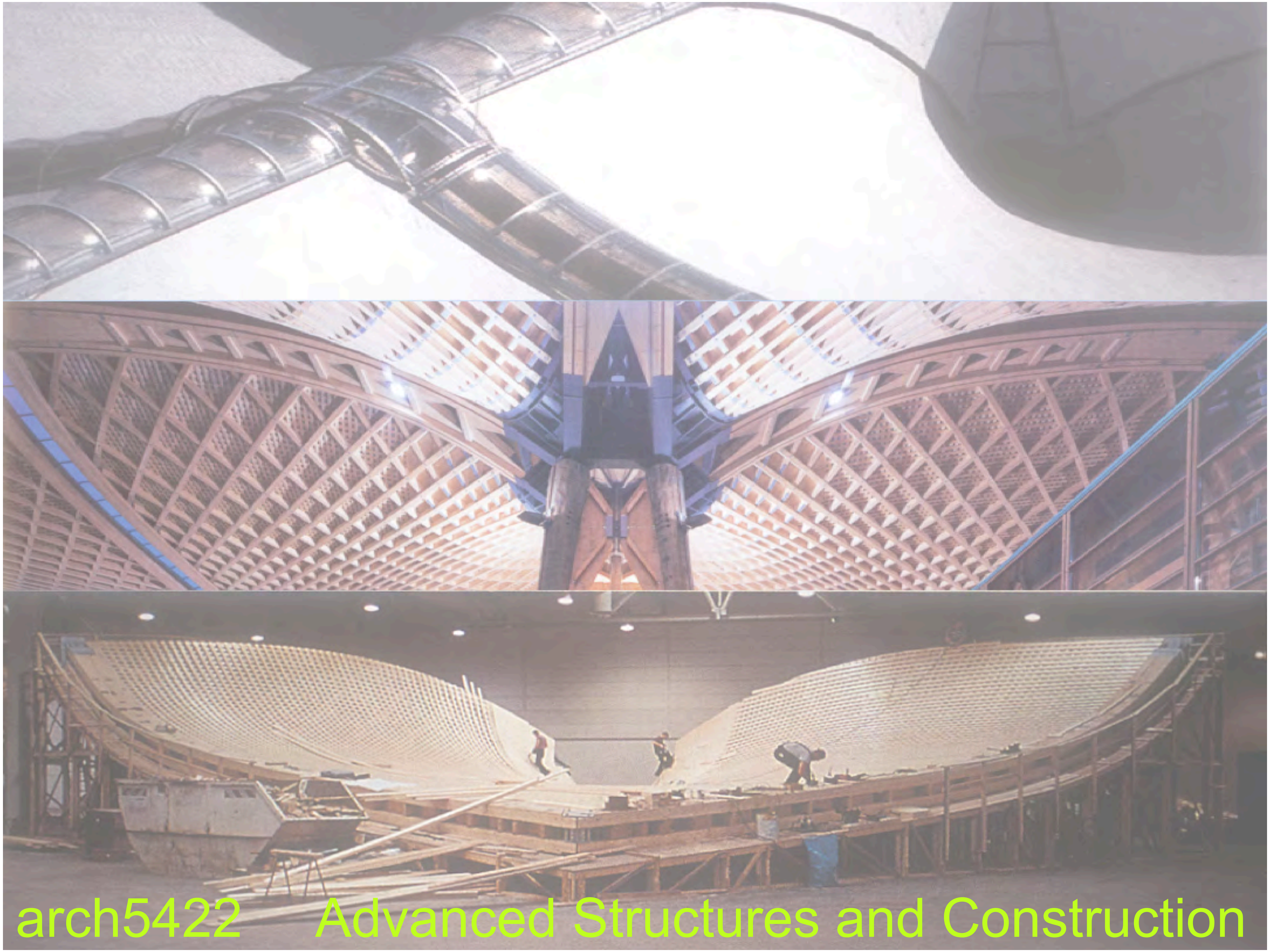


arch5422 Advanced Structures and Construction

2.0 Lateral Forces

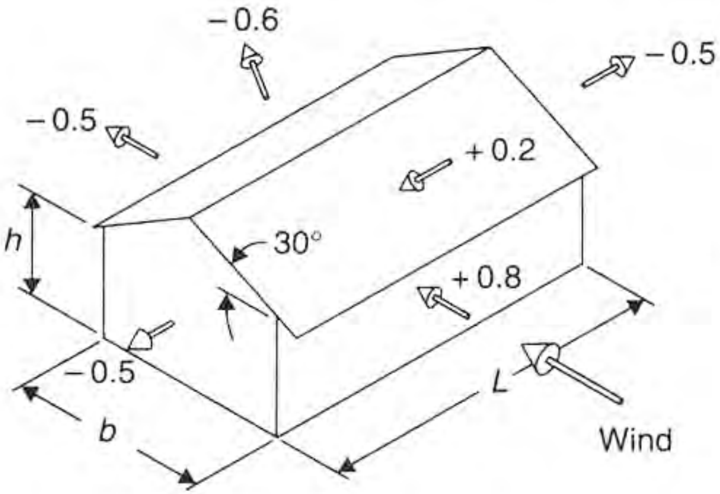
Building Loads

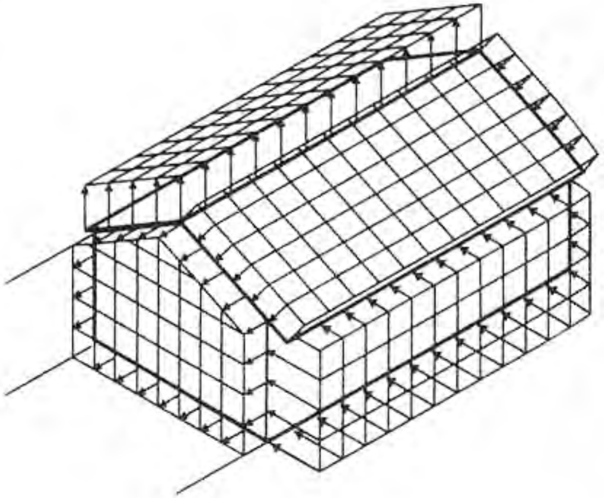
- Types of loads on buildings:
  - Vertical Loads (gravity)
    - Dead Loads: building mass (all permanent parts of a building including structure, permanent partitions, stairs, mechanical equipment and the building enclosure)
    - Live Loads (also called imposed): people, non-built-in furniture, snow, water
  - Lateral Loads
    - Wind
    - Earthquake (seismic)
    - Sub-grade pressure (soil and/or water)
    - Impact loads: blast, tsunami, avalanche
  - Other: Temperature (differential)

- Types of Structure Systems and lateral resistance
  - Wall and pier structure (shear wall)
  - Post and Beam (no lateral resistance)
  - Pin connected steel frames (diagonal bracing)
  - Rigid frames both steel and reinforced concrete (stiffness achieved through rigidity of beam/column connections)
  - Three dimensional rigid forms: space frames, shell structures, etc. (over-all form does not require bracing)
  - Membrane and suspension structures (must be tied back or stiffened; ends must be laterally braced)

Loads which are constant and unchanging (like gravity) are called **static loads.** Some loads(wind, earthquake) vary in intensity and occur suddenly for an instant or over a brief time period. These are called **dynamic loads**.

Wind force





For $h/b/L = 1:8:16$

Wind force = $C_d q_h A$

C_d = pressure coefficient
(+ pressure – suction)

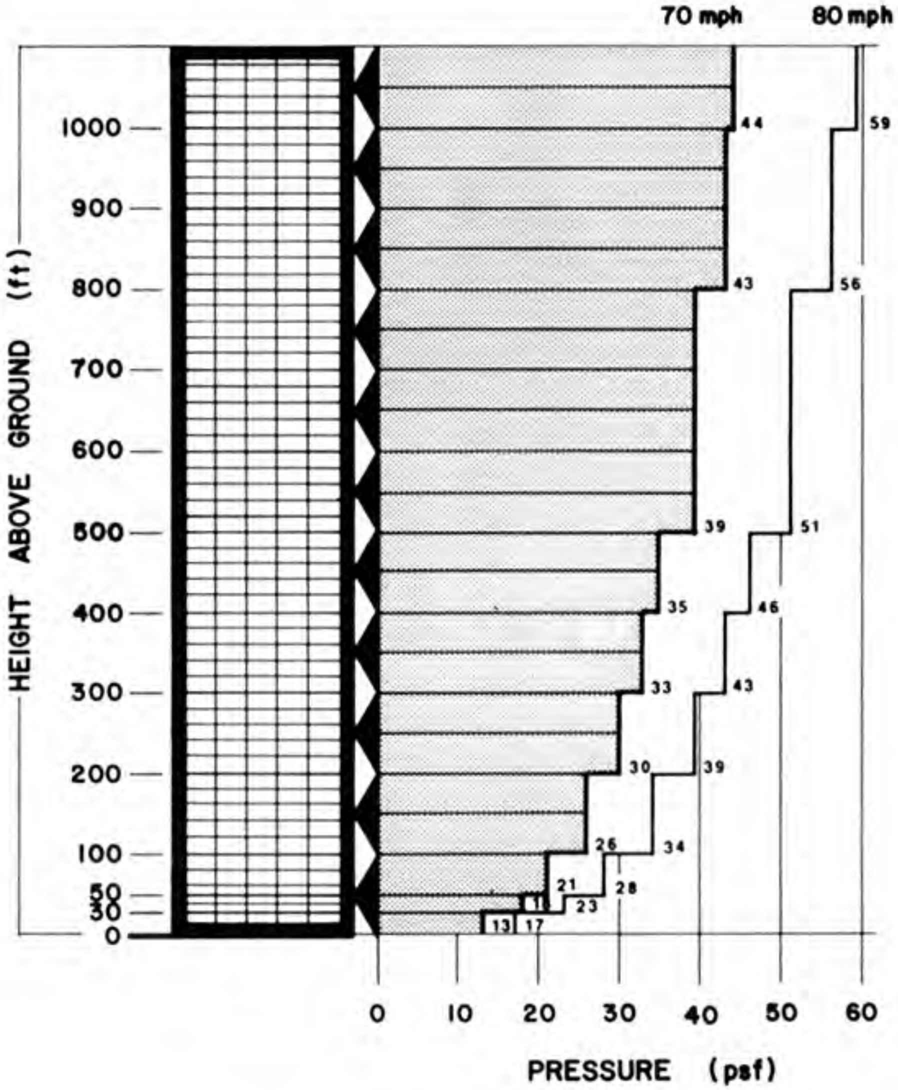
q_h = velocity pressure = $\frac{1}{2}\rho v^2$

A = exposed surface area

Wind loads are dynamic in nature but are applied to buildings as a static wind pressure. The applied force is a percentage of the velocity pressure, q_h dependent on the position and angle of the building's surface. Negative pressure coefficient C_d indicates suction.

The velocity pressure equation above is known as the *Bernoulli equation.* For normal atmospheric conditions, the constant p = .00256. Typical design wind loads are on the order of about 1 to 2 kN/m^2.

Illustrations from *Structures* 6th Ed. by Daniel L. Schodek and Martin Bechthold



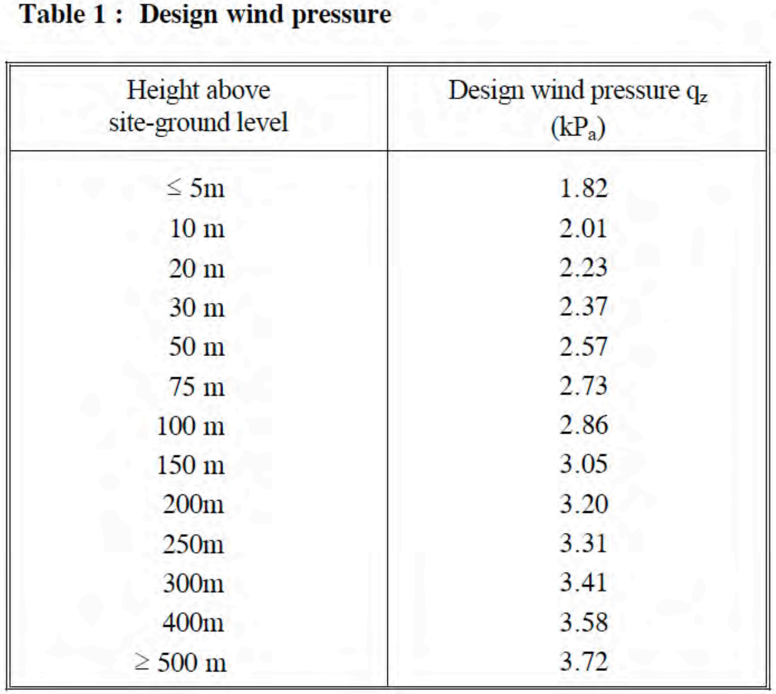


Table 1 : Design wind pressure

Height above site-ground level	Design wind pressure q_z (kP_a)
≤ 5m	1.82
10 m	2.01
20 m	2.23
30 m	2.37
50 m	2.57
75 m	2.73
100 m	2.86
150 m	3.05
200m	3.20
250m	3.31
300m	3.41
400m	3.58
≥ 500 m	3.72

Example of stipulated wind pressures at set heights.
Building Code of New York City ca. 1990.
60 psf = 2.87 kN/m^2.

Required wind pressures at set heights for Hong Kong.
Code of Practice on Wind Effects in Hong Kong 2004
http://www.bd.gov.hk/english/documents/code/windcode2004.pdf

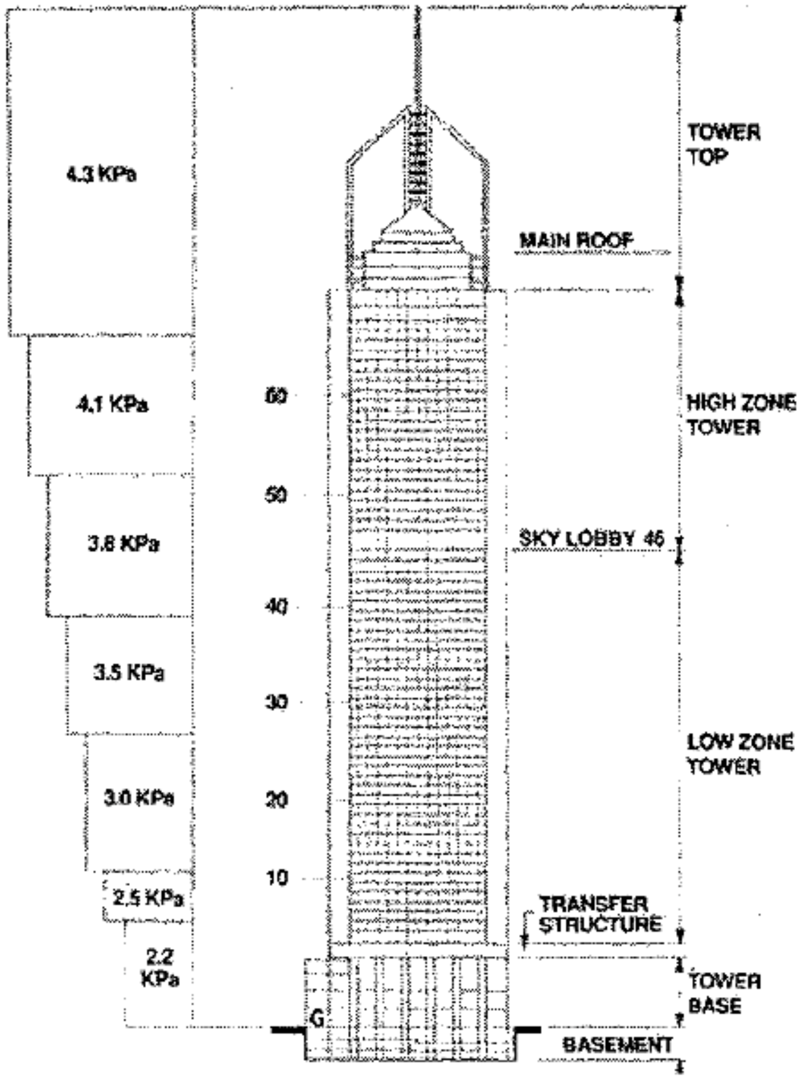


Figure 2.3-2 Design Wind Pressure

Central Plaza Dennis Lau & Ng Chun Man | CTBUH 1995 Wanchai, Hong Kong

Tallest reinforced concrete tower in Asia 1992-1996. 78 floors at 374m. Triangular floor plan. Lateral resistance to wind results in an expenditure on structure of approx. HK$1 million for every additional 1 meter in height. This led designers to develop a very efficient floor to floor dimension of 3.6m. Design wind pressures determined by the Code of Practice on Wind Effects 1983, Building Authority Hong Kong.

Wind pressure on buildings

The wind pressure formula that determines the wind pressure acting on a surface due to a given wind speed is formulated from the Bernoulli equation (Daniel Bernoulli 1700-1782)

q (pressure in psf) = $1 / 2\, p\, V^2$ where p is air mass density and V is the wind speed in mph

Then, $q = 0.00256\, V^2$ (for a standard atmosphere at sea level and temperature 15deg, the air density is 0.0765 lb/ft^3.)

Wind speed is measured by weather stations worldwide. The maximum wind speed is determined as the fastest velocity at 30ft above ground based on a recurrence period of 50 years.

Since the velocity of the wind increases with height, the pressure on the building will vary at different heights. This variation is calculated by formula and the results given in graphic charts such as Table 1 of the Code of Practice on Wind Effects in Hong Kong 2004.

Another factor that affects wind speed is context, or the type of exposure to wind of the surrounding area. Four exposure conditions are used.

Exposure A: large, dense cities	$a = 3.0$	$z_g = 1500$ ft
Exposure B: urban and suburban areas, also forested areas	$a = 4.5$	$z_g = 1200$ ft
Exposure C: flat, open country and slightly rolling landscape	$a = 7.0$	$z_g = 900$ ft
Exposure D: unobstructed coastal areas	$a = 10.0$	$z_g = 700$ ft

The factors "a" and "z_g" are used in the following exposure coefficient formula: $K_z = 2.58\, (z / z_g)^{2/a}$

The final consideration is the shape of the building in plan. For a typical rectangular hi-rise, the shape coefficient $C_p = 1.3$

The full equation then for wind pressure taking into account the height above the ground (z), the exposure condition (K_z), and the shape coefficient C_p is:

$$q = 0.00256\, V^2\, K_z\, C_p$$

Therefore, for an exposure condition C, the wind pressure at 250ft high due to a 100mph wind speed on a rectangular bldg. is:

$$q = 0.00256\, (100\text{mph})^2 \times (2.58)\, (250 / 900)^{2/7}\, (1.3) \quad = \quad 59.5 \text{ psf } (2.85 \text{ kN/m}^2)$$

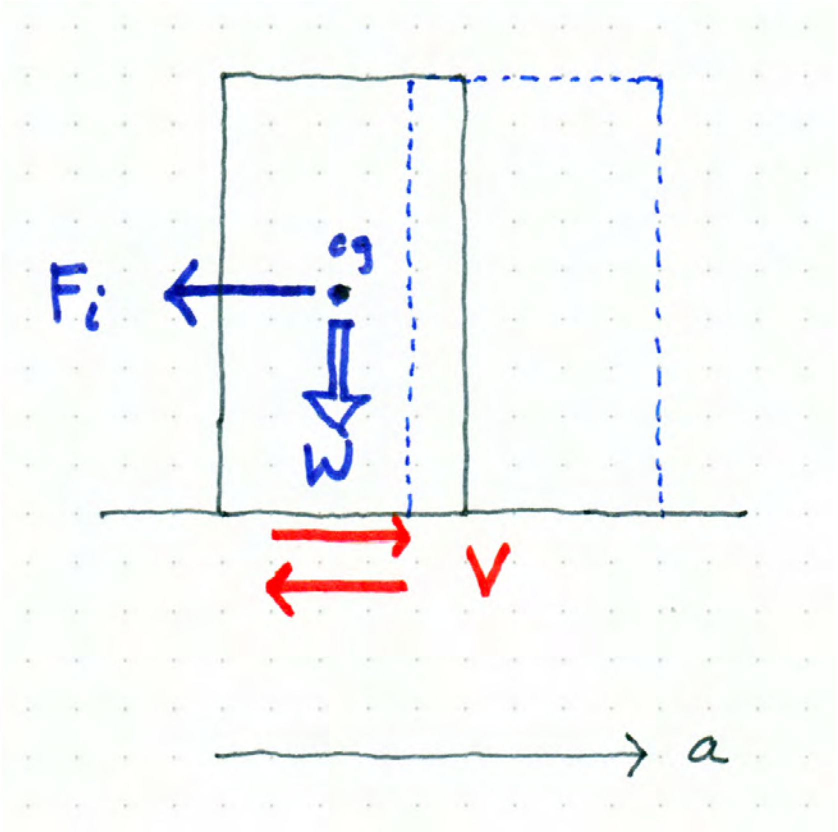
To convert wind pressure into kN/m^2
First, divide the wind speed (if given in km/hr) by 1.609 to get mph, substitute, and multiply the calculated pressure by .04788 to get kN/m^2.

Note: to calculate the complex exponential $(250/900)^{2/7}$ it is convenient to refer to the following website:
http://www.analyzemath.com/Calculators_2/power_calculator.html

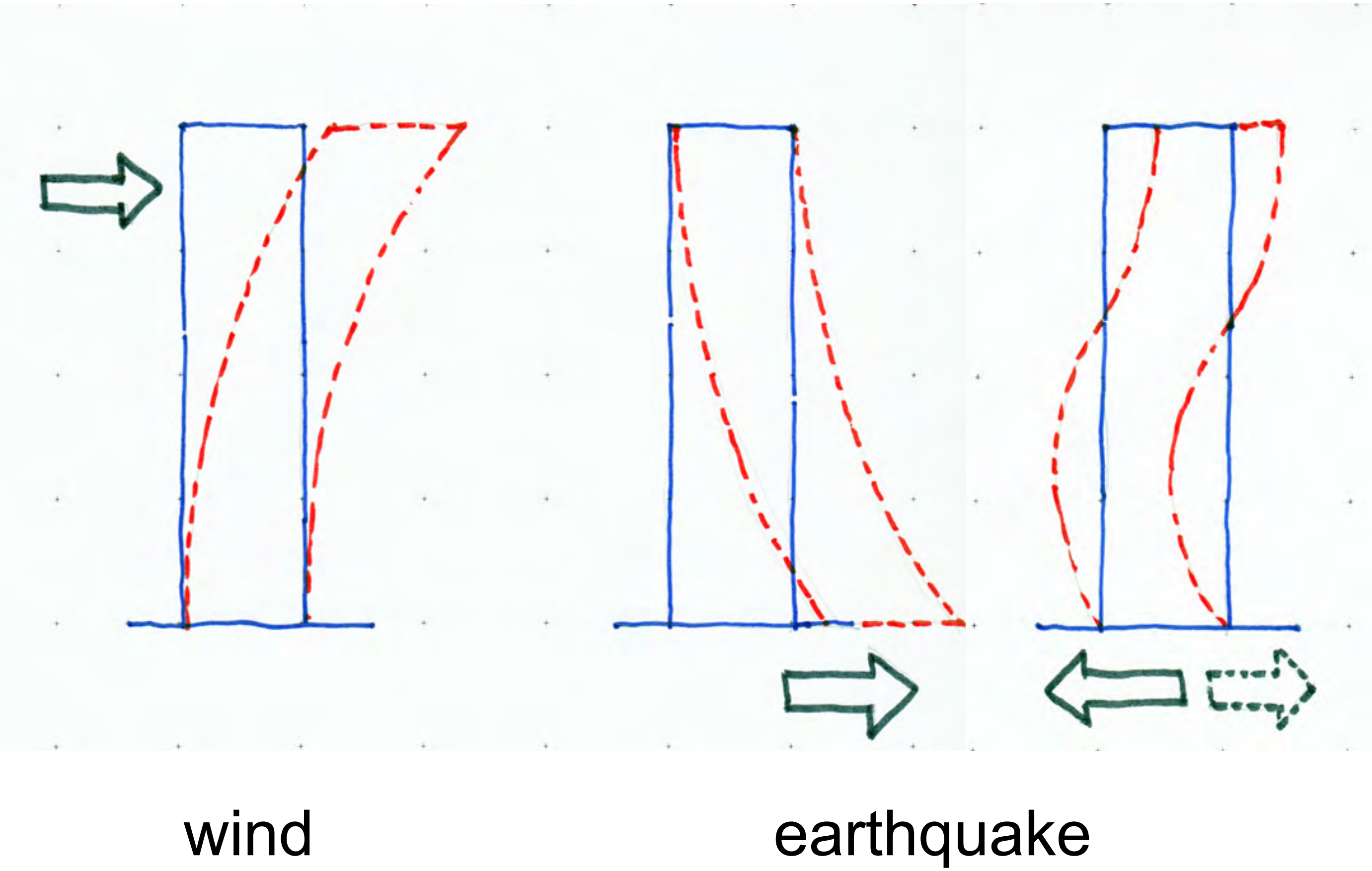
Earthquake force

Earthquake forces are the result of sudden and extreme ground movements. The ground during an earthquake can move in a complex pattern (up/down, laterally, rotating) producing dynamic movements in the structure. This phenomenon is called *ground shaking* and is the primary concern of earthquake resistant design. Other associated destructive aspects of an earthquake include:

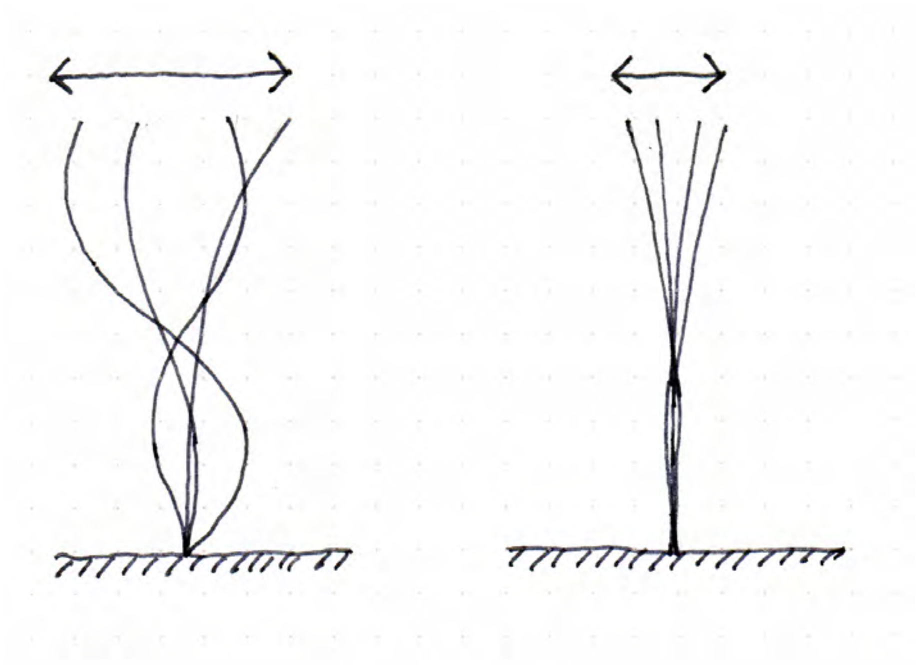
- surface fault ruptures (which may engulf a structure)
- ground failure or *subsidence* (ground becomes soft and may liquify)
- tsunami



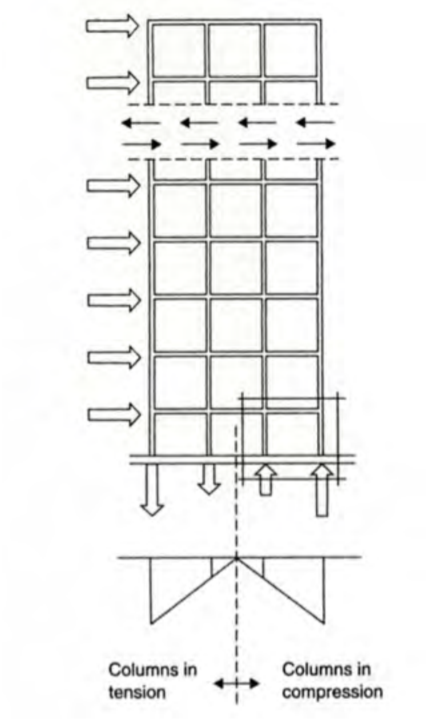
If a building were completely rigid (and weightless), the lateral movement of the ground during an earthquake (the acceleration force, a) would simply move the entire building as a unit with it. However, a building has *weight* that generates an inertial force, F_i (resistance to sudden movement) in the opposite direction. At the base of the building these opposing forces create shear (V) in the structure of the building at the ground. This is referred to as base shear.

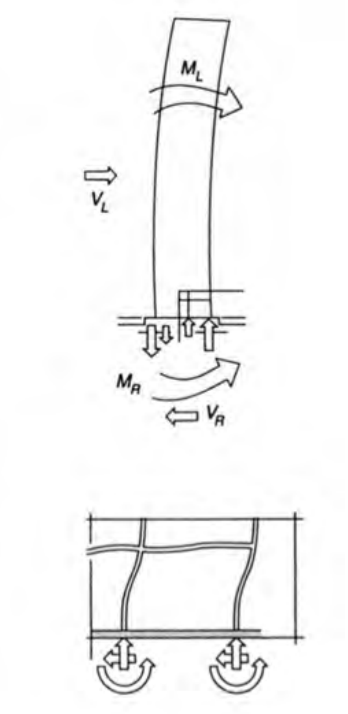


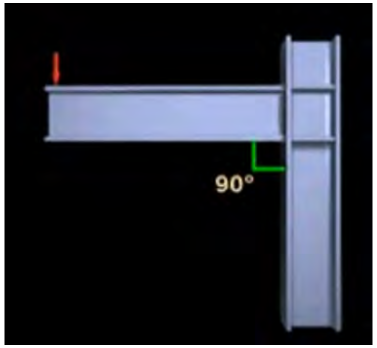
Buildings, however, are not entirely rigid. A flexible structure will have a more complex response to earthquake acceleration force. This response results in *vibratory movements* that depend on the relative stiffness of the building and its *natural period of vibration.*



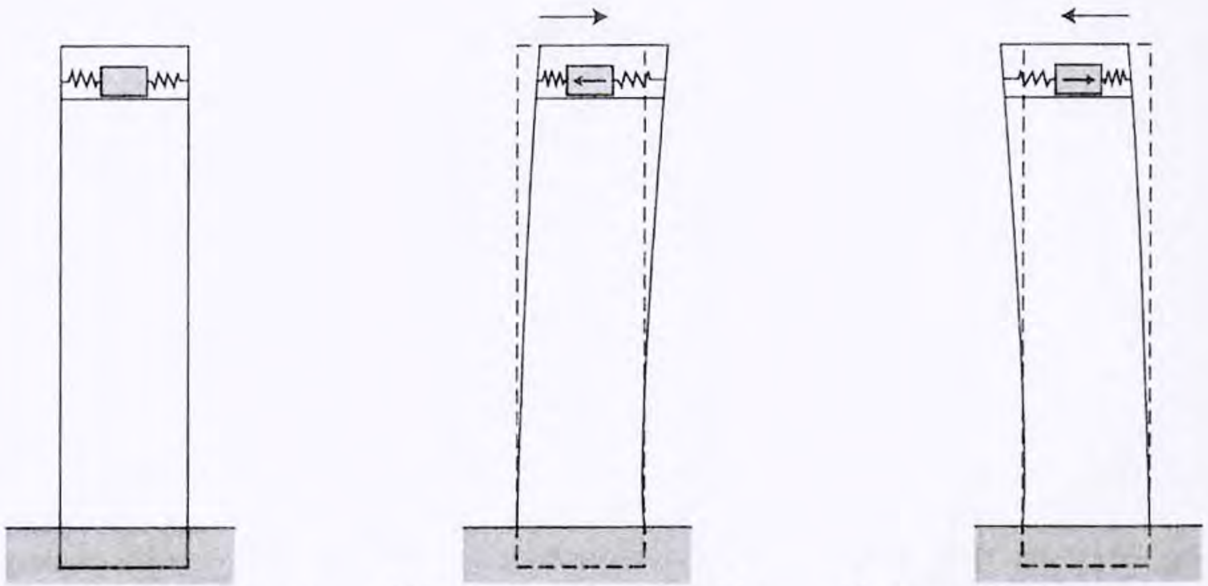
The stiffness of columns in a tall building affects the vibration of the structure. If the columns are of low stiffness, they are less able to restore the deflected structure to its original position. The top of the structure moves slowly back and forth. This is a *long natural period of vibration*. If the columns are more rigid, they provide stronger restoring forces which bring the deflected structure back to the original shape more quickly. The oscillation of the top of the structure is more rapid. The *natural period of vibration* is short.







All buildings have *damping* mechanisms that absorb energy and cause the vibrational movements to come to rest. The deflection of the beams and columns in a steel frame absorbs energy and resists the vibrational movement. Other mechanisms may be more destructive, such as the cracking of partitions. As an alternative, special devices to minimize the movement caused by lateral forces have been developed. One such device is a *tuned mass damper.*



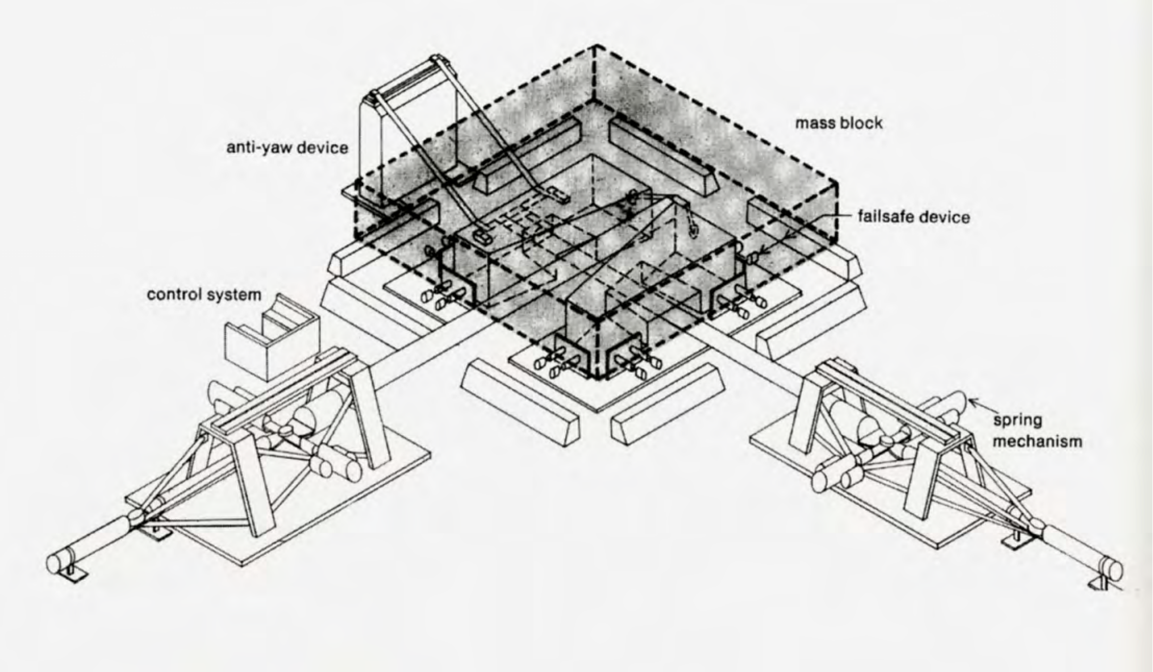
(a) Initial position: the heavy mass is connected with tuned springs to the building. Its natural frequency is usually similar to that of the tower.

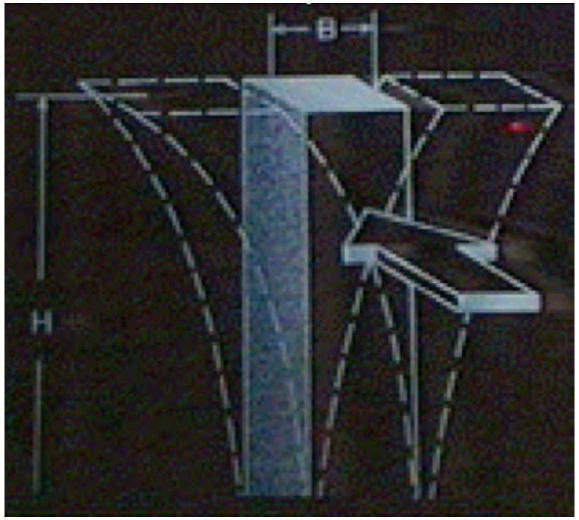
(b) Upon lateral movement of the tower top the mass tends to stay in its original position. This delay causes the springs to deform.

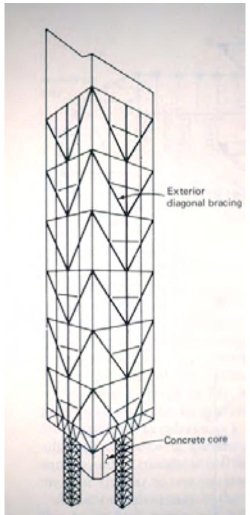
(c) The mass oscillates in the exact opposite direction as does the building. The resulting forces dampen the tower movement.

A tuned mass damper in a high-rise building. The heavy mass or pendulum swings in a controlled way to counter the swinging movement induced by dynamic loads.

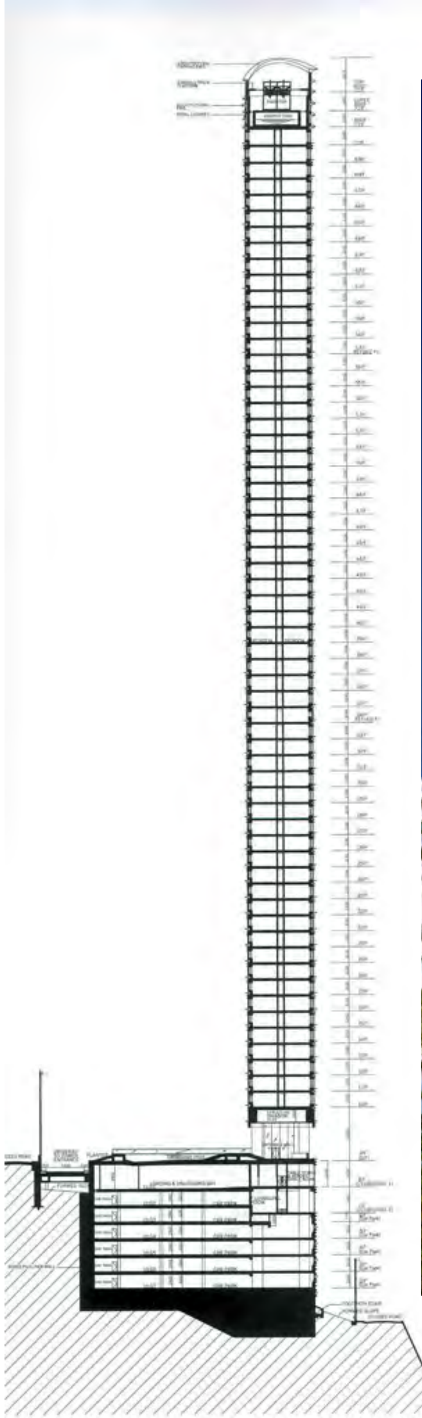
Illustrations from *Structures* 6th Ed. by Daniel L. Schodek and Martin Bechthold



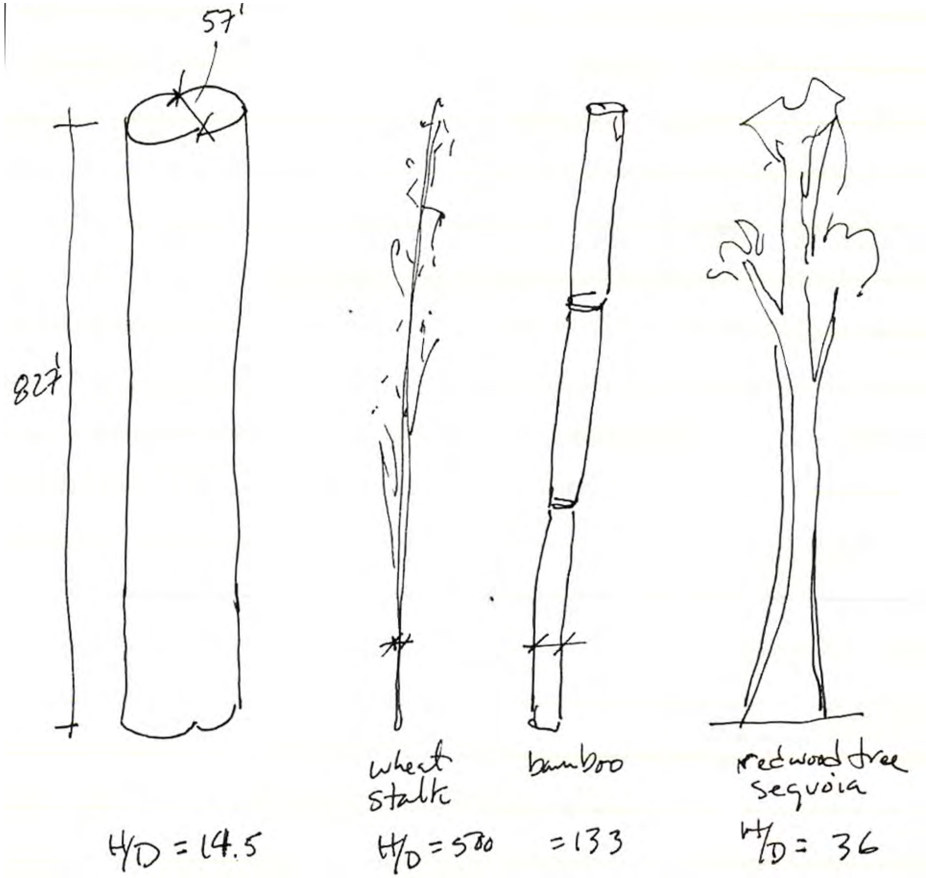




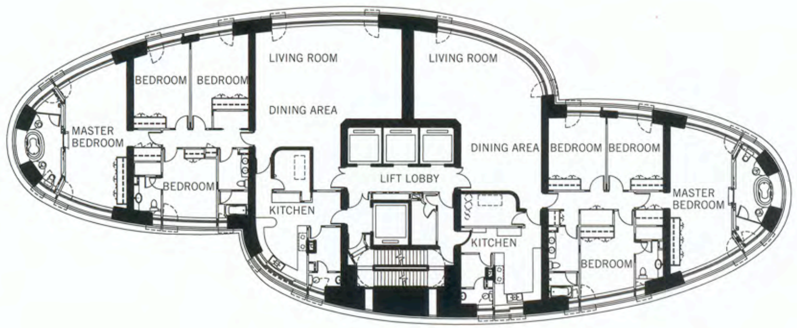
The 1977 Citicorp Tower was one of the first tall buildings to use a *tuned mass damping* device. Essentially a large concrete block. Today other types of mass damping include water tanks. The Summit and the Highcliff residential towers in Hong Kong use a specially designed water tank as a tuned mass damping device.

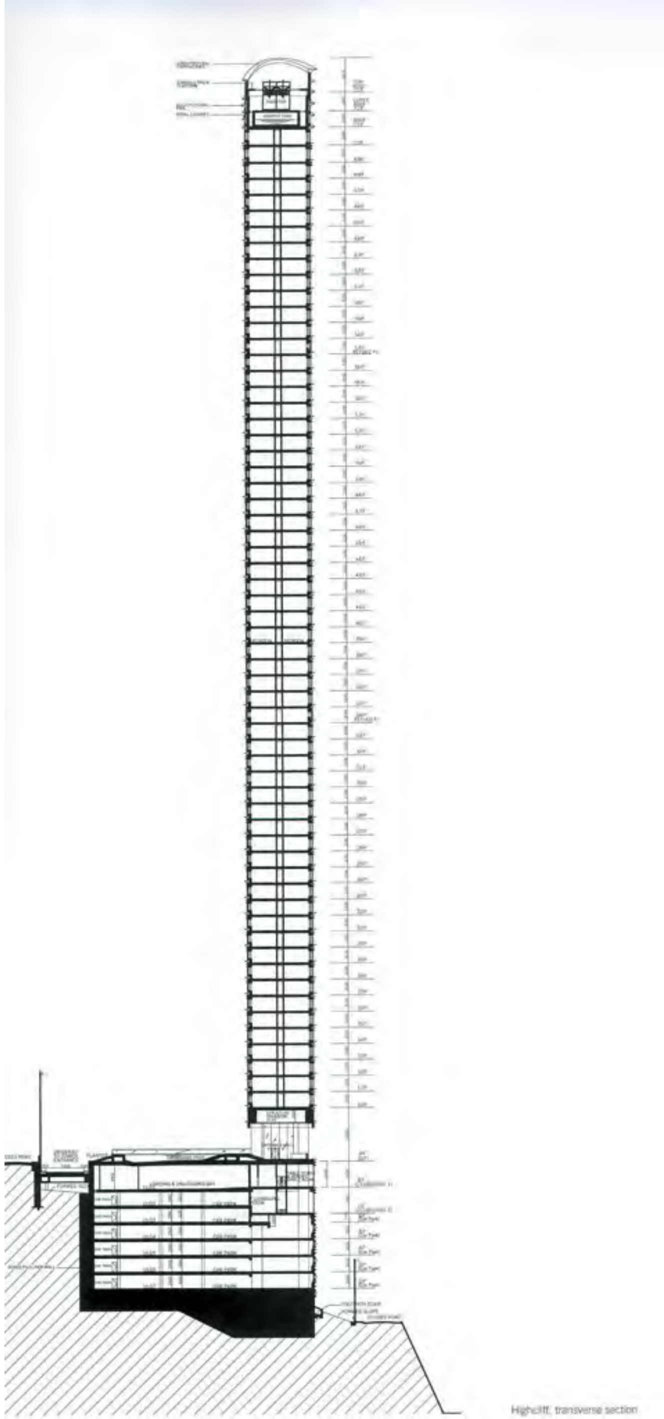


Highcliff, transverse section

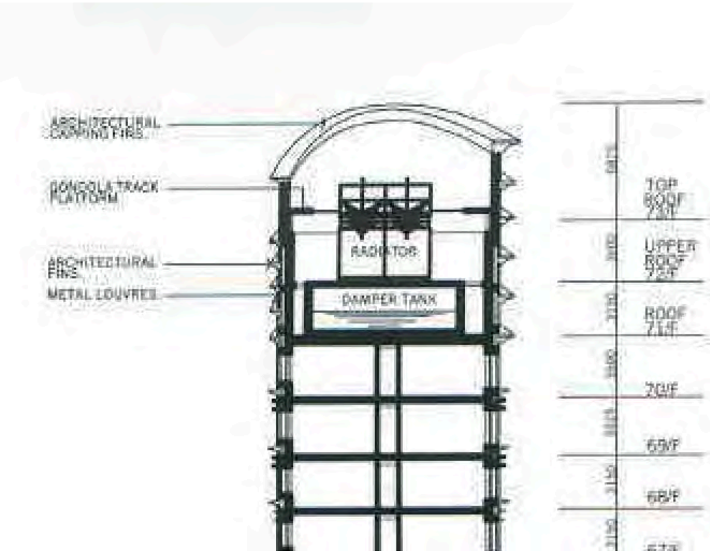


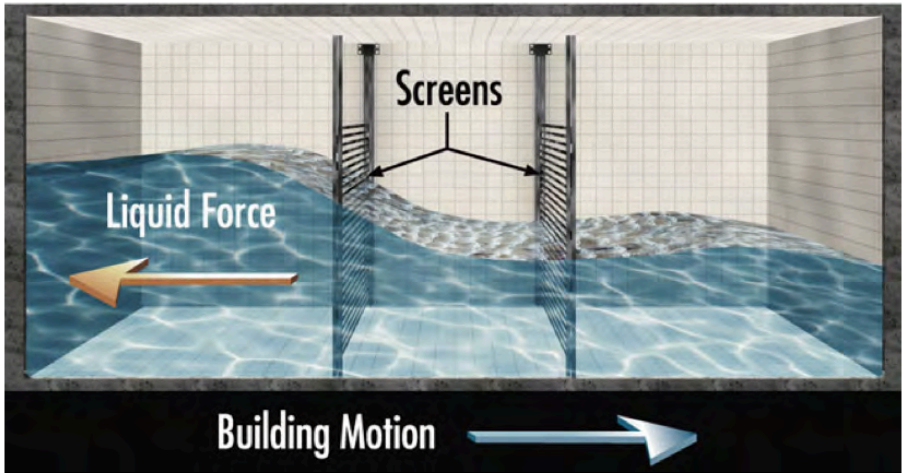

築


LIVING ROOM
LIVING ROOM
BEDROOM
BEDROOM
MASTER BEDROOM
DINING AREA
BEDROOM
KITCHEN
LIFT LOBBY
DINING AREA
BEDROOM
BEDROOM
MASTER BEDROOM
KITCHEN
BEDROOM



Highcliff, transverse section



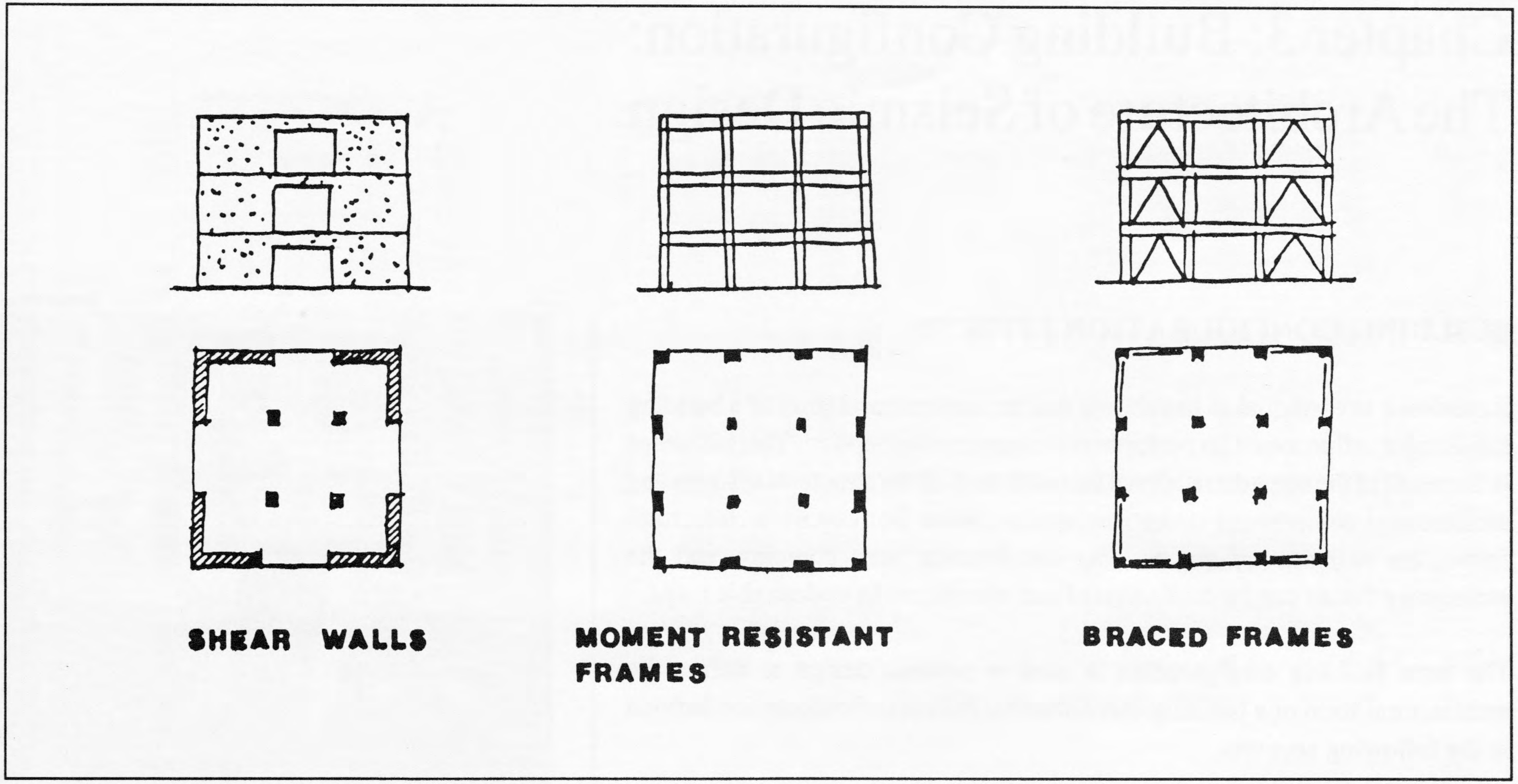


Tuned Liquid Dampener

Design for earthquake force

Seismic design considerations……

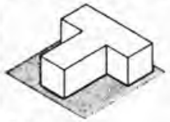
- Lightweight construction (steel and wood framing) is preferred to heavy construction (concrete and masonry).
- Regular symmetrical building layout in plan (regular distribution of weight and lateral force resisting structures such as shear walls).
- Unvarying (no change) lateral force resisting elements from ground to top of building.
- Energy absorbing ductile structures (steel frame) versus rigid and brittle structure (masonry wall).
- In special cases, support elements that allow the building some movement at ground level (base isolation devices) are effective in mitigating the destructive seismic base shear forces.

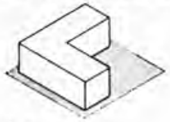


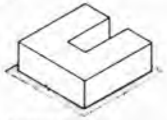
Regularity in the distribution of both mass and lateral force resisting systems is the most important design factor in achieving better earthquake resistant performance.
In a building with a complex shape, different parts of the structure will react to the seismic forces unevenly, creating torsion effects.

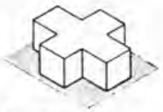
"IRREGULAR STRUCTURES OR FRAMING SYSTEMS" (SEAOC)

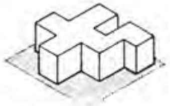
A. BUILDINGS WITH IRREGULAR CONFIGURATION

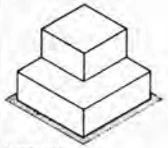

T-shaped plan

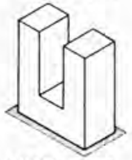

L-shaped plan

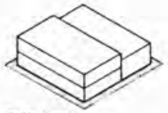

U-shaped plan


Cruciform plan


Other complex shapes

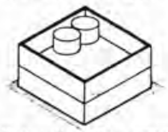

Setbacks


Multiple towers

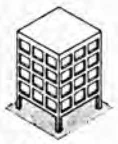

Split levels

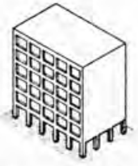

Unusually high story

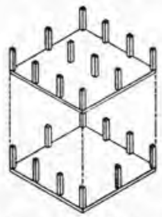

Unusually low story


Outwardly uniform appearance but nonuniform mass distribution, or converse

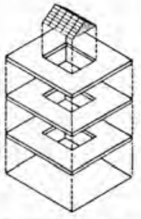
B. BUILDINGS WITH ABRUPT CHANGES IN LATERAL RESISTANCE


"Soft" lower levels


Large openings in shear walls

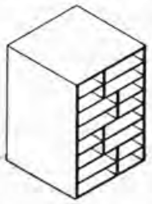

Interruption of columns

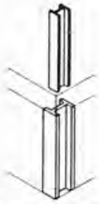

Interruption of beams

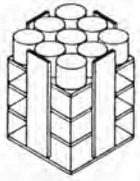

Openings in diaphragms

C. BUILDINGS WITH ABRUPT CHANGES IN LATERAL STIFFNESS


Shear walls in some stories,
moment-resisting frames in others


Interruption of vertical-resisting elements

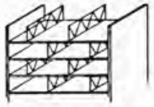

Abrupt changes in size of members

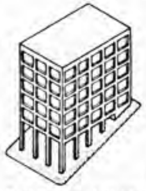

Drastic changes in
mass/stiffness ratio

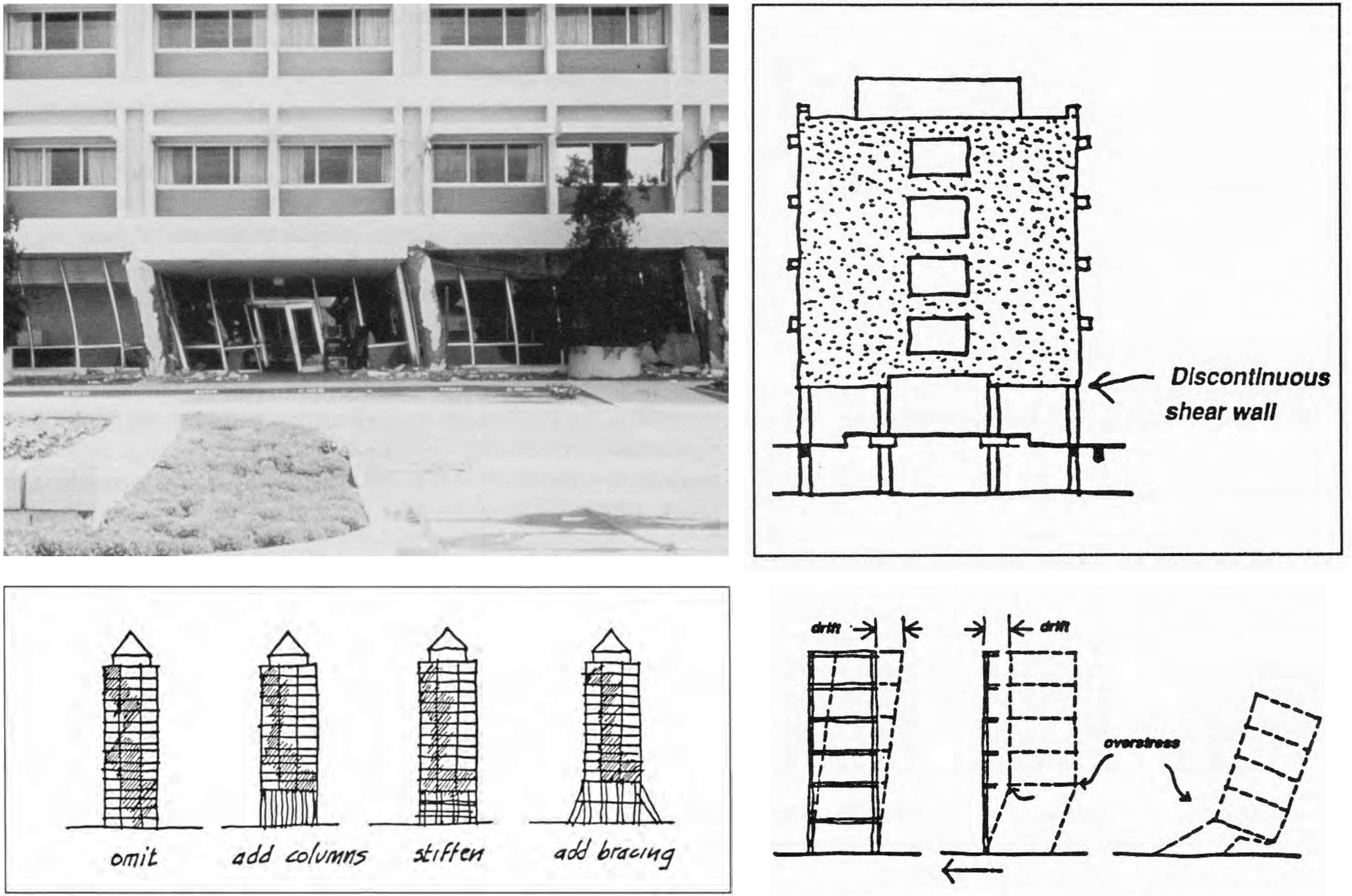
D. UNUSUAL OR NOVEL STRUCTURAL FEATURES


Cable-supported structures

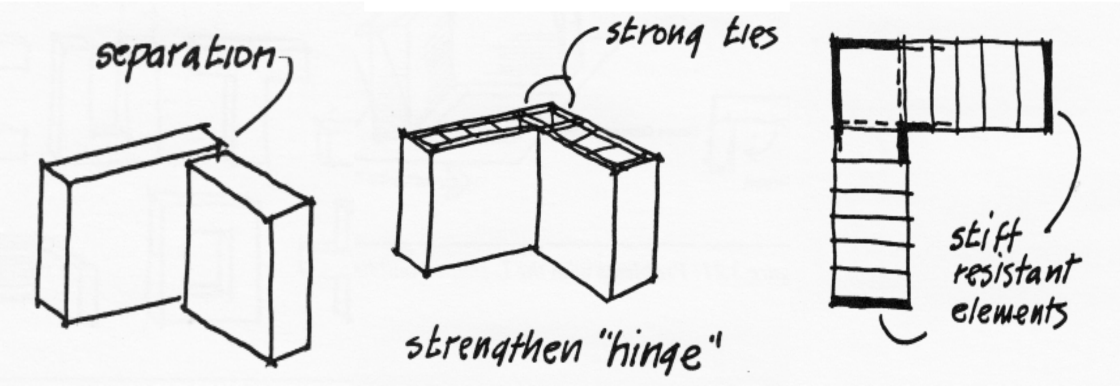

Shells

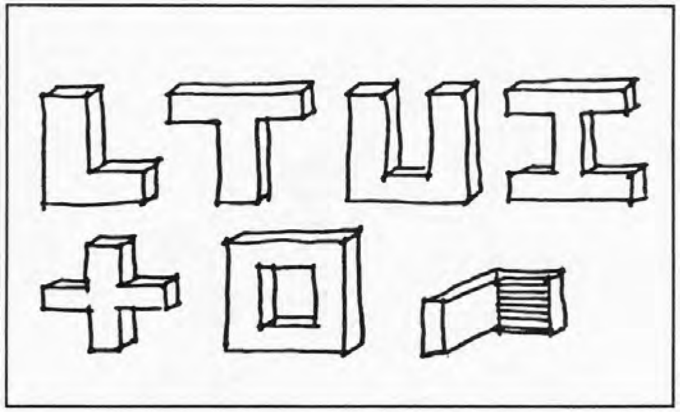

Staggered trusses


Buildings on hillsides

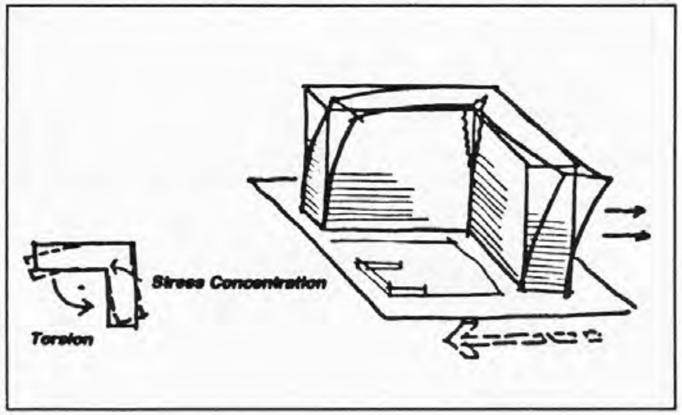


Abrupt change in resistance is illustrated by the ground level “soft story”.





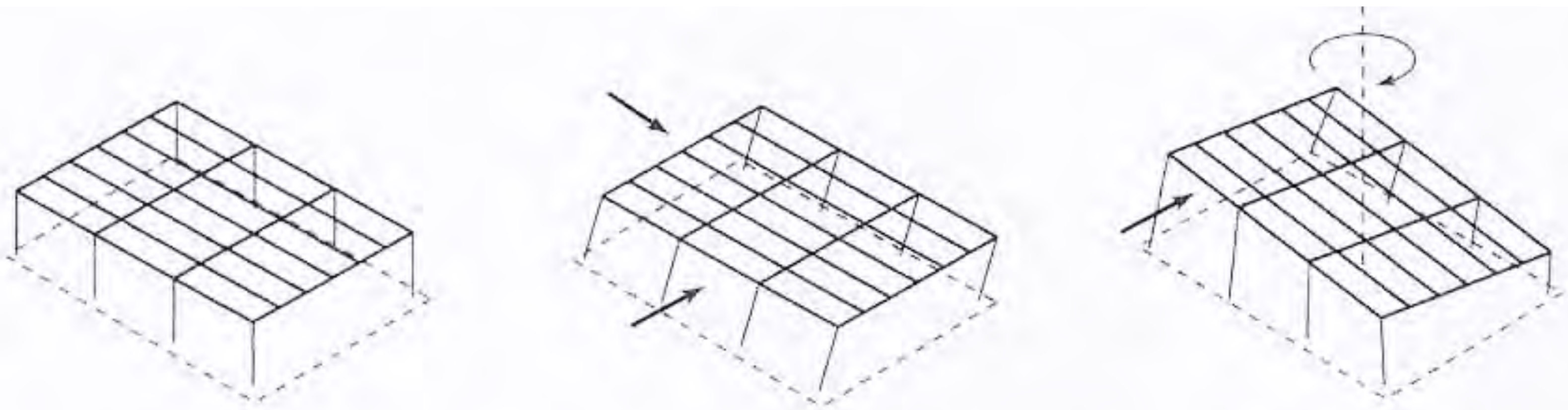

Collapse of the L-shaped San Marco Building in the 1925 Santa Barbara California earthquake.



Building shapes with inside corners and wings are susceptible to damage due to torsional forces.

Lateral force resisting systems:

low rise structures



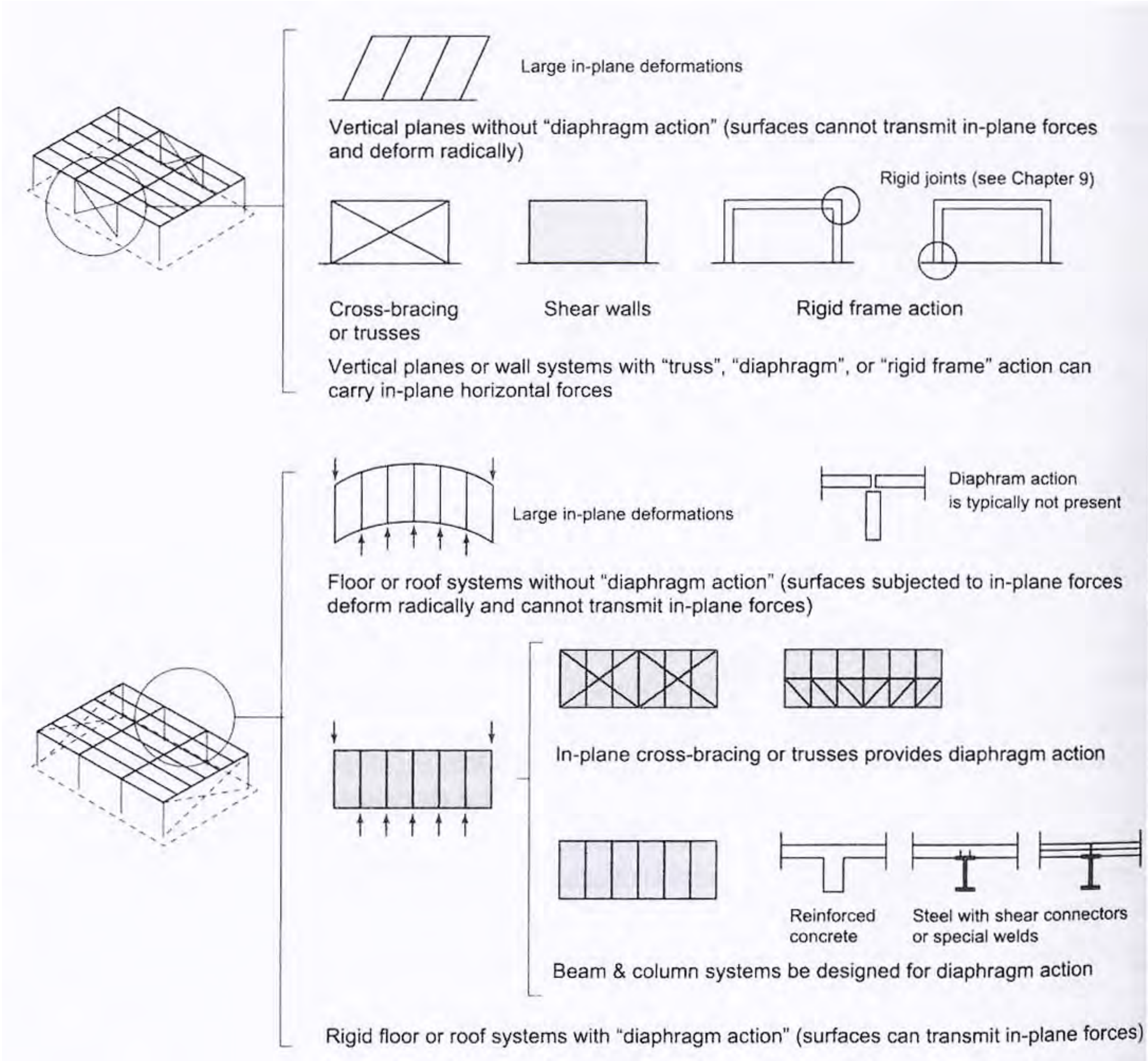
(a) Basic structure without lateral stability devices

(b) Major lateral deformations ("racking") due to horizontally-acting wind or earthquake loadings.

(c) Torsional deformations.

Typical effects of laterally acting wind or earthquake forces.

Illustrations from *Structures* 6th Ed. by Daniel L. Schodek and Martin Bechthold



Vertical planes without “diaphragm action” (surfaces cannot transmit in-plane forces and deform radically)

Vertical planes or wall systems with “truss”, “diaphragm”, or “rigid frame” action can carry in-plane horizontal forces

Diaphram action is typically not present

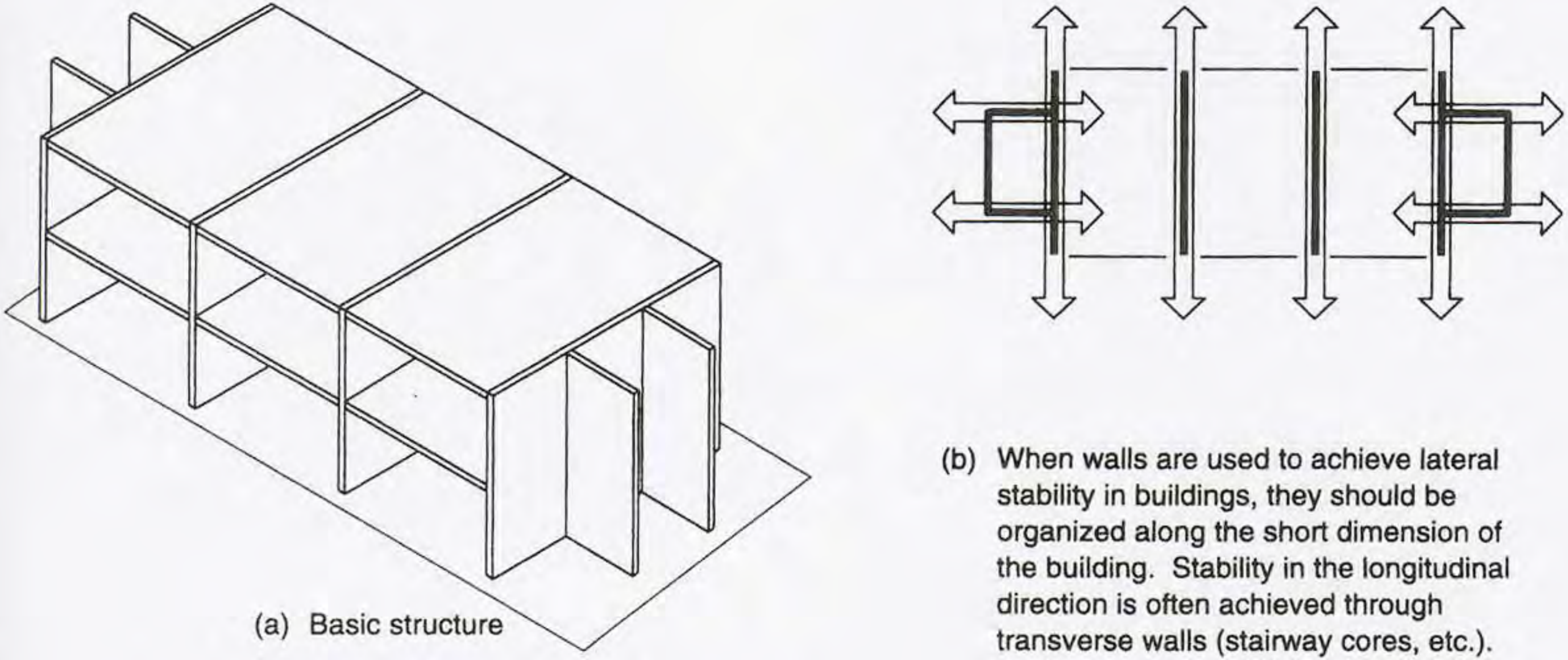
Floor or roof systems without “diaphragm action” (surfaces subjected to in-plane forces deform radically and cannot transmit in-plane forces)

In-plane cross-bracing or trusses provides diaphragm action

Beam & column systems be designed for diaphragm action

Rigid floor or roof systems with “diaphragm action” (surfaces can transmit in-plane forces)

Illustrations from *Structures* 6th Ed. by Daniel L. Schodek and Martin Bechthold

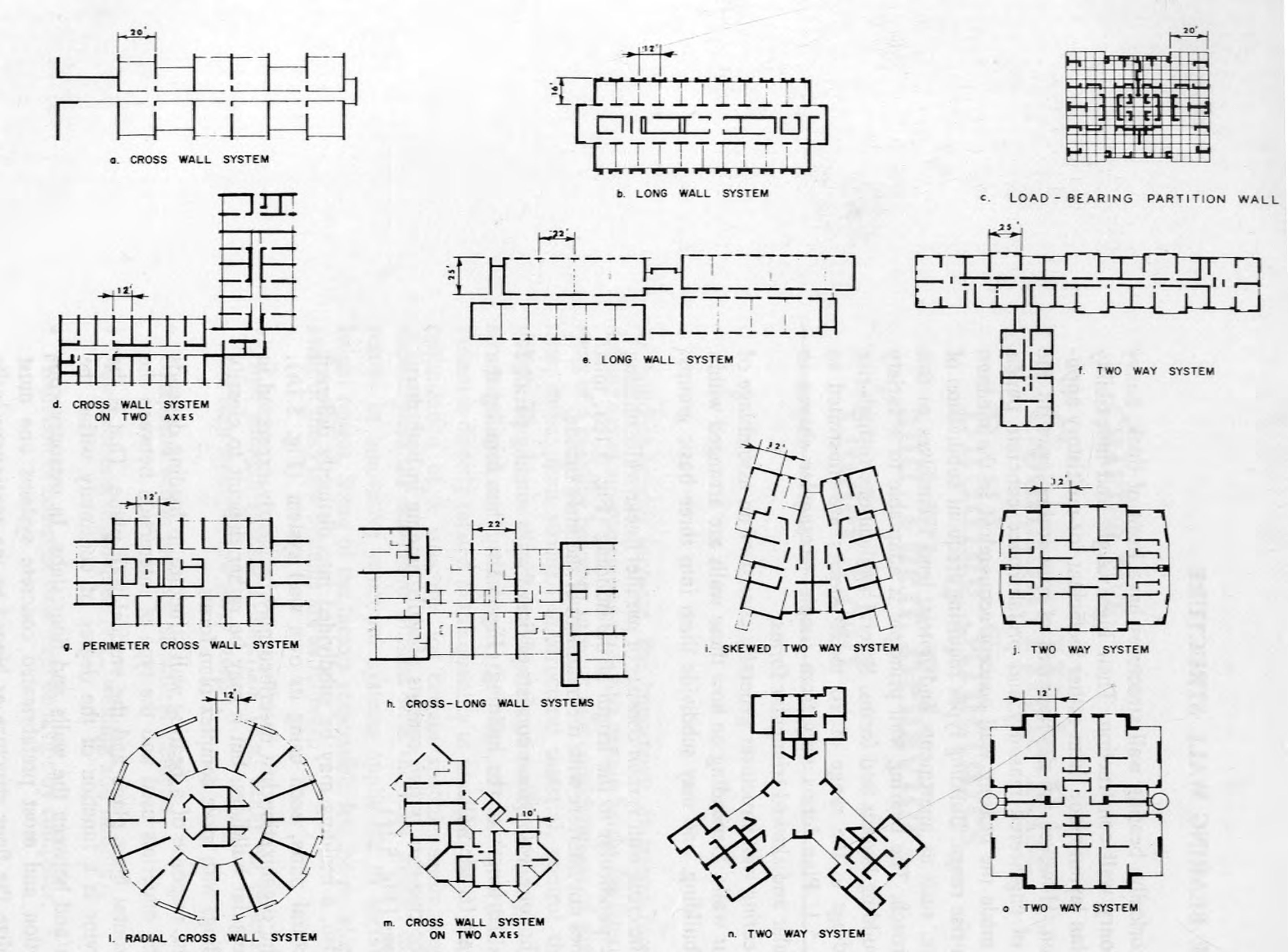


(a) Basic structure

(b) When walls are used to achieve lateral stability in buildings, they should be organized along the short dimension of the building. Stability in the longitudinal direction is often achieved through transverse walls (stairway cores, etc.).

Structural bearing wall systems as lateral force resisting shear planes (concrete masonry must be reinforced).

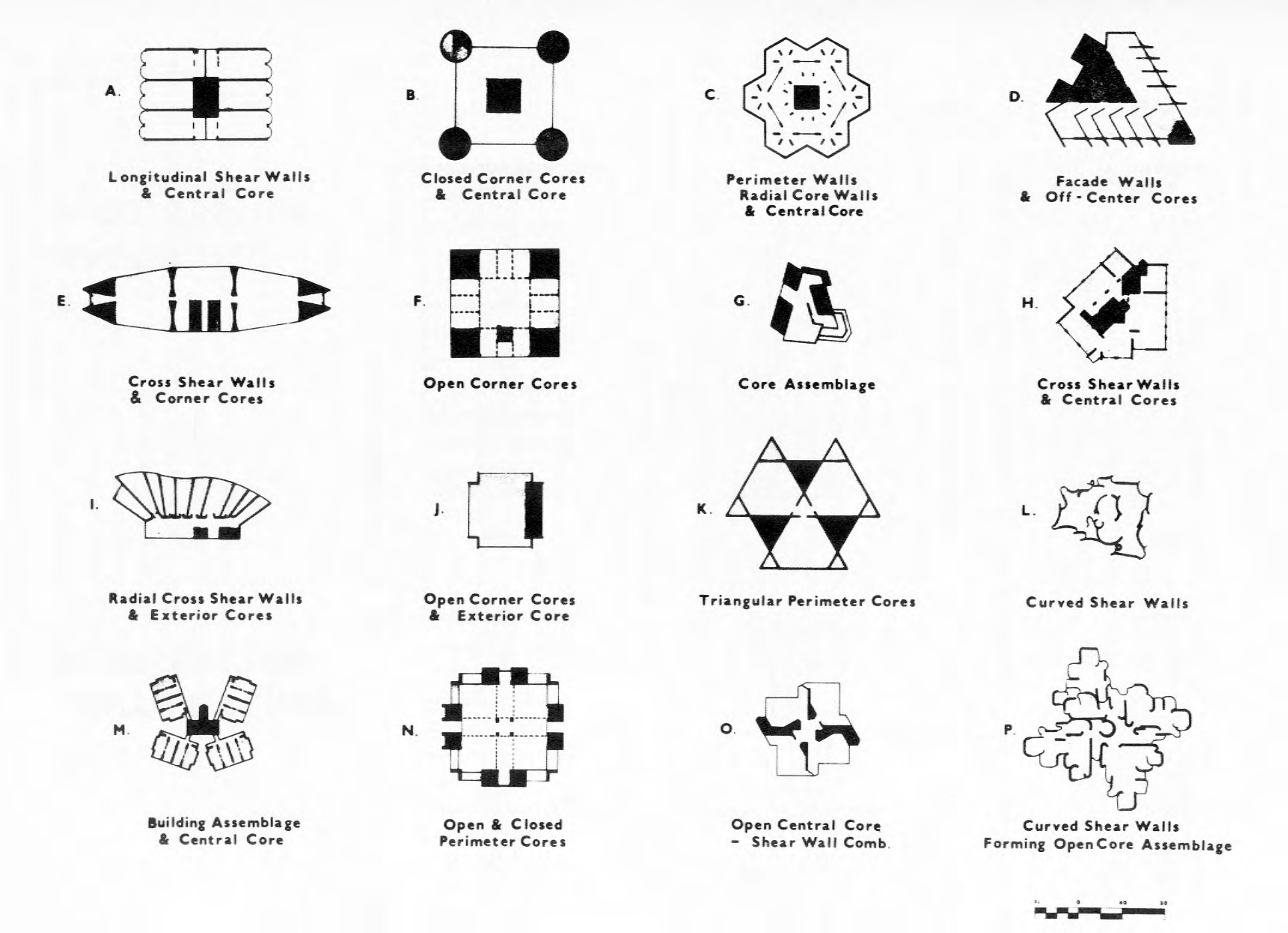
Illustrations from *Structures* 6th Ed. by Daniel L. Schodek and Martin Bechthold



1 Bearing wall system

Three types: *cross wall system, long wall system and two-way system.*

Illustrations from Horizontal-Span Building *Structures*. Wolfgang Schueller

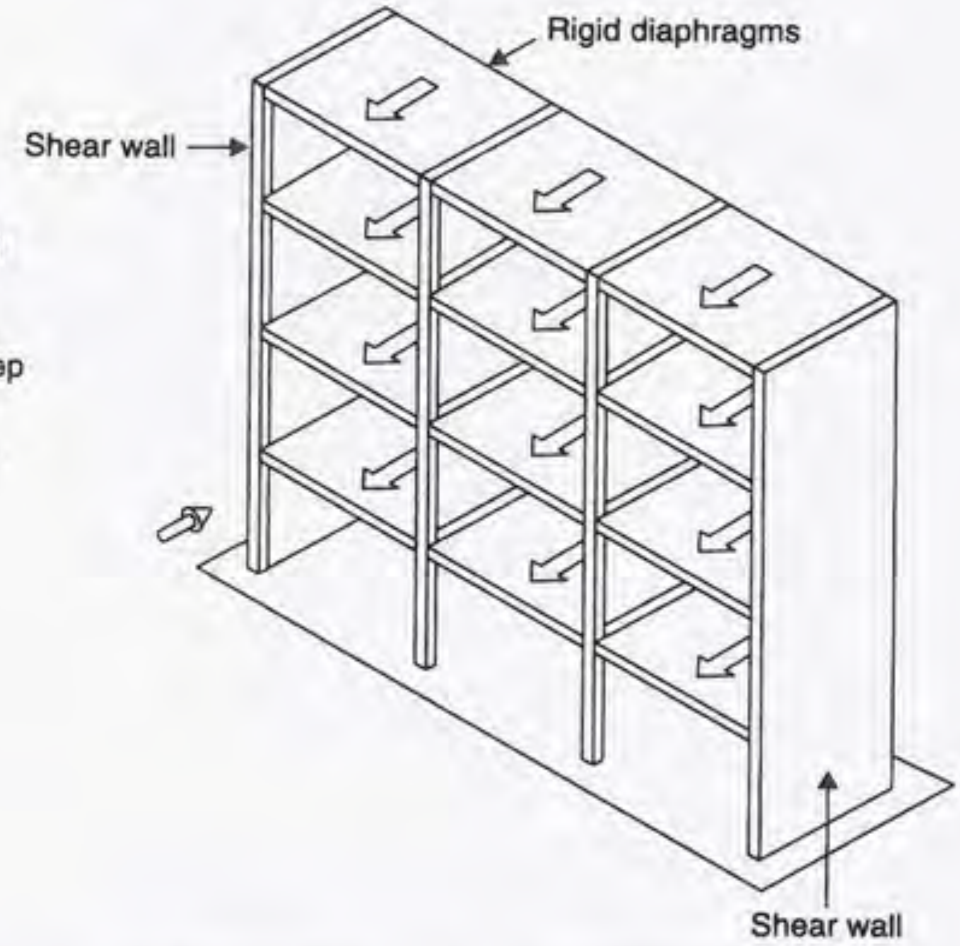


2 Wall-core system

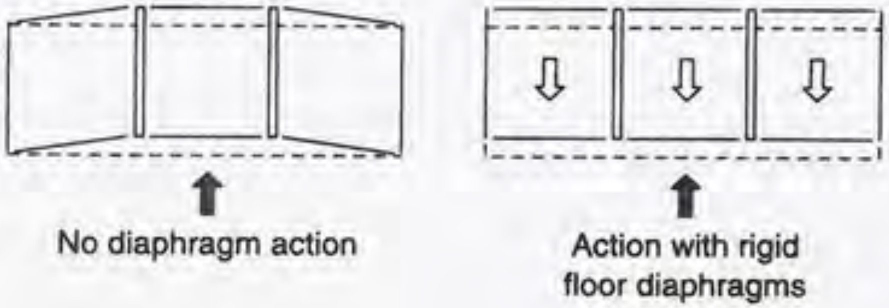
Lateral force resistance is shared between load bearing wall structure and service core structures.

Illustrations from Horizontal-Span Building *Structures*. Wolfgang Schueller

(a) When the primary method of carrying horizontal forces in a tall structure is by shear walls, the horizontal floor planes are usually designed as rigid diaphragms (in which the floors act like deep thin beams in the horizontal direction) to carry forces from the building face to the shear walls.

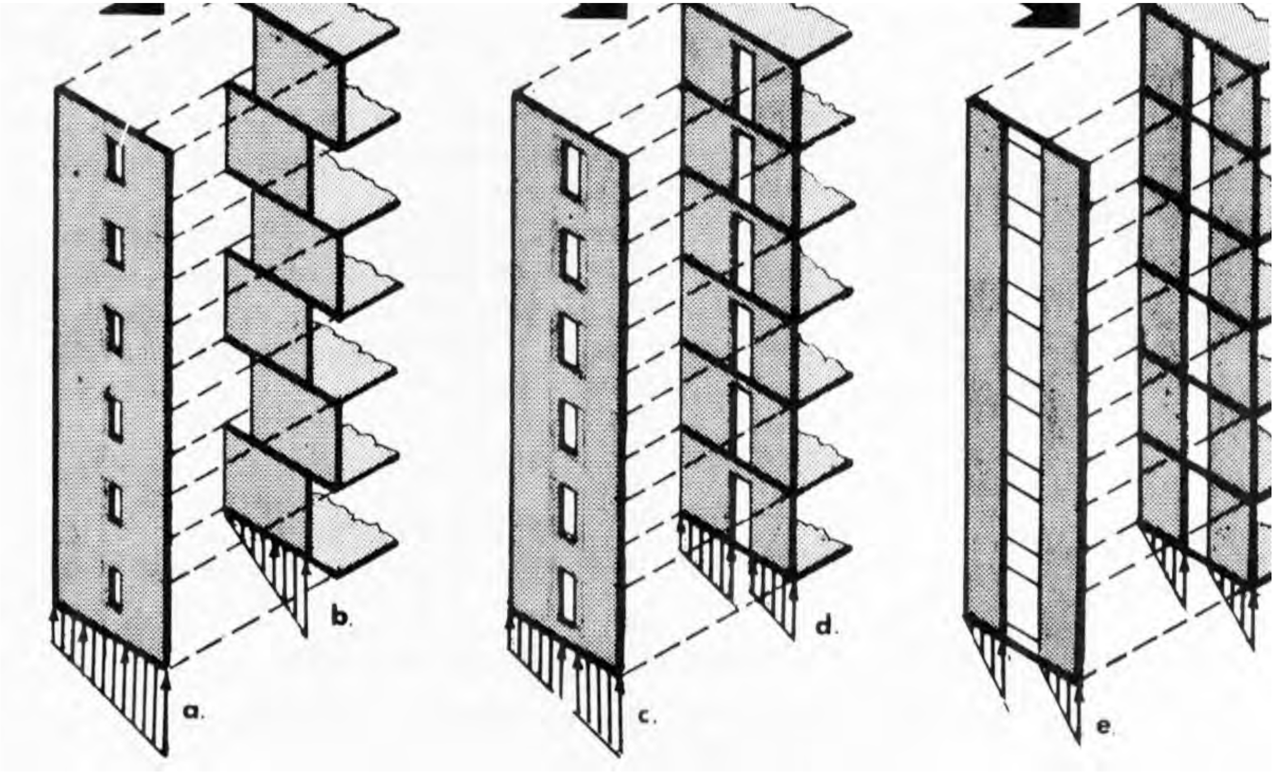


(b) If the floors do not serve as diaphragms, interior frames must carry a major portion of the horizontal forces and many of the advantages of using shear walls are not obtained. Interior frames are usually less stiff than shear walls so they deflect more. Diaphragm action in the floors would prevent this.


No diaphragm action

Action with rigid floor diaphragms

Illustrations from *Structures* 6th Ed. by Daniel L. Schodek and Martin Bechthold

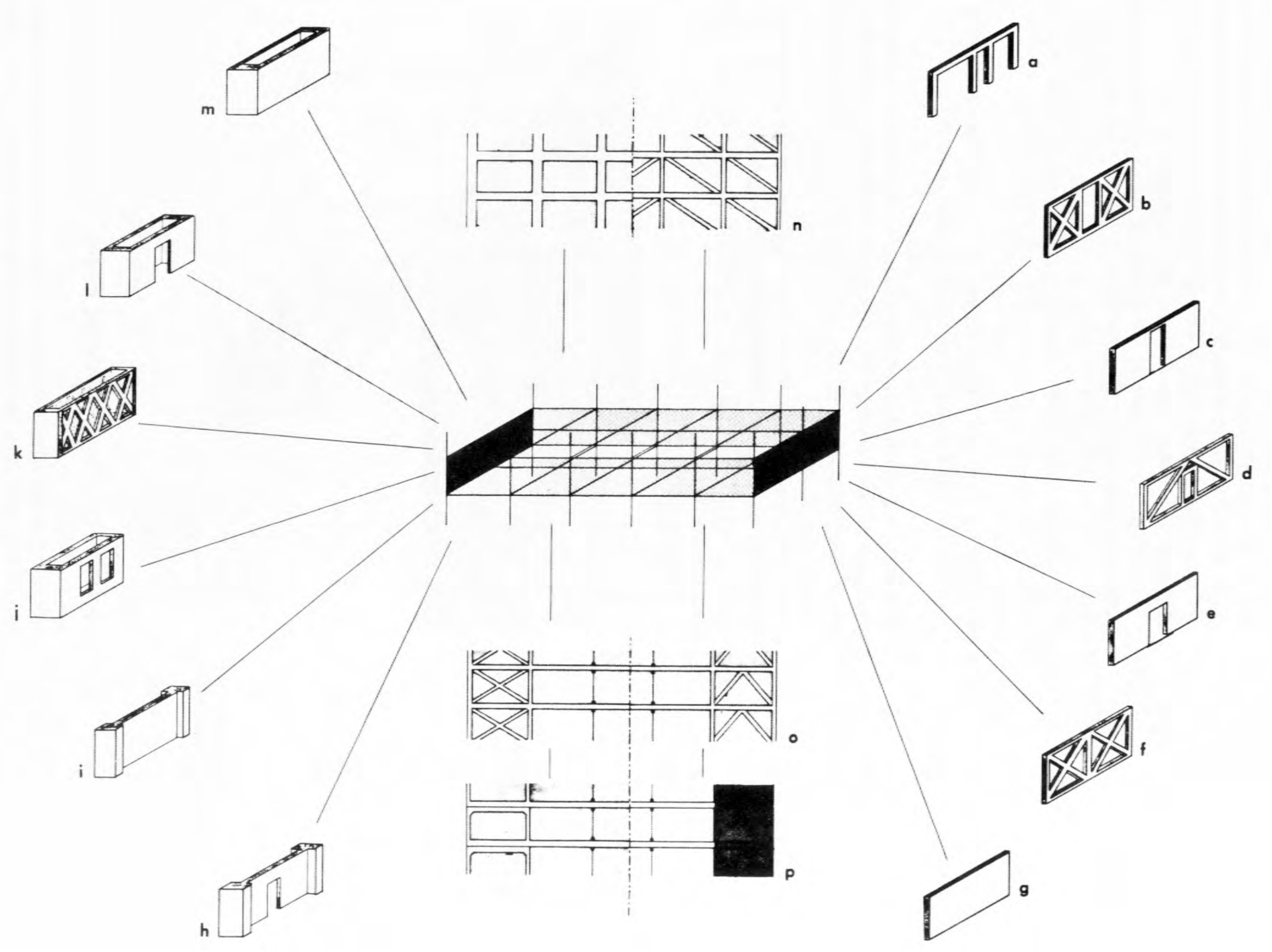


Shear walls.

Openings in shear walls can reduce the effectiveness of lateral force resistance.

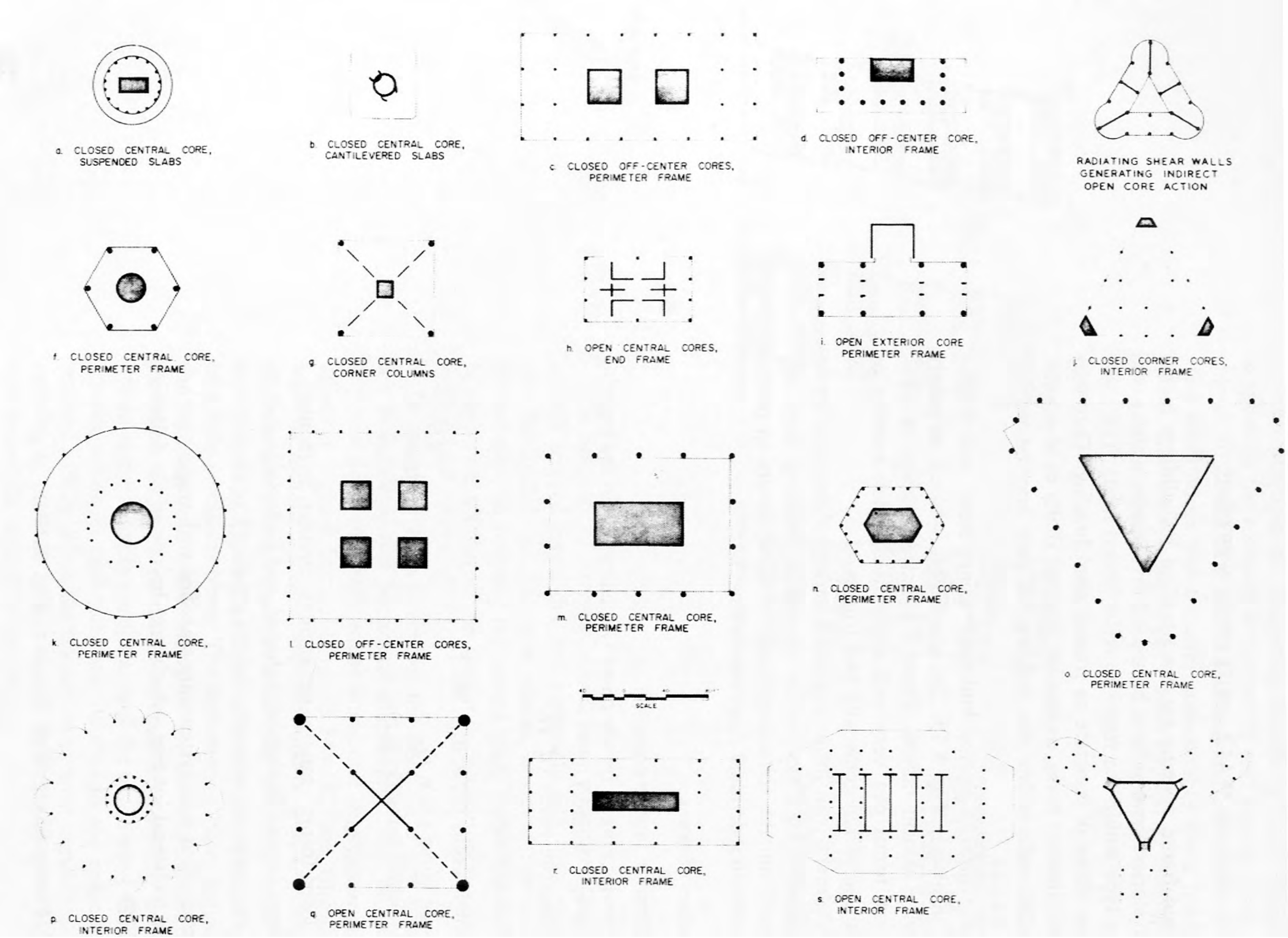
In fig. a the openings in the wall are small and do not significantly affect performance, The wall acts as a single panel to resist overturning. In fig. e the opening in the wall is continuous and causes the end-wall to act as two independent shear walls with each resisting half the lateral force. However, the total amount of lateral force the two walls can resist is much less than the amount that can be resisted by the nearly solid shear wall as shown in fig. a.

Illustrations from Horizontal-Span Building *Structures*. Wolfgang Schueller



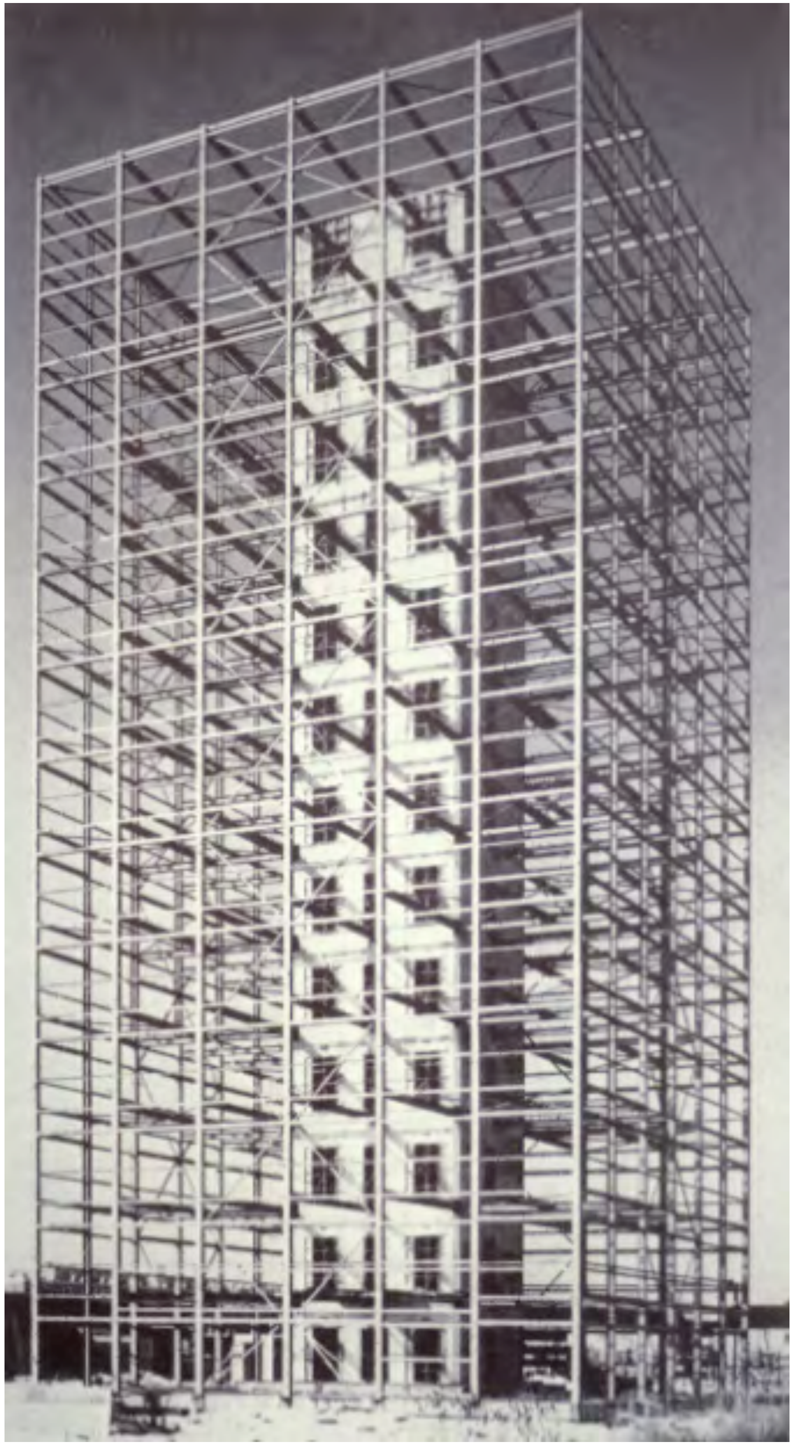
Examples of different configurations of shear resisting panels.

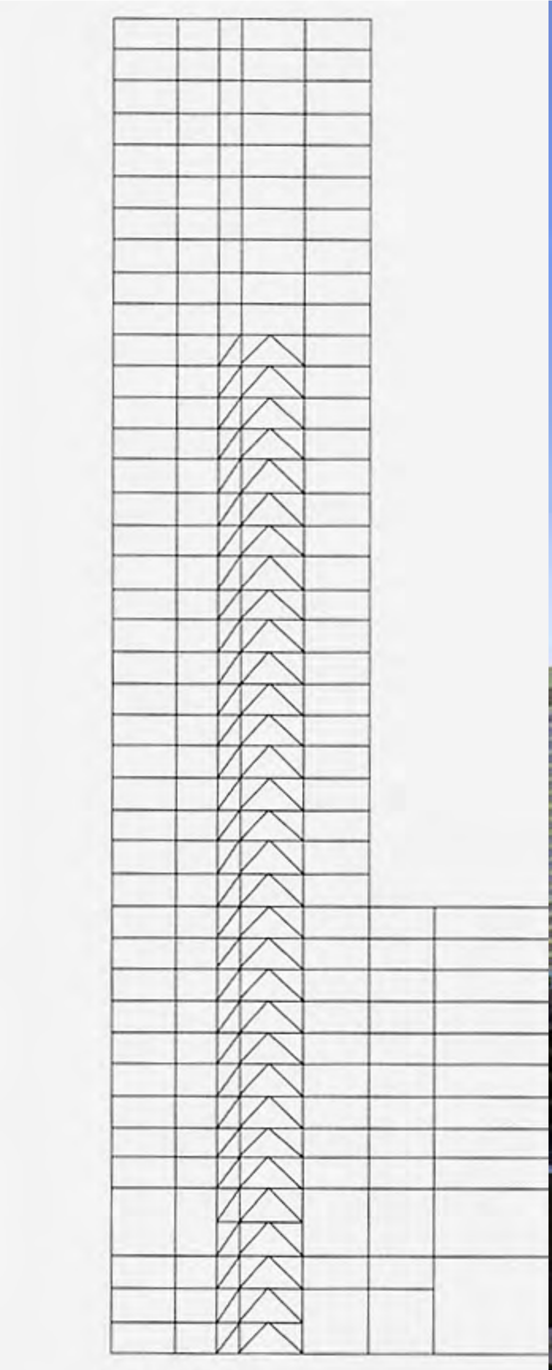
Illustrations from Horizontal-Span Building *Structures*. Wolfgang Schueller



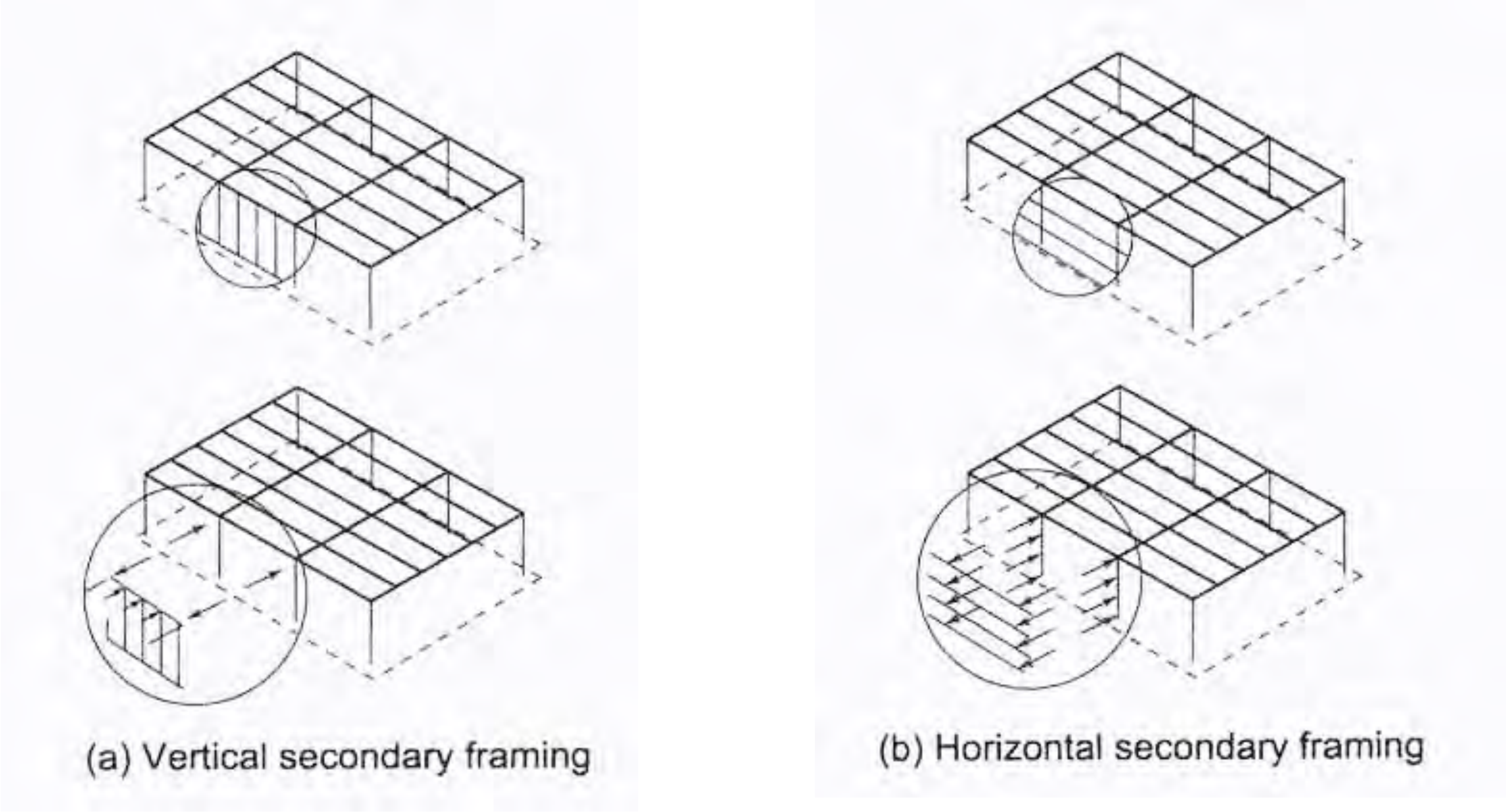
3 Core-frame system The structural core acts as a shear wall. The frame may contribute also to the lateral stiffness, depending on the type of frame. A hinged frame contributes nothing and only carries vertical loads. A rigid frame contributes significantly.

Illustrations from Horizontal-Span Building *Structures*. Wolfgang Schueller





Structural grid

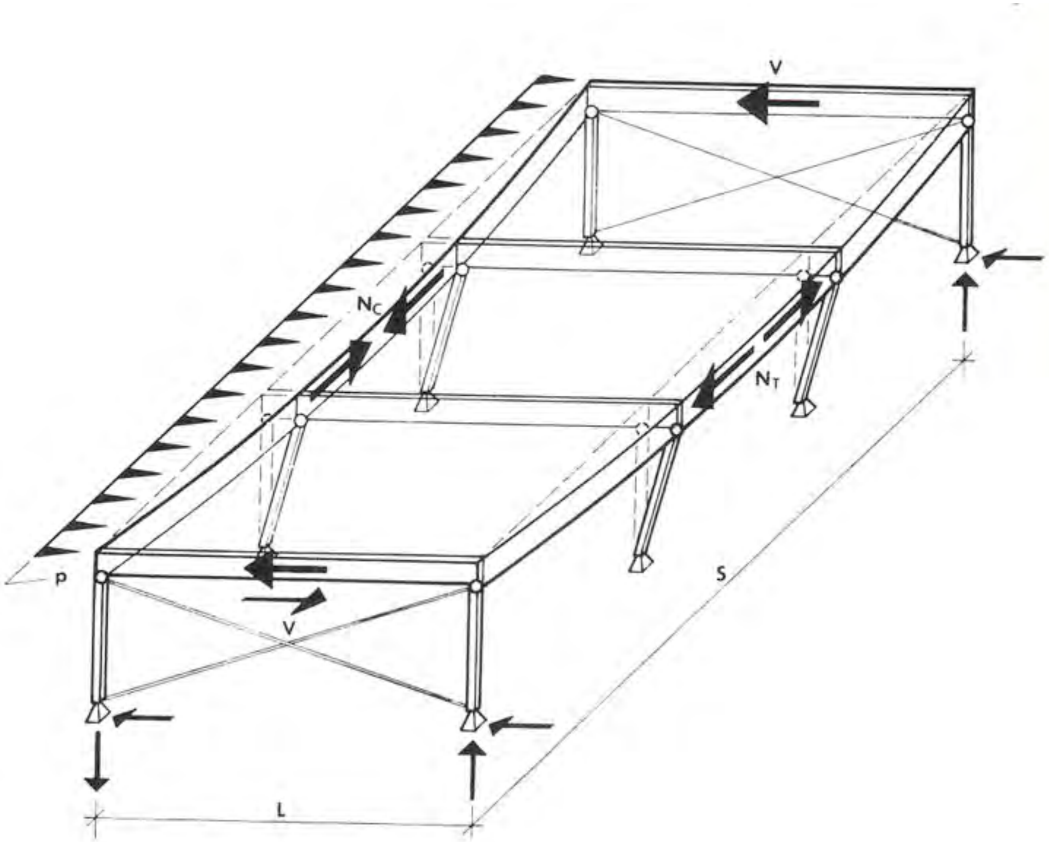


(a) Vertical secondary framing

(b) Horizontal secondary framing

The surfaces between structural columns in a frame structure have secondary framing elements that transfer the wind force to either the ground and roof beams: (a) vertical secondary framing (wind columns) or to the columns: (b) horizontal secondary framing (wind girts).

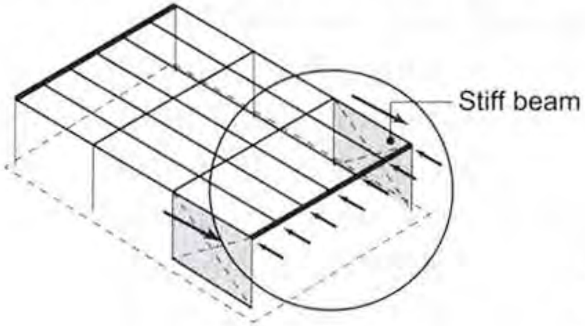
Illustrations from *Structures* 6th Ed. by Daniel L. Schodek and Martin Bechthold



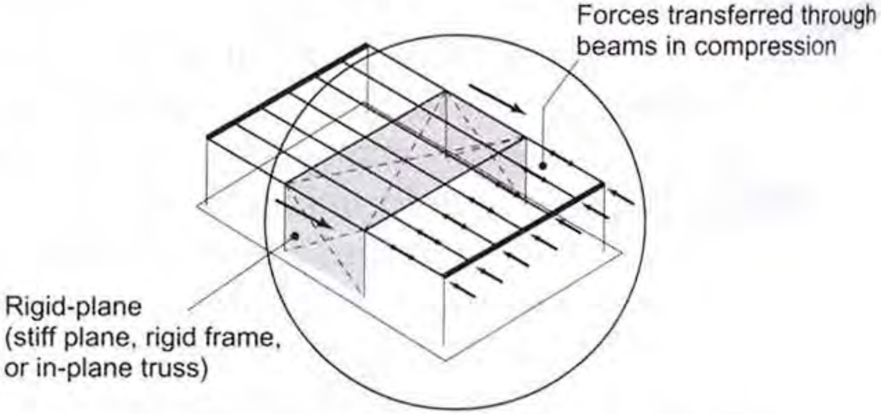
This diagram shows a one-story frame with diagonal bracing in the end bay frames but no stiffening of the two interior frames. Wind loads transmitted from the envelope to the roof beam (by secondary framing columns not shown) cause the interior frames to ‘rack’ distorting the roof plane. The roof beams on the edges of the long sides have no stiffness to resist the lateral forces applied along their length. Consequently they develop axial forces (N_C and N_T) analogous to the top and bottom chords in a frame laying on its side.

Illustration from Horizontal-Span Building *Structures*. Wolfgang Schueller

LOADINGS ON TRANSVERSE FACES

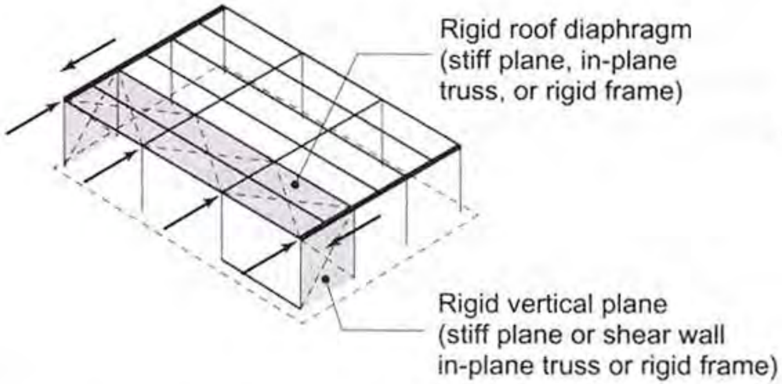


(a) Forces from secondary framing are resisted by an edge beam with high lateral strength and stiffness and carried directly to side shear walls or diaphragms (typically small structures only)

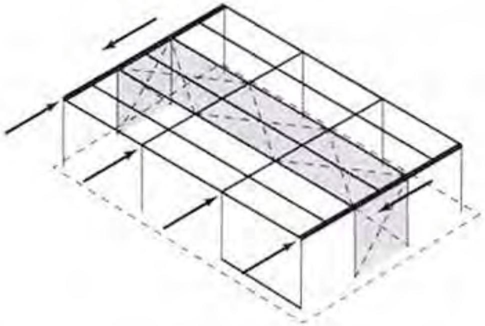


(b) Forces are transferred through roof members to roof diaphragm which transfers loads to side diaphragms (roof members must be designed to carry compressive forces as well as normal bending from vertical loads)

LOADINGS ON LONGITUDINAL FACES

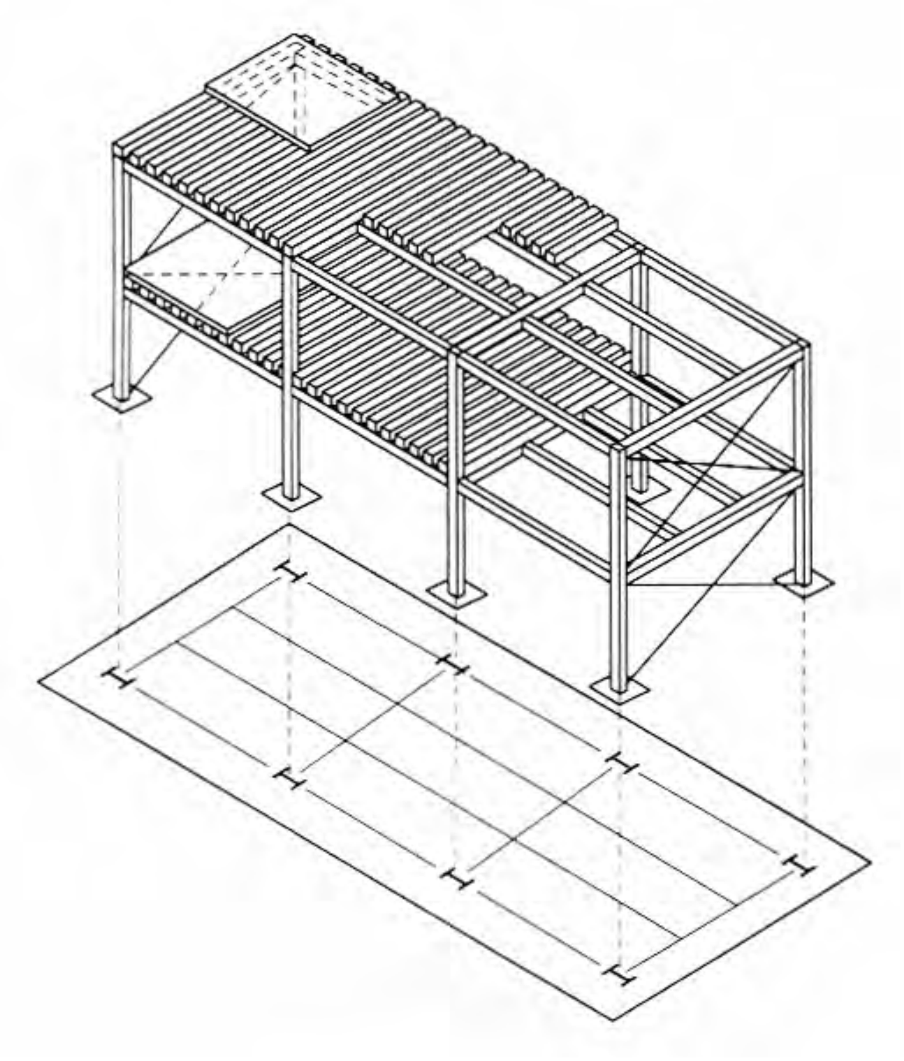


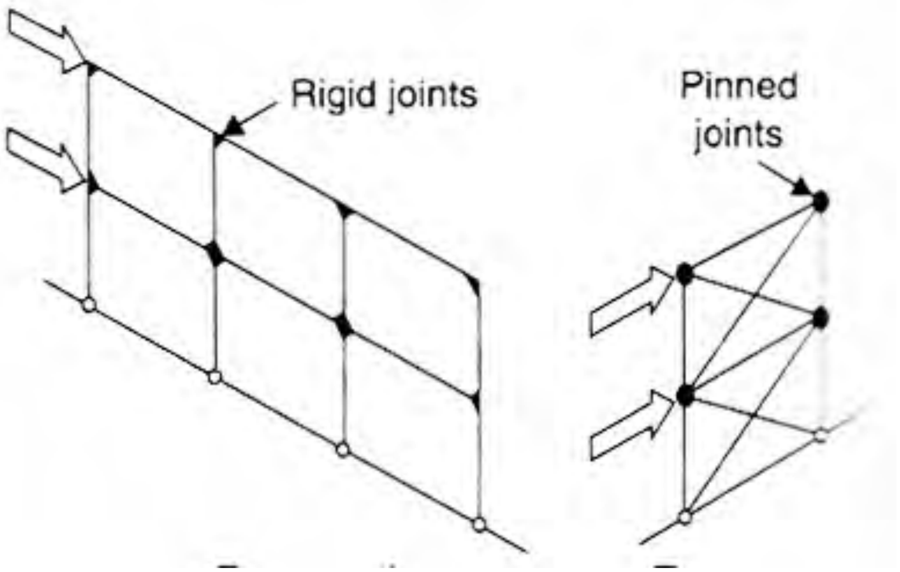
(c) Forces from secondary framing are picked up by rigid roof plane or diaphragm and transmitted to rigid side planes



(d) Horizontal and vertical rigid planes or diaphragms can be anywhere as long as loads can be transmitted to them

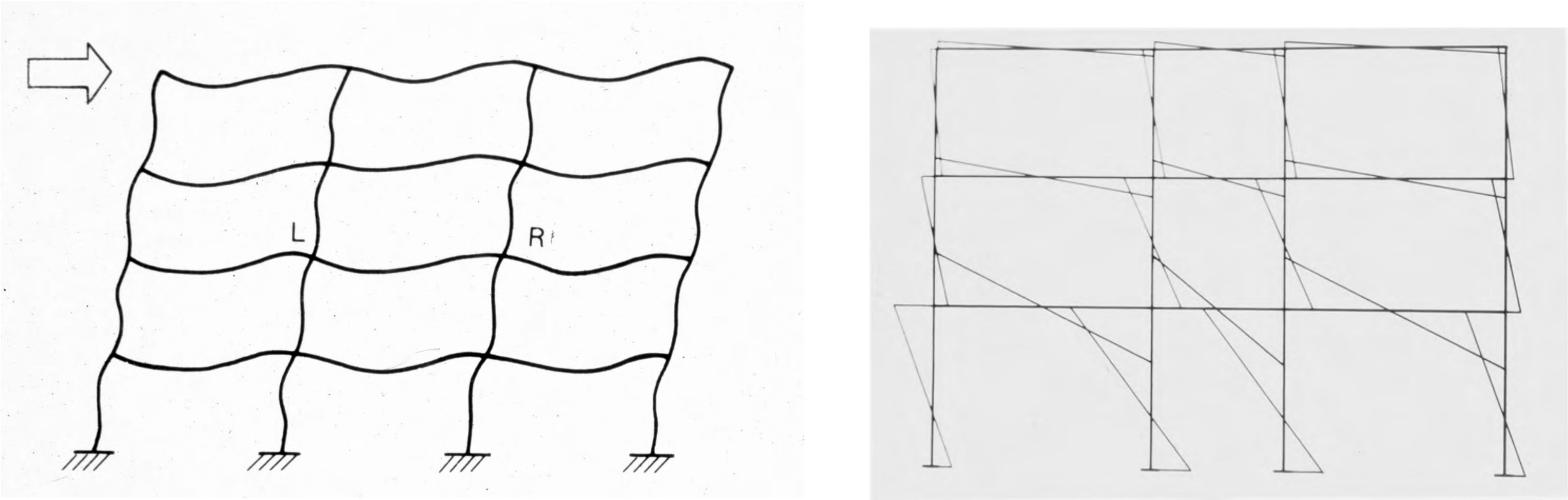
Illustrations from *Structures* 6th Ed. by Daniel L. Schodek and Martin Bechthold





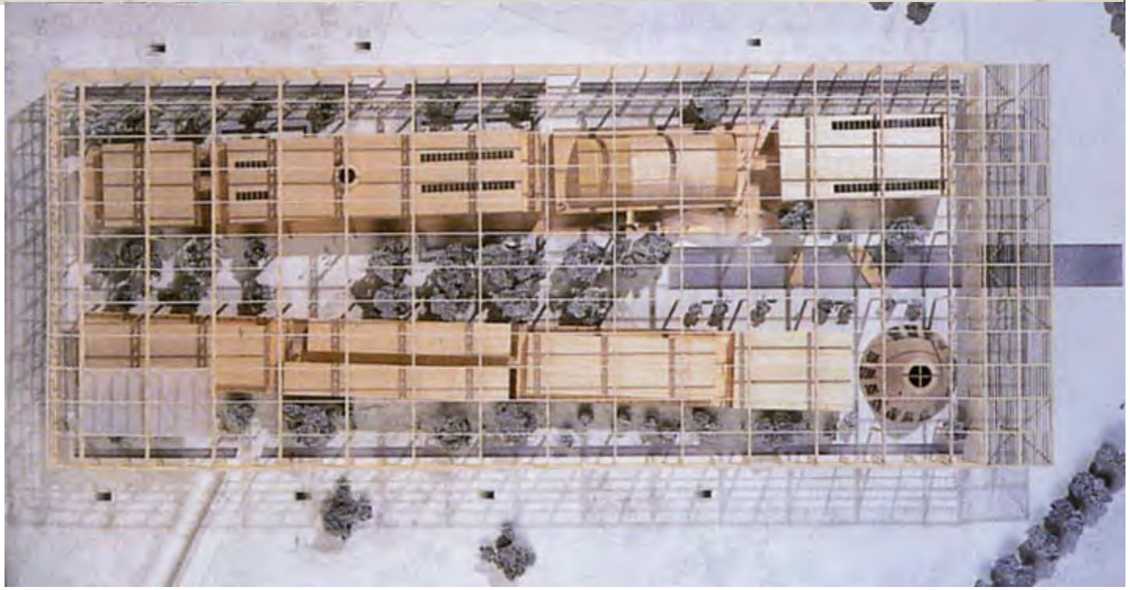
The short dimension of frame systems is the most critical. Efficient lateral load resisting mechanisms such as cross bracing with tension members is often used. In the long direction frame action is often employed upon for lateral resistance. This requires the frame elements (columns and beams) to be rigidly connected at the joints.

Illustrations from *Structures* 6th Ed. by Daniel L. Schodek and Martin Bechthold

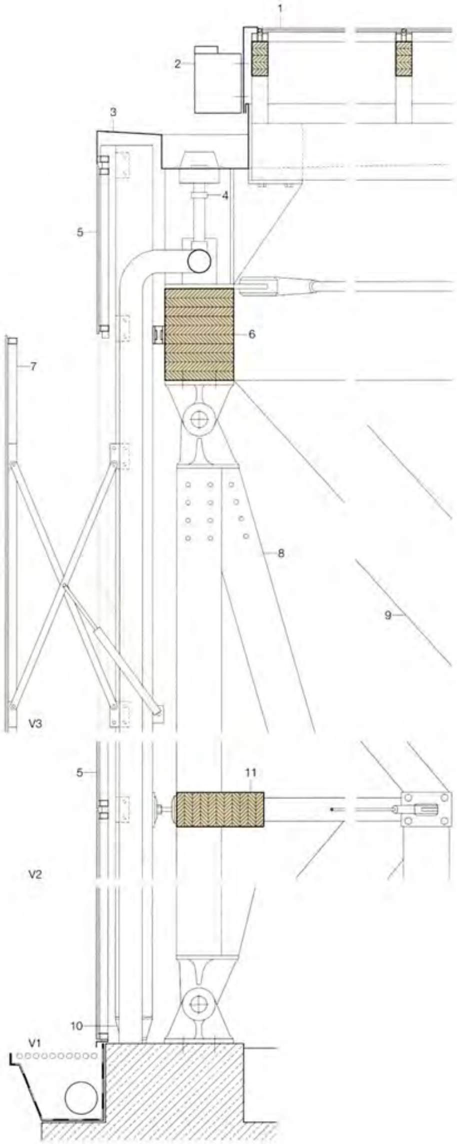


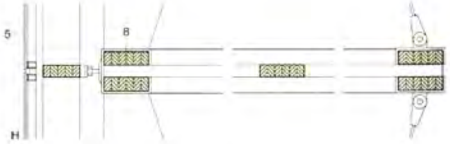
Distribution of bending moments in a portal frame under lateral loading.

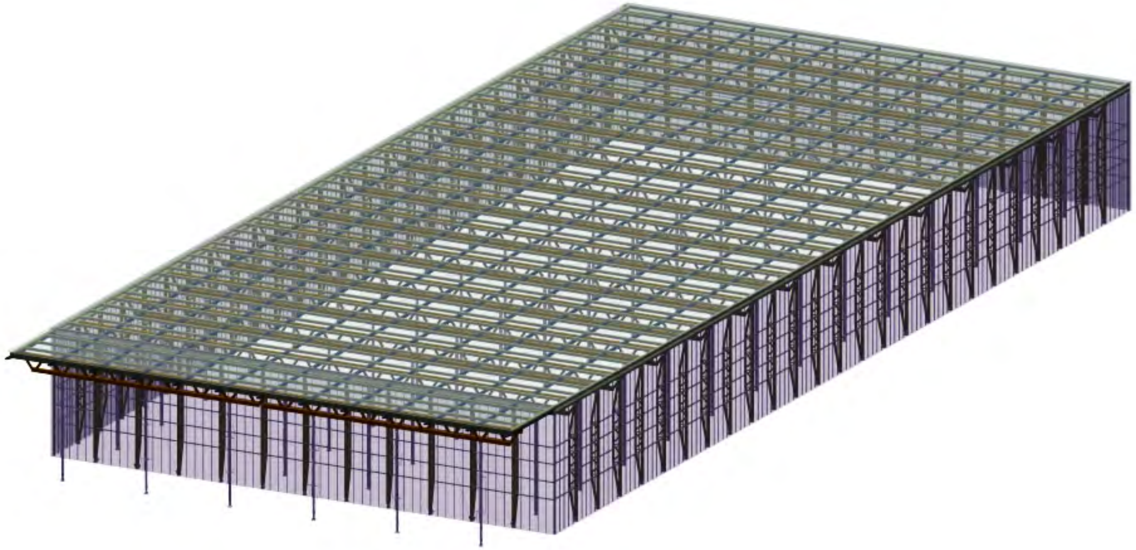
Note the mid-span and mid-floor height locations of inflection points. These are points on the moment diagram where the curvature changes and hence the moment force changes from sign (e.g. from positive to negative bending moment). At this point the moment is zero.

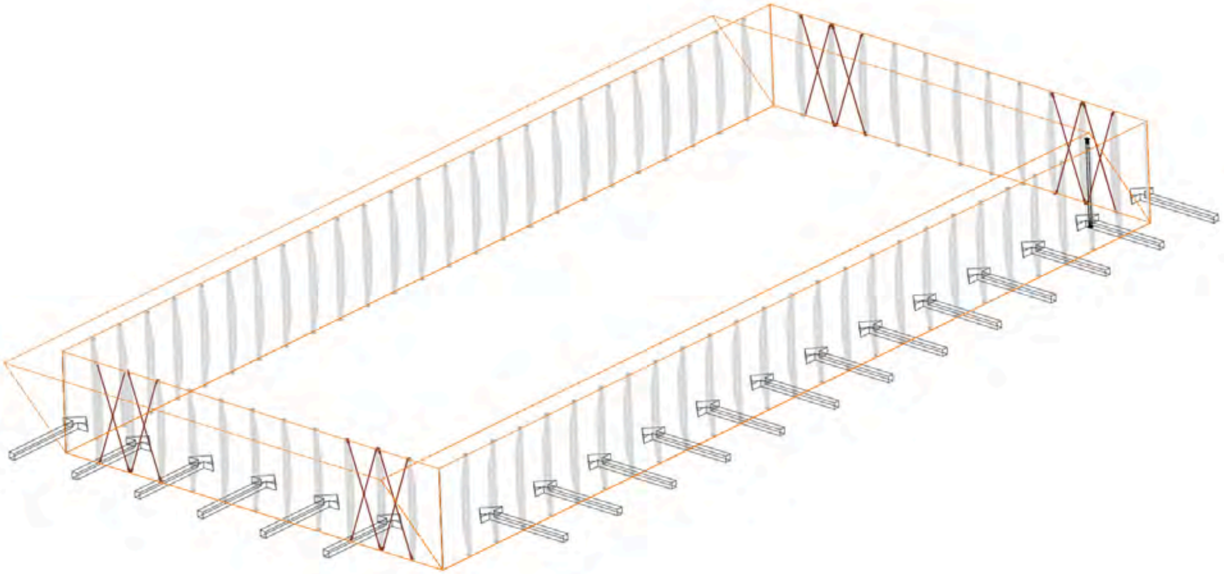


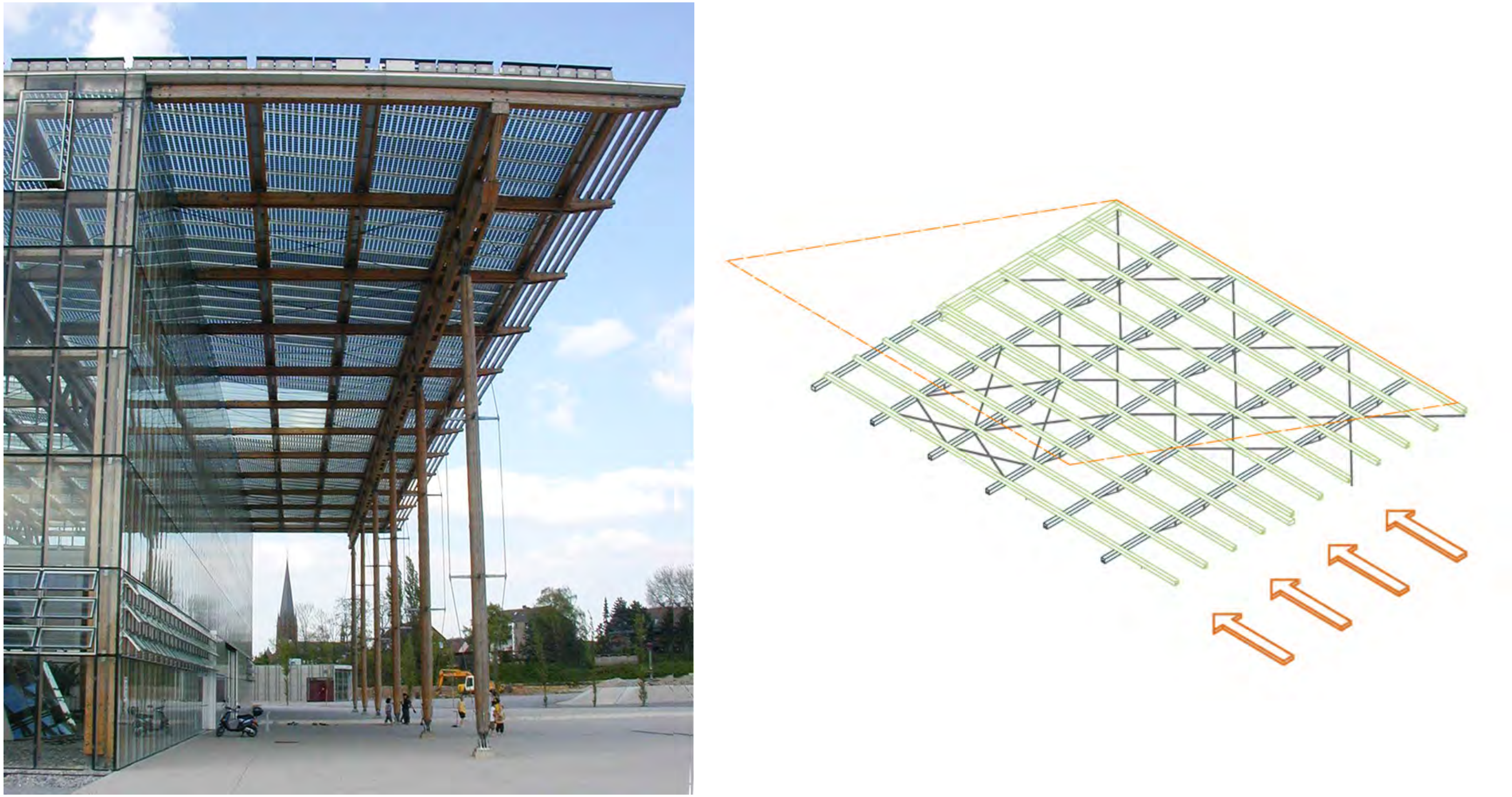
Vocational Training Center Jourda & Perraudin, arch. Herne-Sodingen, Germany 1998


1
2
3
4
5
6
7
8
9
V3
5
11
V2
10
V1

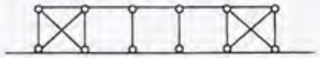

5
8
H



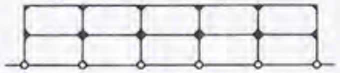




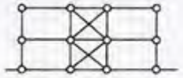
Diagonal (cross bracing) in the roof plane of the Vocational Training Center resists distortion (dashed line) under the lateral loading along its edge.



(a) Pinned frame with diagonal bracing

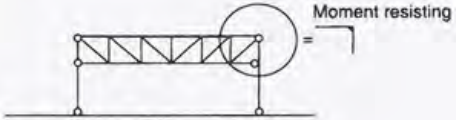


(b) Typical rigid frame structure

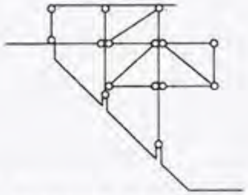


(c) Pinned frame with diagonal bracing

(d) Series of stable 3-hinged arches

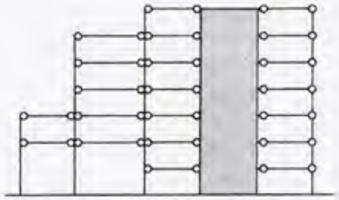


(e) Frame made using truss rigidly connected to columns

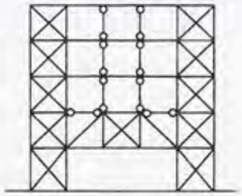


(f) House with diagonal bracing

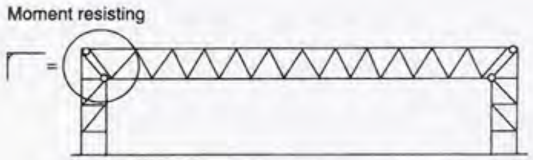
(g) Rigid frame with some pins



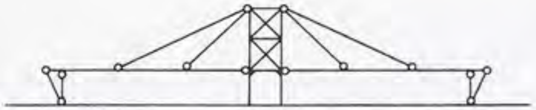
(h) Multistory structure with shear walls and continuous columns



(i) Multistory building using diagonally-braced rigid frame side towers



(j) Rigid frame made of trussed members



(k) Cable-stayed structure with stable center tower (diagonals and rigid connections)

Key:

┐ Rigid moment resisting connection

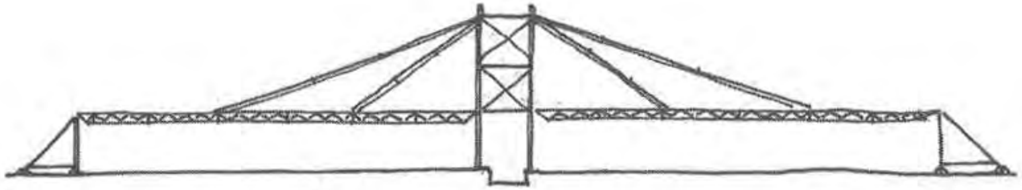
┐ Pinned connection

☐ Shear wall

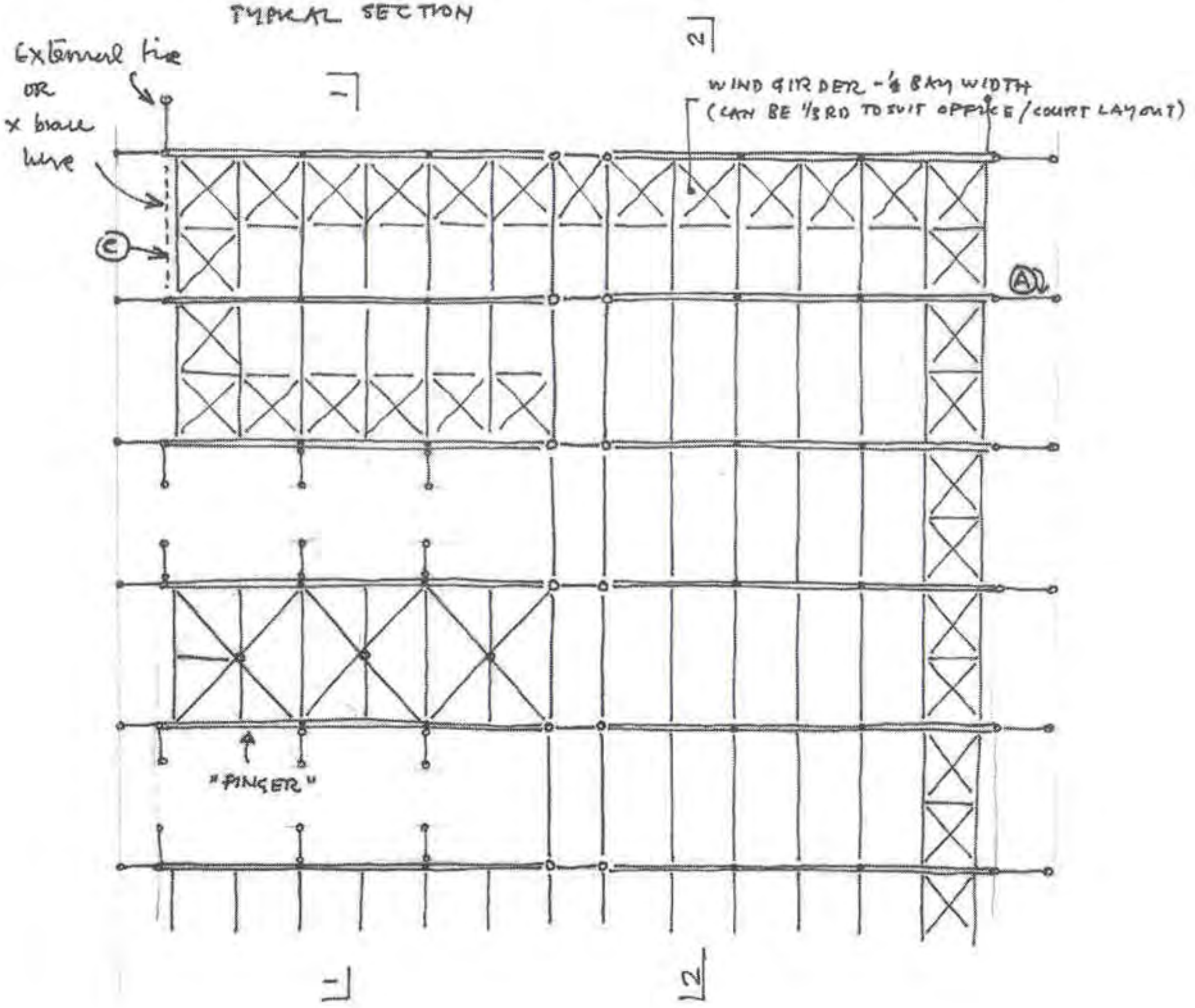
Common approaches to providing lateral stability in real buildings.

Illustrations from *Structures* 6th Ed. by Daniel L. Schodek and Martin Bechthold

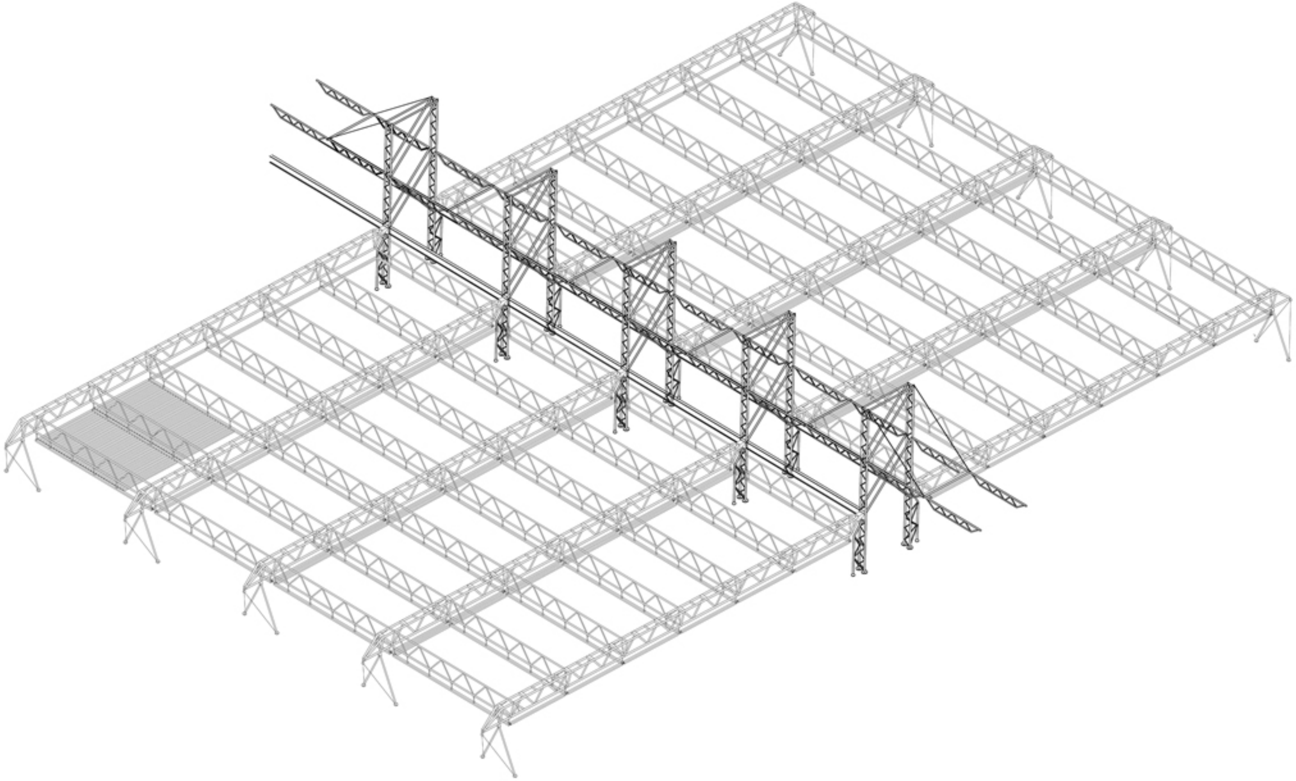
INMOS Microprocessor Factory Richard Rogers Partnership / Anthony Hunt, Engr. Newport, UK ca. 1982

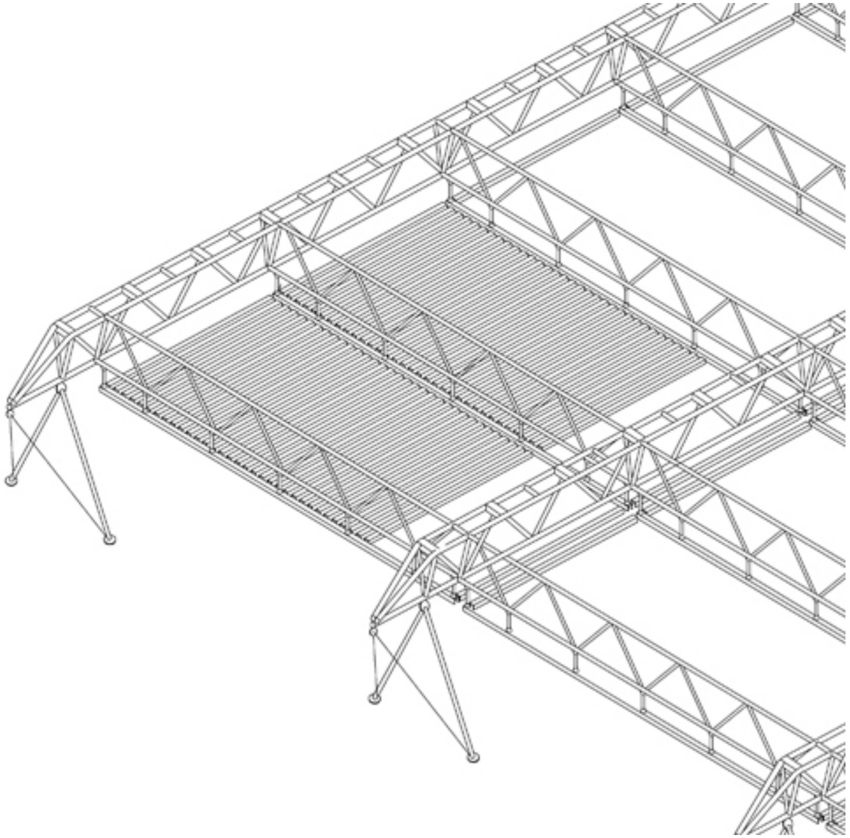


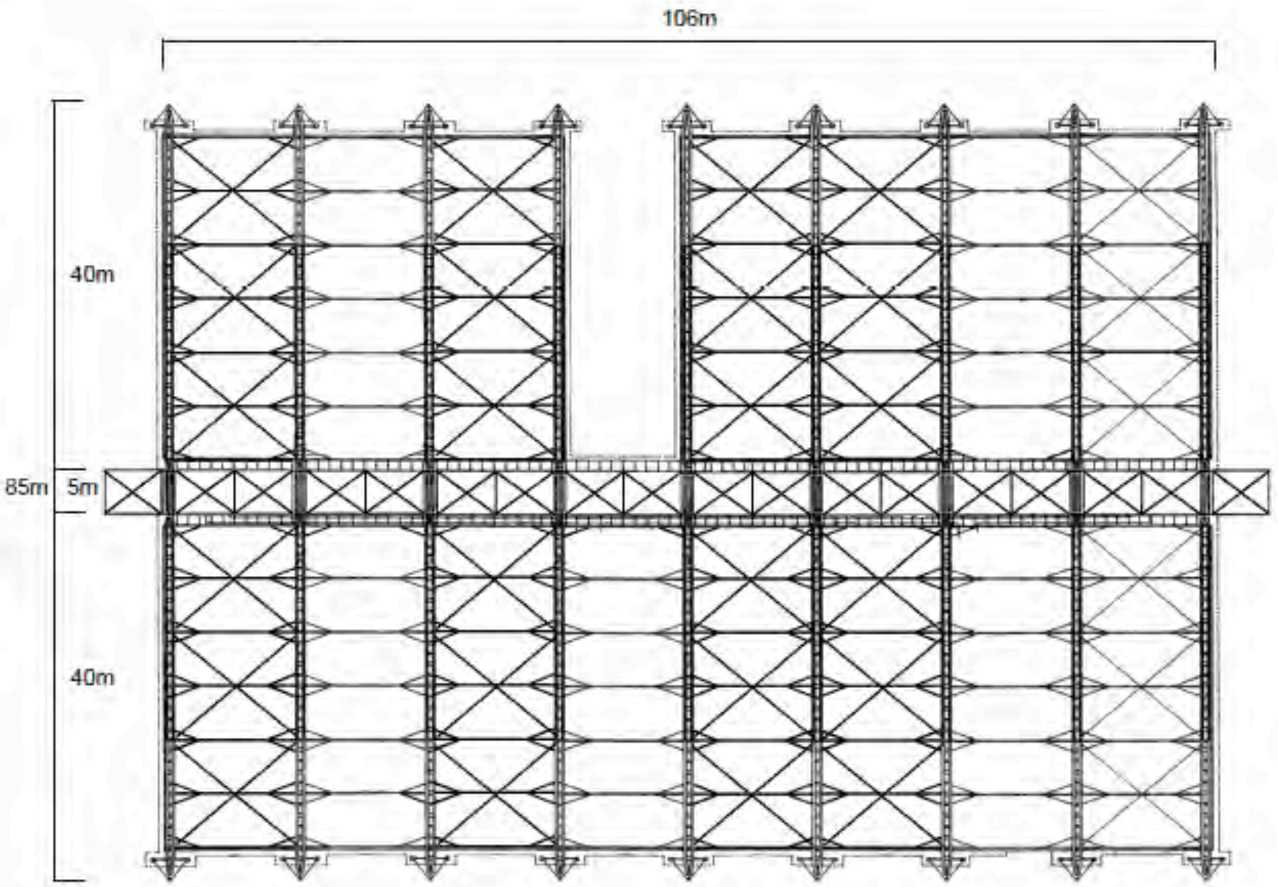
TYPICAL SECTION



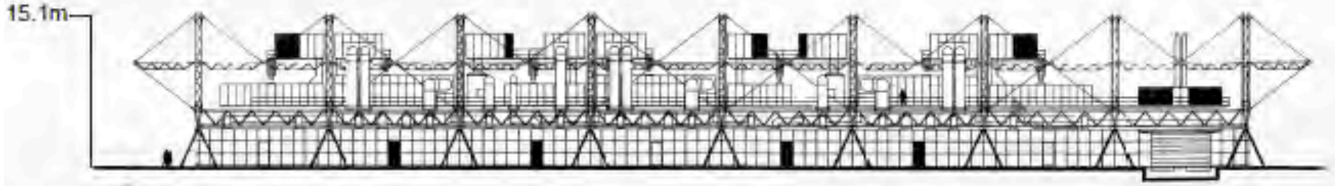
PART PLAN



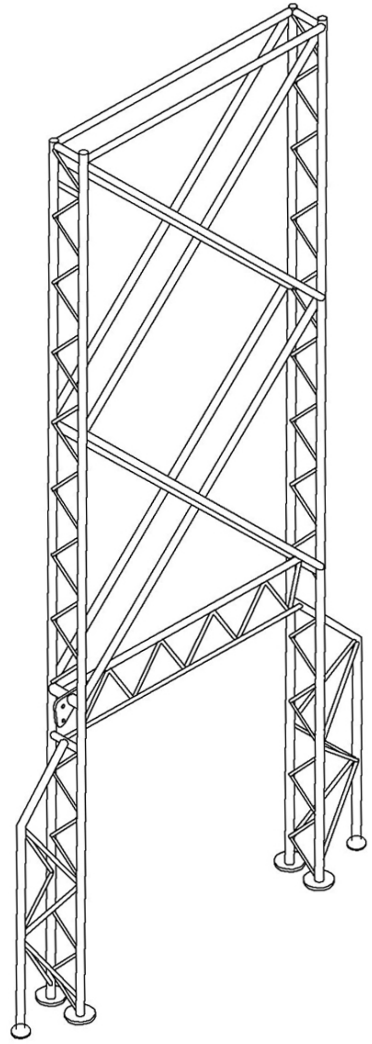




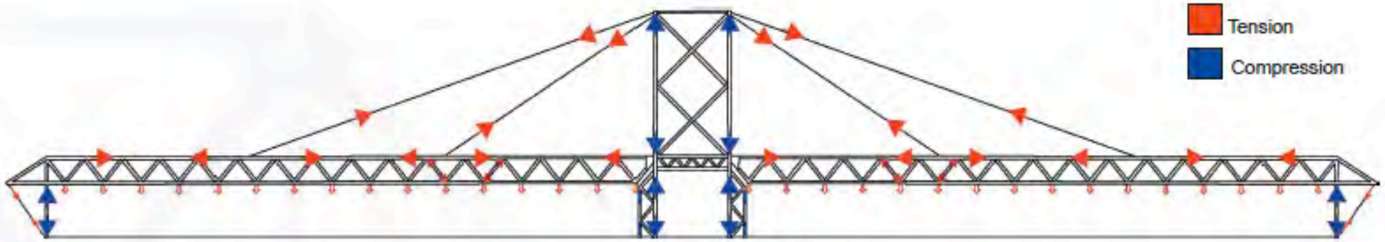
Structural Plan



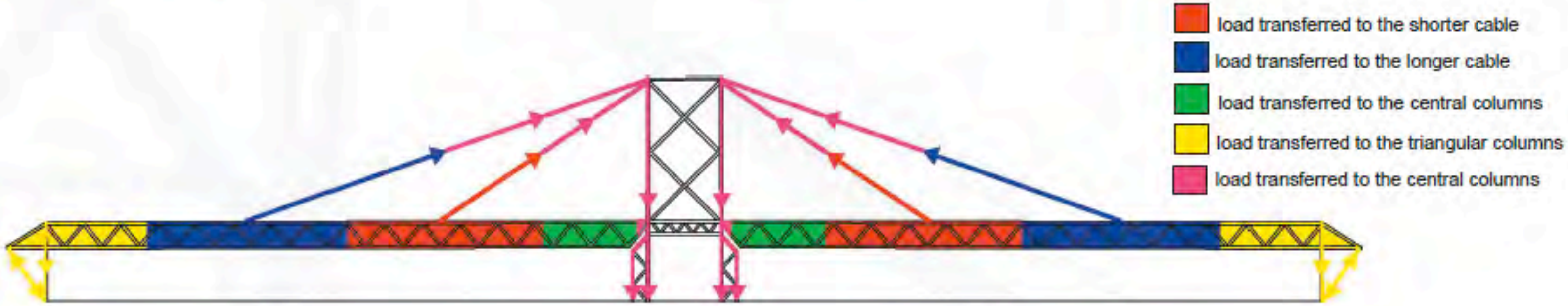
North-West Elevation



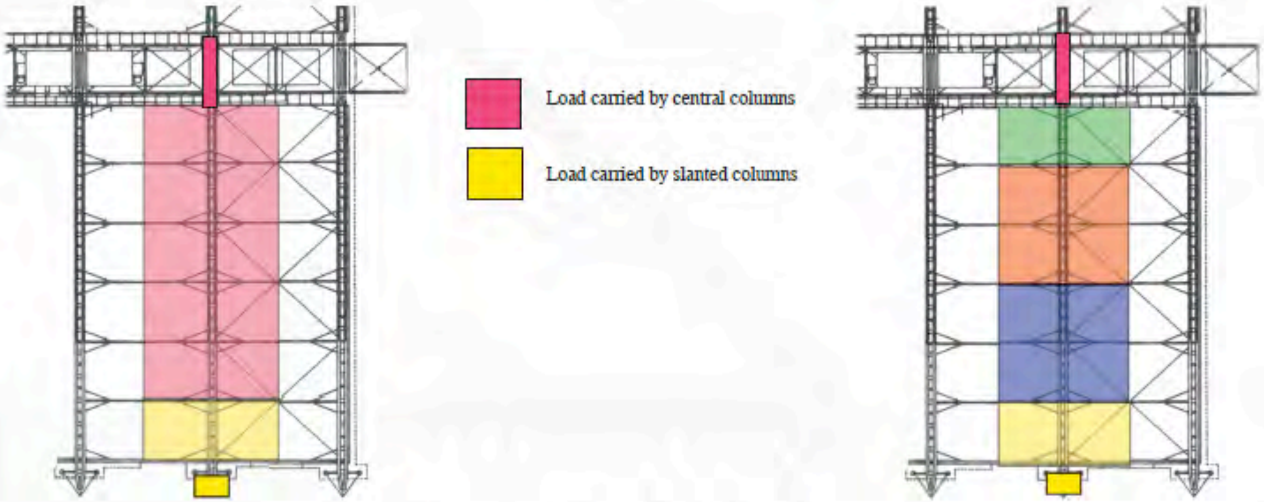
Load Diagrams



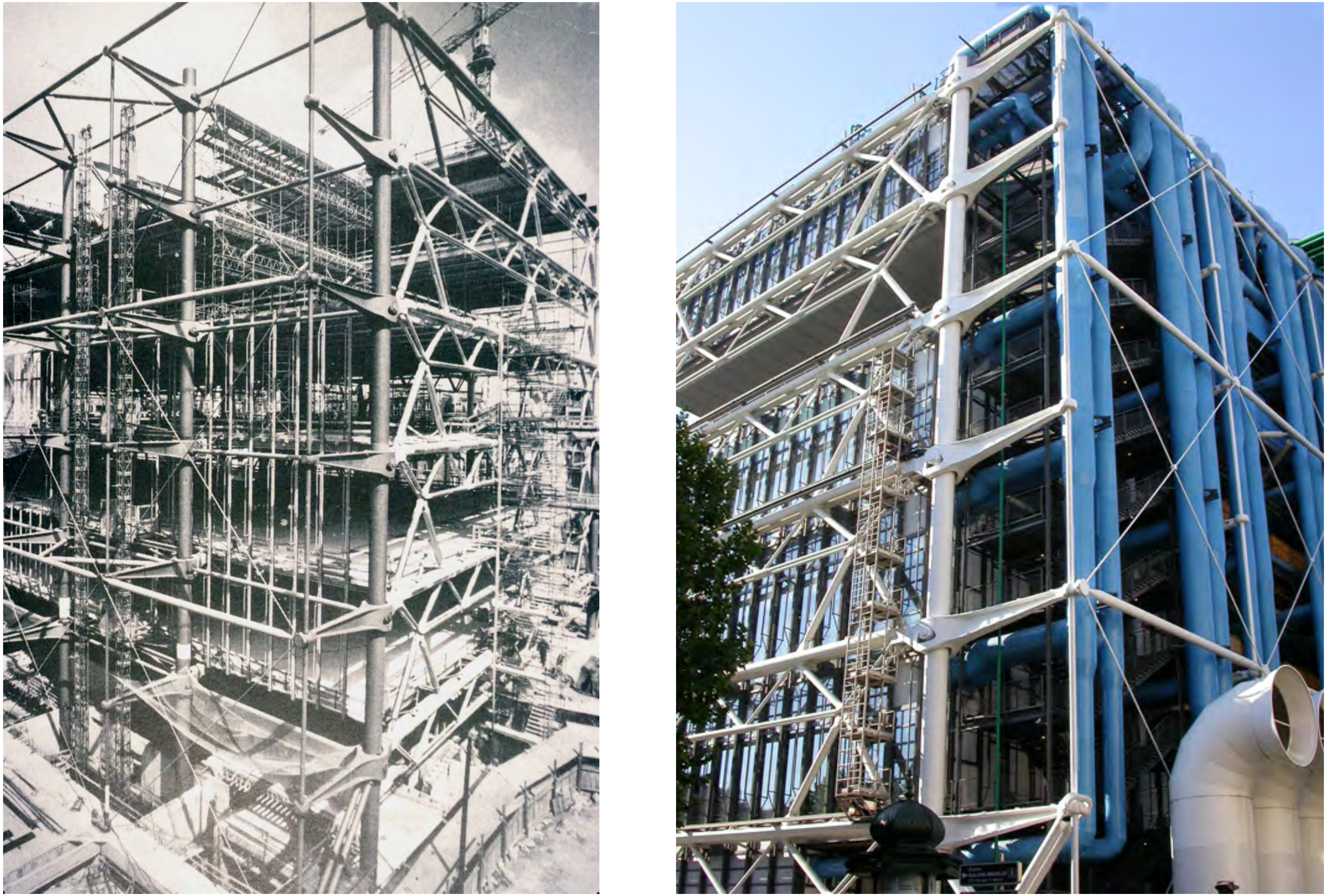
Members under compression and tension



Distribution of loads among the members in elevation



Distribution of loads among the members in plan



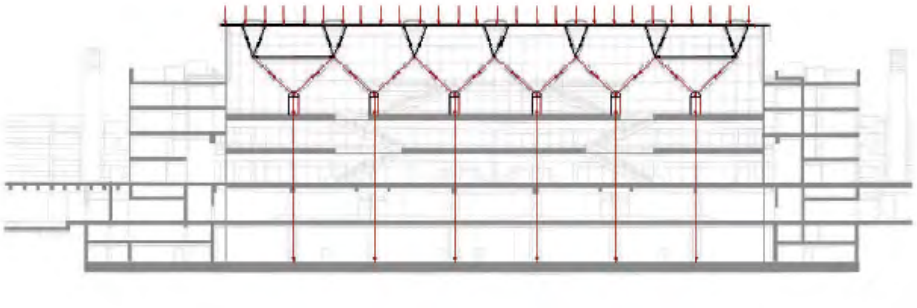
Centre Pompidou. Stiff compress struts connecting trusses together at their ends and mid-points to form a braced shear wall. On the long sides the crossed tension rods keep the frames from racking sideways.

Maintenance building at Fiumicino Airport, Rome Italy.

Ricardo Morandi   ca. 1960

Fuhlsbuttel Air Terminal, Hamburg Germany

Von Gerken, Marg and Partners   1993



Slanted columns. Pairs of slanted columns connected across the top with a continuous beam forms a stiff, lateral force resisting structure similar to a braced frame.

Bodegas Protos Rogers Stirk Harbour + Partners Penafiel, Spain 2010

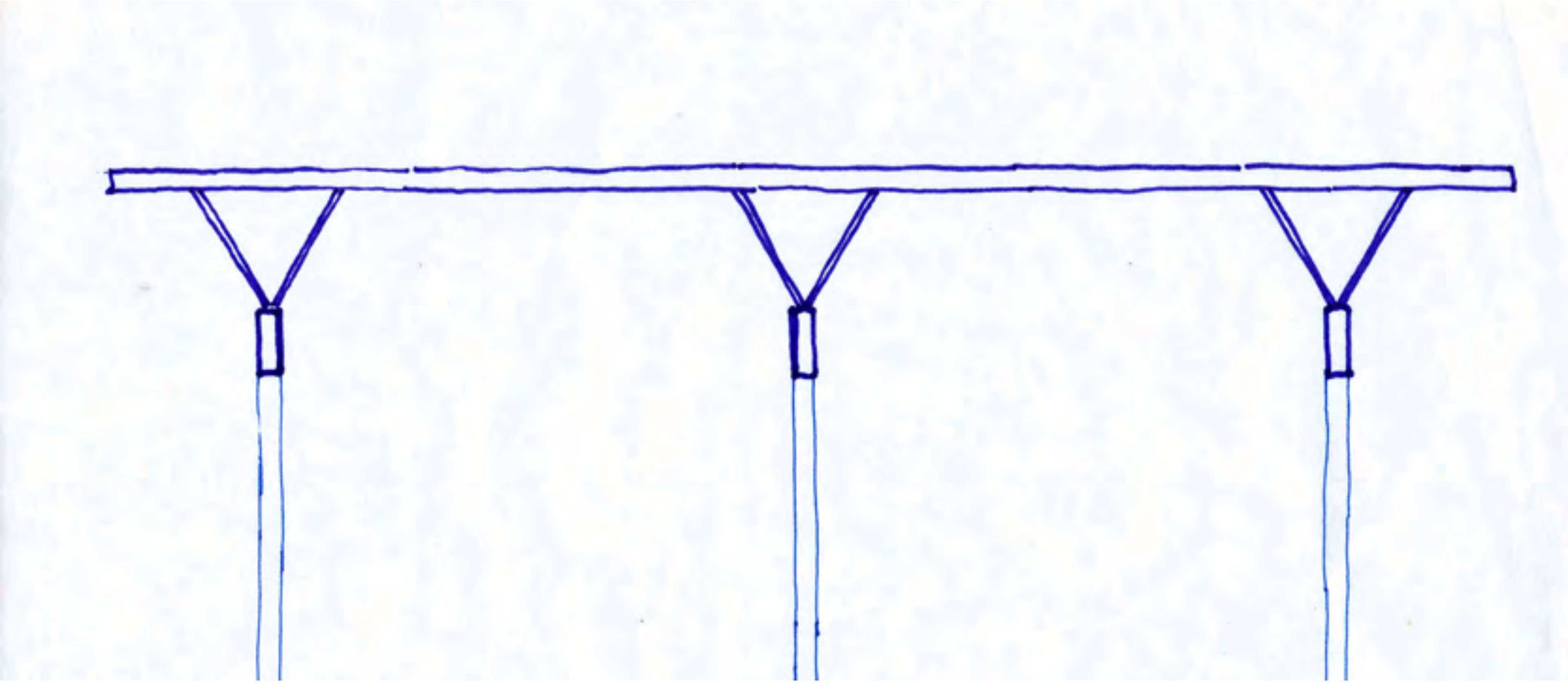
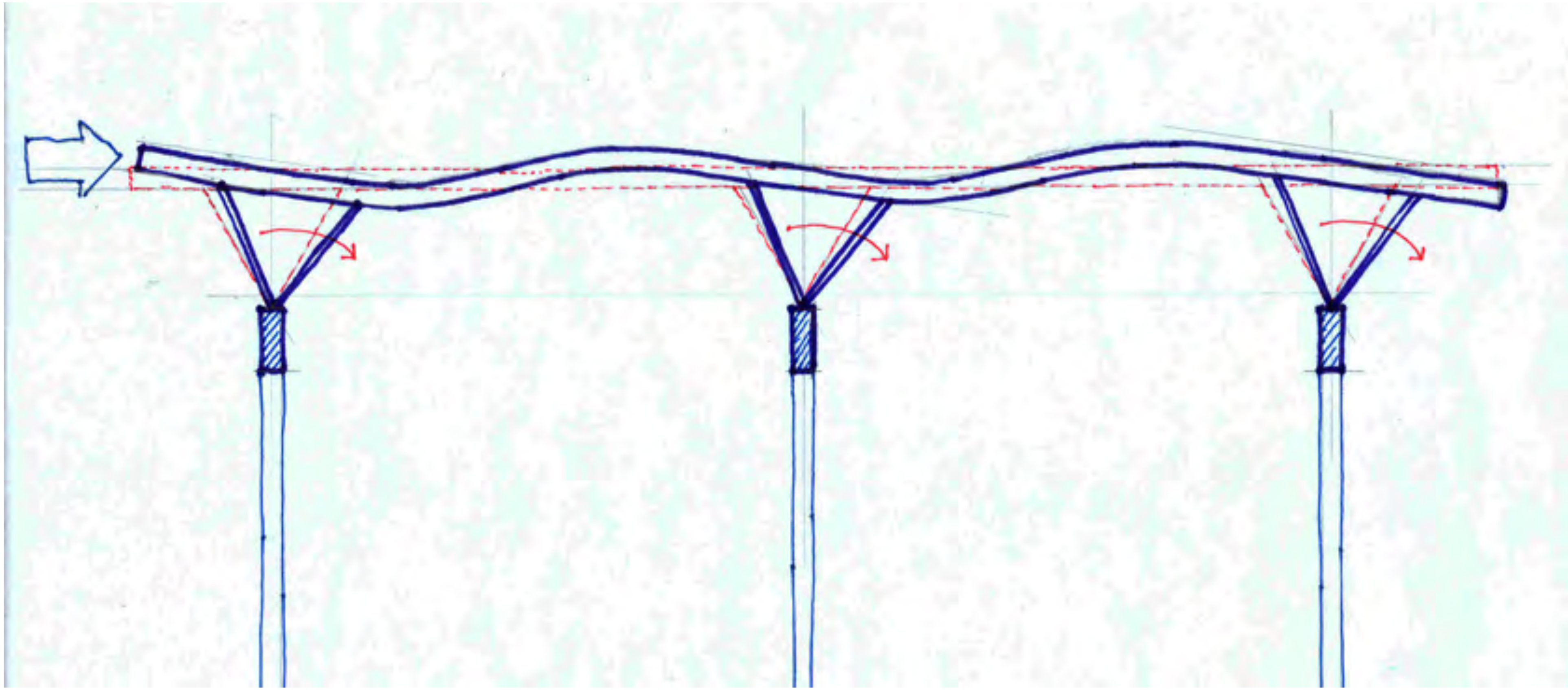
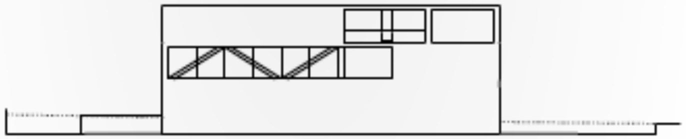


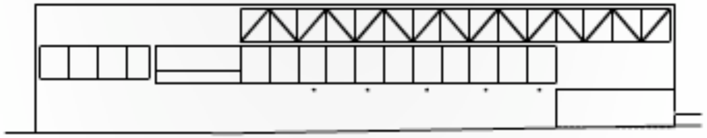
Diagram of roof beam framing structure. Slanted steel struts support the roof beams above the arches. The diagonal struts are pin-connected to the beams, but the stable triangular configuration creates a lateral force resisting mechanism.



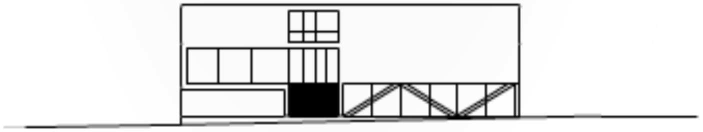
Lateral forces acting from the left side will cause the triangular strut configuration to rotate clockwise. This rotation is resisted by the stiffness of the beams which cannot bend as shown to accommodate the deflected shape.



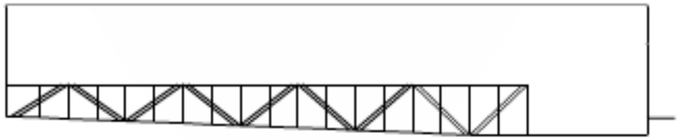
Ansicht Nord → North elevation



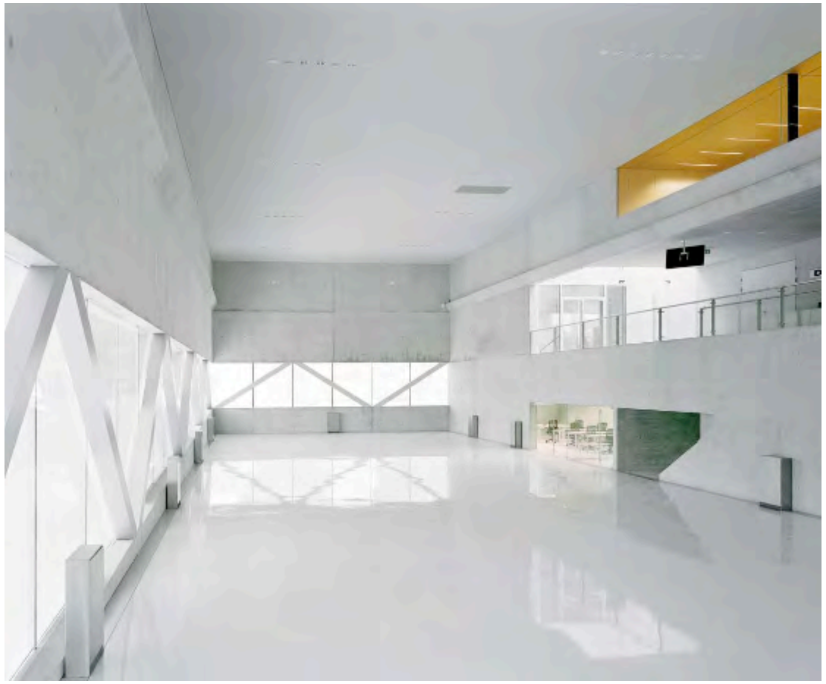
Ansicht West → West elevation



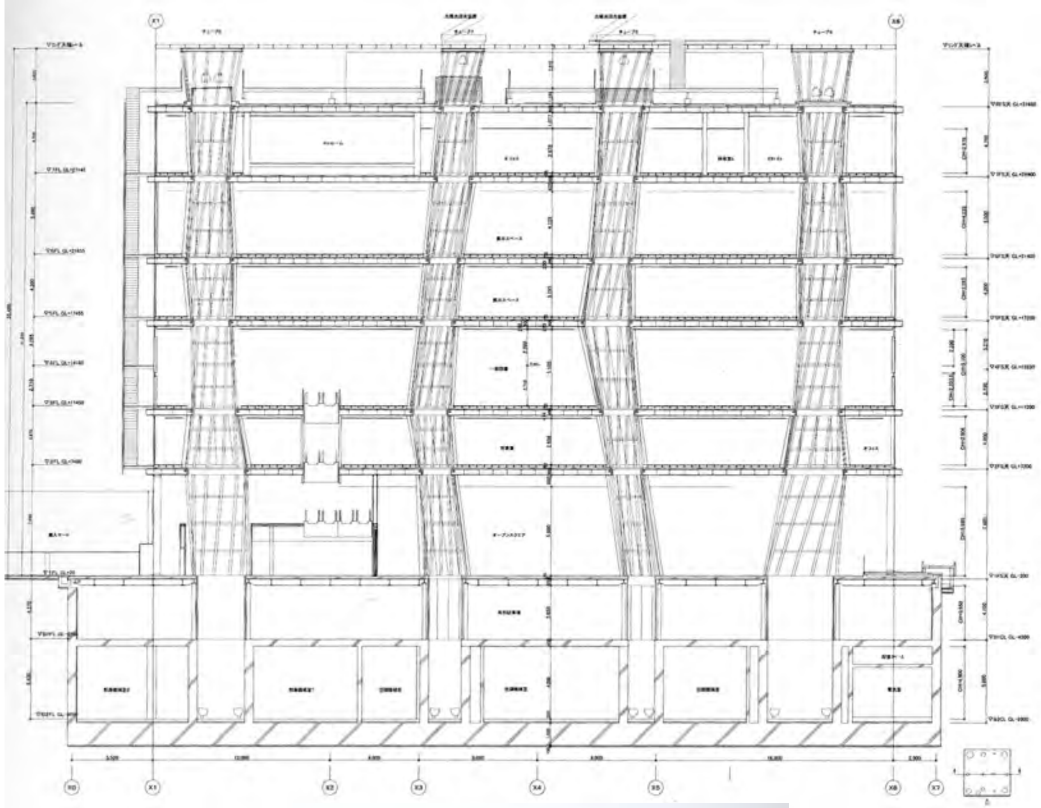
Ansicht Süd → South elevation

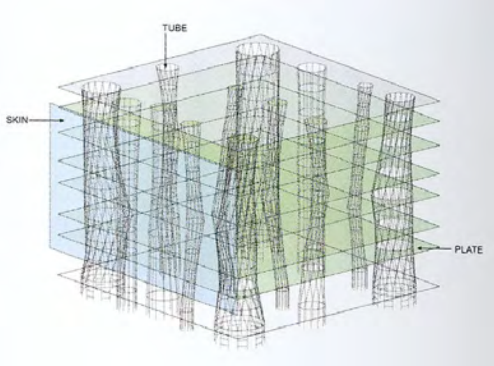


Ansicht Ost → East elevation



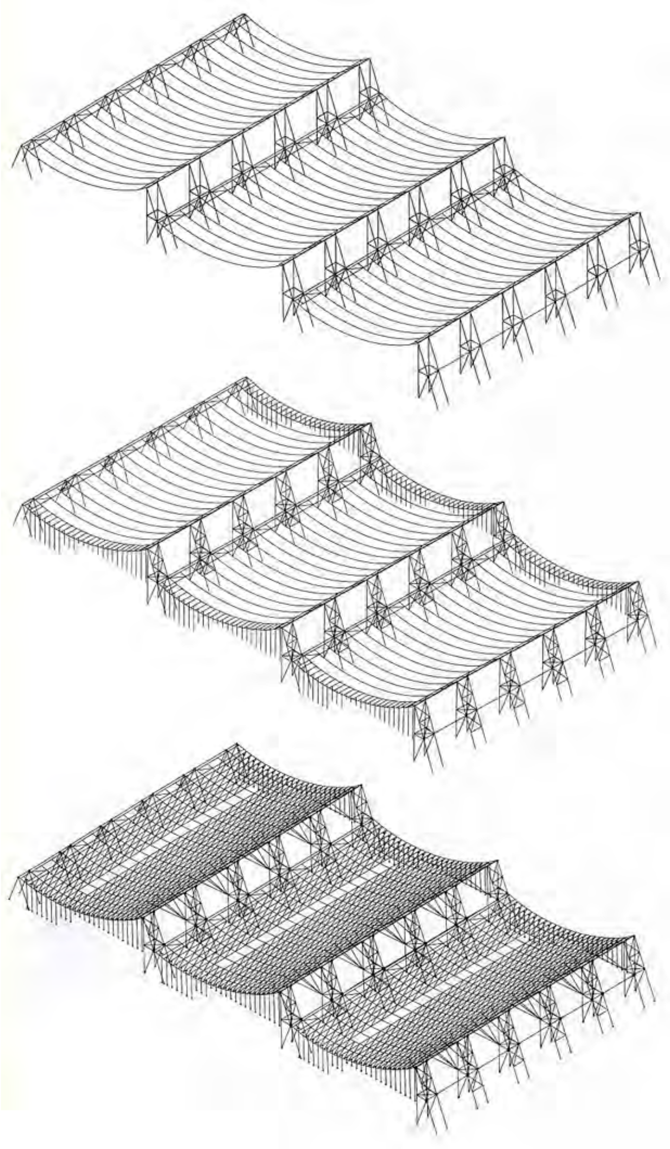
Steel trusses at various levels serve both as horizontal span structure and lateral force resisting elements.

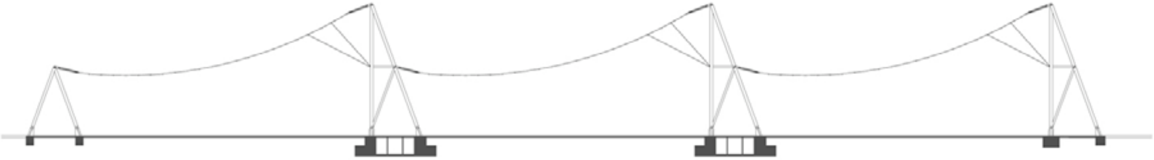




Lateral force system: stiff core-columns acting like “shear walls”

Sendai Mediatheque Toyo Ito & Associates 2000



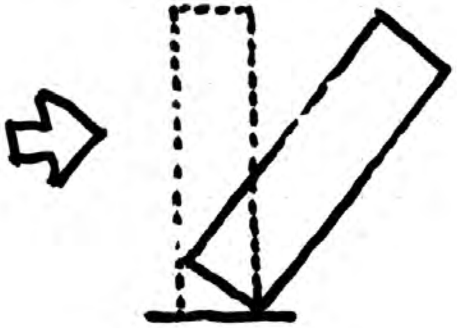


Lateral force system: braced columns acting like “shear walls”. Hall 26 Thomas Herzog Hanover Expo 2000

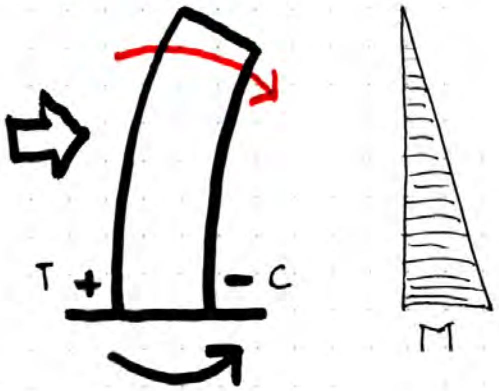

Casey Jones


WH SMITH
Budget
Europcar
SAMSUNG

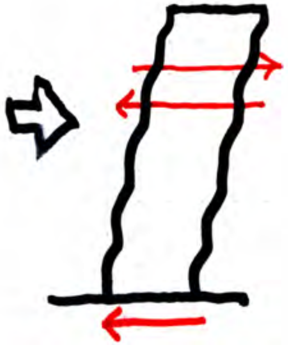
Lateral forces on hi-rise structures



overturning

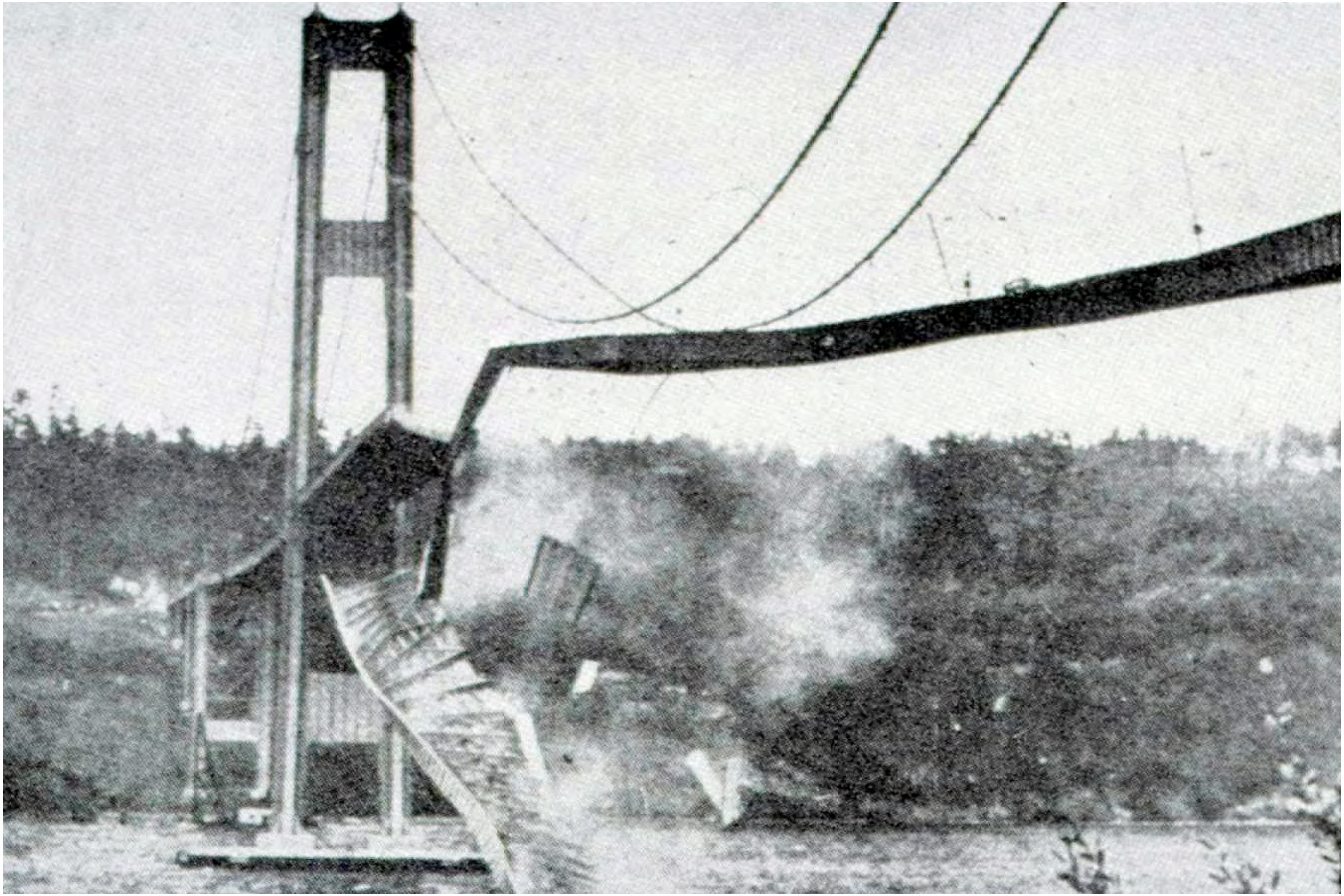


bending



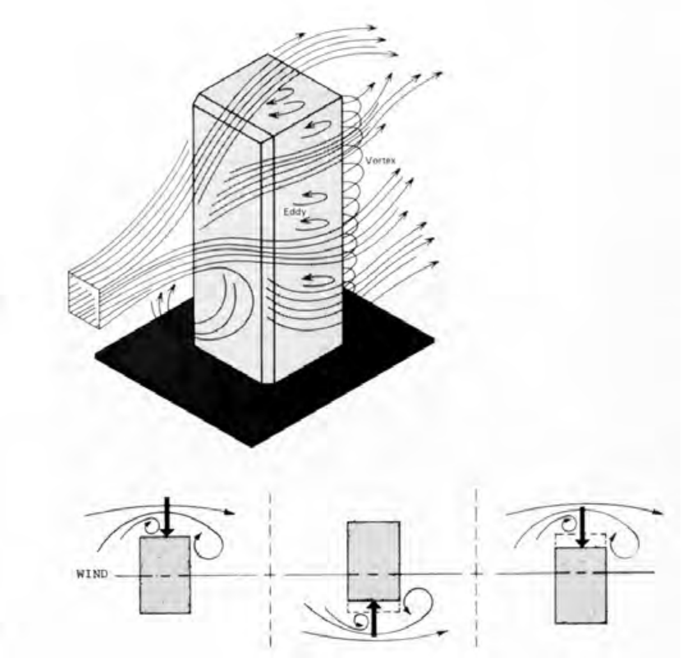
shear racking

Effects of lateral forces on a tall building.

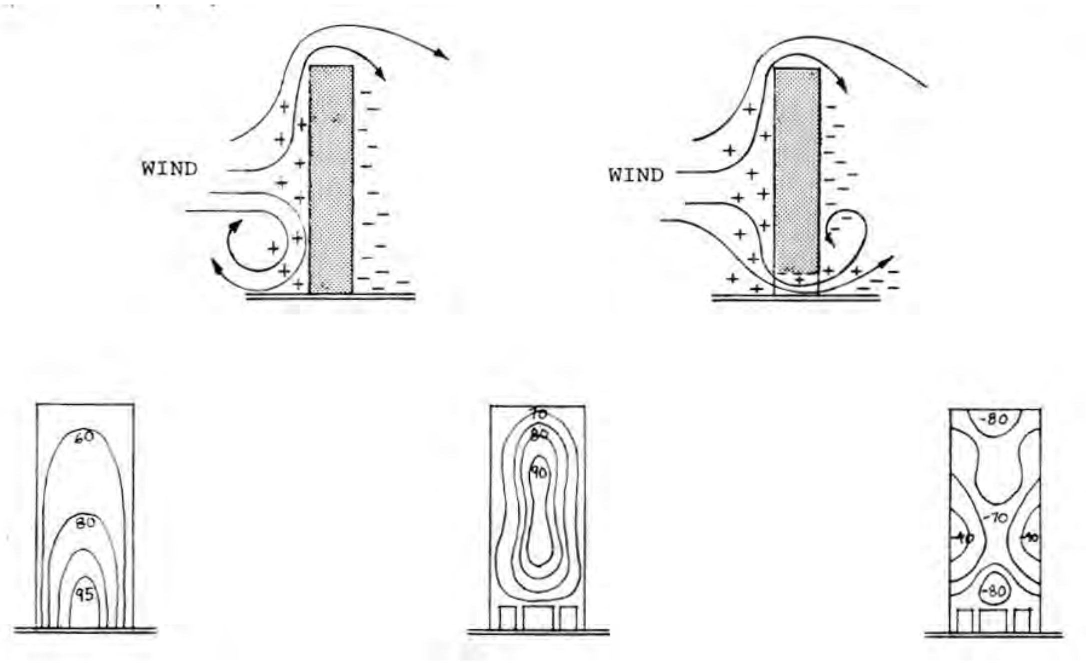


Tacoma Narrows Bridge (collapsed under moderately strong winds in 1940) Washington State, USA

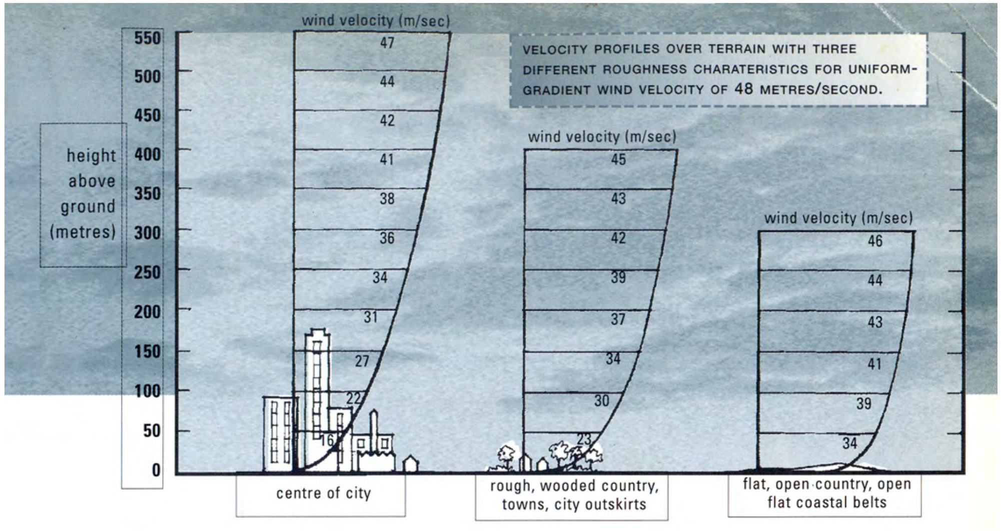
The Tacoma Narrows Bridge collapse led to research into the effects of wind induced resonating forces on structures. This led to fundamental changes in the design approach to the structures with respect to the stiffness of the structure/building as well as its fundamental period of oscillation or resonance.



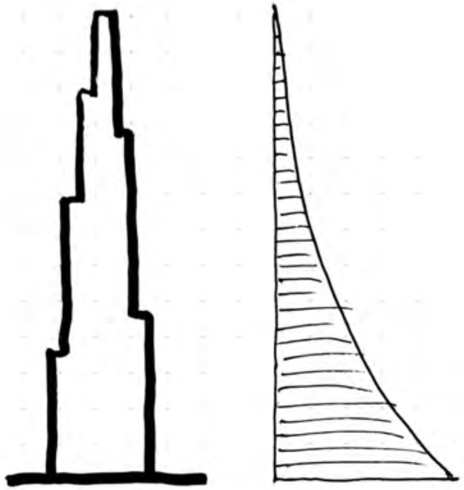
Wind forces on a tall building.



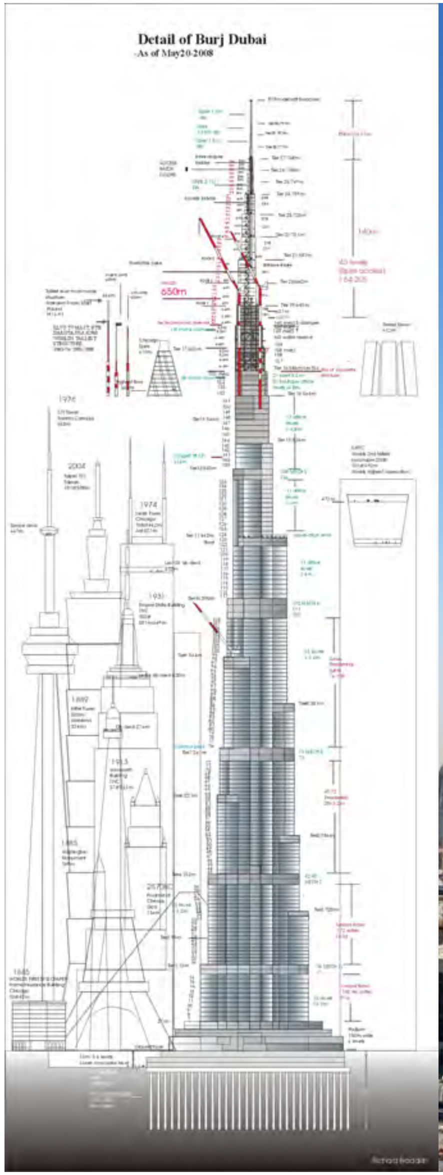
Example of variation of wind pressures as measured by a research study at MIT.

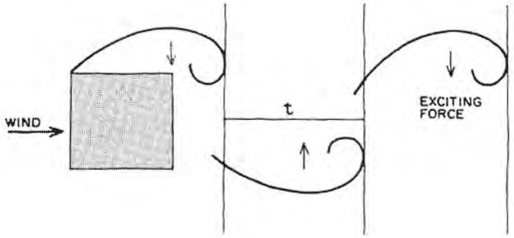


Wind profiles for three different ground conditions.



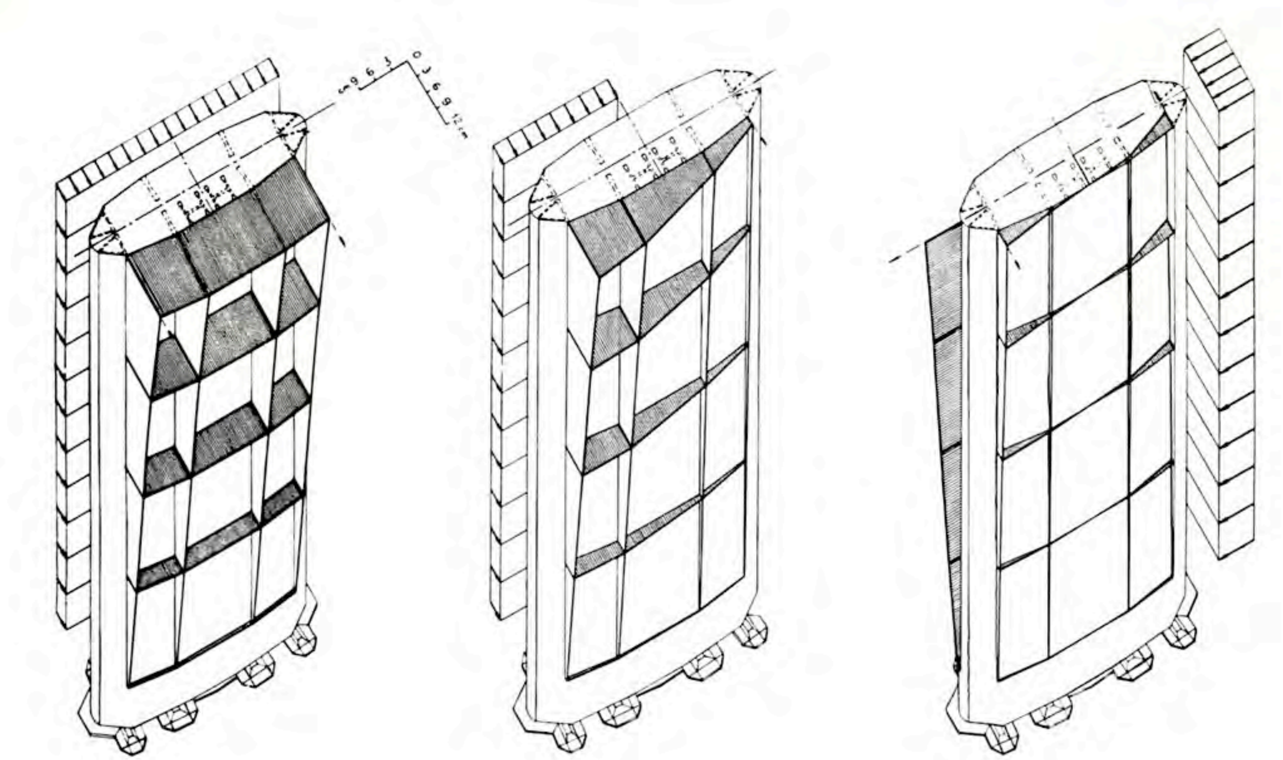
Set backs on a tall building reduces the surface area exposed to wind at the top where wind force is greatest.

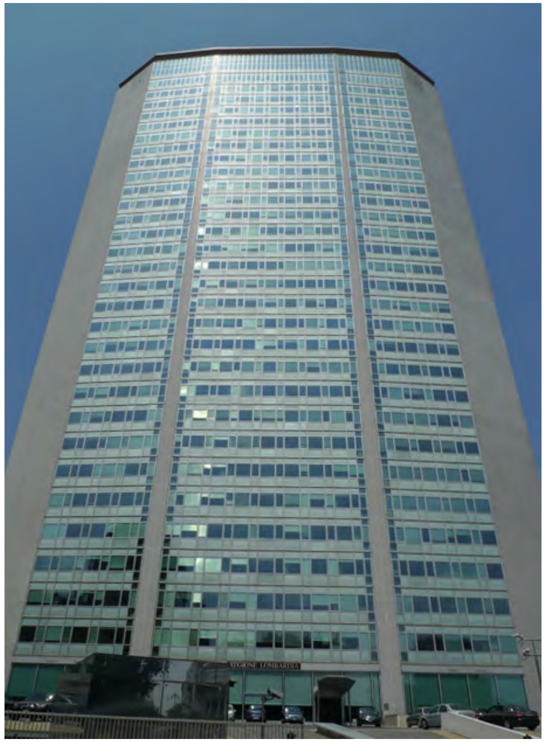


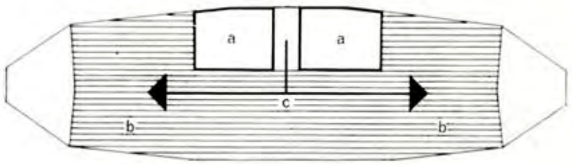


Wind induced sway of tall buildings.

As wind hits the surface of a tall building it will wrap around the side of the structure creating wind currents called “eddies” that create negative pressures. The wind fluctuates from side to side of the tall building and this constant fluctuation will cause the building to deflect laterally. If the frequency of the changing pressure from side to side matches the natural resonance frequency of the tower, it will be magnified and deflections will increase dramatically. To counter this effect it has been found that the tapered shape of a tower as well as certain asymmetries in the profile will disrupt the wind currents and counter the effect of sway. Also large openings in a tower, especially near the top, will have a similar effect.





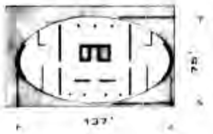


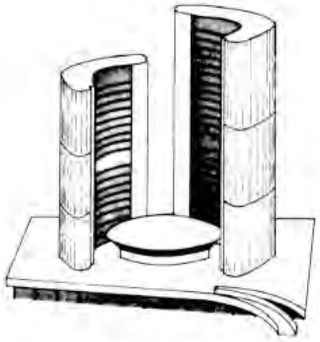
Pirelli Headquarters Tower   Milan, Italy

Gio Ponti with P. L. Nervi   ca. 1963

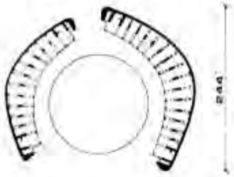
Wind tunnel tests measured the deflection of the Pirelli tower and demonstrated the torsional deflection resulting from the asymmetric placement of the cores.

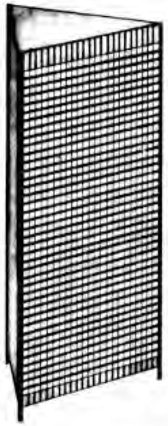
B ELLIPTICAL CYLINDER



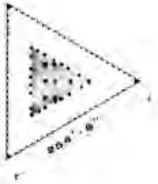


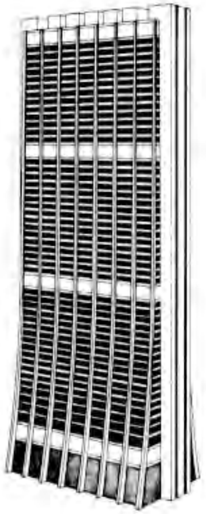
C VERTICAL SHELL





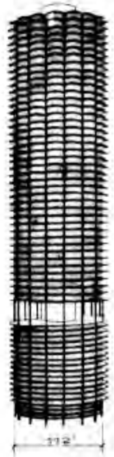
A TRIANGULAR PRISM





D TAPERED FORM

E PYRAMID

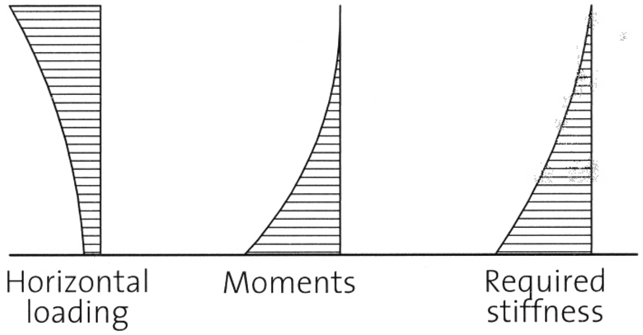


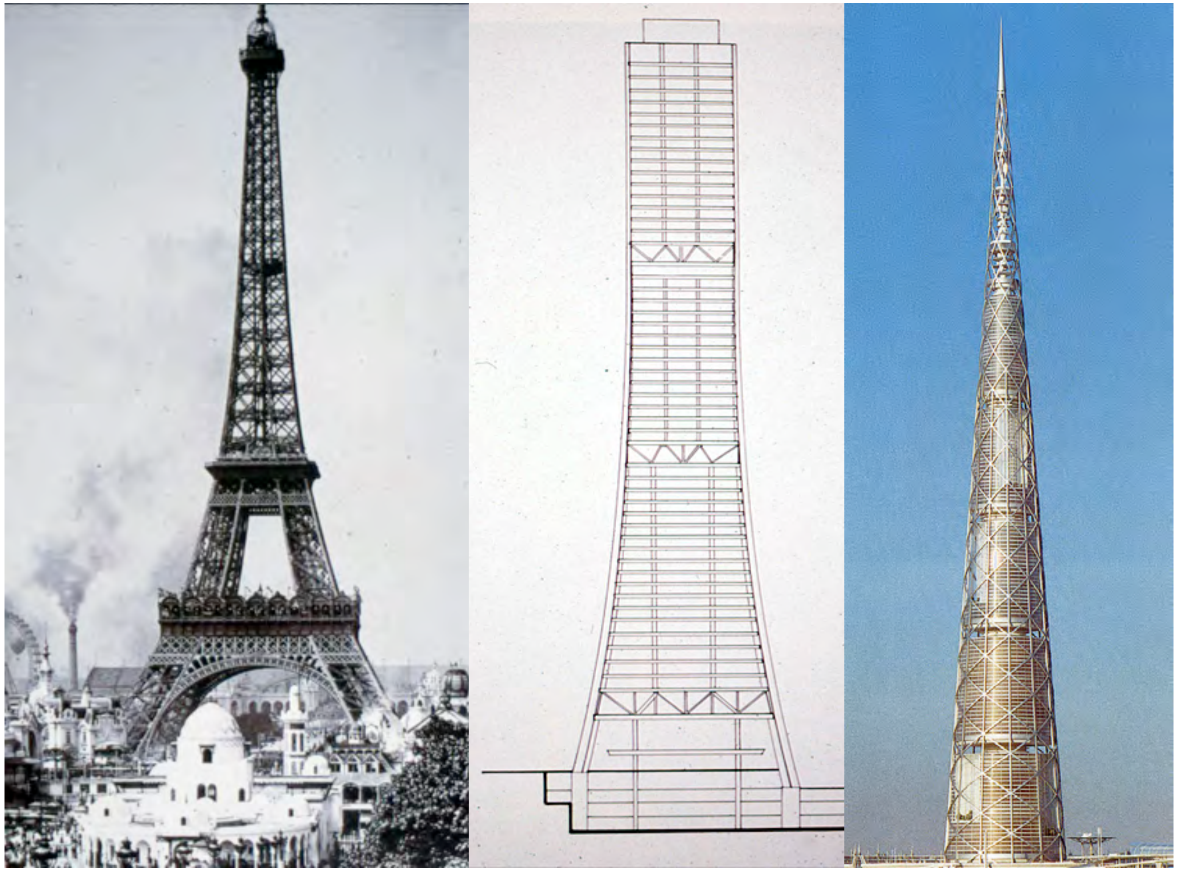
F ROUND CYLINDER

Tall buildings with efficient shapes.

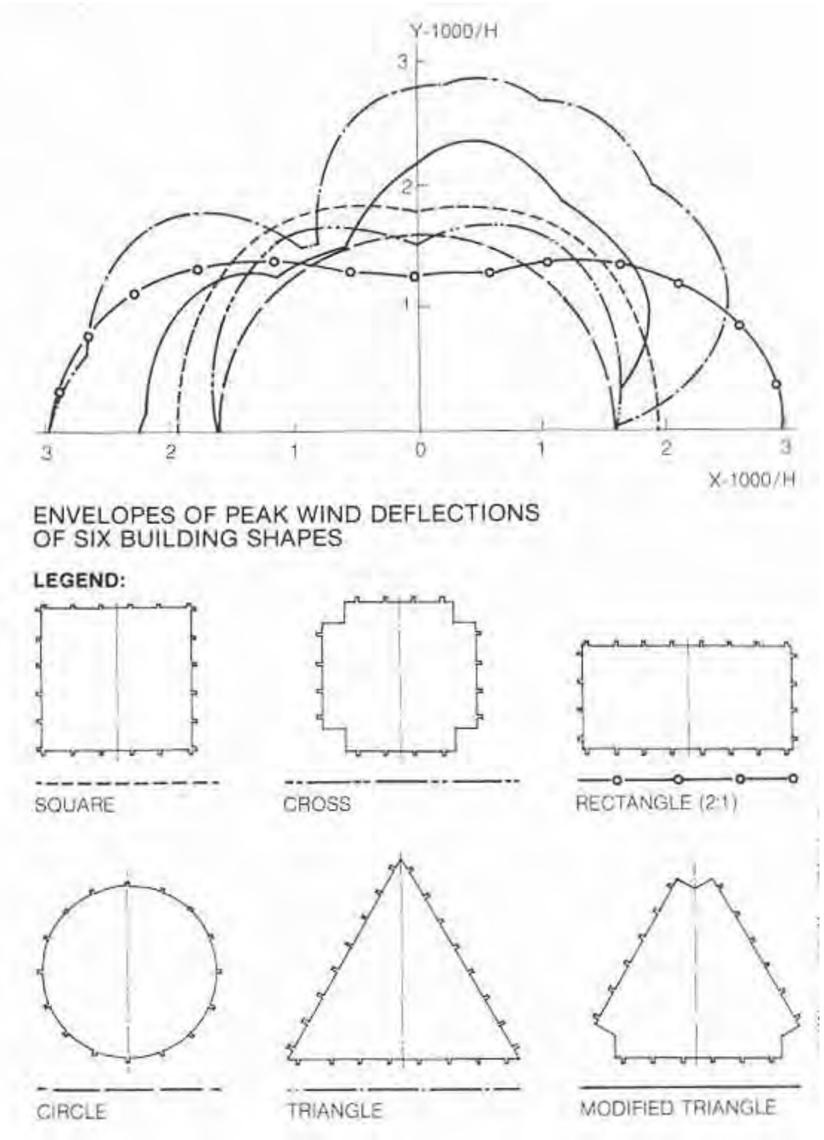
A rounded shape in plan allows wind to flow more easily around a tall building. Building Codes allow the wind pressure for octagonal and hexagonal shapes to be reduced 20% while circular and elliptical shapes may be reduced by 40%.

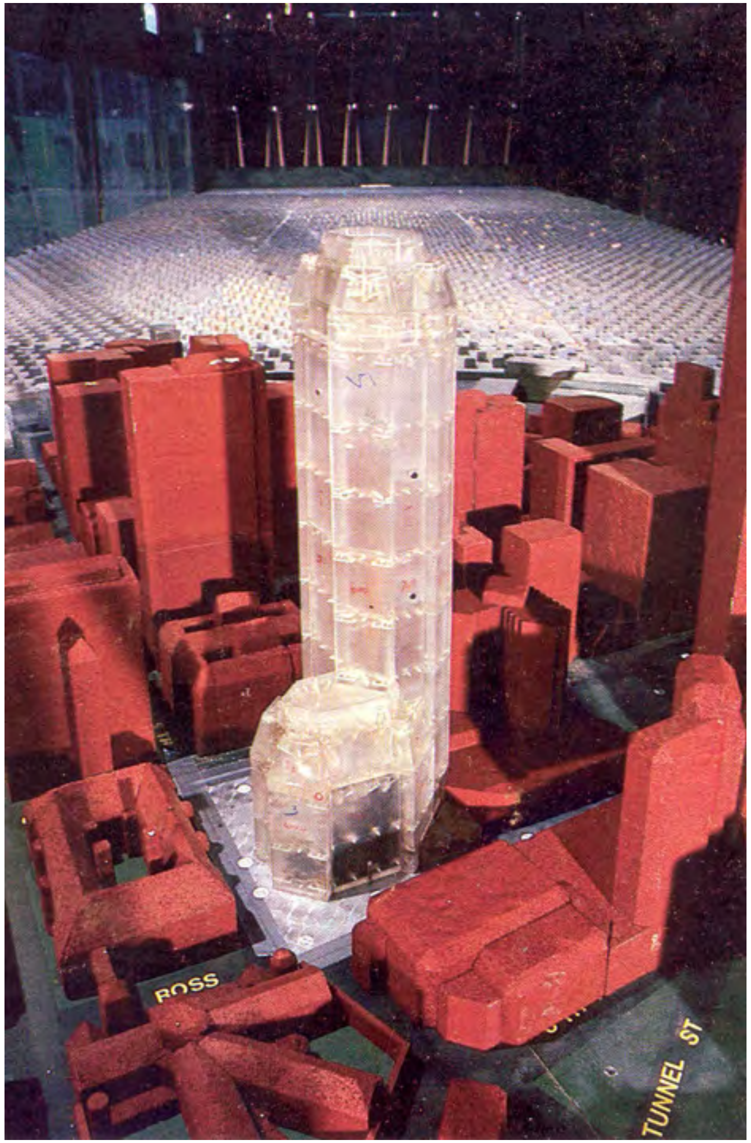
The tapering of a building as it rises effects a large reduction in wind loads and therefore drift. At higher elevations where wind speeds are high, there is less building surface providing resistance to the wind, thereby lessening the amount of wind force on the structure.





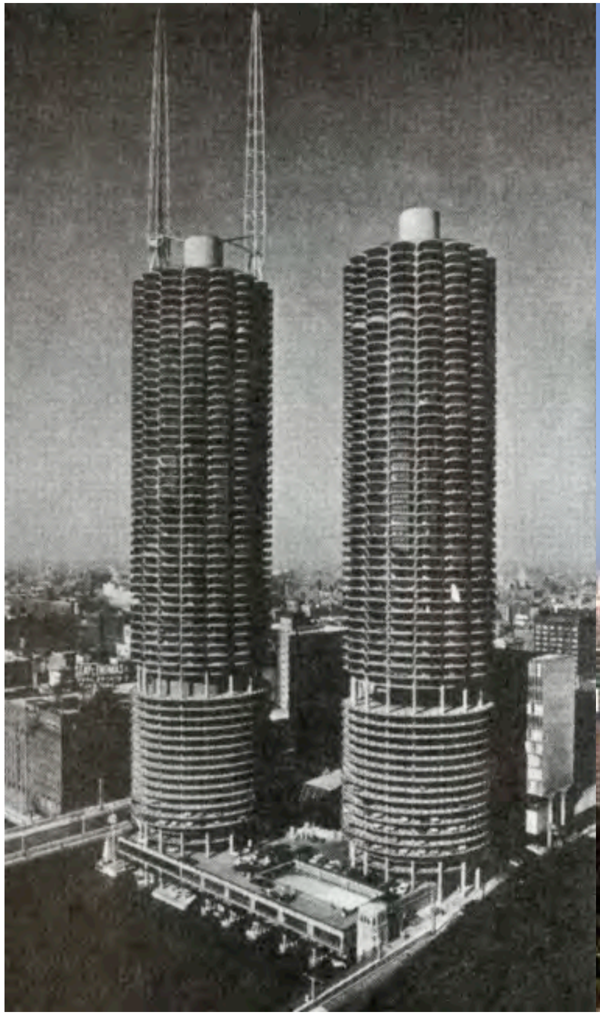
The profile of the tall building is shaped to reflect the bending moment diagram. The wider base provides a larger resisting moment to overturning without a corresponding increase in the column stress.



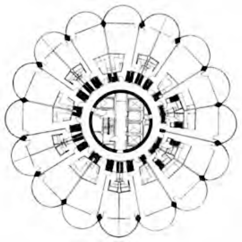


Influence of plan configuration on the amount of wind pressure on a tall building.

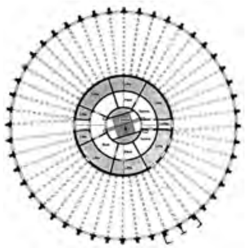
1967 wind study in conjunction with the design of the U.S. Steel Building in Pittsburg to determine variations in wind pressure on different tall building plan configurations. Besides demonstrating the advantage of circular over square or rectangular shapes, the study offered a way to calculate the effect on wind pressure of slight changes in the building profile.



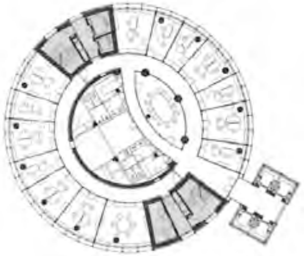
Marina City 1962



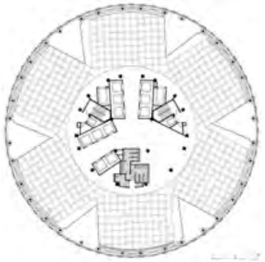
Hopewell Centre 1980

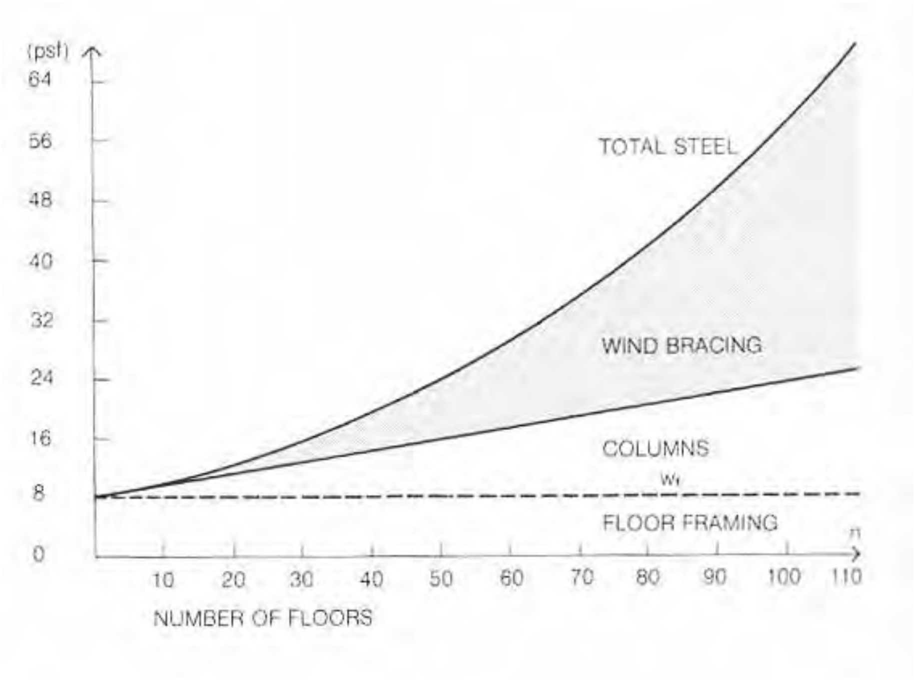


RWE Headquarters 1996



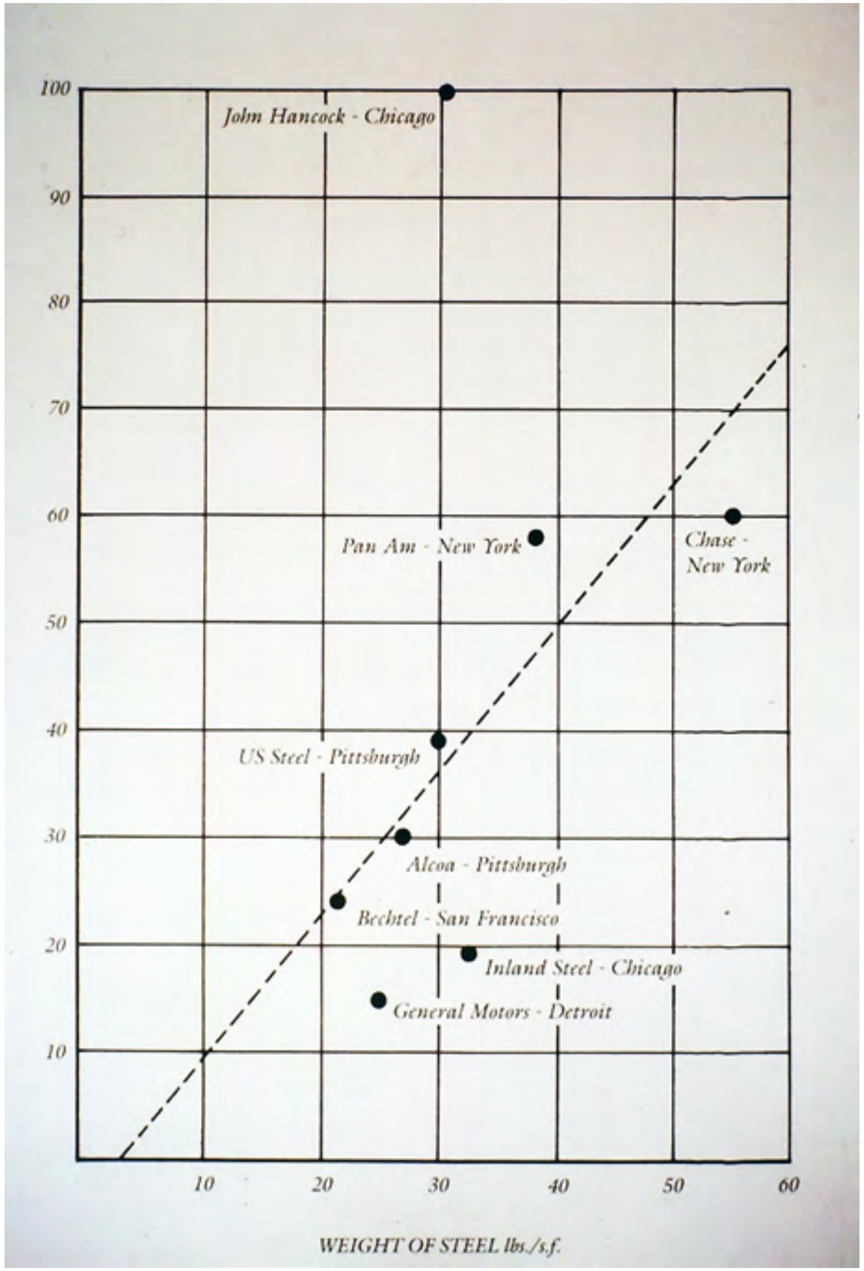
Swiss Re Tower 2003

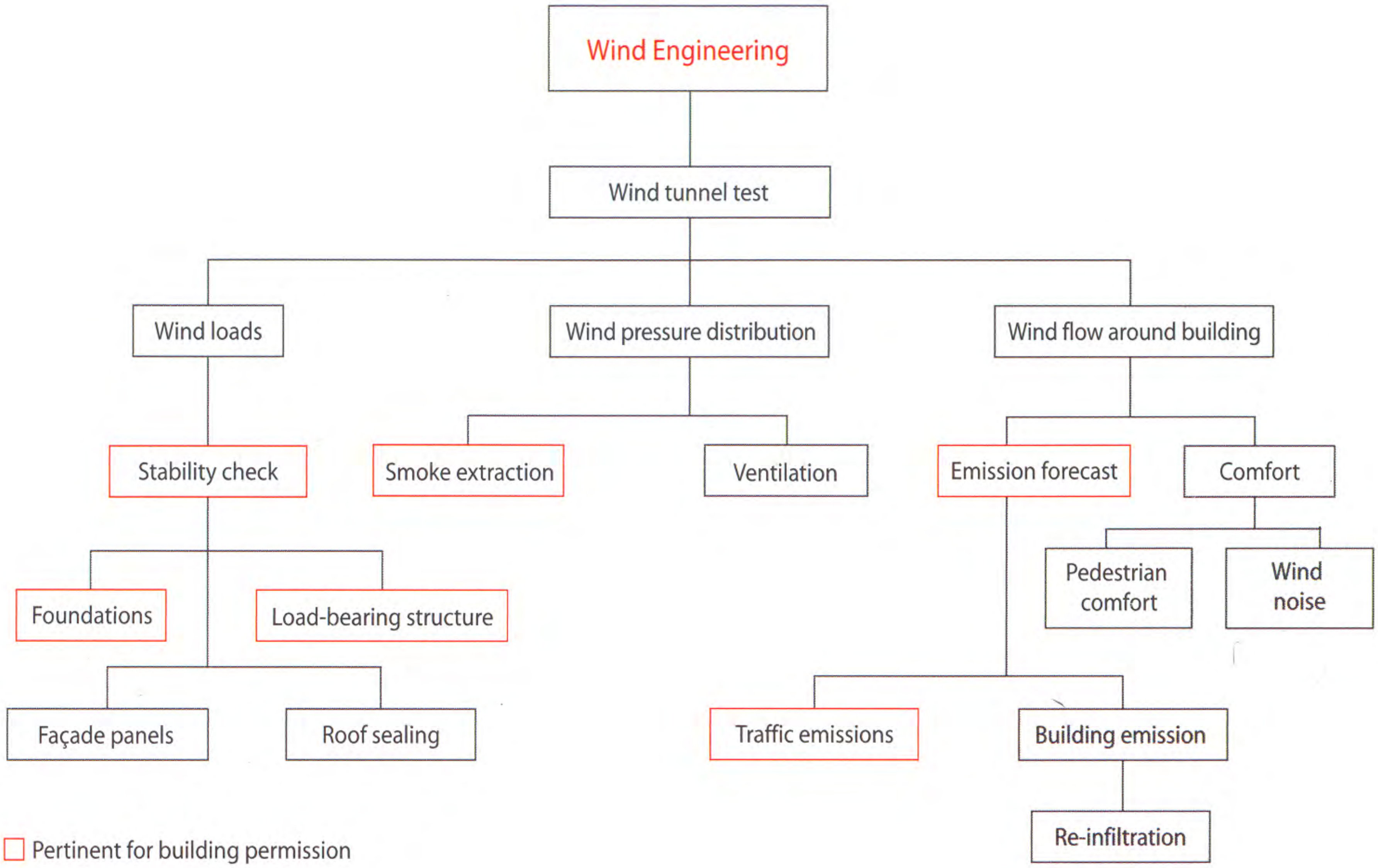




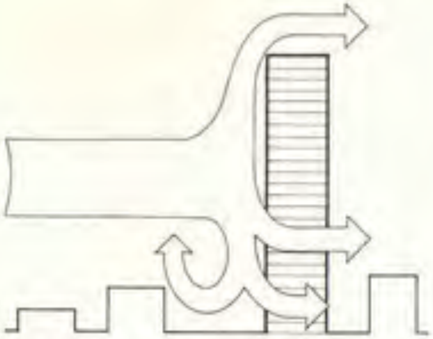
Comparison of proportional weight of steel in a steel frame building with regard to building height.

At about 50 stories (200m) the weight of steel required in the structure designed to resist the lateral loads (wind bracing) is approximately equal to the weight of steel for the vertical load bearing structure (columns) and also the steel required for the horizontal structure (floor framing). The amount of steel in the floor framing is constant and depends on the span between columns. In a typical steel frame with a span of 8-10m the weight is approximately 8 psf (383 N/m^2 or Pa).

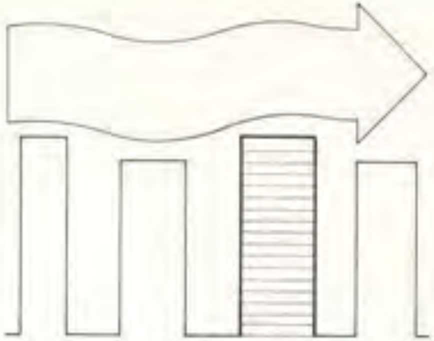




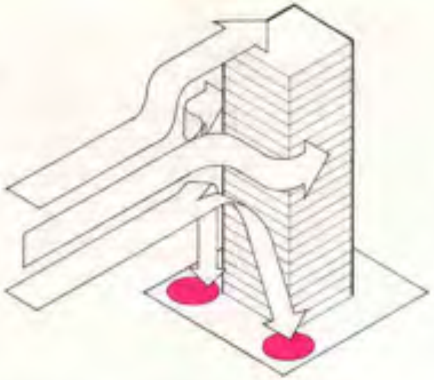
Schematic presentation of areas covered by wind engineering



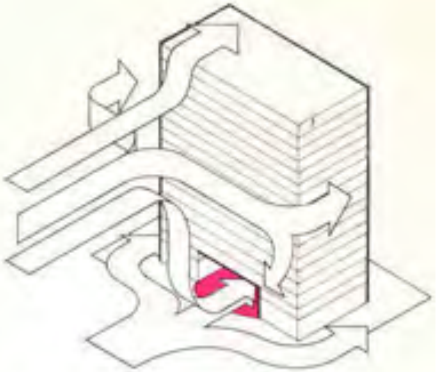
A BUILDING SIGNIFICANTLY TALLER THAN ITS SURROUNDINGS CAN EXPERIENCE HIGH WIND LOADS AND CONCENTRATE PEDESTRIAN LEVEL WINDS



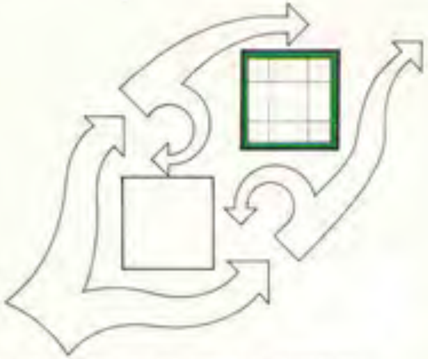
A BUILDING OF SIMILAR HEIGHT TO ITS SURROUNDINGS MAY BE PROTECTED FROM LARGE WIND LOADS AND CONCENTRATED PEDESTRIAN WINDS



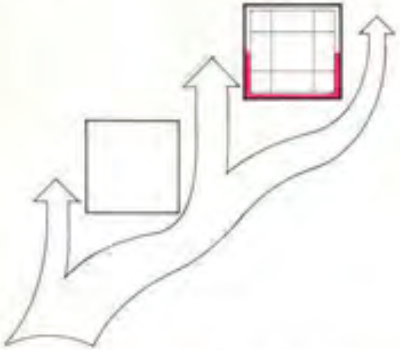
A TALL BUILDING CONCENTRATES WIND AT ITS BASE



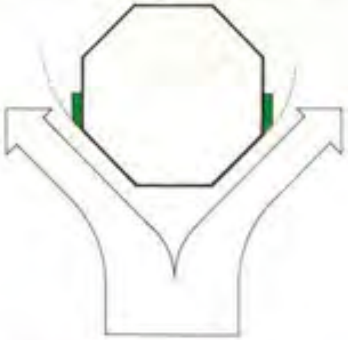
OPENINGS THROUGH A BUILDING AT THE BASE MAY INDUCE HIGH VELOCITIES IN THE OPENING



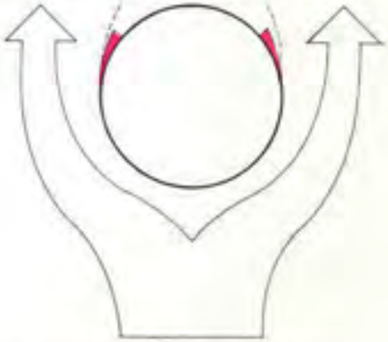
ADJACENT BUILDING PLACEMENT MAY PROTECT FROM HIGH WINDS REDUCING WIND LOADS AND PEDESTRIAN LEVEL WINDS



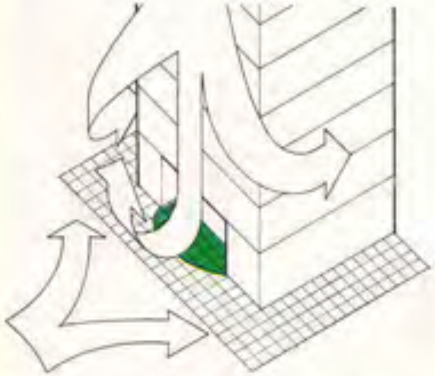
ADJACENT BUILDING PLACEMENT MAY DEFLECT WIND RESULTING IN HIGHER WIND LOADS AND PEDESTRIAN LEVEL WINDS



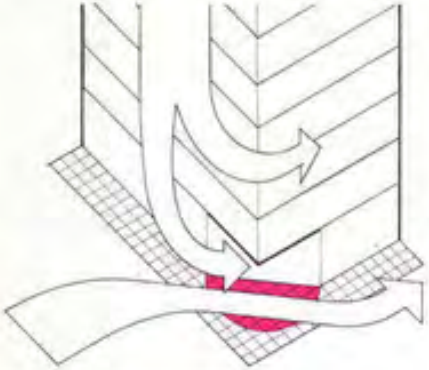
MULTI-SIDED BUILDINGS MAY NOT PERMIT FULL DEVELOPMENT OF LOCAL PRESSURES, FRAME LOADS, OR PEDESTRIAN LEVEL WINDS



CIRCULAR BUILDINGS MAY REDUCE FRAME LOADS AND PEDESTRIAN LEVEL WINDS BUT INCREASE LOCAL CLADDED LOADS AT THE POINTS WHERE THE WIND SEPARATES FROM THE BUILDING

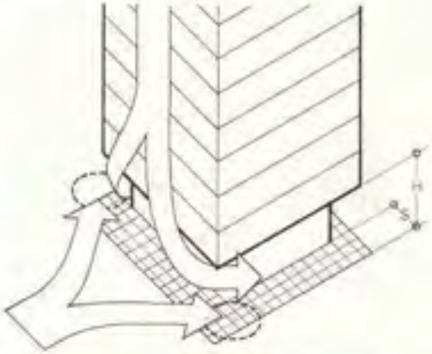


RECESSED ENTRY PROVIDES LOW WINDS AT DOOR LOCATIONS



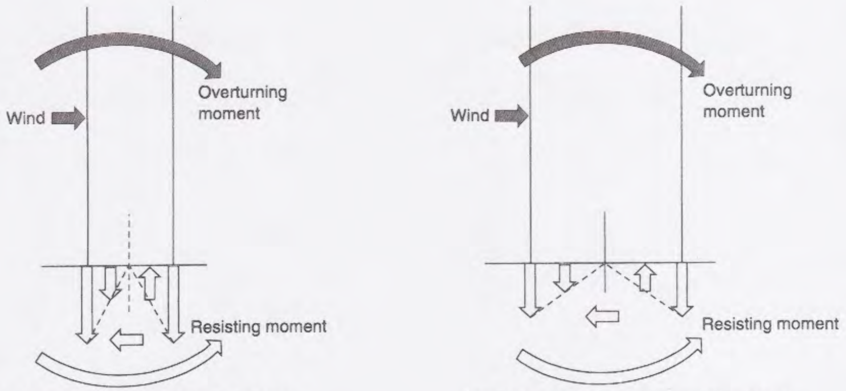
CORNER ENTRY MAY ACCENTUATE WIND CONCENTRATION AT BUILDING CORNER

A LOW PEDESTAL BUILDING CONCENTRATES WIND ON THE ROOF, NOT AT THE BASE



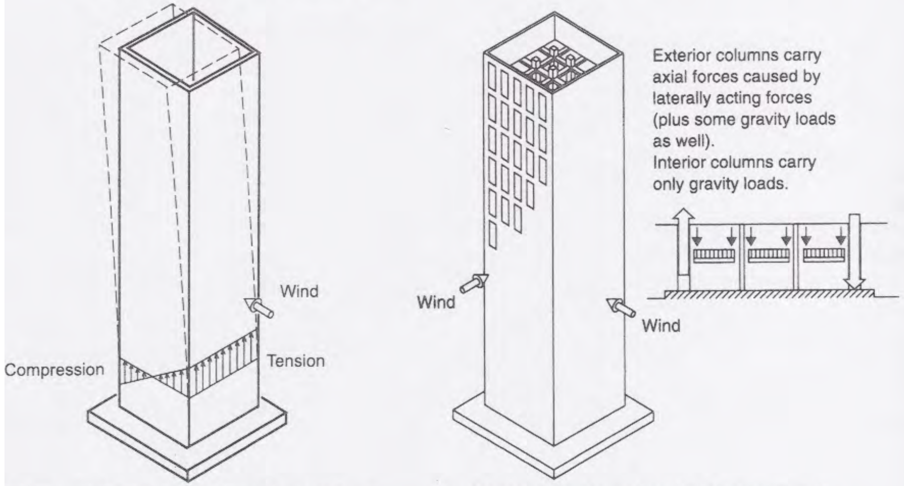
SETBACK ALL AROUND THE BUILDING MAY IMPROVE OR WORSEN WIND CONCENTRATION DEPENDING UPON S AND H

WIND EFFECTS ON TALL BUILDINGS



(a) Wind forces acting against the face of a tall building produce an overturning moment that must be balanced by an internal resisting moment provided by forces developed in column members. The structure acts much like a vertical cantilever beam.

(b) The magnitude of the forces developed in the columns are generally proportional to the moment arm separating the columns. Smaller column forces are developed in wider buildings than in those of more slender proportions.



Exterior columns carry axial forces caused by laterally acting forces (plus some gravity loads as well).
Interior columns carry only gravity loads.

(c) For very tall structures, an efficient structure often results from conceiving of the building as a laterally loaded cantilever beam and distributing material to achieve a large moment of inertia.

(d) Many structures have been built on the principle described in (c). The structures must, however, be responsive to lateral forces in all directions. A tube type of structure results in which the exterior columns provide all the resisting moment to overturning lateral forces. Interior columns are designed to carry only gravity loads.

FIGURE 14.17 Very tall buildings can usefully be conceived of as vertical cantilever beams.

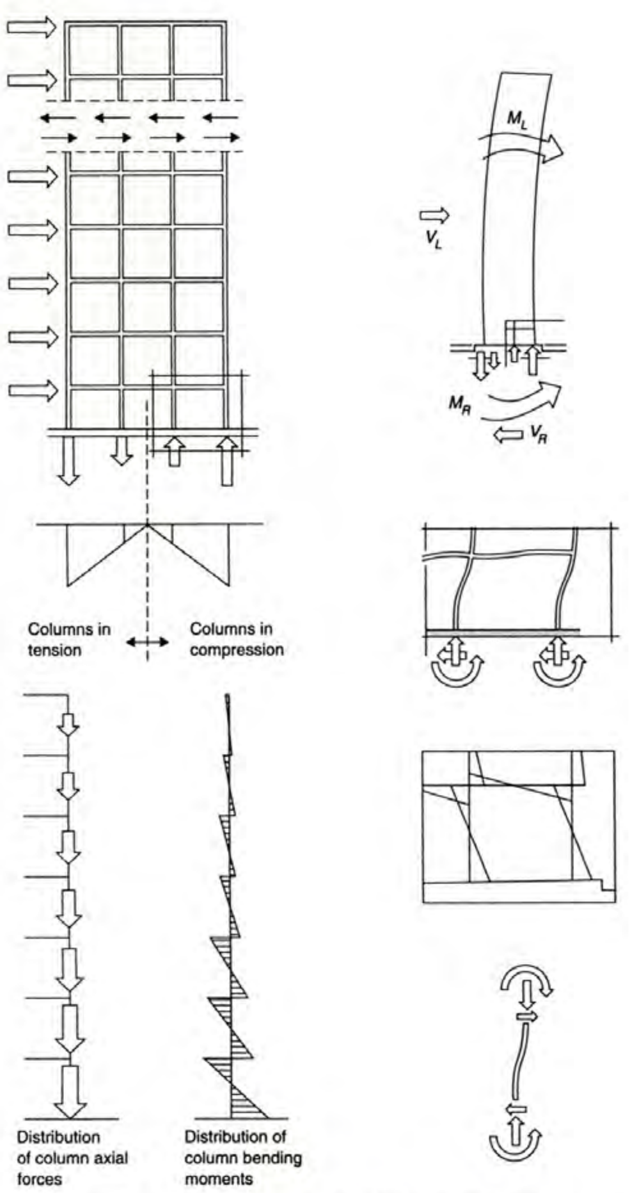
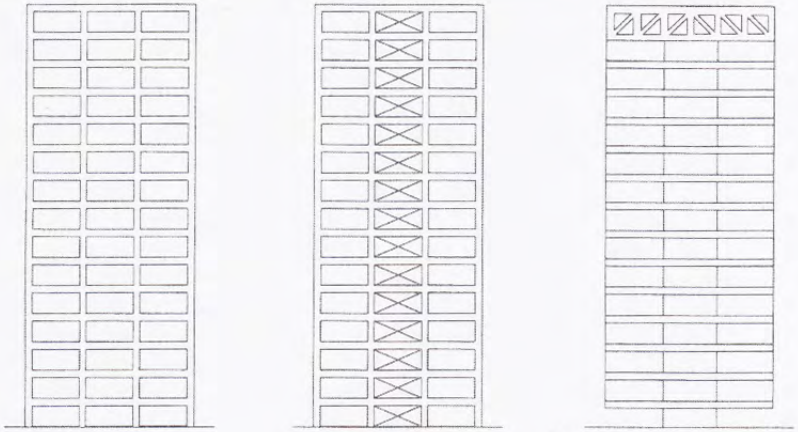


FIGURE 9.13 Multistory frames.

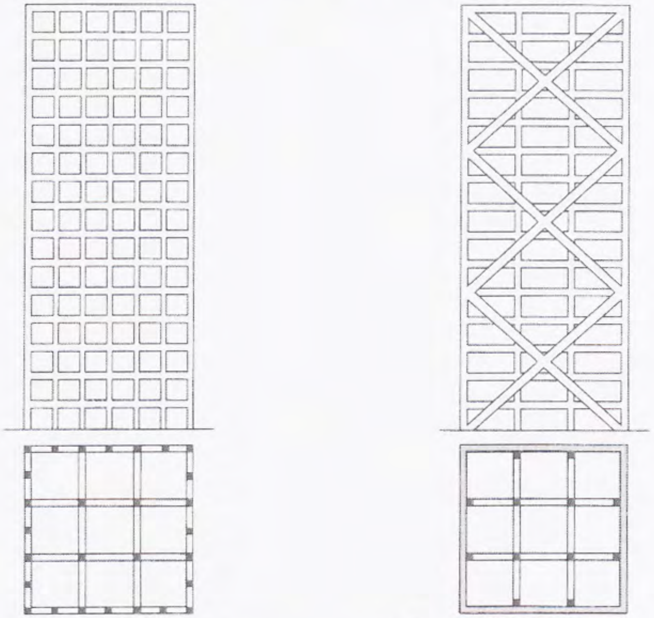
Illustrations from *Structures* 6th Ed. by Daniel L. Schodek and Martin Bechthold



(a) Frame.

(b) Braced frame.

(c) Suspended structure, reinforced concrete core.



(d) Tube structure. The exterior columns are closely spaced. Horizontal spandrel beams are rigidly connected to columns to form an exterior tube, which carries all lateral forces and some gravity forces. Interior columns carry only vertical forces.

(e) Trussed frame. The lateral stiffness of very tall structures can be markedly increased by superimposing major diagonal bracing members. Lateral forces are again taken by the exterior trusswork and frame. Interior columns carry only vertical forces.

FIGURE 14.18 Typical structural approaches in high-rise construction.

Illustrations from *Structures* 6th Ed. by Daniel L. Schodek and Martin Bechthold

Reference

Code of Practice on Wind Effects in Hong Kong 2004

http://www.bd.gov.hk/english/documents/code/windcode2004.pdf

Structures. Daniel L. Schodek and Martin Bechthold. See Chapter 14 Structural Systems: Design for Lateral Loadings. **TA 645 S37 2008**

Buildings at risk: seismic design basics for practicing architects. Christopher Arnold. **TA 658.44 B85 1994**