique aspects to steel construction:

- Steel is fabricated off-site (above left)
- On-site erection is a rapid process (above right)
- This gives use of structural steel some scheduling advantages
- Coordination of all parties is essential for achieving potential advantages

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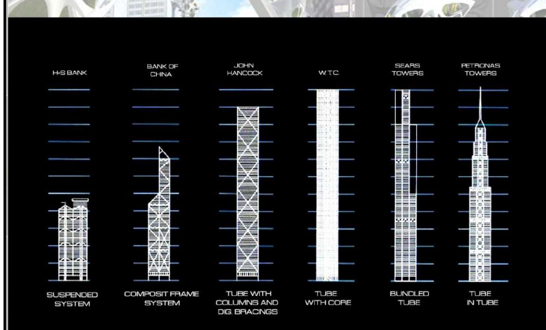
EXAMPLES OF STEEL STRUCTURAL SYSTEMS



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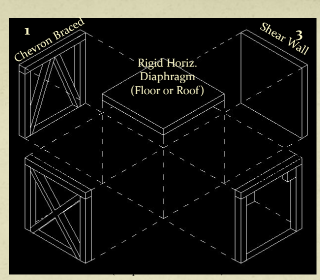
Initial System Planning



- The type of lateral load resisting system to be used in a structure should be considered early in the planning stage
- Lateral stability as well as architectural needs must be met
- The three common lateral load resisting systems are:
  1. Braced Frames 2. Rigid Frames 3. Shear Walls

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Braced Frames and Rigid Frames


braced frames (left) and rigid frames (right)

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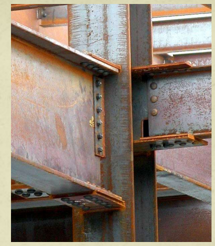
Steel Frame Connection Types

The Specification for Structural Steel Buildings (AISC 2005) defines two types of connections:

- Simple Connections (above left)
- Moment Connections (above right)
  - Fully-Restrained
  - Partially-Restrained

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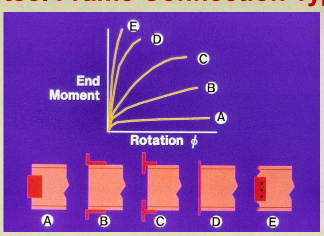
Steel Frame Connection Types



- All connections have a certain amount of rigidity
- Simple connections (A above) have some rigidity, but are assumed to be free to rotate
- Partially-Restrained moment connections (B and C above) are designed to be semi-rigid
- Fully-Restrained moment connections (D and E above) are designed to be fully rigid

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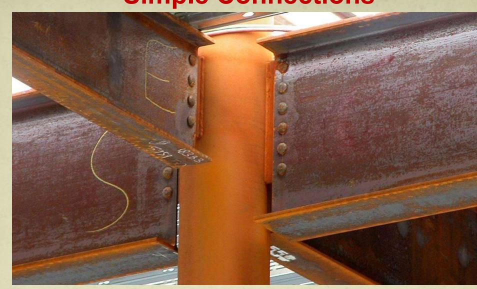
Simple Connections



- Designed as flexible connections
- Connections are assumed to be free to rotate
- Vertical shear forces are the primary forces transferred by the connection
- Require a separate bracing system for lateral stability
- The following few slides show some common simple framing connections

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Common Simple Connections

Single Plate Connection (Shear Tab)

A plate is welded to the supporting member and bolted to the web of the supported beam

Double Angle Connection

The in-plane pair of legs are attached to the web of the supported beam and the out-of-plane pair of legs to the flange or web of the supporting member

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(Green, Sputo, and Veltri)

Common Simple Connections

Shear End Plate Connection

A plate is welded perpendicular to the end of the supported web and attached to the supporting member

Single Angle Connection

One leg is attached to the web of the supported beam and the other leg to the flange or web of the supporting member

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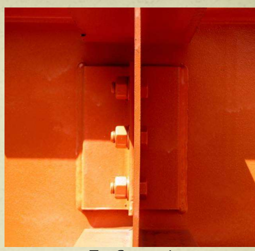
(Green, Sputo, and Veltri)

Common Simple Connections

Seated Connection

An angle is mounted with one leg vertical against the supporting column, and the other leg provides a "seat" upon which the beam is mounted

A stabilizer connection is also provided at the top of the web



Tee Connection

The stem of a WT section is connected to the supported member and the flange attached to the supporting member

(Green, Sputo, and Veltri)

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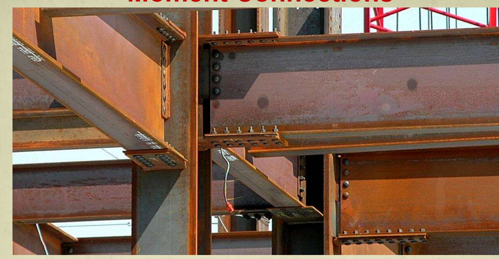
Moment Connections



- Designed as rigid connections which allow little or no rotation
  - Used in rigid frames
- Moment and vertical shear forces are transferred through the connection
- Two types of moment connections are permitted:
  - Fully-Restrained
  - Partially-Restrained

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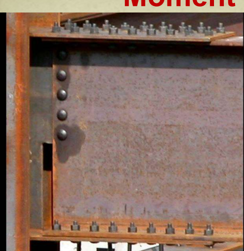
Moment Connections



Fully-Restrained (FR) Connections

- Have sufficient strength to transfer moments with negligible rotation between connected members
- The angle between connected members is maintained

Partially-Restrained (PR) Connections

- Have sufficient strength to transfer moments, but the rotation between connected members is not negligible
- The angle between connected members may change

(AISC 2005)

Common Connections

Welded Flange Plate Connection

Bolted Flange Plate Connection

Top and bottom flange-plates connect the flanges of the supported member to the supporting column

A single plate connection is used to transfer vertical shear forces

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Common Connections

Bolted Extended End-Plate Connection

A plate is welded to the flanges and web of the supported member and bolted with high-strength bolts to the supporting column

Welded Flange Connection

Complete-joint-penetration groove welds directly connect the top and bottom flanges of the supported member to the supporting column

A shear connection on the web is used to transfer vertical shear forces

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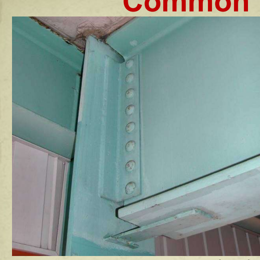
Common Connections



PR Moment Connection – Wind Only

A double angle simple connection transfers vertical shear forces while top and bottom flange plates resist moment forces produced by wind

Note that the size of the flange plate is relatively small in comparison to the beam flange

Top and Bottom Angle with Shear End Plate Connection

Angles are bolted or welded to the top and bottom flanges of the supported member and to the supporting column

A shear end plate on the web is used to transfer vertical shear forces

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Rigid Frames

- Rigid frames, utilizing moment connections, are well suited for specific types of buildings where diagonal bracing is not feasible or does not fit the architectural design
- Rigid frames generally cost more than braced frames (AISC 2002)

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Braced Frames

- Diagonal bracing creates stable triangular configurations within the steel building frame (AISC 2002)
- "Braced frames are often the most economical method of resisting wind loads in multi-story buildings (AISC 1991)."
- Some structures, like the one pictured above, are designed with a combination braced and rigid frame to take advantage of the benefits of both

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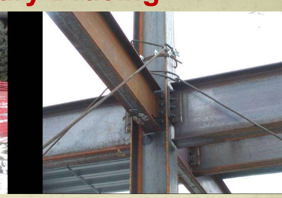
Temporary Bracing



- Structural steel frames require temporary bracing during construction
- Temporary bracing is placed before plumbing up the structural frame
- This gives the structure temporary lateral stability
- Temporary bracing is removed by the erector

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Temporary Bracing

- In a braced frame, temporary bracing is removed after final bolt-up is complete and the permanent bracing system is in place
- In a rigid frame, temporary bracing is removed after final bolt-up is complete

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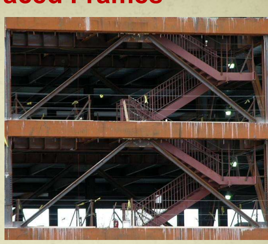
Concentric Braced Frames



- Bracing is concentric when the center lines of the bracing members intersect
- Common concentric braced frames used in buildings today include:
  - X brace (above left)
  - Chevron (above right)
  - Two story X's
  - Single diagonals
- X bracing is possibly the most common type of bracing
- Bracing can allow a building to have access through the brace line depending on configuration (AISC 2002)

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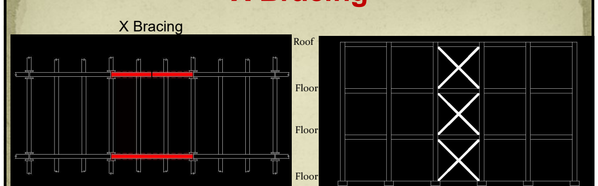
X Bracing



Typical floor plan with X bracing

X-braced building elevation

- The diagonal members of X bracing go into tension and compression similar to a truss
- The multi-floor building frame elevation shown above has just one braced bay, but it may be necessary to brace many bays along a column line
- With this in mind it is important to determine the locations of the braced bays in a structure early in a project

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(AISC 2002)

X Bracing

- Connections for X bracing are located at beam to column joints
- Bracing connections may require relatively large gusset plates at the beam to column joint
- The restriction of space in these areas may have an impact on the mechanical and plumbing systems as well as some architectural features

(AISC 2002)

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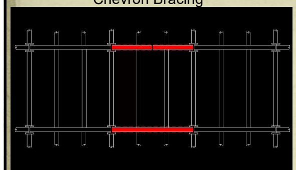
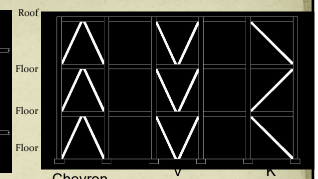
Chevron Bracing

Chevron Bracing



Typical floor plan with Chevron bracing



Elevation with several bracing configurations

- The members used in Chevron bracing are designed for both tension and compression forces
- Chevron bracing allows for doorways or corridors through the bracing lines in a structure
- A multi-floor frame elevation using Chevron bracing is shown above

(AISC 2002)

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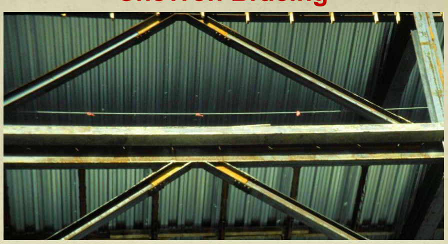
Chevron Bracing



- Chevron bracing members use two types of connections
- The floor level connection may use a gusset plate much like the connection on X braced frames
- The bracing members are connected to the beam/girder at the top and converge to a common point
- If gusset plates are used, it is important to consider their size when laying-out mechanical and plumbing systems that pass through braced bays (AISC 2002)

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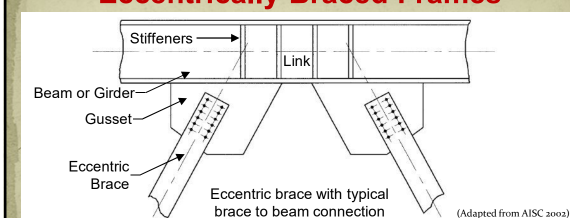
Eccentrically Braced Frames



Eccentric brace with typical brace to beam connection

(Adapted from AISC 2002)

- Eccentric bracing is commonly used in seismic regions and allows for doorways and corridors in the braced bays
- The difference between Chevron bracing and eccentric bracing is the space between the bracing members at the top gusset connection
  - In an eccentrically braced frame bracing members connect to separate points on the beam/girder
- The beam/girder segment or “link” between the bracing members absorbs energy from seismic activity through plastic deformation (AISC 2002)

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Eccentrically Braced Frames

- Eccentrically braced frames look similar to frames with Chevron bracing
- A similar V shaped bracing configuration is used

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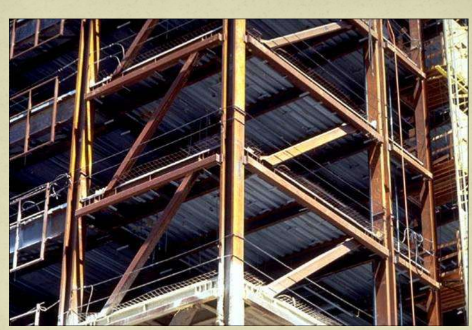
Eccentrically Braced Frames



Eccentric single diagonals may also be used to brace a frame

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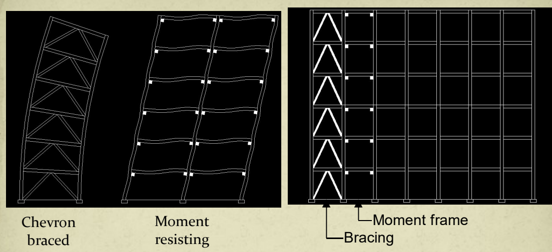
Combination Frames



Combination Frame

- As shown above (left) a braced frame deflects like a cantilever beam while a moment resisting frame deflects more or less consistently from top to bottom
- By combining the two systems, reduced deflections can be realized
- The combination frame is shown above right

(AISC 1991)

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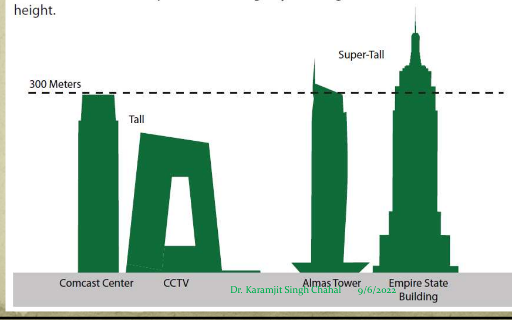
What is a Super-Tall Building?

Again, opinions on this differ internationally. Although great heights are now being achieved with built tall buildings (in excess of 800 meters/2600 feet), as of early 2010 there were 43 buildings in excess of 300 meters completed and occupied globally. The CTBUH thus defines "super-tall" as being any building over 300 meters/984 feet in height.



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