Architectural Structures: Form, Behavior, and Design

Arch 331

Dr. Anne Nichols

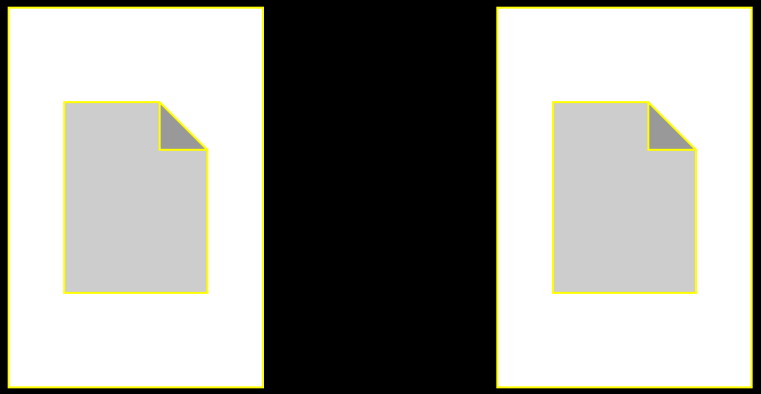
Summer 2014

lecture one

structural behavior, systems, and design

www.greatbuildings.com

Syllabus & Student Understandings



Course Description

- *statics*
  - *physics of forces and reactions on bodies and systems*
  - *equilibrium (bodies at rest)*
- *structures*
  - *something made up of interdependent parts in a definite pattern of organization*
- *design*
  - *assessing and meeting structural requirements of parts and the whole*

Course Description

- *mechanics of materials*
  - *external loads and effect on deformable bodies*
  - *use it to answer question if structure meets requirements of*
    - *stability and equilibrium*
    - *strength and stiffness*
  - *other principle building requirements*
    - *economy, functionality and aesthetics*

Structure Requirements

- *stability & equilibrium*
  - *STATICS*

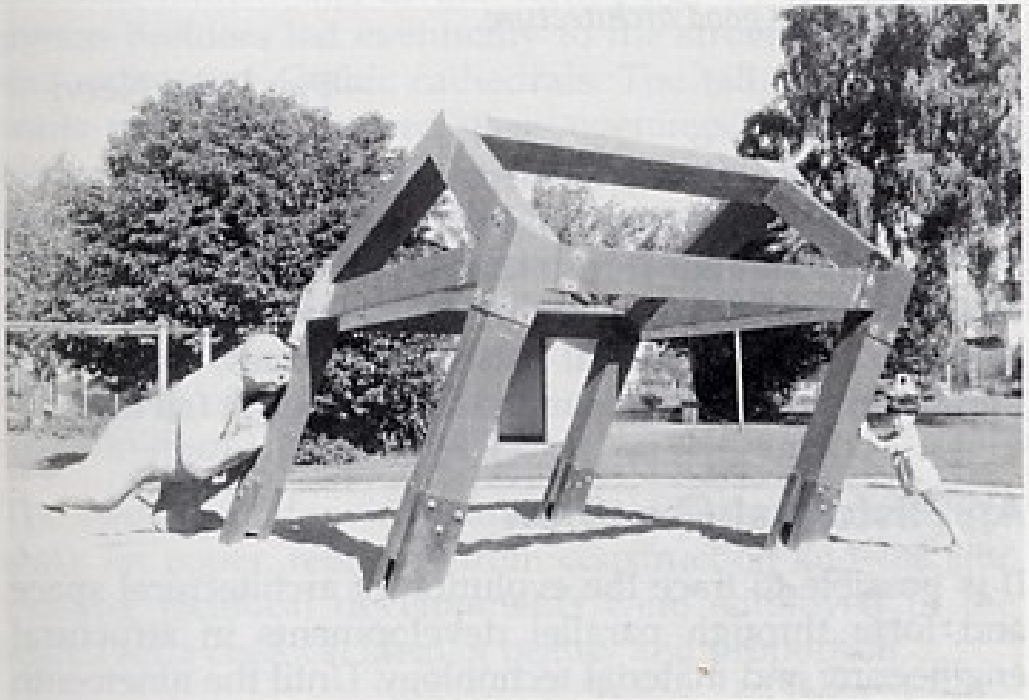


Figure 1.16 Equilibrium and Stability?—*sculpture by Richard Byer. Photo by author.*

Structure Requirements (cont)

- *strength & stiffness*
  - *concerned with stability of components*

Figure 1.15 Stability and the strength of a structure—the collapse of a portion of the UW Husky stadium during construction (1987) due to a lack of adequate bracing to ensure stability. Photo by author.

Structural System Selection

- *kind & size of loads*
- *building function*
- *soil & topology of site*
- *systems integration*
- *fire rating*
- *construction ($$, schedule)*
- *architectural form*

Knowledge Required

- external forces
- internal forces
- material properties
- member cross sections

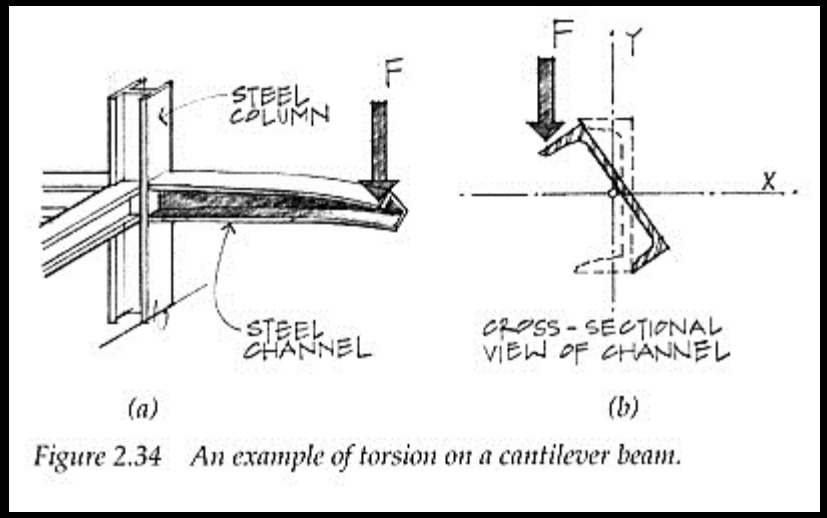


Figure 2.34 An example of torsion on a cantilever beam.

- ability of a material to resist breaking
- structural elements that resist excessive
  - deflection
  - deformation

Problem Solving

1. *STATICS:*

   equilibrium of external forces, internal forces, stresses

2. *GEOMETRY:*

   cross section properties, deformations and conditions of geometric fit, strains

3. *MATERIAL PROPERTIES:*

   stress-strain relationship for each material obtained from testing

Relation to Architecture

"The geometry and arrangement of the load-bearing members, the use of materials, and the crafting of joints all represent opportunities for buildings to express themselves. The best buildings are not designed by architects who after resolving the formal and spatial issues, simply ask the structural engineer to make sure it doesn't fall down." -Onouye & Kane

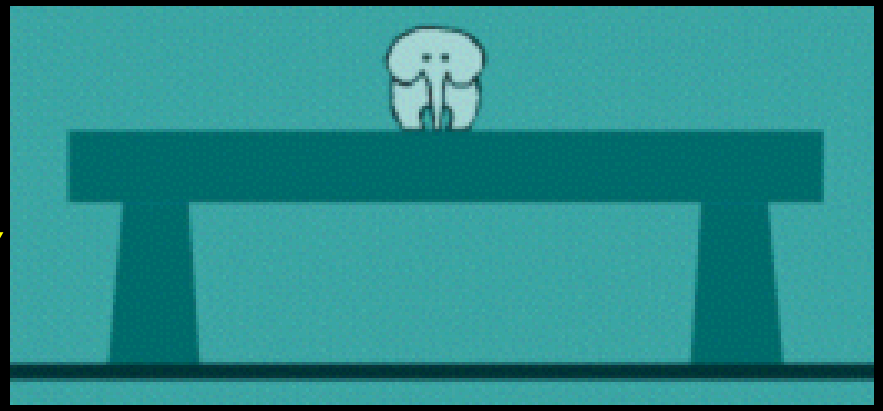
Statics and Strength of Materials for Architecture and Building Construction

Architectural Space and Form

- *evolution traced to developments in structural engineering and material technology*
  - *stone & masonry*
  - *timber*
  - *concrete*
  - *cast iron, steel*
  - *tensile fabrics, pneumatic structures.....*

Architectural Space and Form

- *structure is a device for channeling loads that result from the use and/or presence of the building to the ground*
  - *span a roof*
  - *hold up a floor*
  - *cross a river*
  - *suspend a canopy*



www.pbs.org/wgbh/buildingbig/

Structural Action

- *axial tension*
- *axial compression*
- *bending*

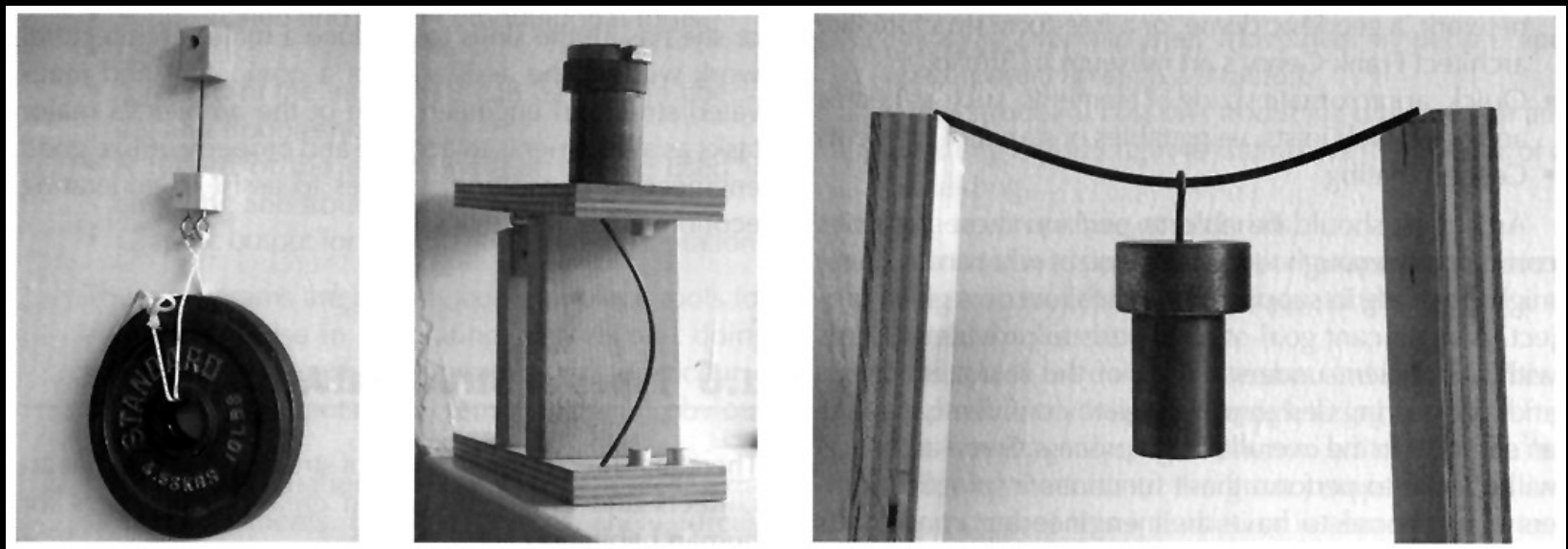
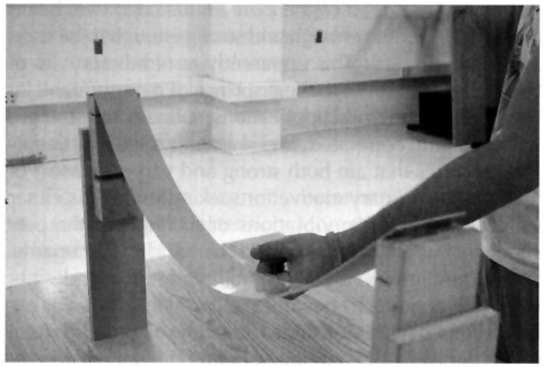


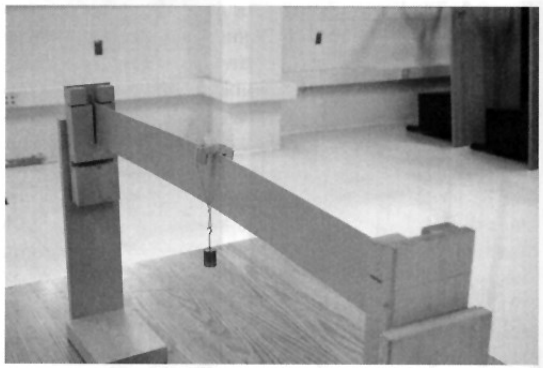
Figure 1.2 (a) Axial tension, (b) axial compression, and (c) bending.

Structural Action

- *member breadth & depth*

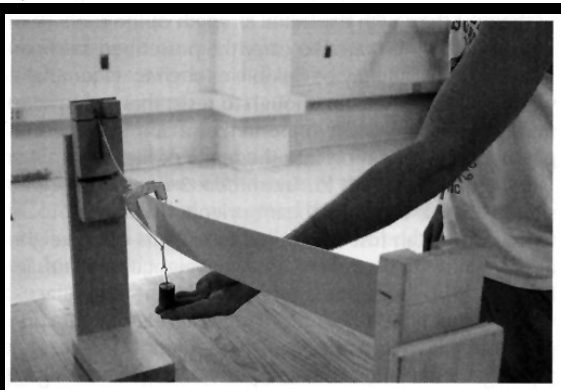


(a)

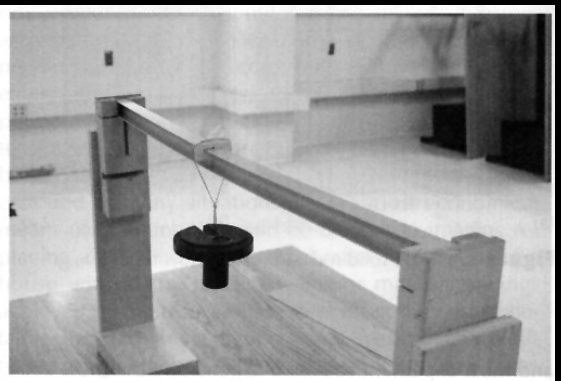


(b)

Figure 1.4 (a) A very shallow beam and (b) a deep beam.



(a)

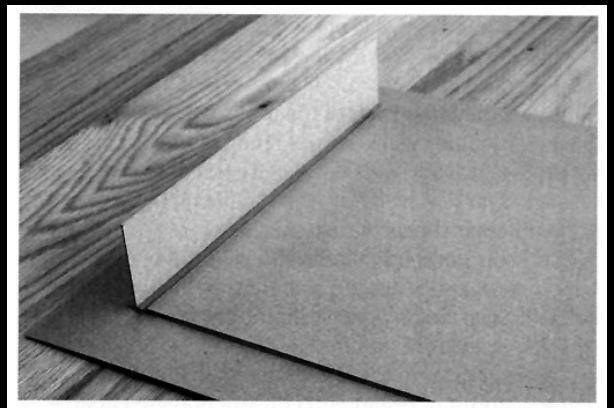


(b)

Figure 1.5 A sheet of material (a) set on edge and (b) configured as an I-beam.

Structural Action

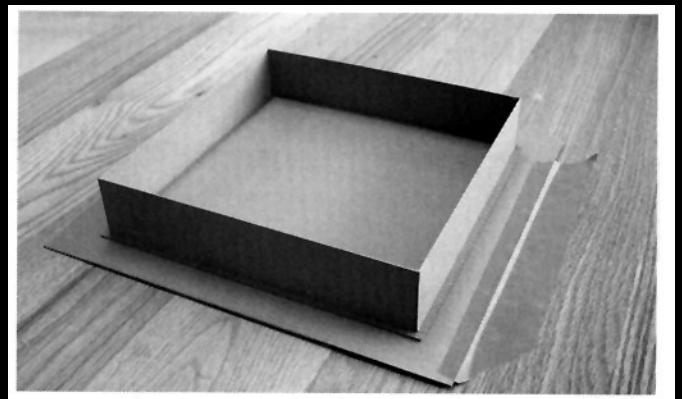
- *stabilization*



(a)

(b)

Figure 1.8 (a) A thin wall (b) subjected to lateral force.



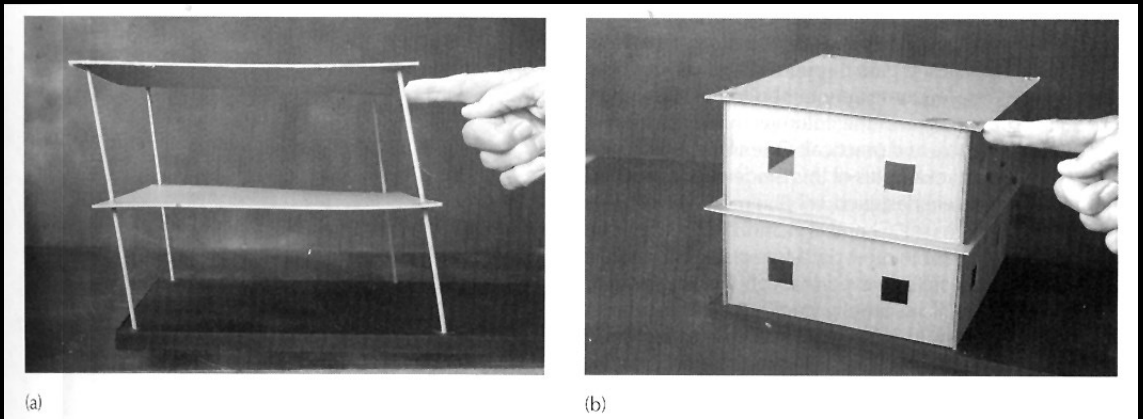
(a)

(b)

Figure 1.9 (a, b) Walls stabilizing each other at the ends.

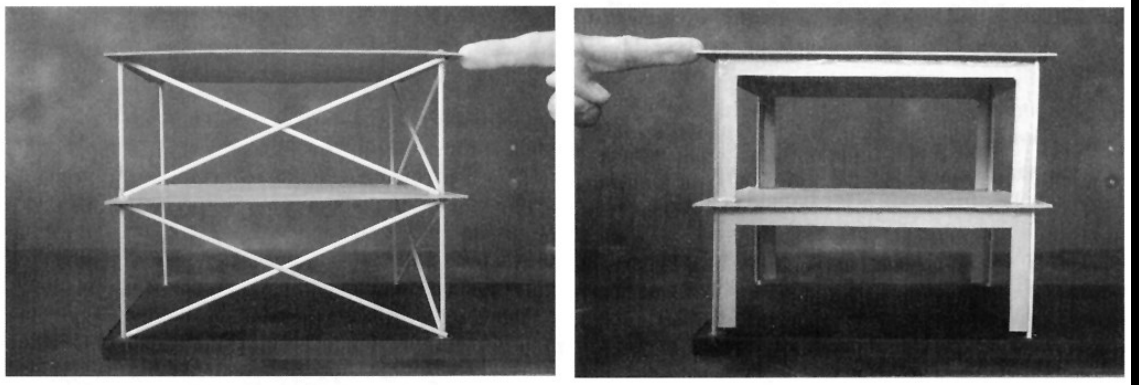
Structural Action

- *shear & bracing*



(a) (b)

Figure 1.29 (a, b) Structural frame stabilized by adding shear panels.

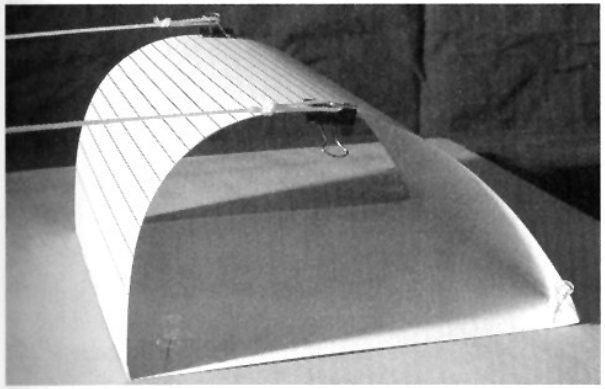


(a) (b)

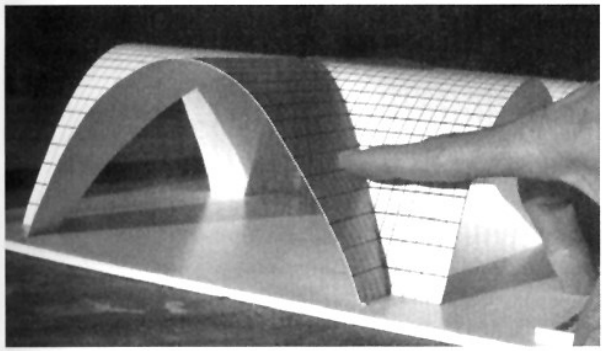
Figure 1.30 Bracing with (a) triangulation and (b) a rigid frame.

Structural Action

- *lateral resistance*



(a)



(b)

Figure 1.32 (a) A thin-shelled barrel vault and (b) a thin-shelled cross vault.

(a)

(b)

Figure 1.33 (a, b) A dome subjected to lateral load.

Structural Action

- *twisting*

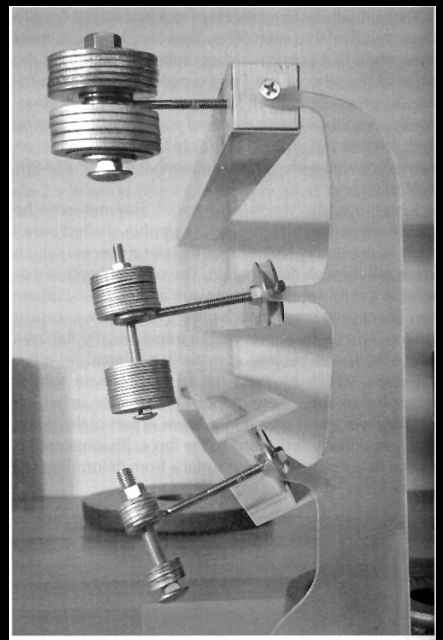
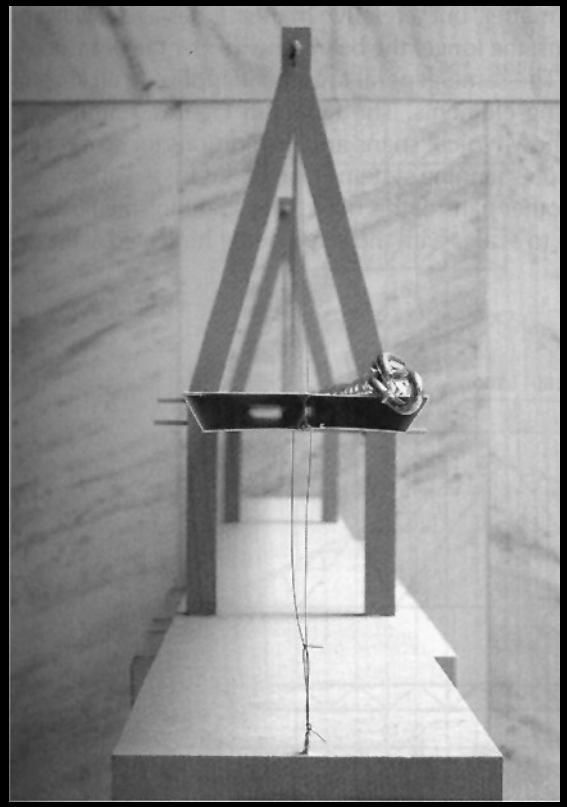
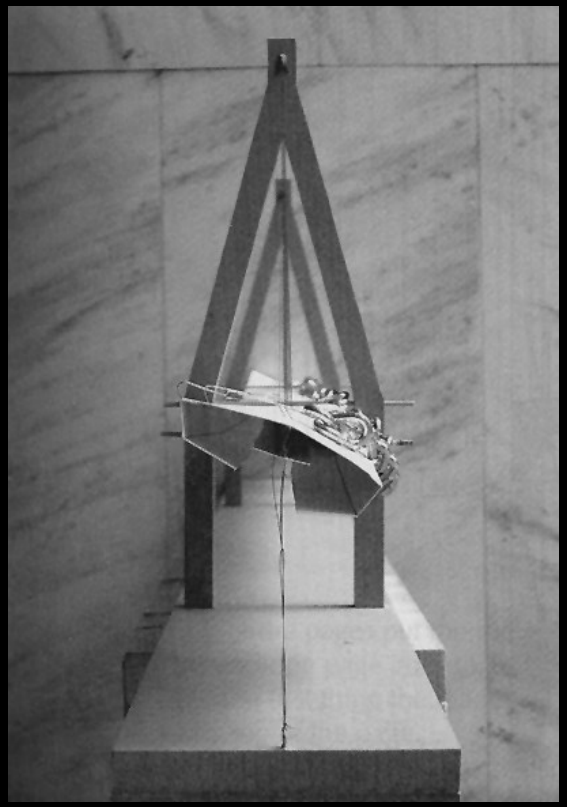


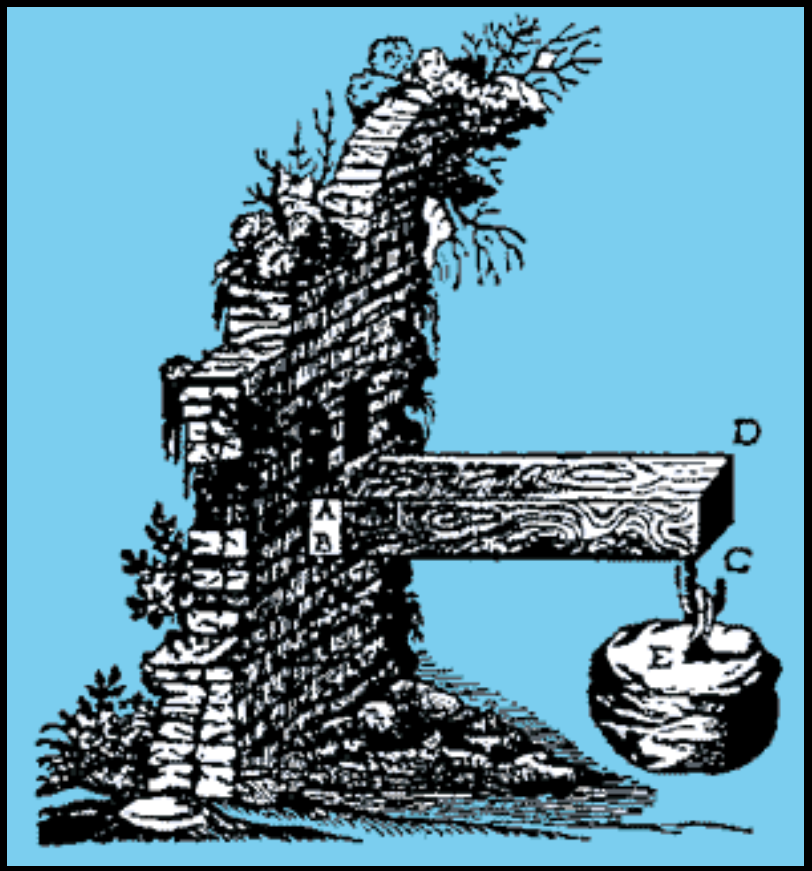
Figure 1.35 Torsion in a tube, a slab, and an I-section.





Structural Design

- *planning*
- *preliminary structural configuration*
- *determination of loads*
- *preliminary member selection*
- *analysis*
- *evaluation*
- *design revision*
- *final design*



Structural Loads

- *STATIC and DYNAMIC*
- *dead load*
  - *static, fixed, includes building weight, fixed equipment*
- *live load*
  - *transient and moving loads (including occupants), snowfall*

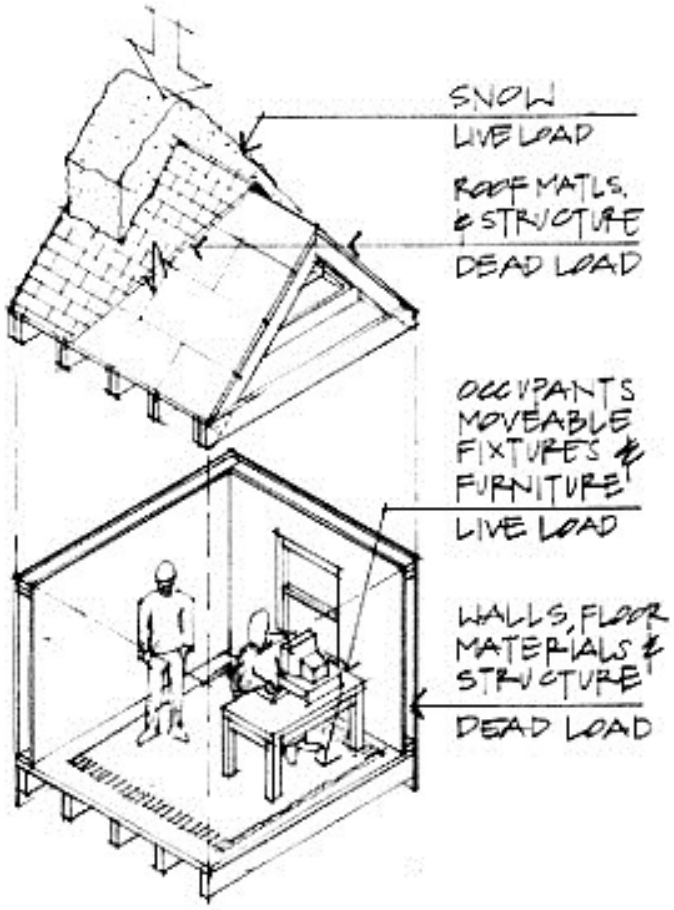


Figure 1.12 Typical building loads.

Structural Loads

- *wind loads*
  - *dynamic, wind pressures treated as lateral static loads on walls, up or down loads on roofs*

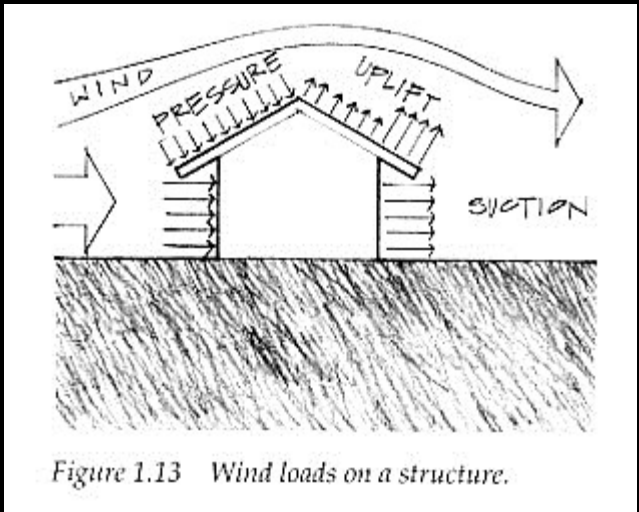


Figure 1.13 Wind loads on a structure.

Structural Loads

- *earthquake loads*
  - *seismic, movement of ground* ↕ ↔

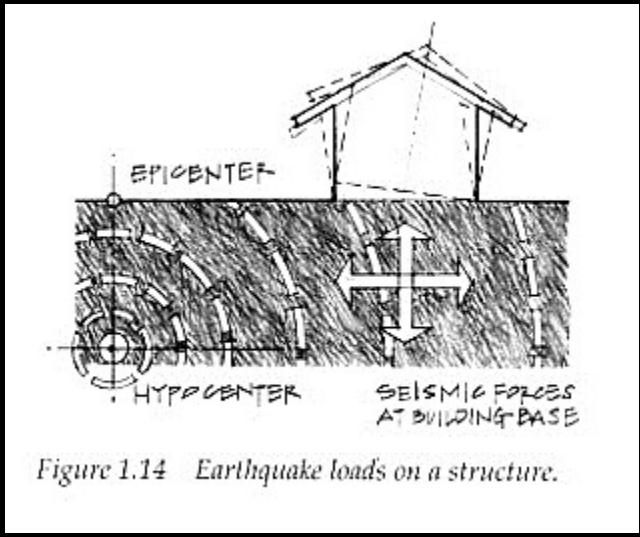
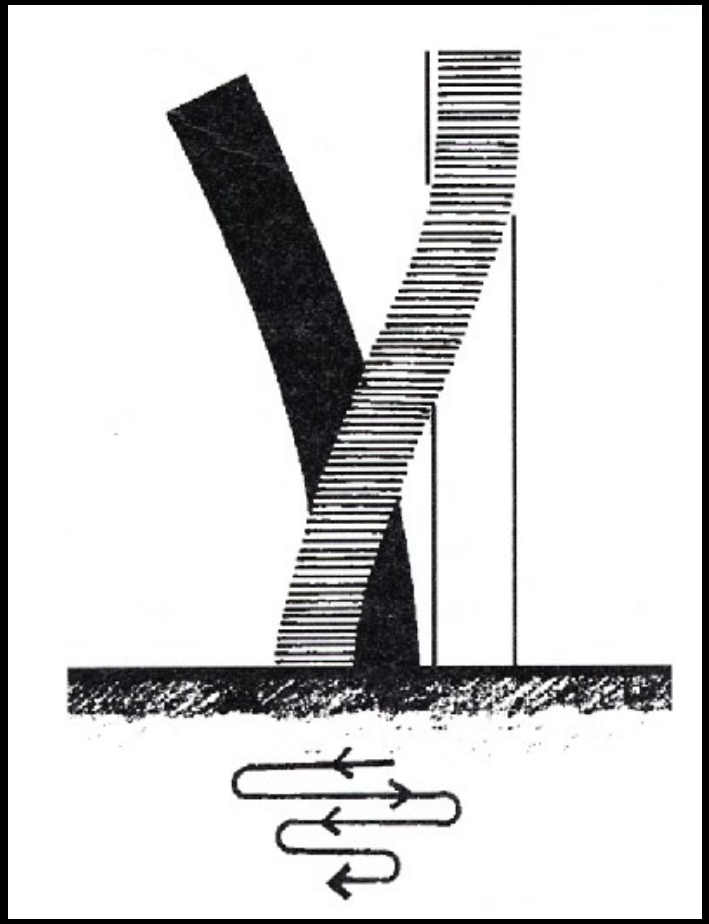
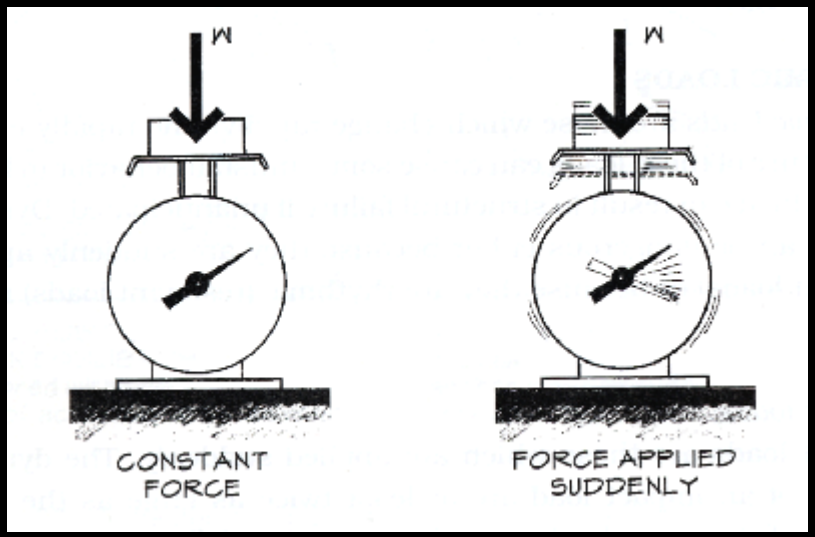


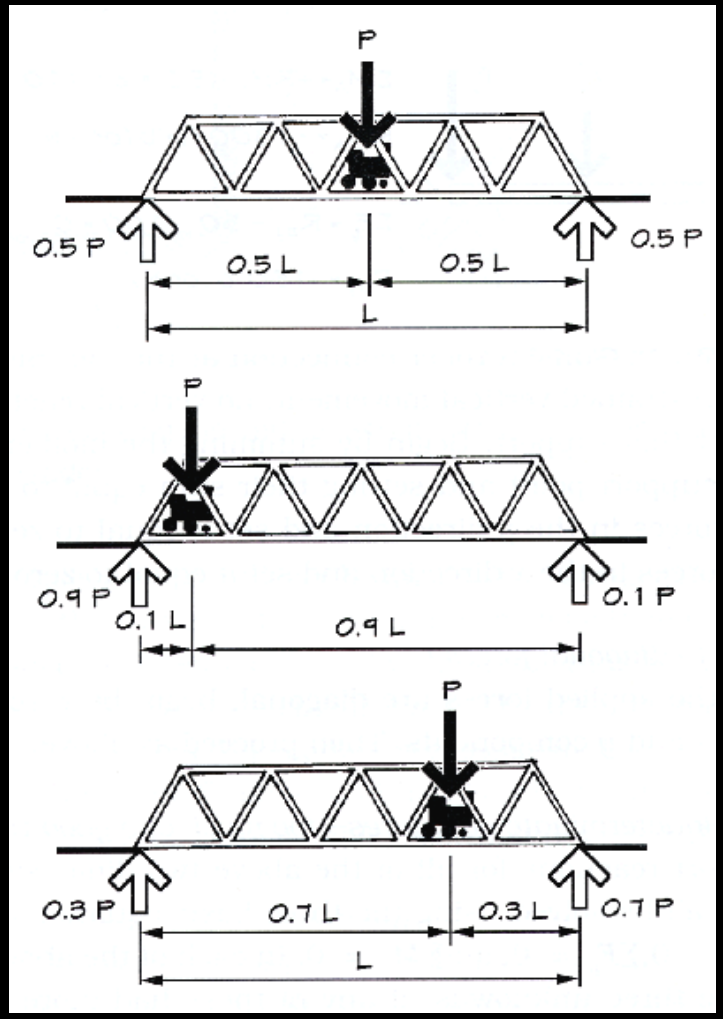
Figure 1.14 Earthquake loads on a structure.



Structural Loads

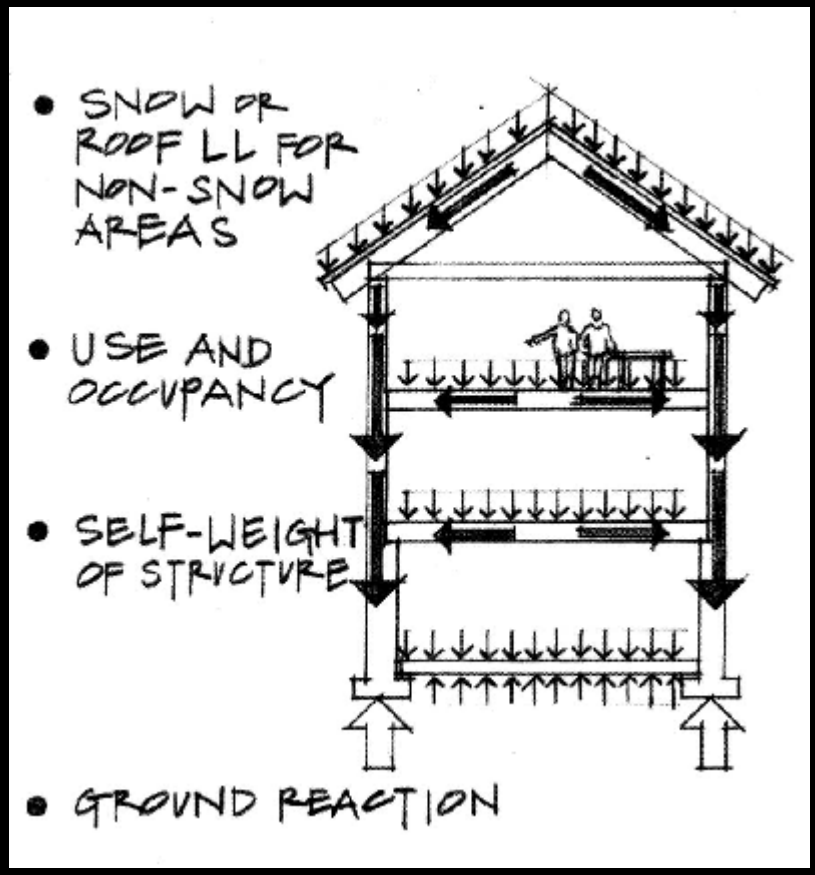
- *impact loads*
  - *rapid, energy loads*





Structural Loads

- *gravity acts on mass (F=m*g)*
- *force of mass*
  - *– acts at a point*
    - *ie. joist on beam*
  - *– acts along a "line"*
    - *ie. floor on a beam*
  - *– acts over an area*
    - *ie. people, books, snow on roof or floor*



Structural Math

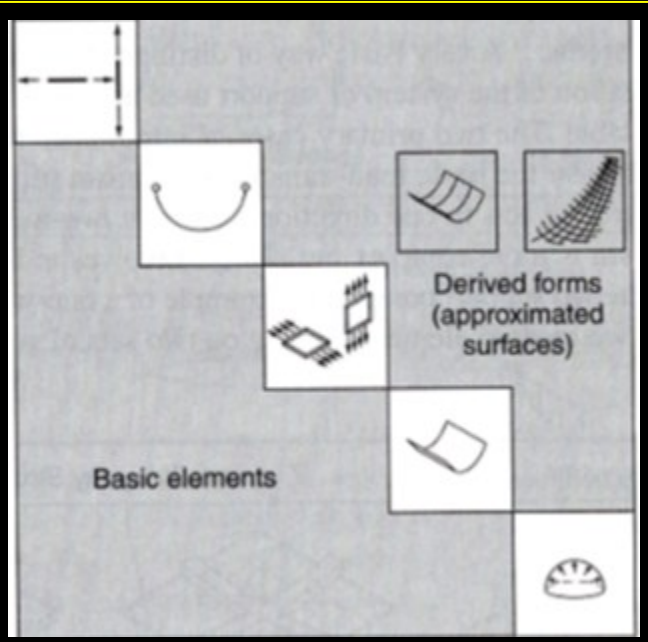
- *quantify environmental loads*
  - *how big is it?*
- *evaluate geometry and angles*
  - *where is it?*
  - *what is the scale?*
  - *what is the size in a particular direction?*
- *quantify what happens in the structure*
  - *how big are the internal forces?*
  - *how big should the beam be?*

Structural Math

- *physics takes observable phenomena and relates the measurement with rules: mathematical relationships*
- *need*
  - *reference frame*
  - *measure of length, mass, time, direction, velocity, acceleration, work, heat, electricity, light*
  - *calculations & geometry*

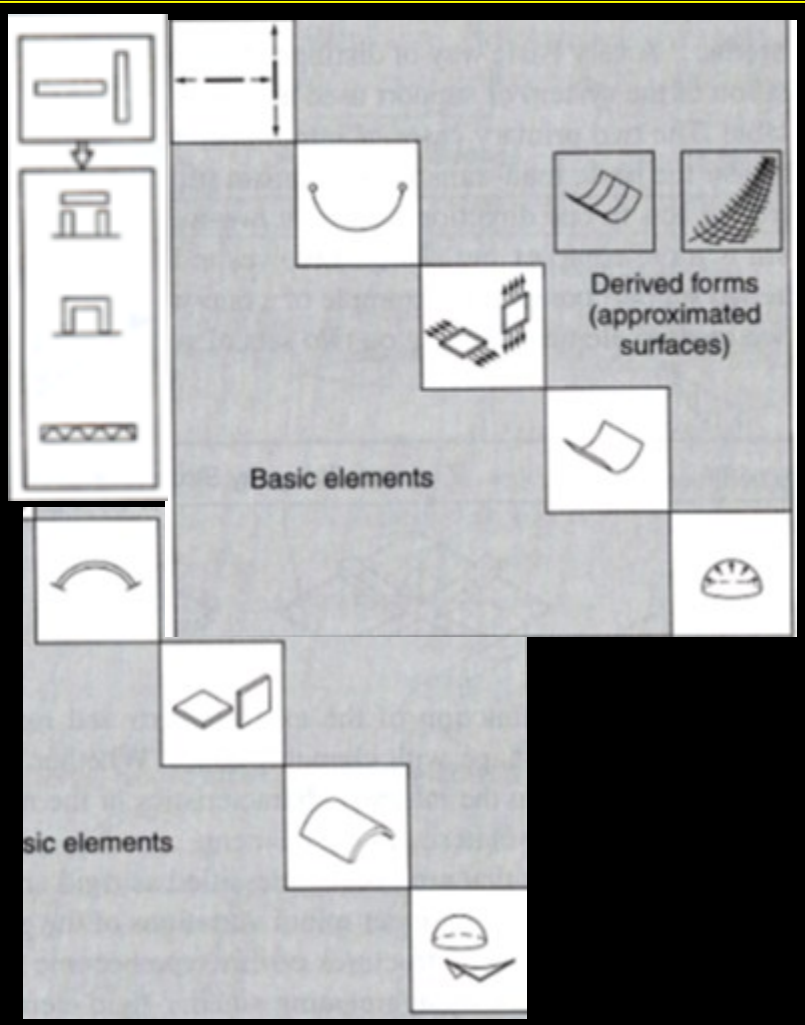
Structural Organization

- *classifications*
  - *geometry*
    - *line-forming*
    - *surface-forming*
  - *stiffness*
    - *rigid*
    - *flexible*
  - *one-way or two-way*
    - *spatial organization and load transfer*
  - *materials*

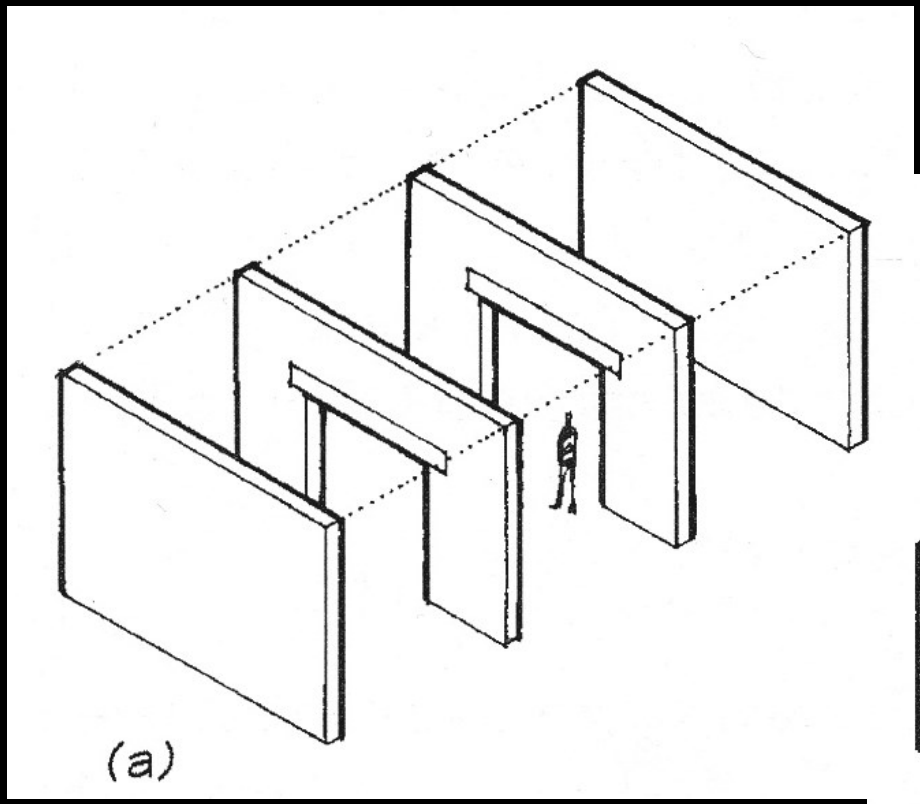


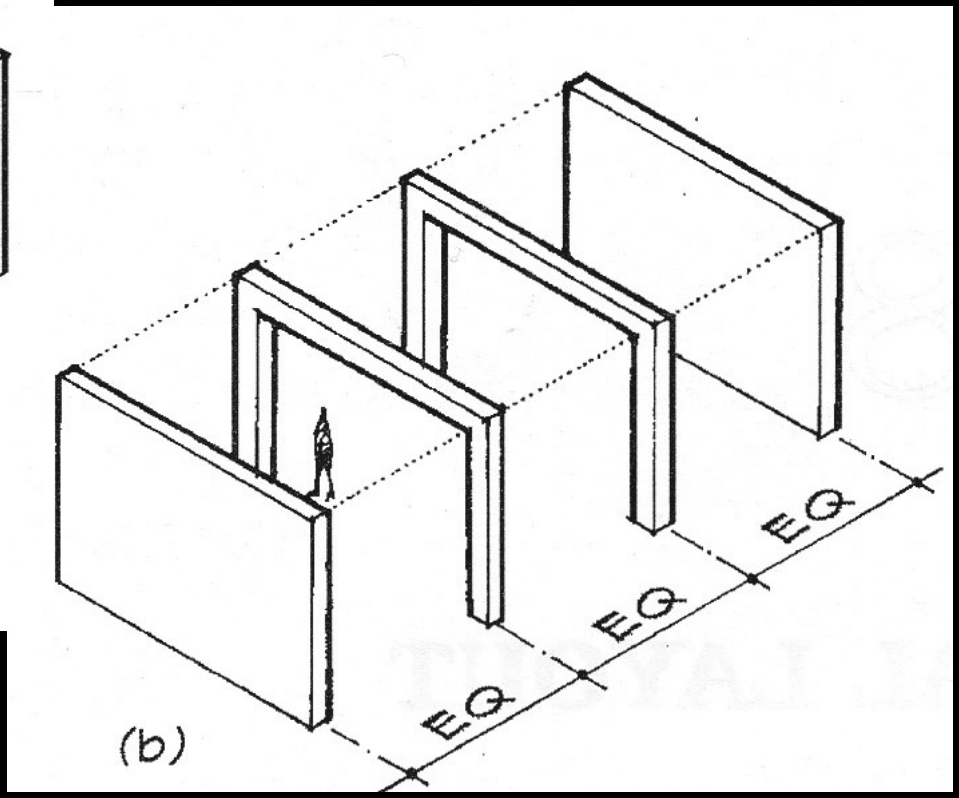
Structural Components

- *bearing walls*
- *columns*
- *beams*
- *flat plates*
- *trusses*
- *arches*
- *shells*
- *cables*



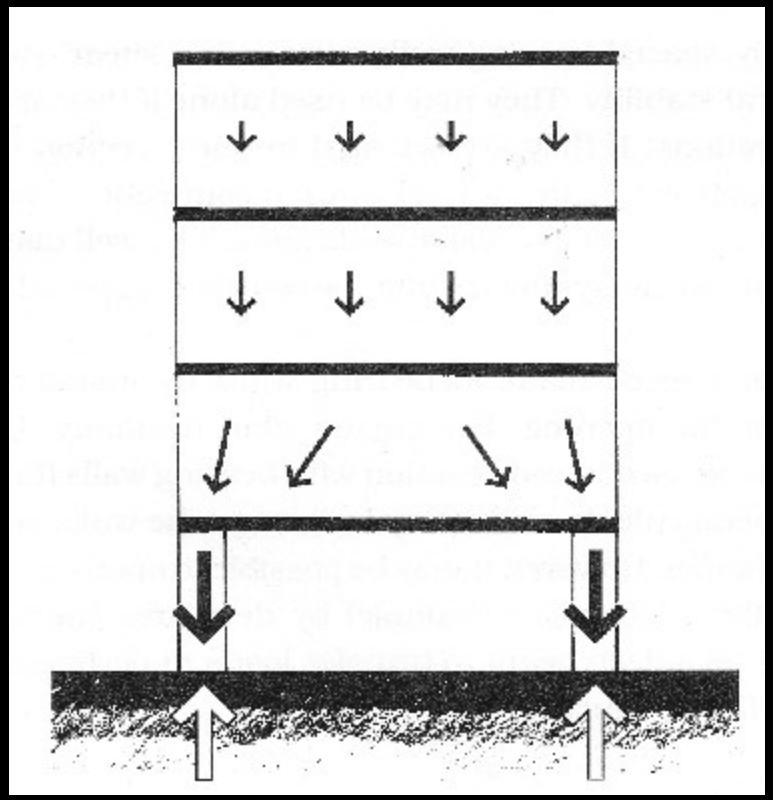
Bearing Walls



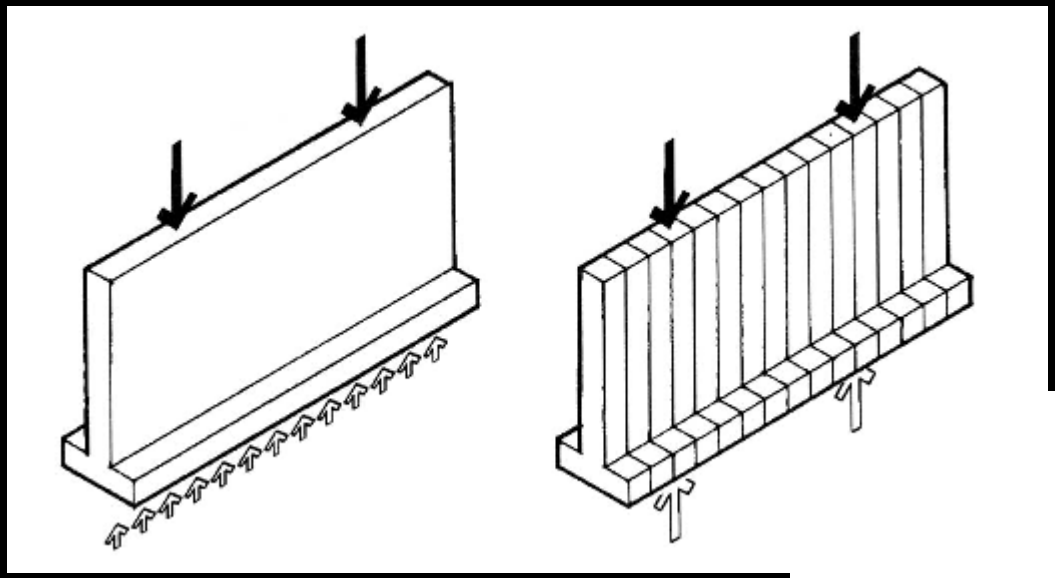


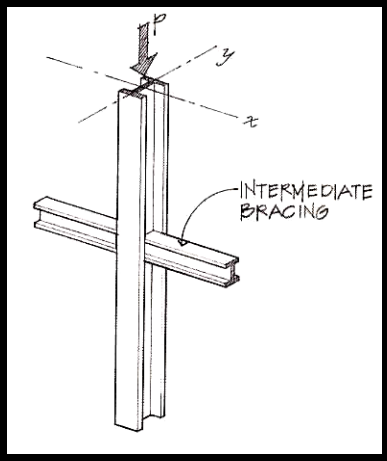
Bearing Walls

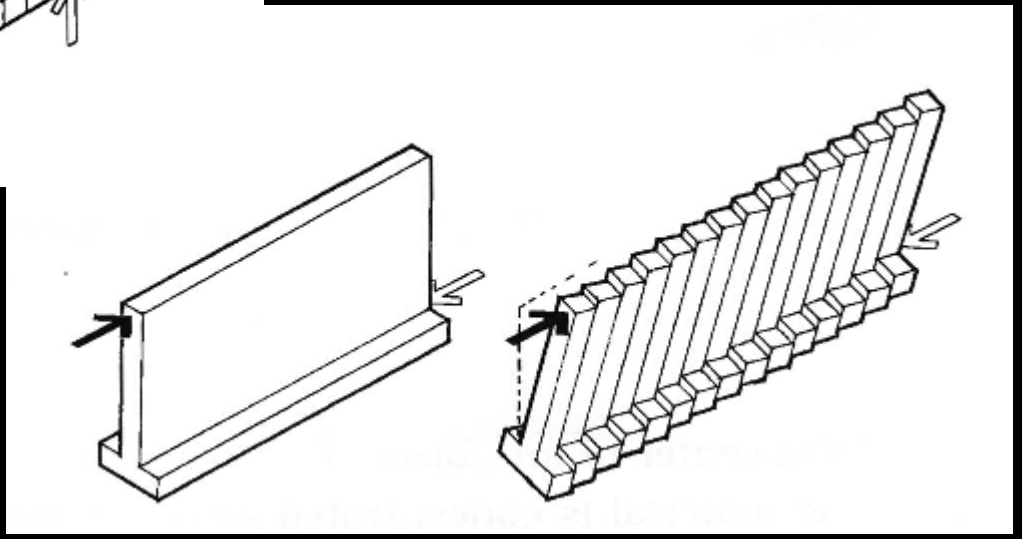
- *behavior as "deep beams"*



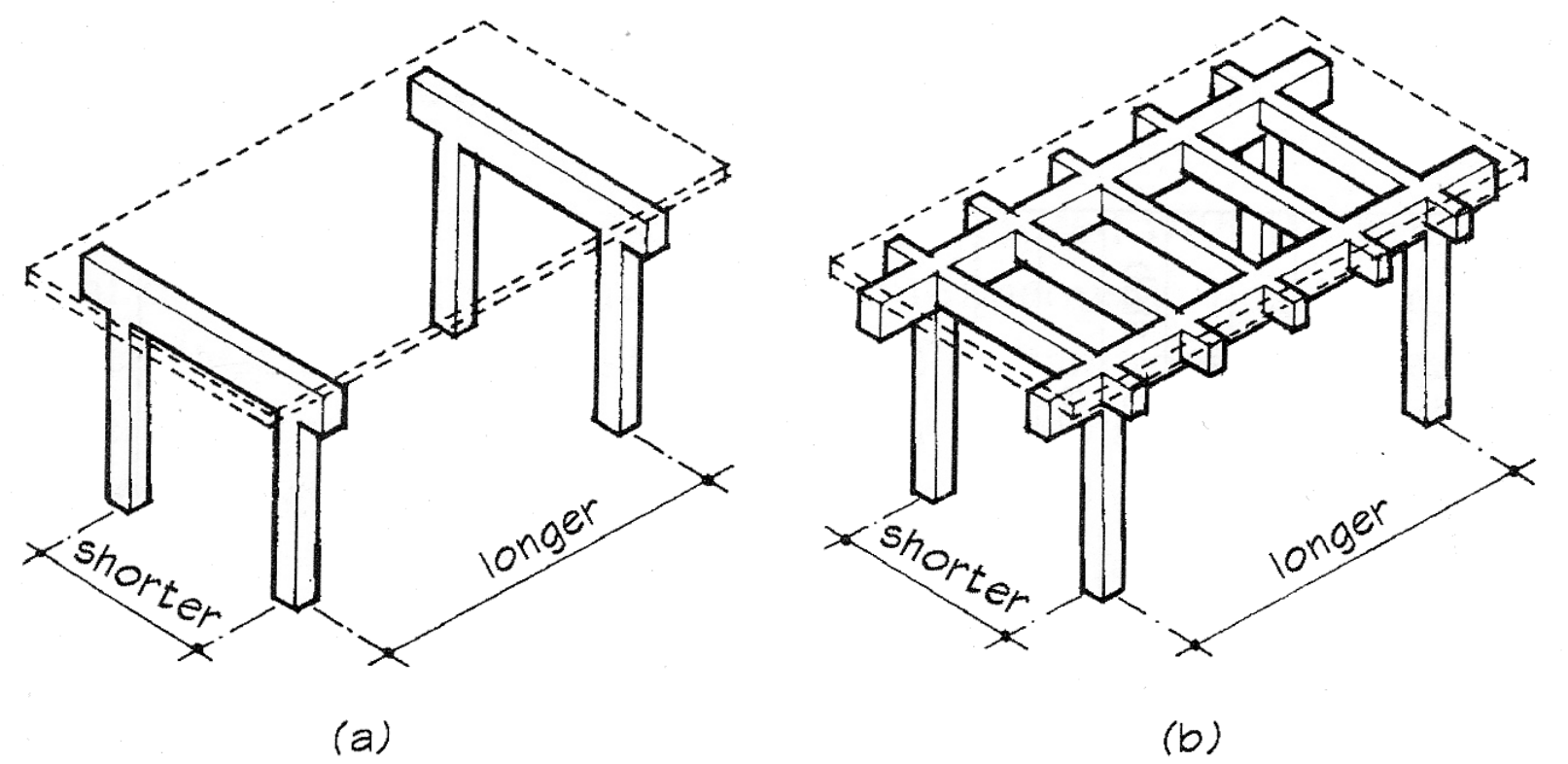
Columns & Walls



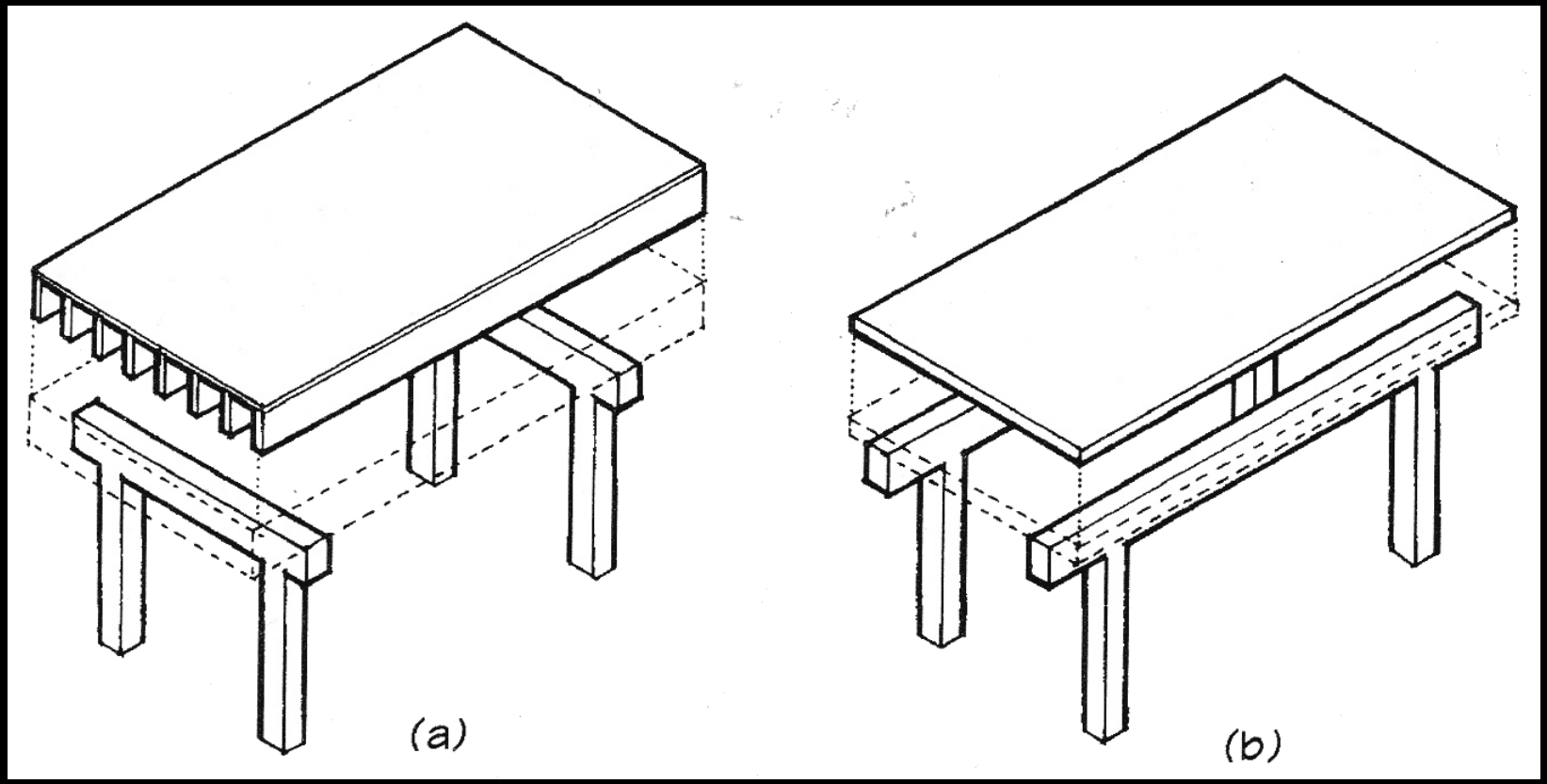




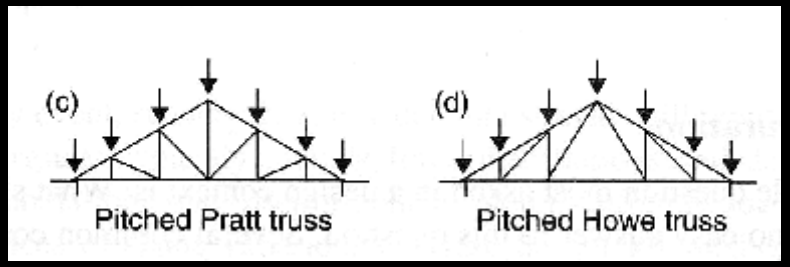
Beams & Plates

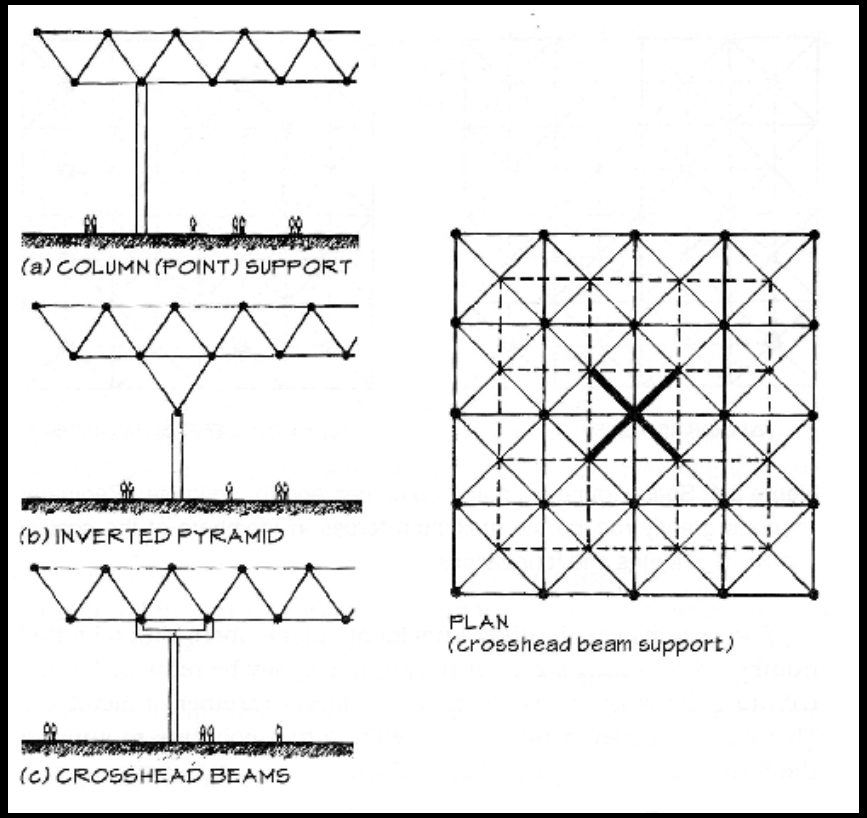


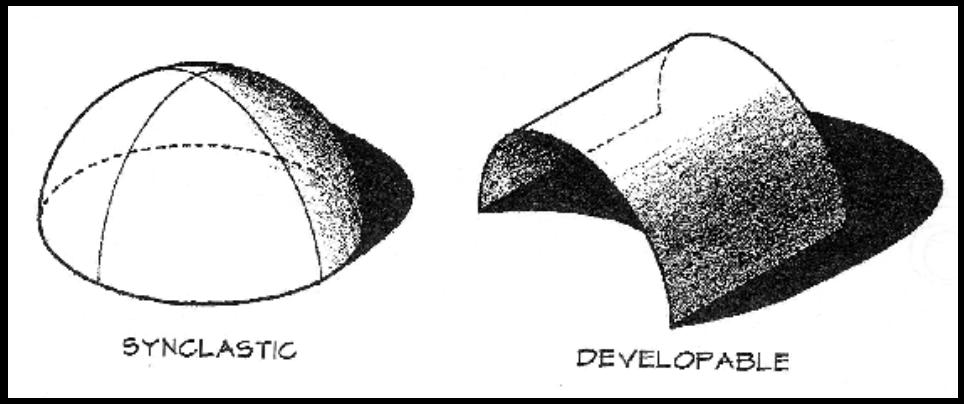
Beams & Plates



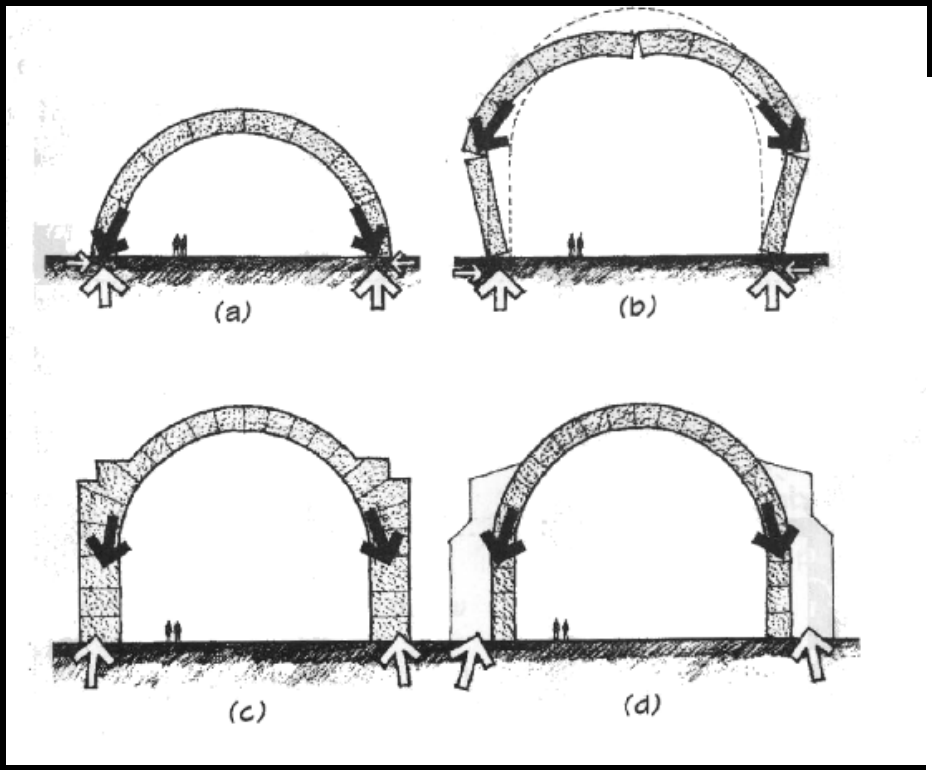
Trusses and Shells

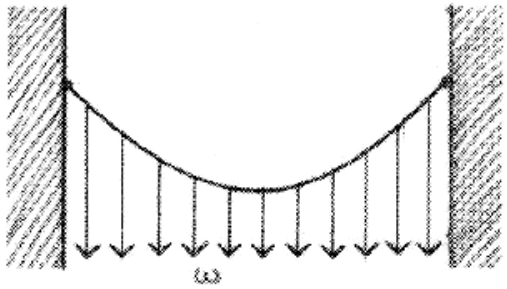




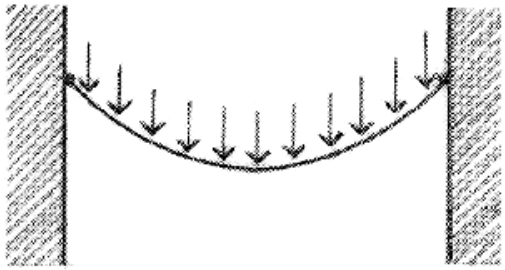


Arches and Cables





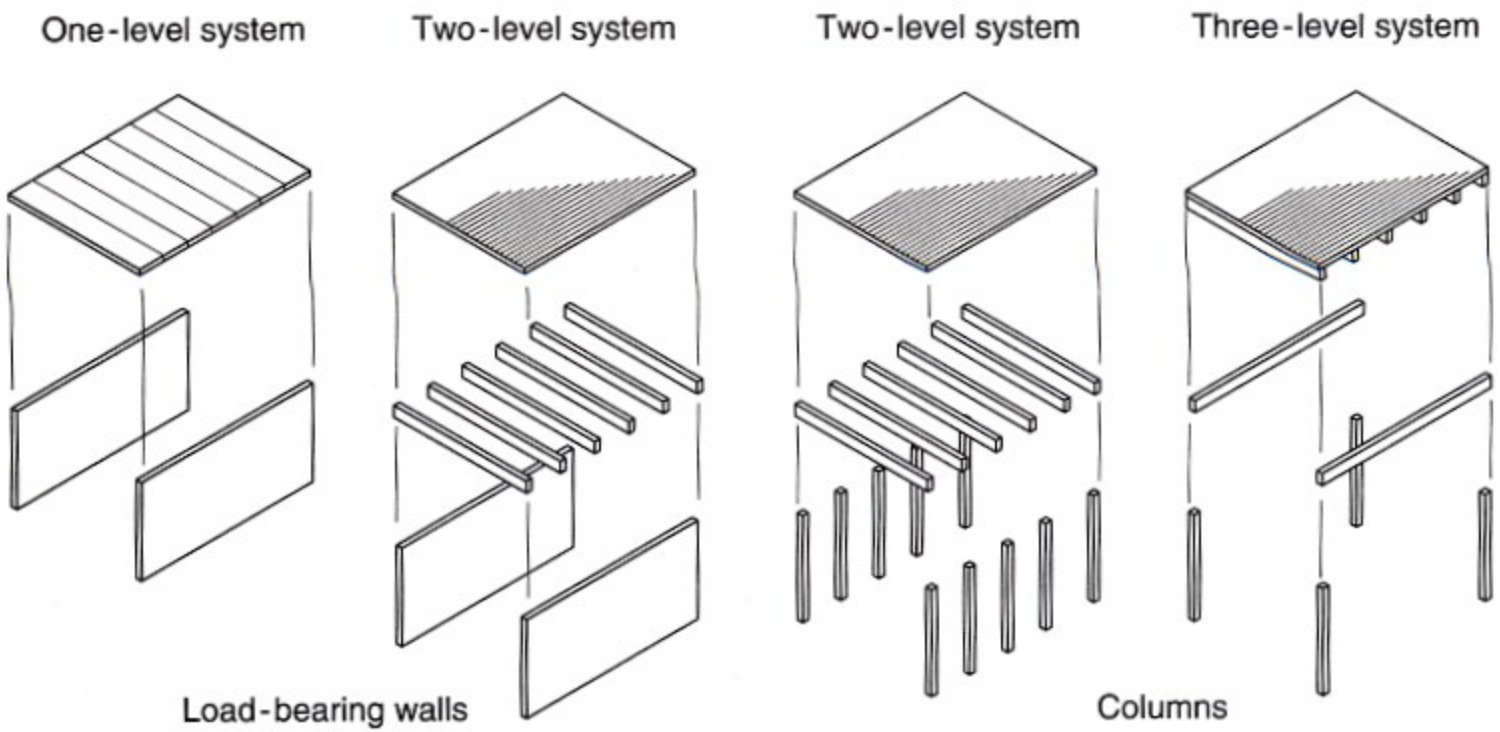
(c) *Uniform loads (horizontally)—parabola.*



(d) *Uniform loads (along the cable length)—catenary.*

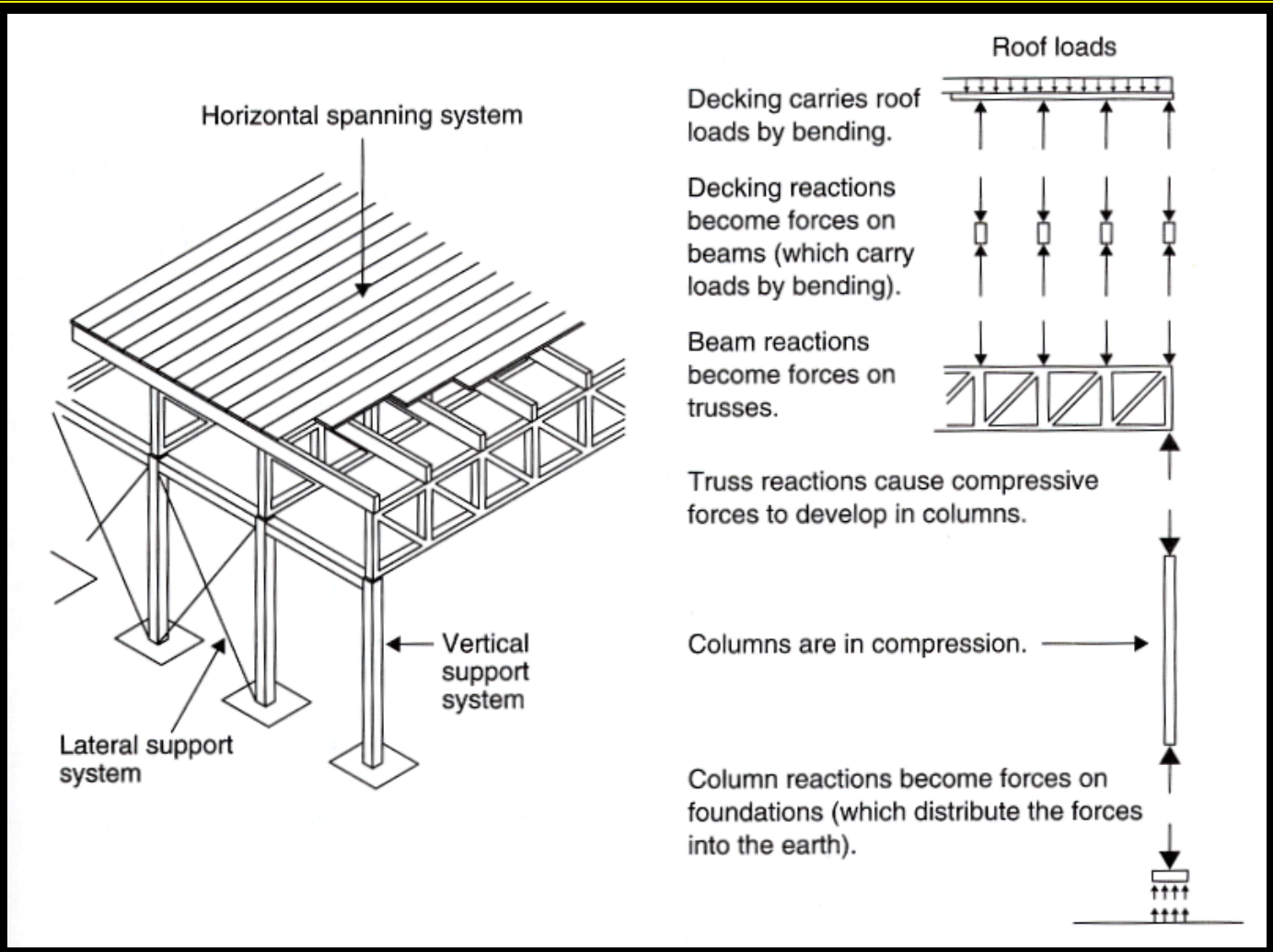
Building Framing

- Components or Assemblages



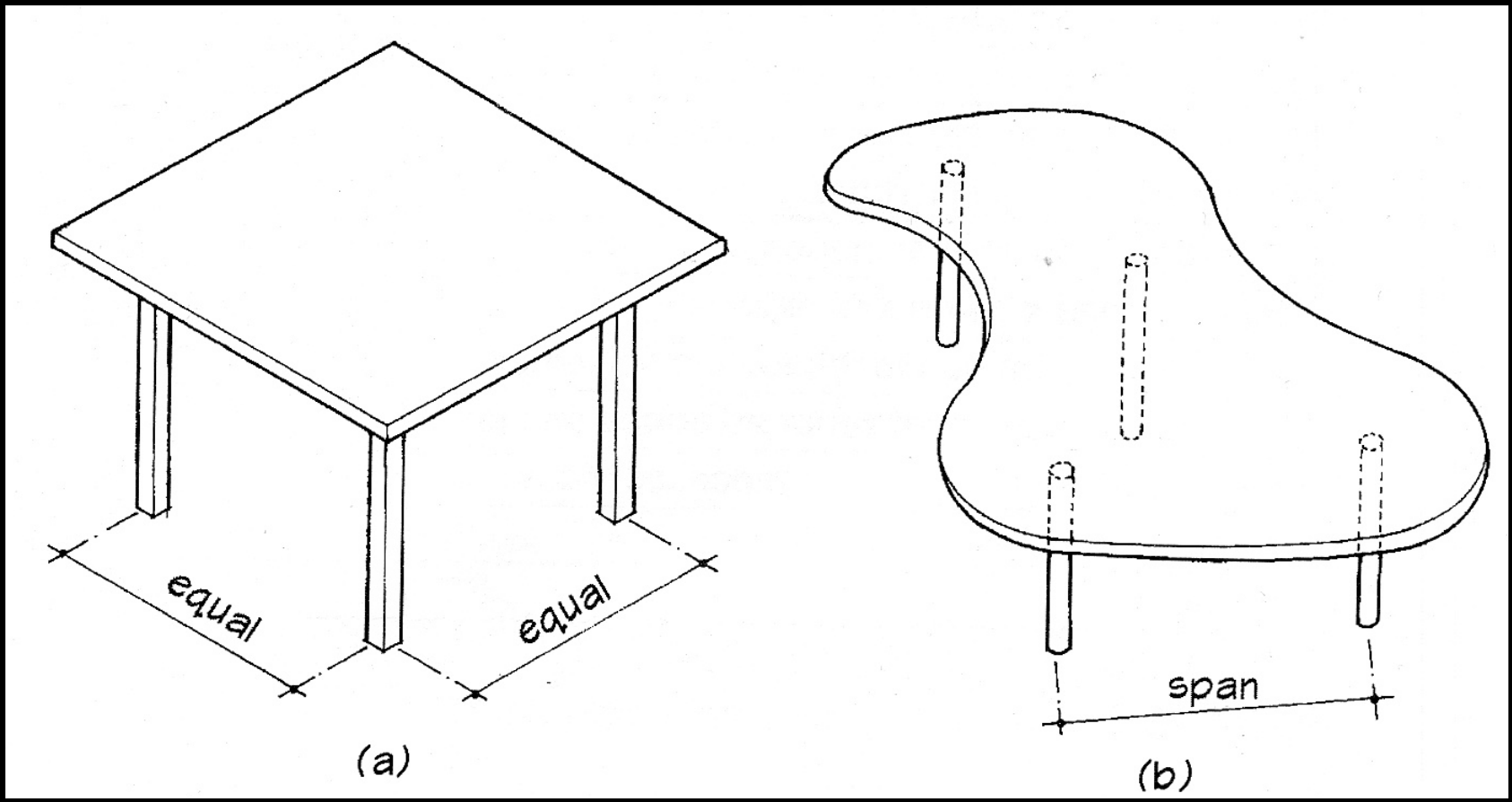
(a) Common types of horizontal spanning systems (one, two, and three level systems) used in relation to different types of load-bearing wall and columnar vertical support systems.

Building Framing



System Selection

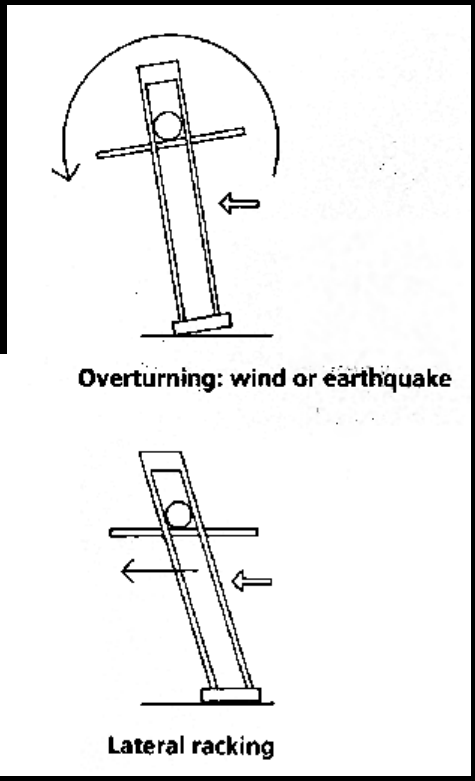
- *evaluation of alternatives*



DESIGN CRITERIA	Light-frame timber	Heavy-frame timber	Masonry bearing wall	Steel frame (hinge connections)	Steel frame (rigid connections)	Steel open-web joists	Steel space frame	Steel decking	Site-cast concrete: one-way slab	Site-cast concrete: two-way plate	Site-cast concrete: two-way slab	Site-cast concrete: one-way joists	Site-cast concrete: waffle slab	Precast concrete: solid slab	Precast concrete: hollow-core slab	Precast concrete: single tee	Precast concrete: double tee	RATIONALE
Exposed, fire-resiant construction		■	■						■	■	■	■	■	■	■	■	■	Inherently fire-resistive construction
Irregular building form	■		■						■	■	■							Simple, site-fabricated systems
Irregular column placement										■	■		■					Systems without beams in roof or floors
Minimize floor thickness									■	■				■	■			Precast-concrete systems without ribs
Allow for future renovations	■	■	■	■	■	■	■	■	■			■		■	■			Short-span, one-way, easily modified
Permit construction in poor weather	■	■		■	■	■	■	■						■	■	■	■	Quickly erected; avoid site-cast concrete
Minimize off-site fabrication time	■		■						■	■	■	■	■					Easily formed or built on site
Minimize on-site erection time		■		■	■	■		■						■	■	■	■	Highly prefabricated; modular components
Minimize low-rise construction time	■	■		■	■	■		■										Lightweight, easily formed or prefabricated
Minimize medium-rise construction time				■	■	■		■	■	■	■	■	■	■	■	■	■	Precast, site-cast concrete; steel frames
Minimize high-rise construction time				■	■	■		■										Strong; prefabricated; lightweight
Minimize shear walls or diagonal bracing			■		■				■	■	■	■	■					Capable of forming rigid joints
Minimize dead load on foundations	■	■		■	■	■	■	■										Lightweight, short-span systems
Minimize damage due to foundation settlement	■	■		■		■		■						■	■	■	■	Systems without rigid joints
Minimize the number of separate trades on job	■		■															Multipurpose components
Provide concealed space for mech. services	■					■	■								■			Systems that inherently provide voids
Minimize the number of supports							■											Two-way, long-span systems
Long spans						■	■									■		Long-span systems

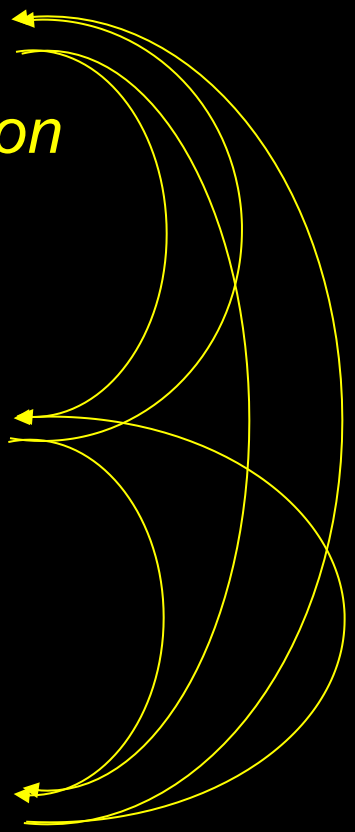
Structural Design Criteria

- components stay together
- structure acts as whole to be stable
  - resist sliding
  - resist overturning
  - resist twisting and distortion
- internal stability
  - interconnectedness
- strength & stiffness



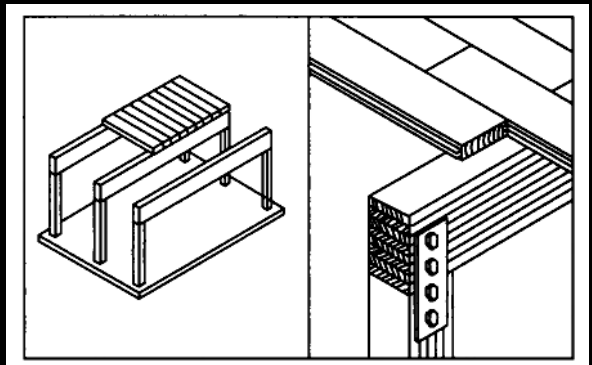
Structural Design Sequences

- *first-order design*
  - *structural type and organization*
  - *design intent*
  - *contextual or programmatic*
- *second-order*
  - *structural strategies*
  - *material choice*
  - *structural systems*
- *third-order*
  - *member shaping & sizing*

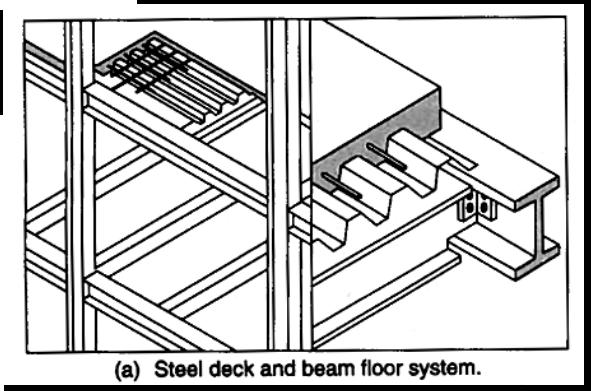


Systems by Materials

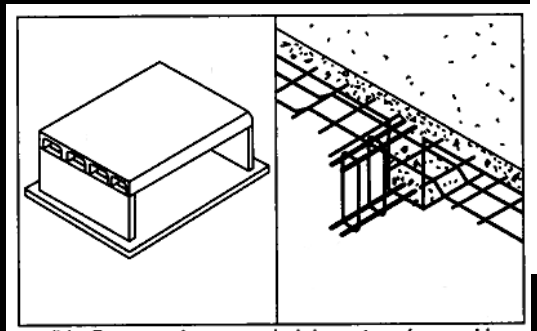
- *Wood*
- *Steel*
- *Concrete*
- *Masonry*
- *Composite*



(b) Heavy timber construction: laminated beams.



(a) Steel deck and beam floor system.



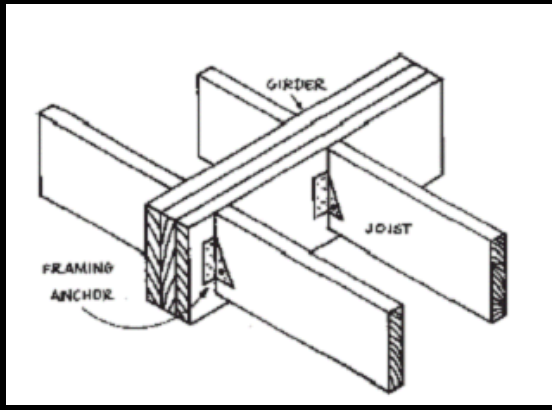
(b) One-way beam-and-slab system (poured in place).

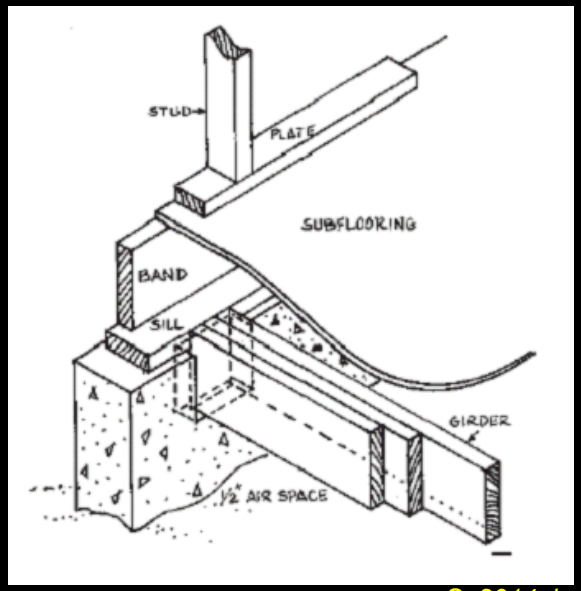
Wood

- *columns*
- *beams*
- *trusses*

Timber Construction

- *all-wood framing systems*
  - *studs, beams, floor diaphragms, shearwalls*
  - *glulam arches & frames*
  - *post & beams*
  - *trusses*
- *composite construction*
  - *masonry shear walls*
  - *concrete*
  - *steel*





Timber Construction

- *studs, beams*
- *floor diaphragms & shear walls*

Timber Construction

- *glulam arches & frames*
  - *manufactured or custom shapes*
  - *glue laminated*
  - *bigger members*

Timber Construction

- *post & beam*

- *trusses*

Timber Construction

- *composite construction*

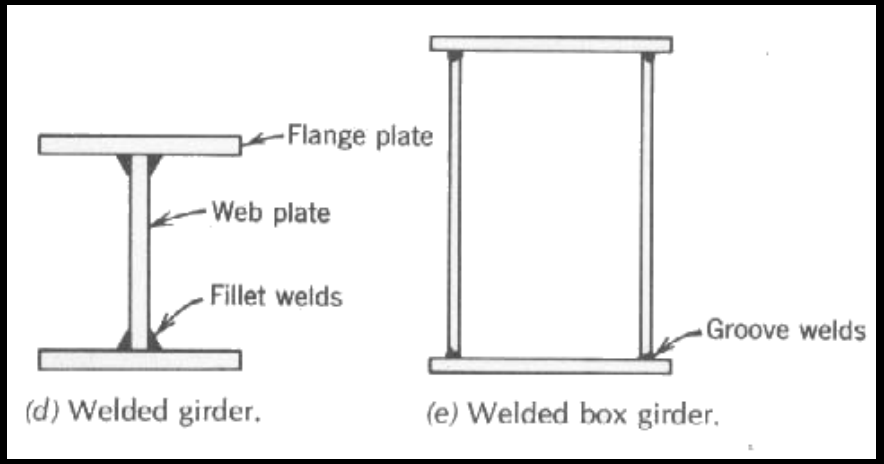
Steel

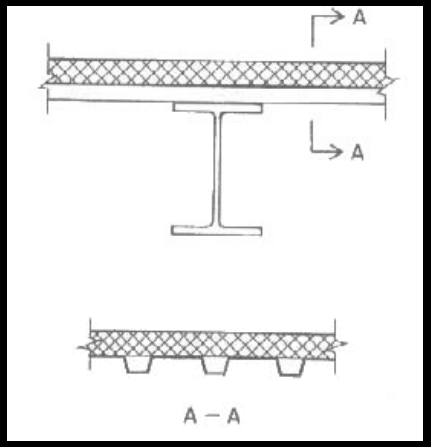
- *cast iron – wrought iron - steel*
- *cables*
- *columns*
- *beams*
- *trusses*
- *frames*

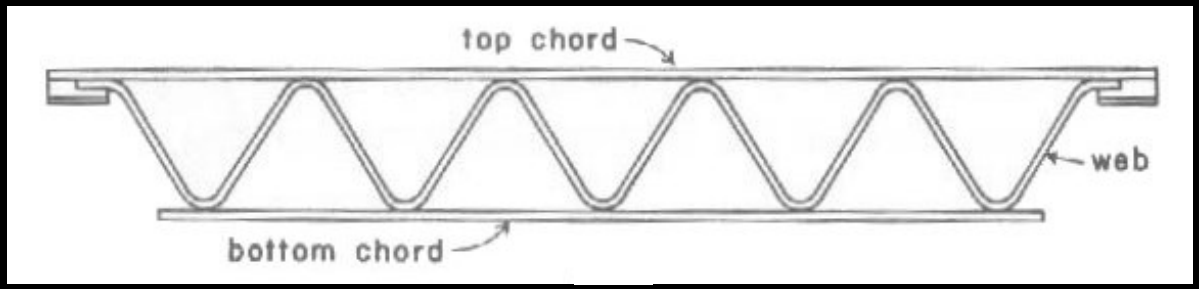
http:// nisee.berkeley.edu/godden

Steel Construction

- *standard rolled shapes*
- *open web joists*
- *plate girders*
- *decking*

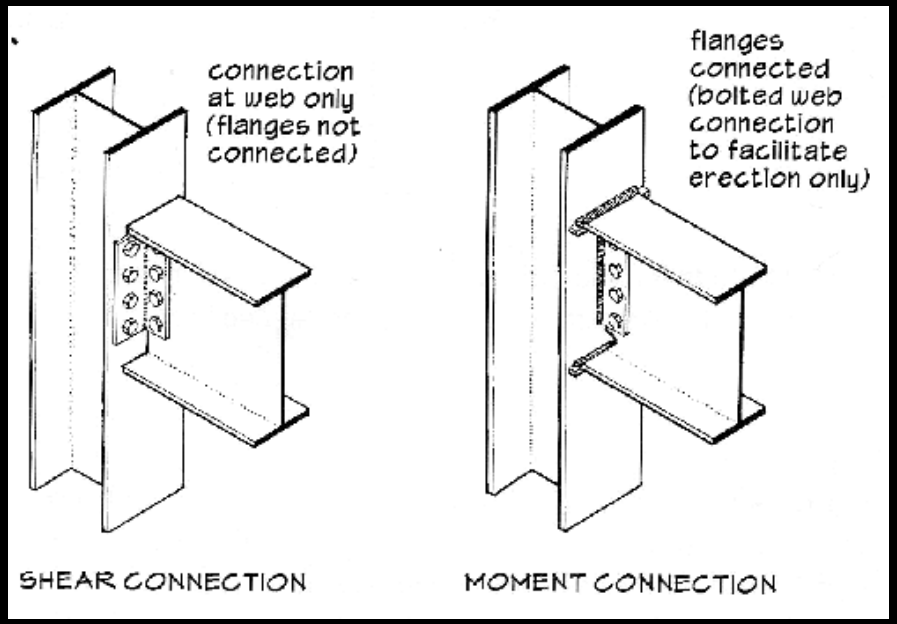


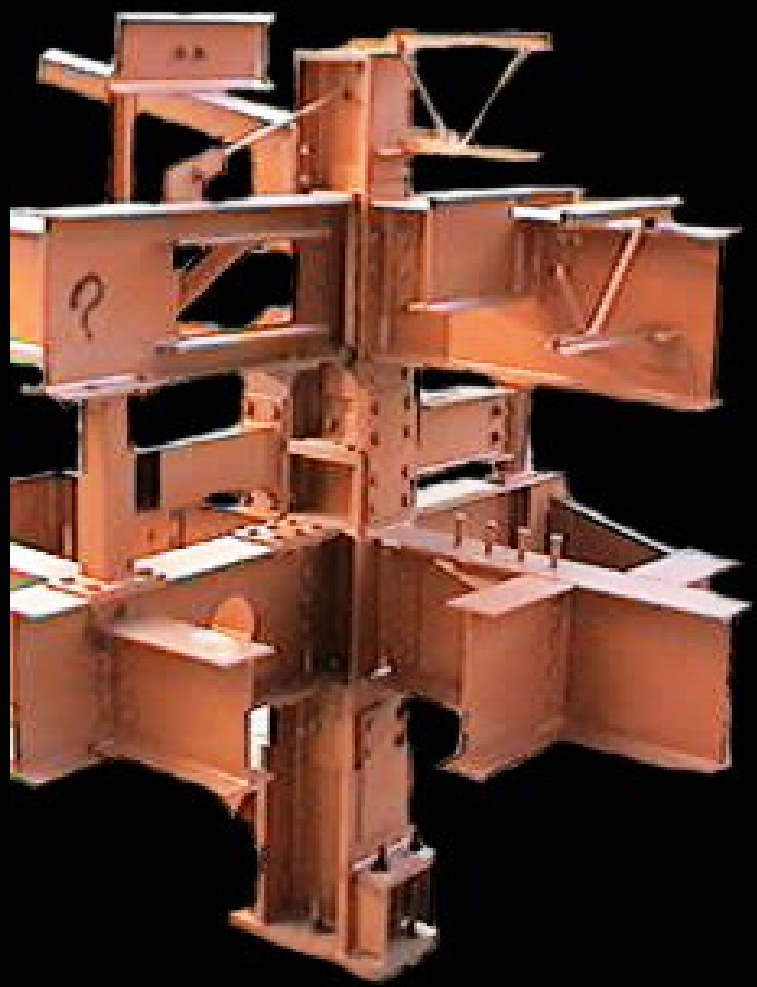




Steel Construction

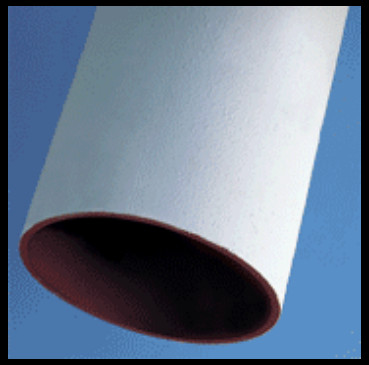
- *welding*
- *bolts*





Steel Construction

- *fire proofing*
  - *cementicious spray*
  - *encasement in gypsum*
  - *intumescent – expands with heat*
  - *sprinkler system*

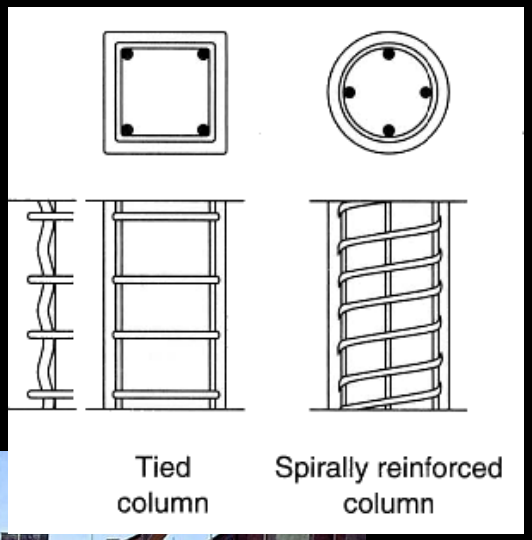


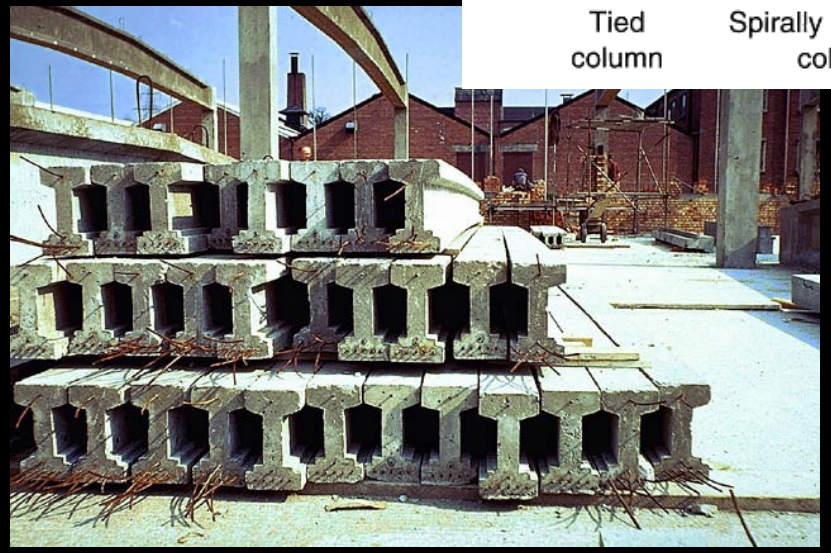
Concrete

- *columns*
- *beams*
- *slabs*
- *domes*
- *footings*

Concrete Construction

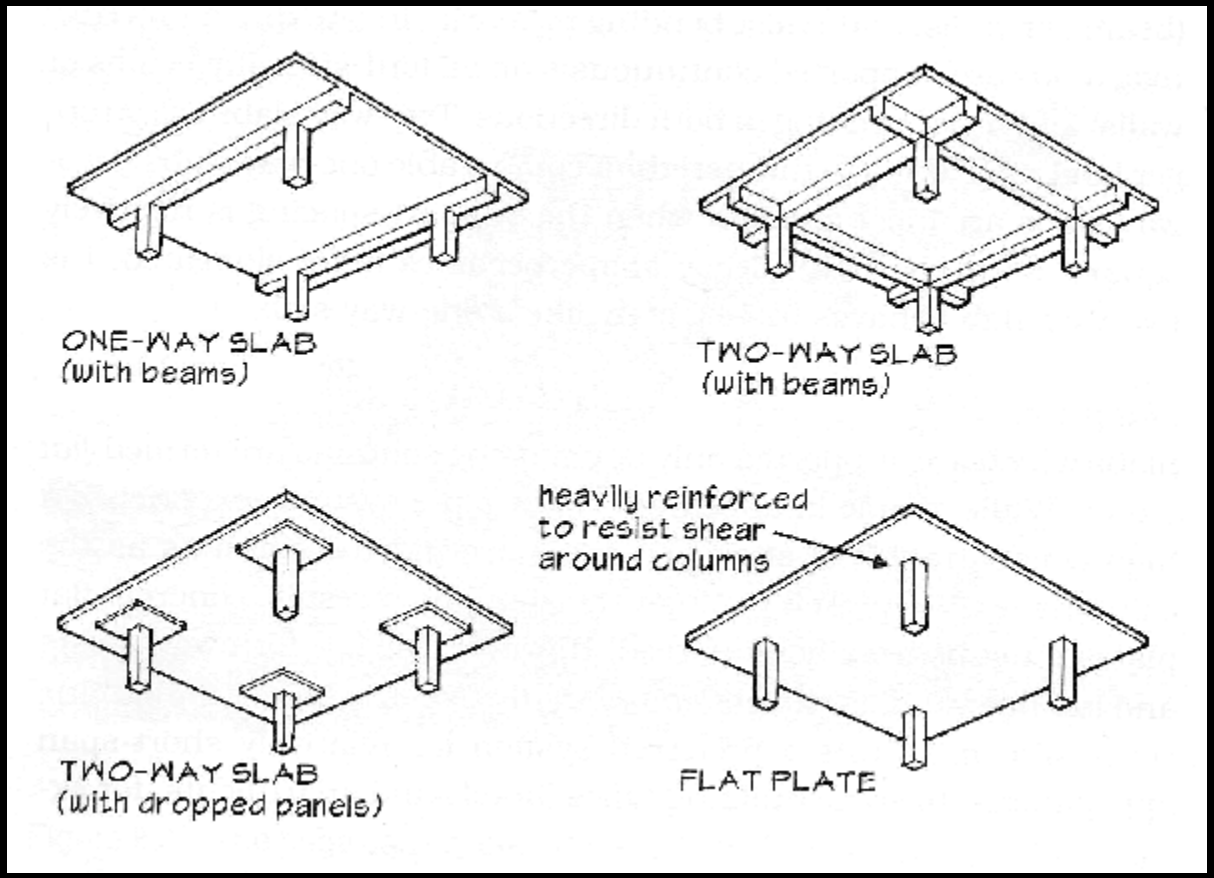
- *cast-in-place*
- *tilt-up*
- *prestressing*
- *post-tensioning*



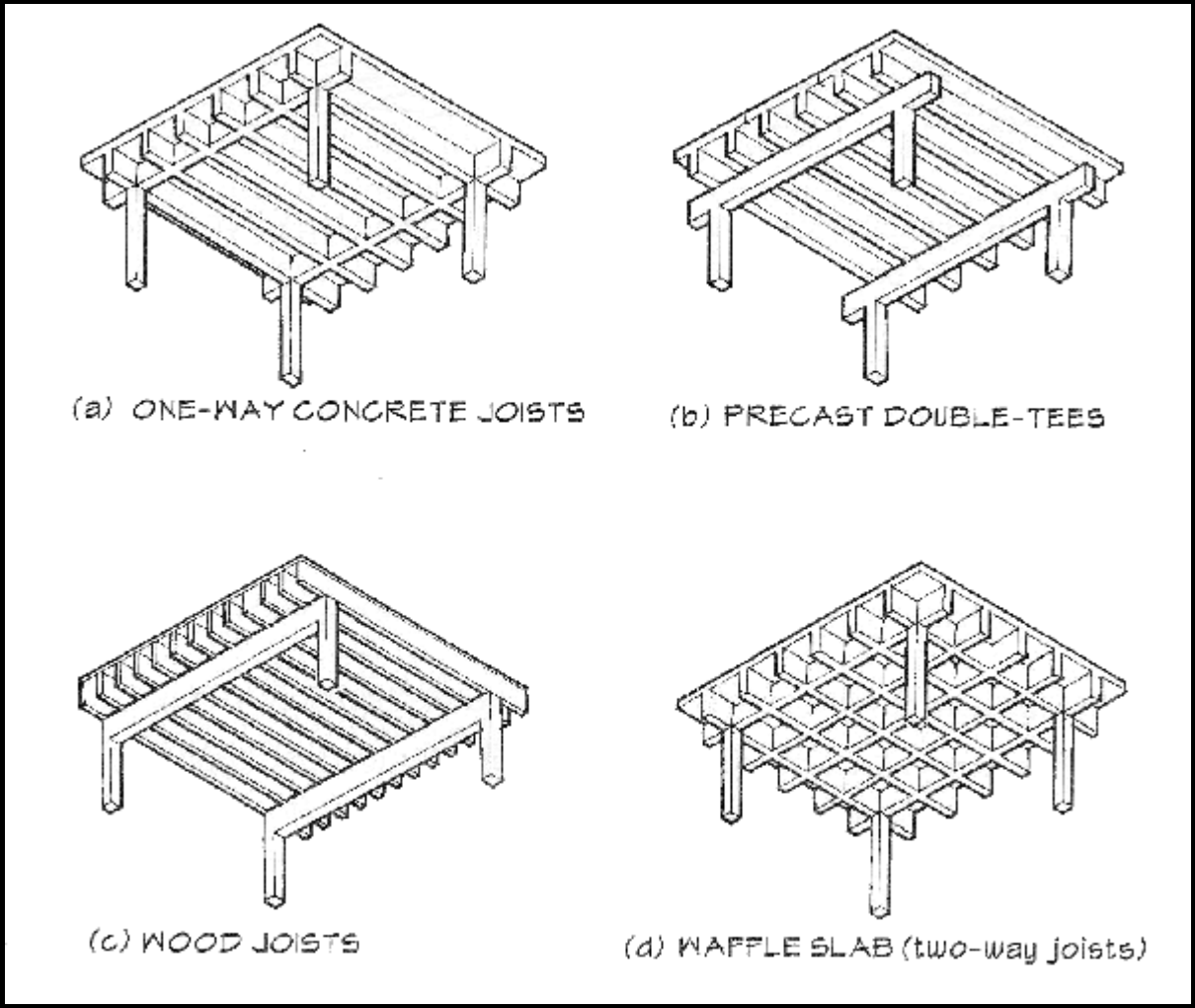


Concrete Floor Systems

- *types & spanning direction*

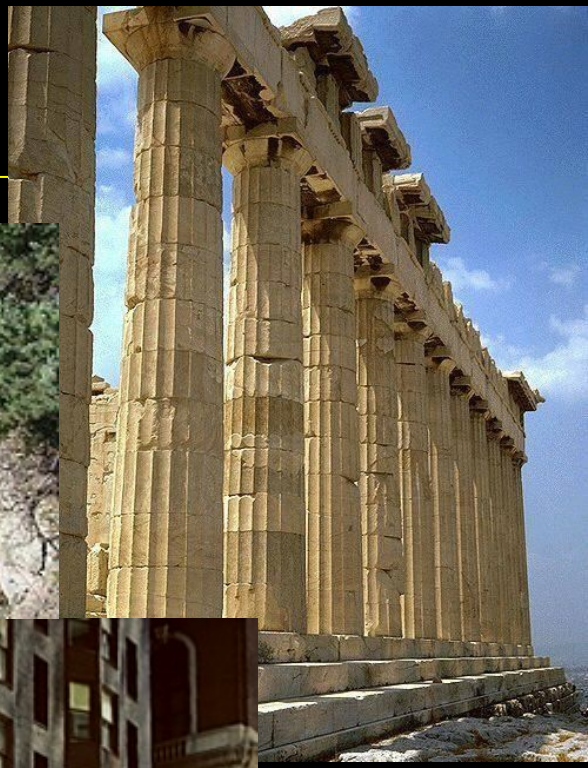


Concrete Floor Systems



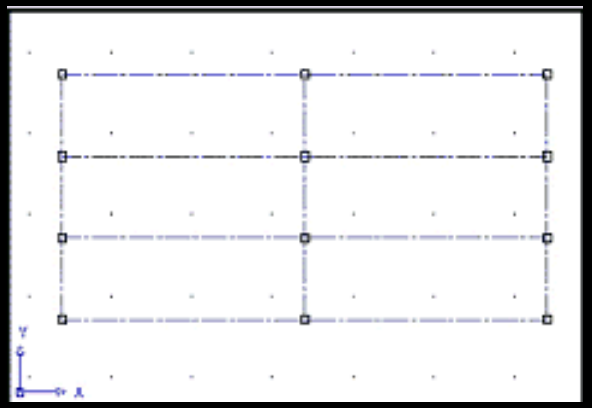
Masonry (& Stone)

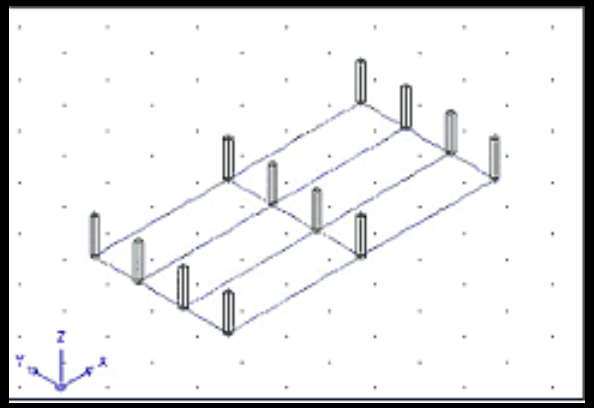
- *columns*
- *walls*
- *lintels*
- *beams*
- *arches*
- *footings*



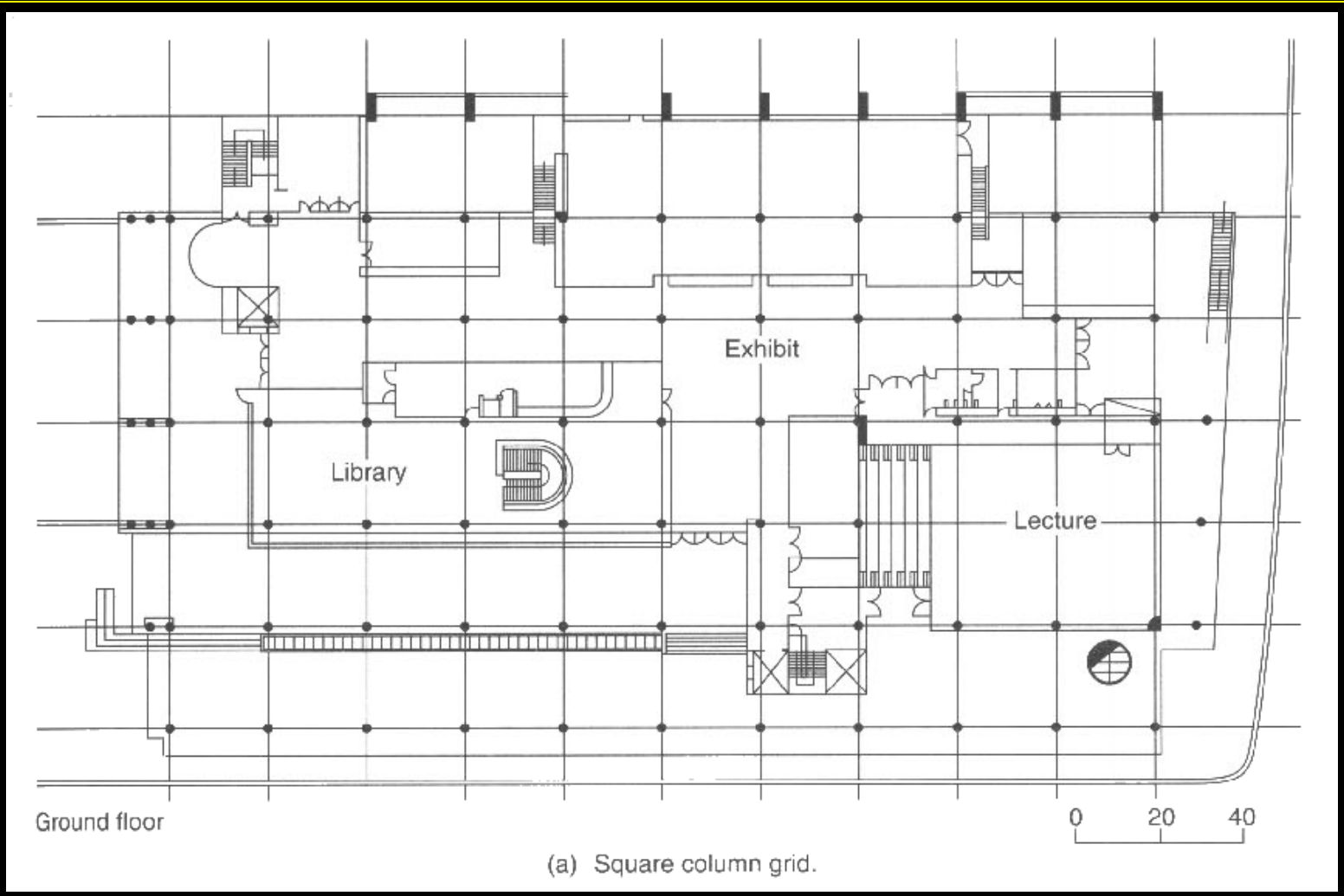
Grids and Patterns

- *often adopted early in design*
  - *give order*
  - *cellular, ex.*
- *vertical and horizontal*
- *square and rectangular*
  - *single-cell*
  - *aggregated bays*





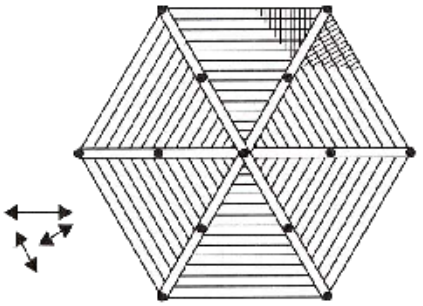
Grids and Patterns



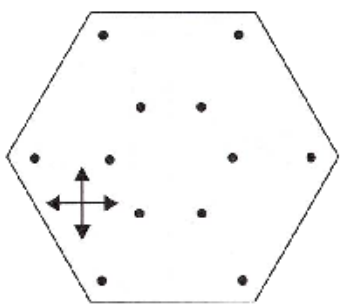
(a) Square column grid.

Systems

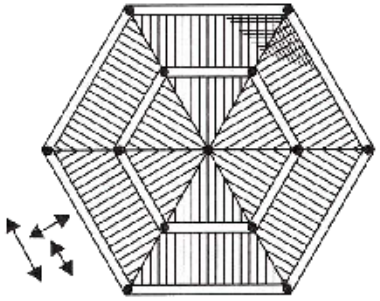
- *total of components*
- *behavior of whole*
- *classifications*
  - *one-way*
  - *two-way*
  - *tubes*
  - *braced*
  - *unbraced*



(a) One-way radial beam-and-column system for a hexagonal or circular configuration.



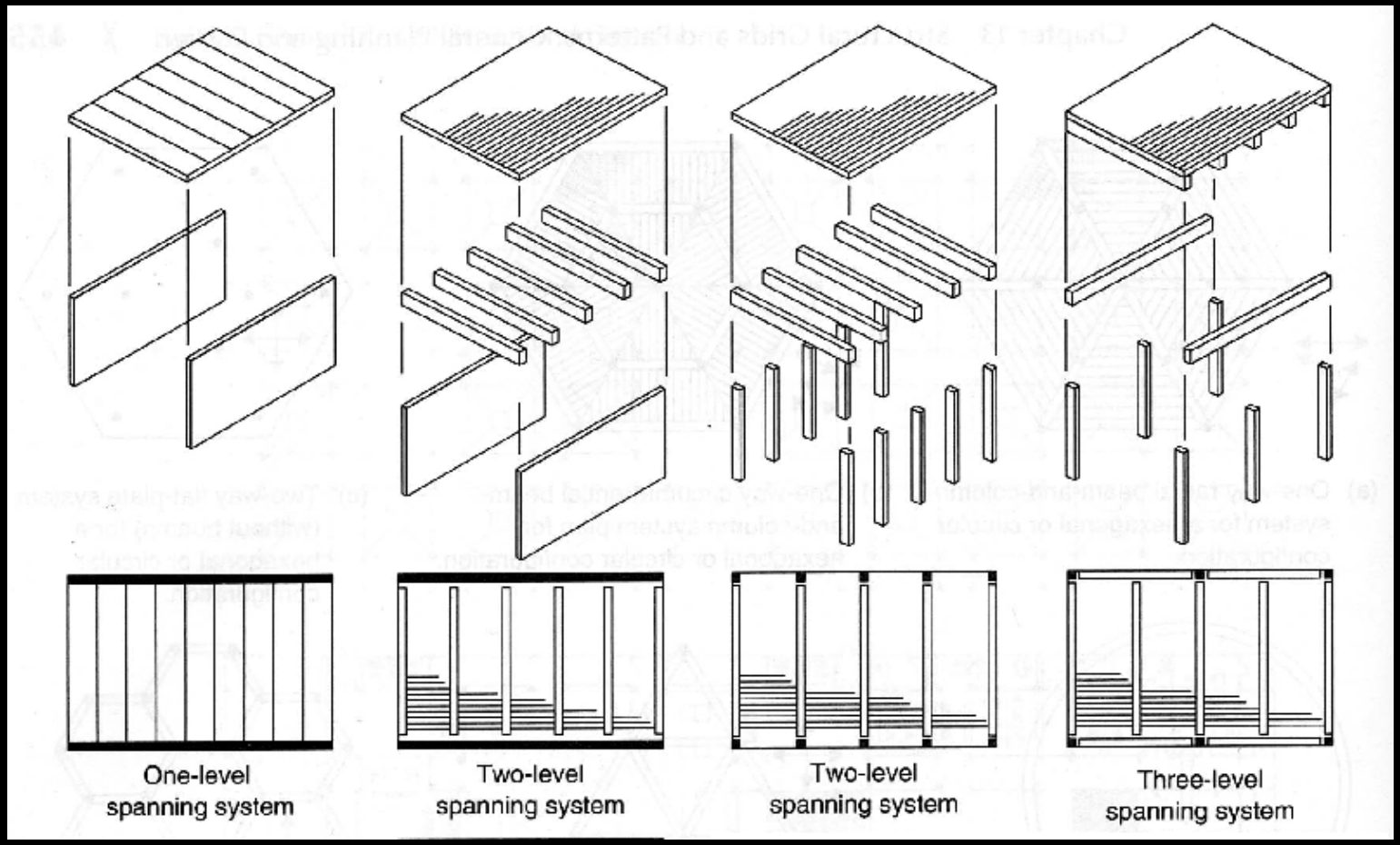
(c) Two-way flat-plate system (without beams) for a hexagonal or circular configuration.



(b) One-way circumferential beam-and-column system plan for hexagonal or circular configuration.

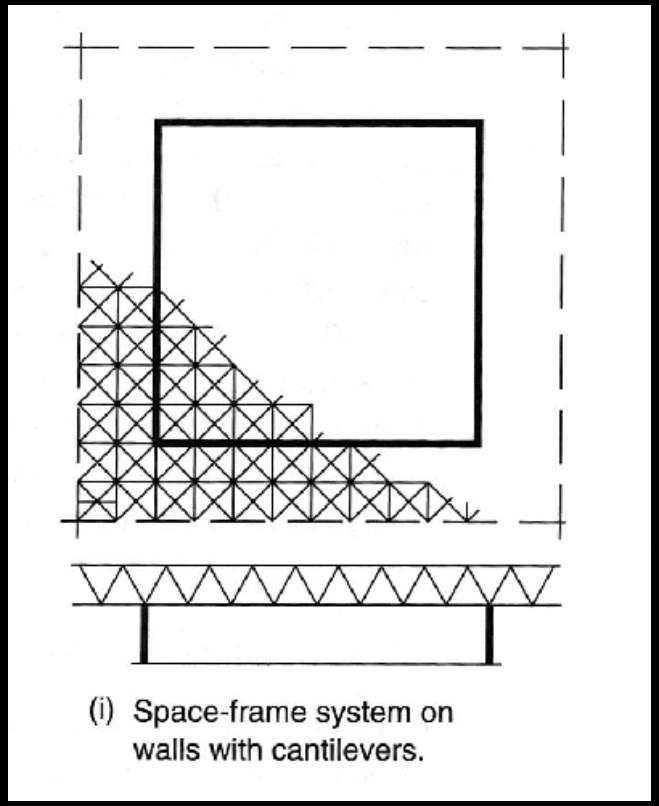
One-Way Systems

- horizontal vs. vertical



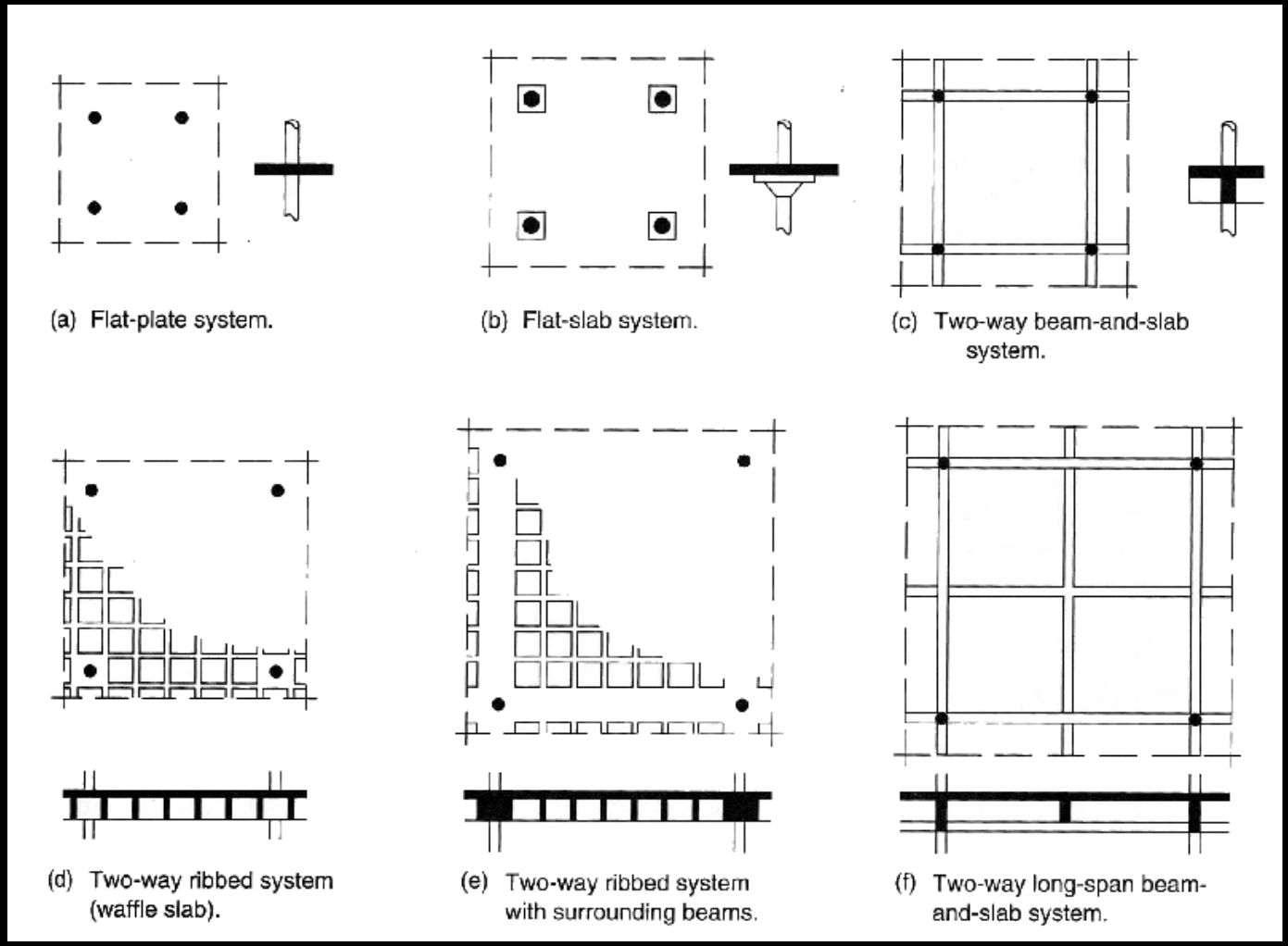
Two-Way Systems

- spanning system less obvious
- horizontal
  - plates
  - slabs
  - space frames
- vertical
  - columns
  - walls



(i) Space-frame system on walls with cantilevers.

Two-Way Systems



(a) Flat-plate system.

(b) Flat-slab system.

(c) Two-way beam-and-slab system.

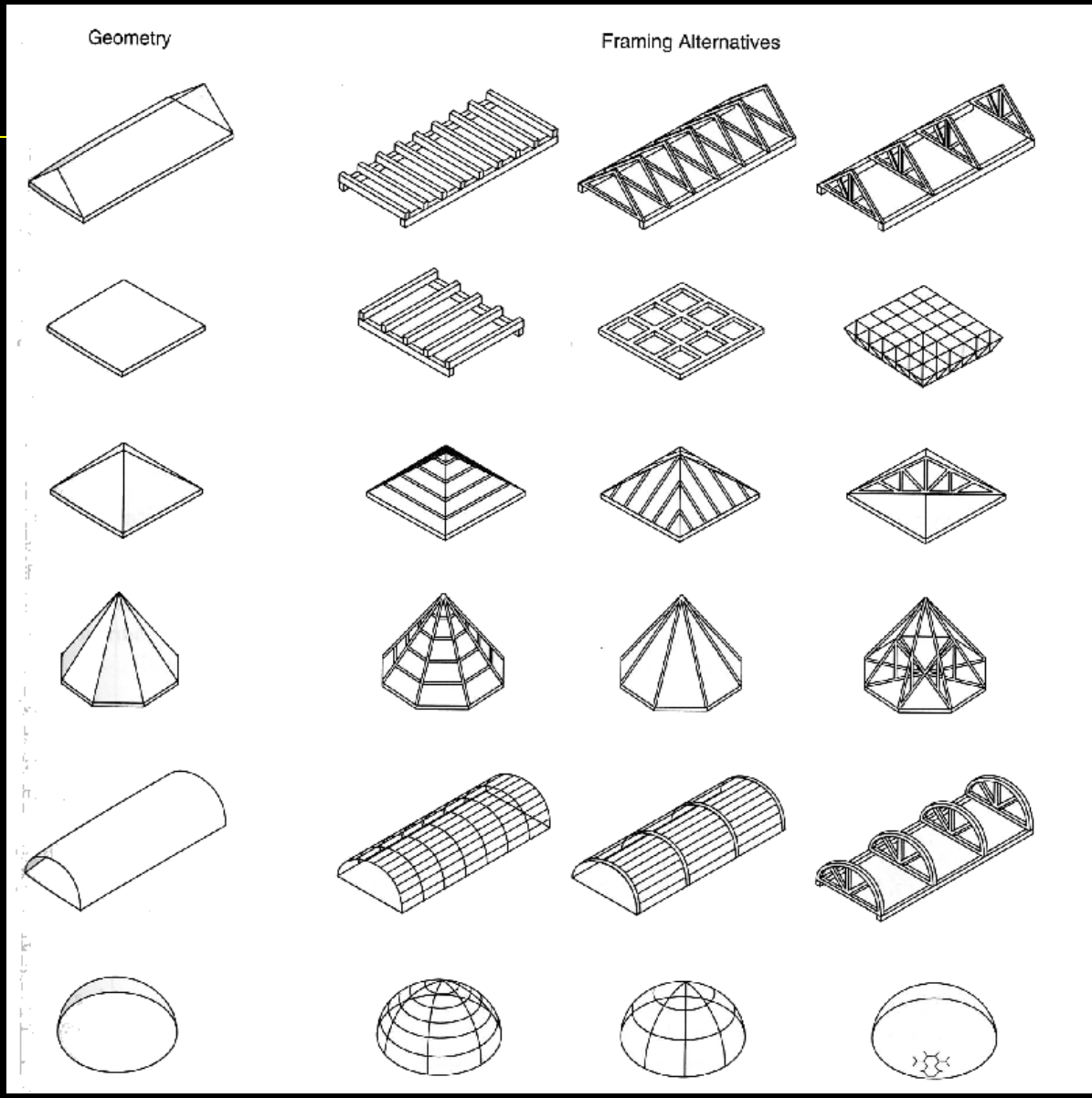
(d) Two-way ribbed system (waffle slab).

(e) Two-way ribbed system with surrounding beams.

(f) Two-way long-span beam-and-slab system.

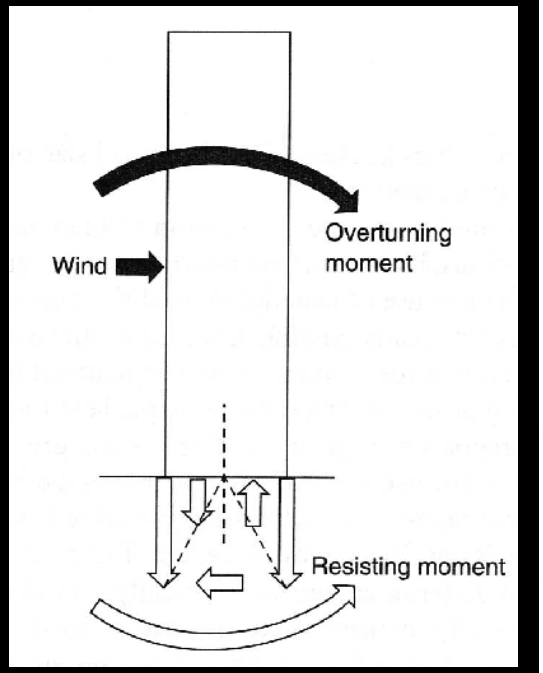
Roof Shapes

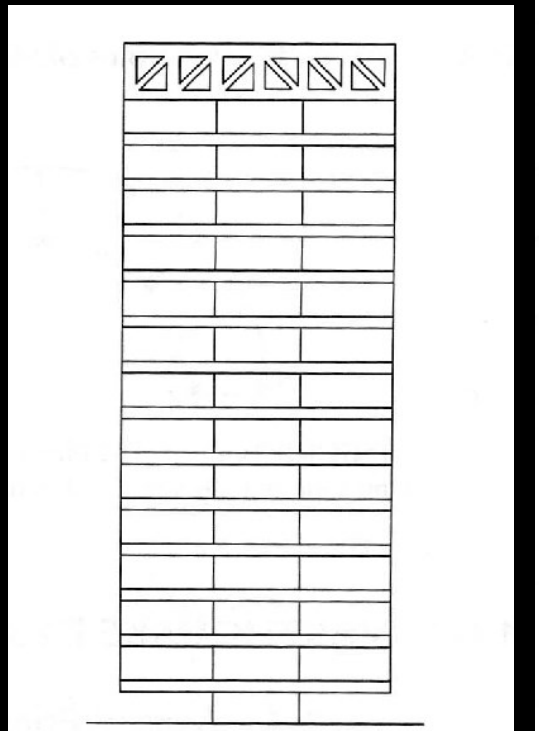
- *coincide*
- *within*



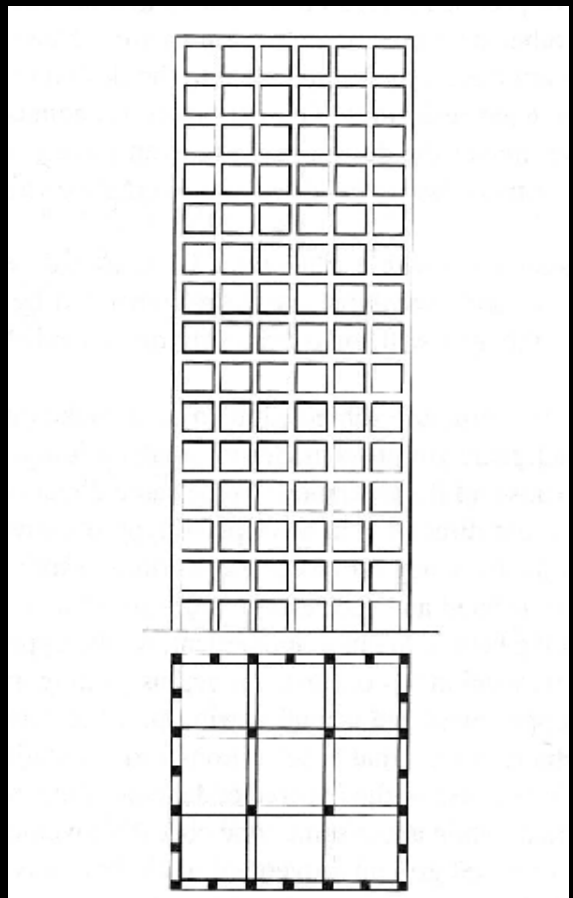
Tubes & Cores

- *stiffness*





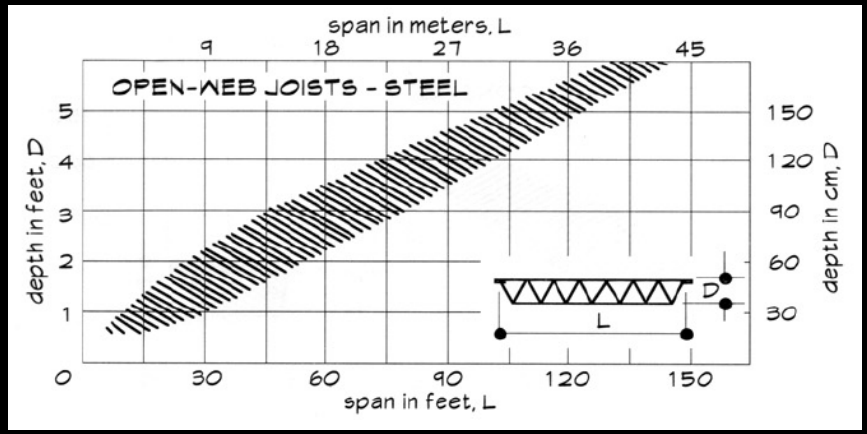
(c) Suspended structure, reinforced concrete core.



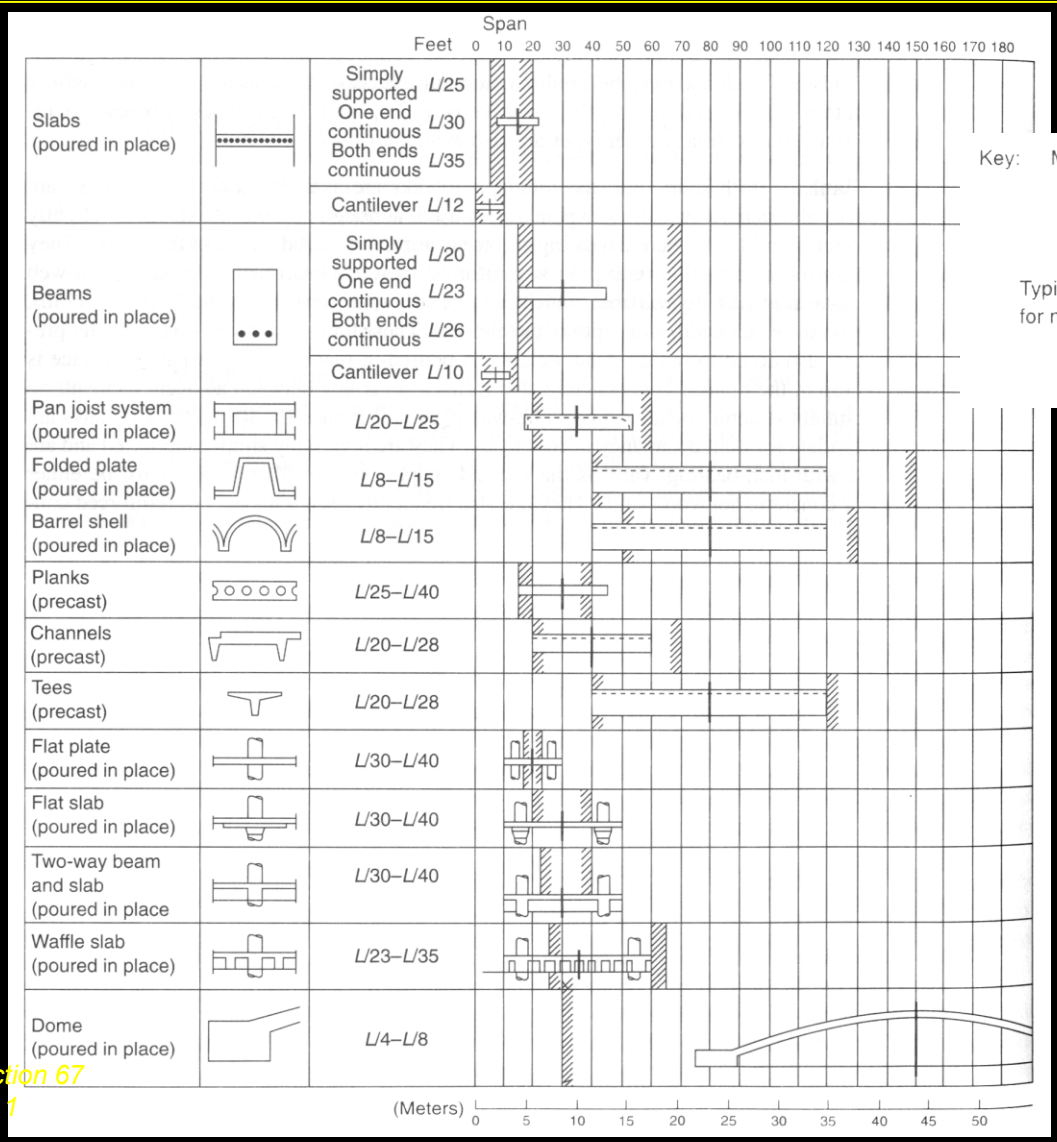
(c) Tube structure. The exterior columns are closely spaced. Horizontal spandrel beams are rigidly connected to columns to form an exterior tube, which carries all lateral forces and some gravity forces. Interior columns carry only vertical forces.

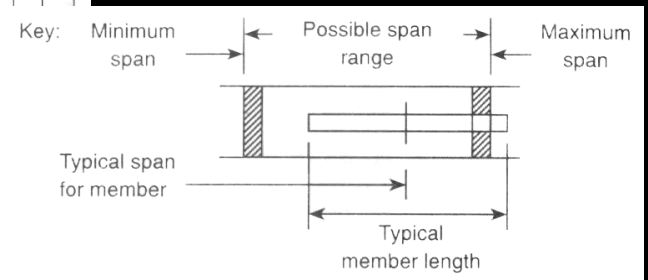
Span Lengths

- *crucial in selection of system*
- *maximum spans on charts aren't absolute limits, but <u>usual</u> maximums*
- *increase L, increase depth^2 required (ex. cantilever)*
- *deflections depend on L*



Approximate Depths



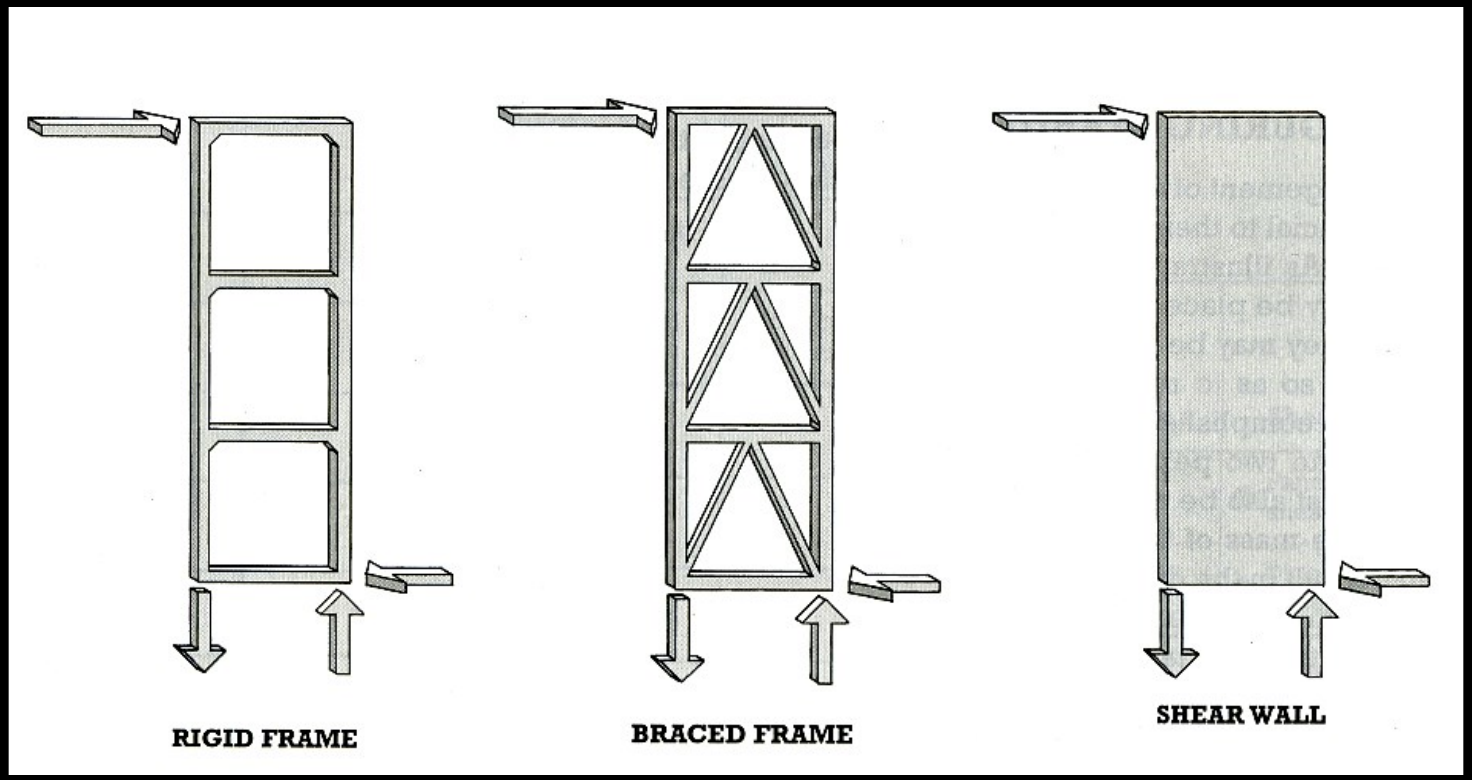


Loading Type and Structure Type

- *light uniform loads*
  - *surface forming elements*
  - *those that pick up first load dictate spacing of other elements*
- *heavy concentrated loads*
  - *member design unique*
- *distributed vs. concentrated structural strategies*
  - *large beam vs. many smaller ones*

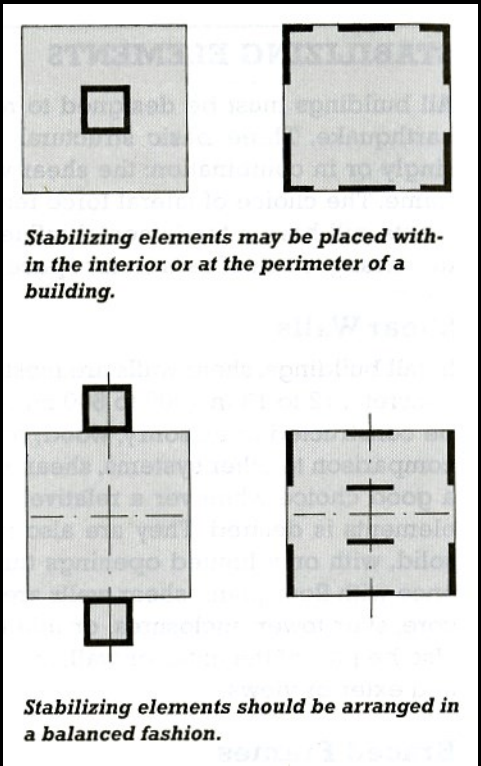
Design Issues

- *lateral stability – all directions*



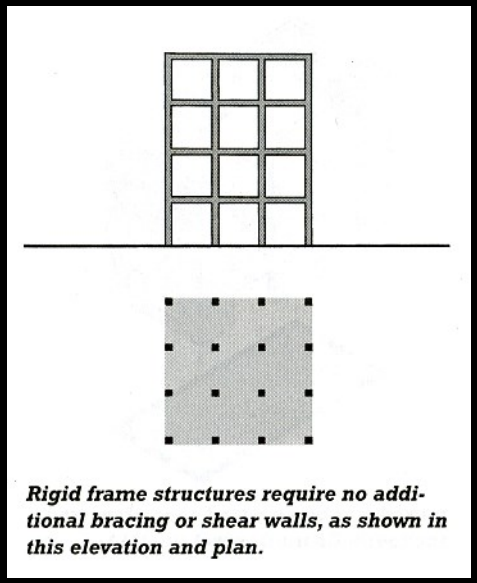
Design Issues

- *configuration*

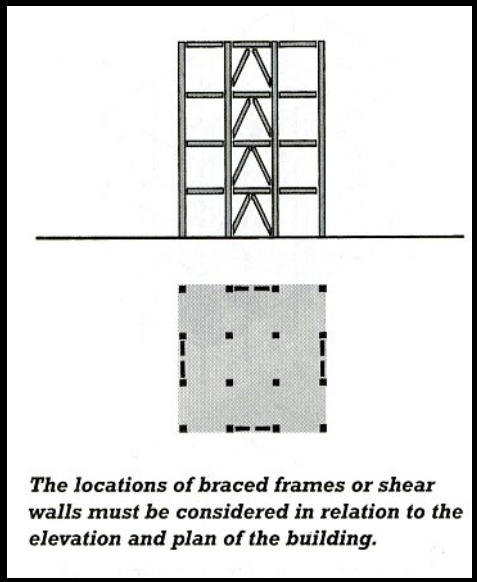


Stabilizing elements may be placed within the interior or at the perimeter of a building.

Stabilizing elements should be arranged in a balanced fashion.



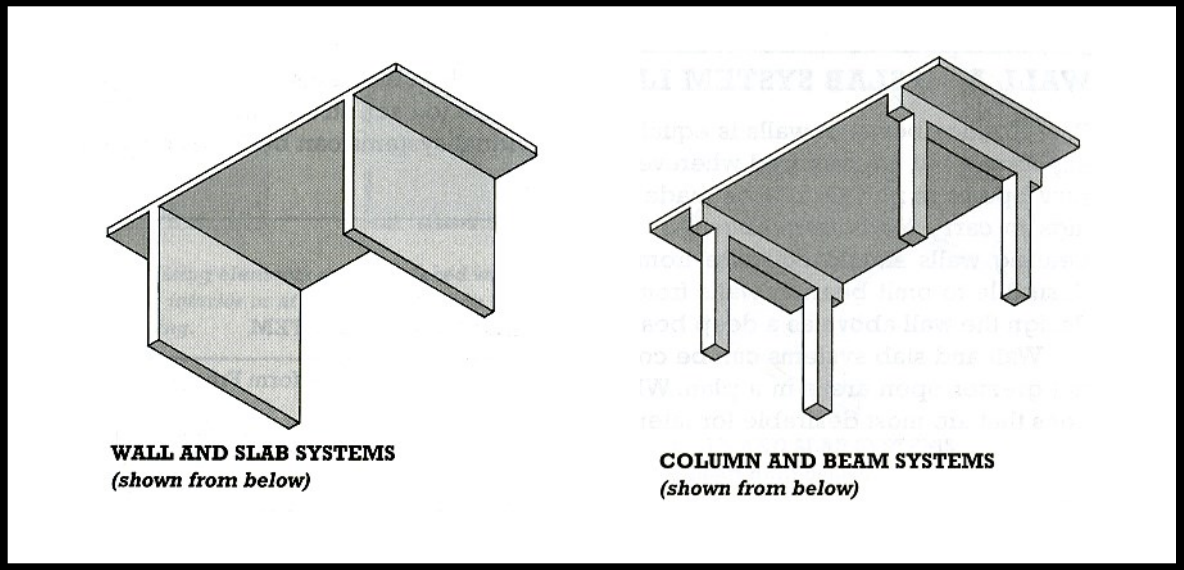
Rigid frame structures require no additional bracing or shear walls, as shown in this elevation and plan.



The locations of braced frames or shear walls must be considered in relation to the elevation and plan of the building.

Design Issues

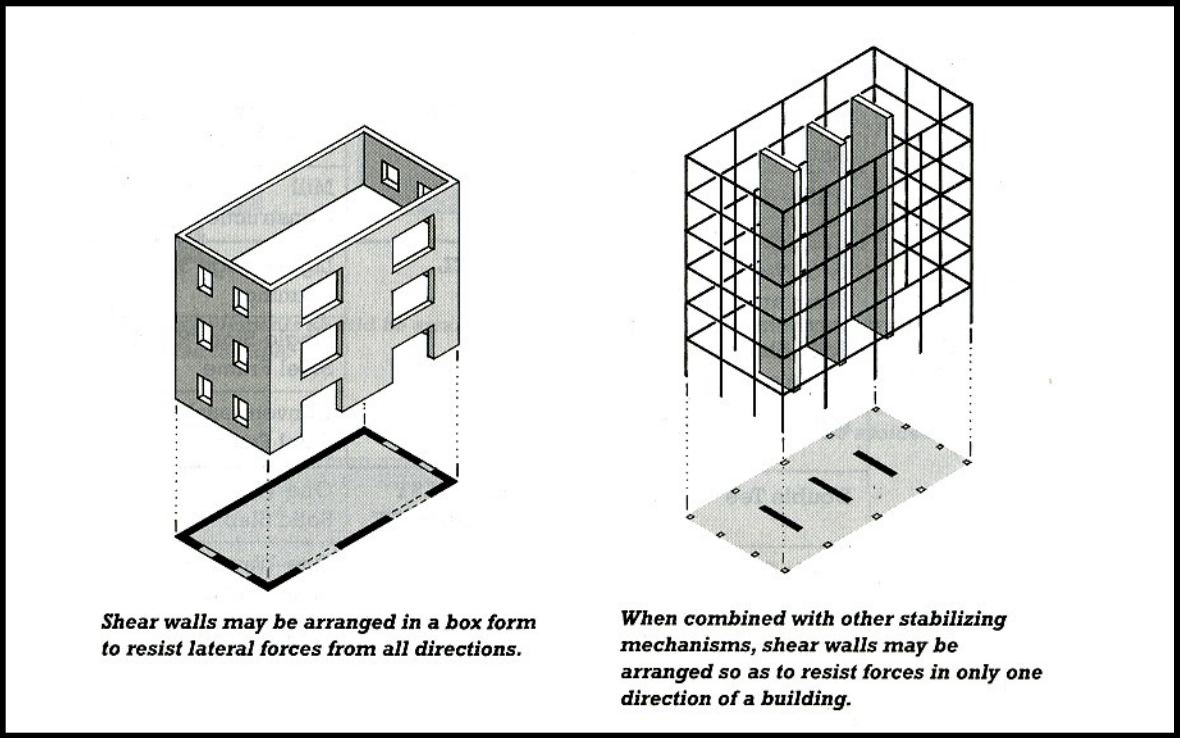
- *vertical load resistance*



walls *columns*

Design Issues

- *lateral load resistance*

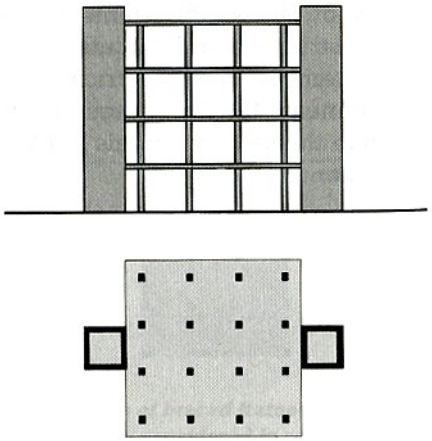


Shear walls may be arranged in a box form to resist lateral forces from all directions.

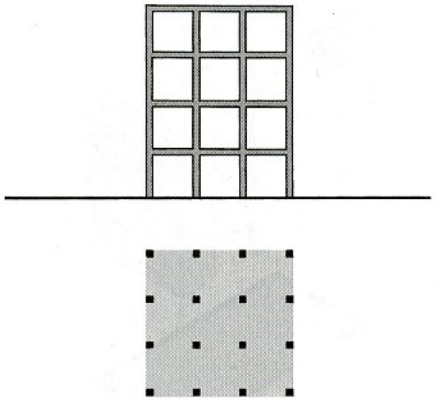
When combined with other stabilizing mechanisms, shear walls may be arranged so as to resist forces in only one direction of a building.

Design Issues

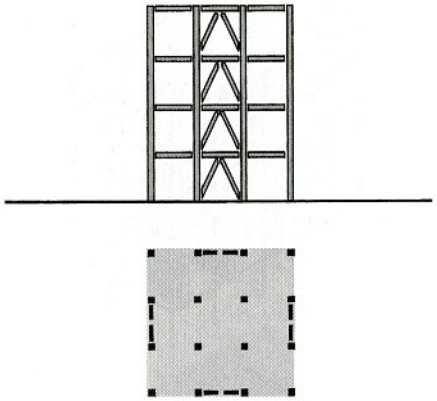
- *lateral load resistance*



Shear walls are commonly used with column and slab systems. In this elevation and plan, the shear walls are shown incorporated into a pair of vertical cores.



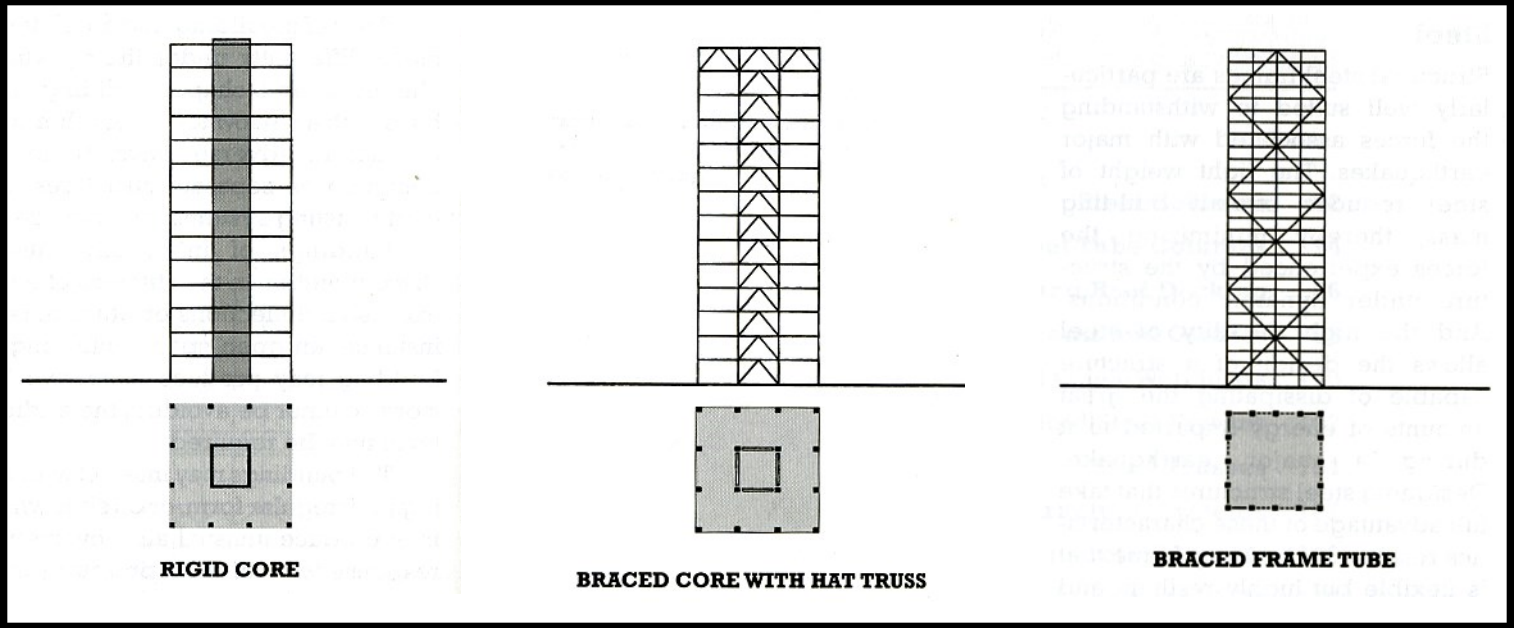
Rigid frame structures require no additional bracing or shear walls, as shown in this elevation and plan.



The locations of braced frames or shear walls must be considered in relation to the elevation and plan of the building.

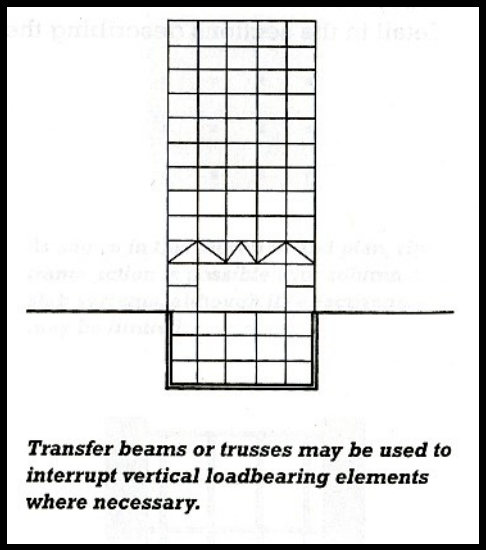
Design Issues

- *multi-story*
  - *– cores, tubes, braced frames*

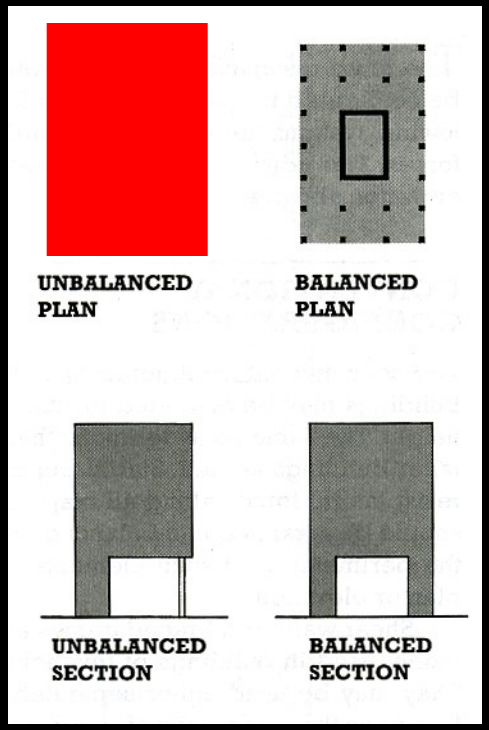


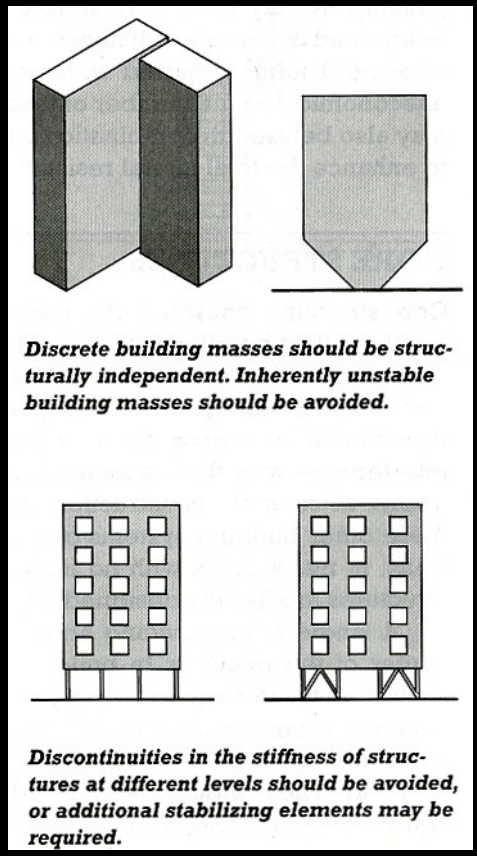
Design Issues

- *multi-story*
  - *– avoid discontinuities*
    - *vertically*
    - *horizontally*



Transfer beams or trusses may be used to interrupt vertical loadbearing elements where necessary.



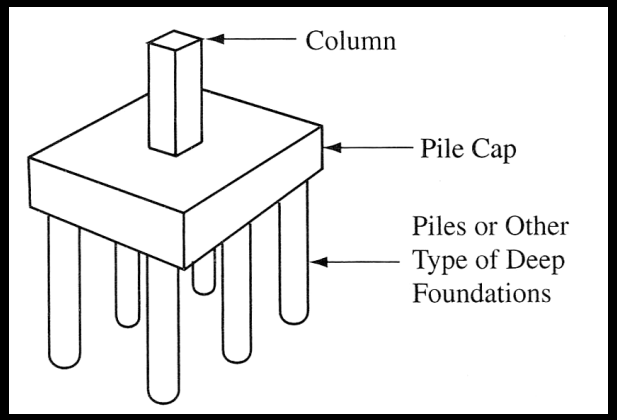


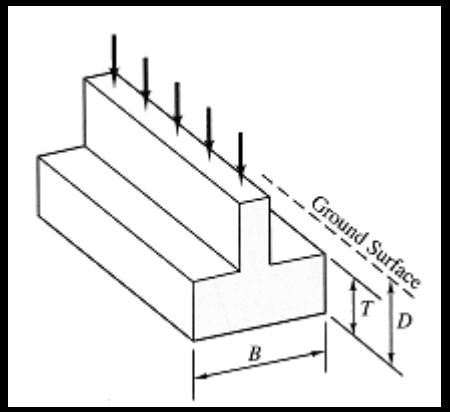
Discrete building masses should be structurally independent. Inherently unstable building masses should be avoided.

Discontinuities in the stiffness of structures at different levels should be avoided, or additional stabilizing elements may be required.

Foundation Influence

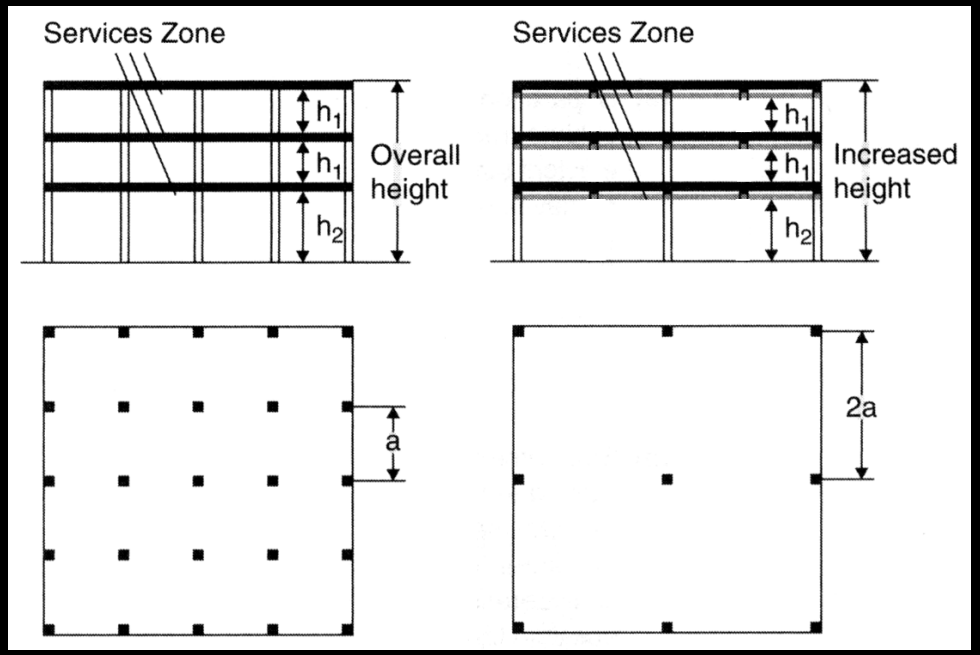
- *type may dictate fit*
  - *piles vs. mats vs. spread*
  - *capacity of soil to sustain loads*
    - *high capacity – smaller area of bearing needing and can spread out*
    - *low capacity – multiple contacts and big distribution areas*





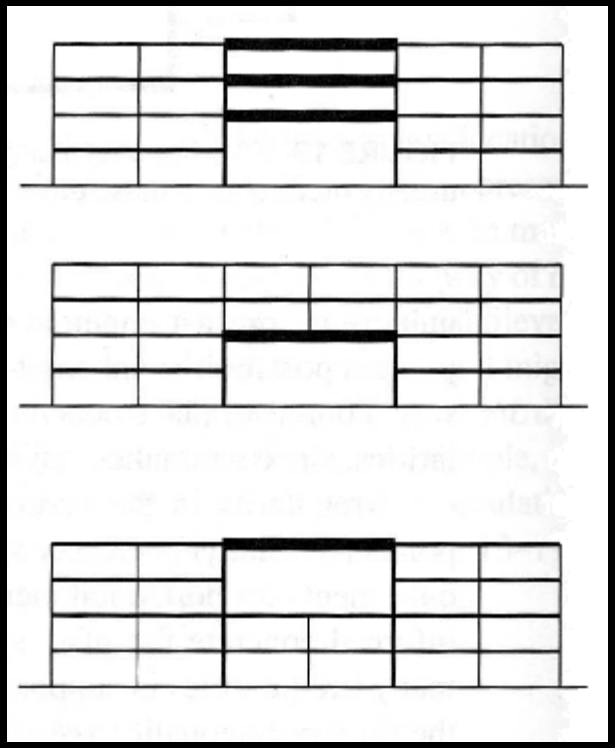
Grid Dependency on Floor Height

- wide grid = deep beams
  - increased building height
  - heavier
  - foundation design
- codes and zoning may limit
- utilize depth for mechanical



Large Spaces

- *ex. auditoriums, gyms, ballrooms*
- *choices*
  - *separate two systems completely and connect along edges*
  - *embed in finer grid*
  - *staggered truss*

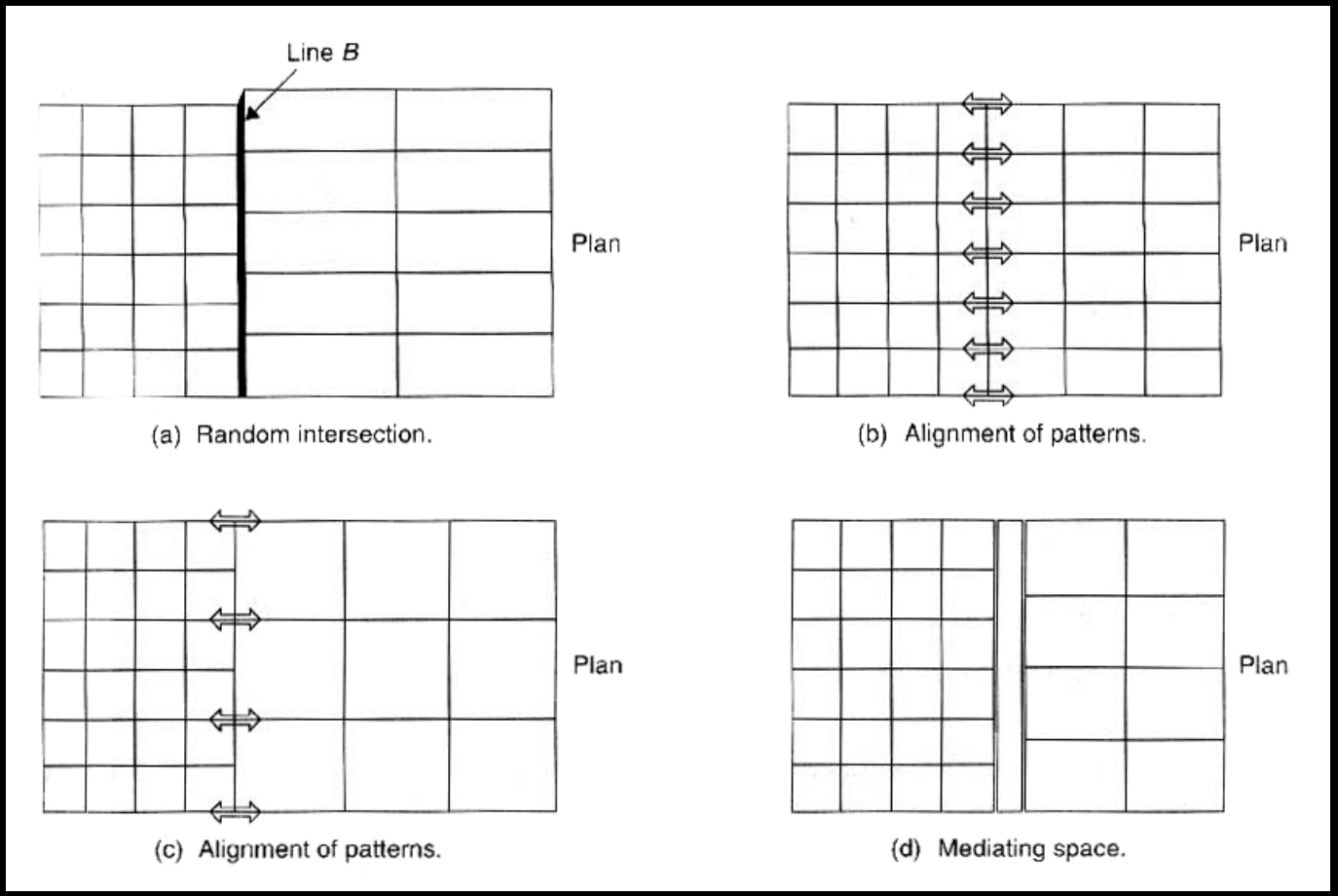


Meeting of Grids

- *common to use more than one grid*
- *intersection important structurally*
- *can use different structural materials*
  - *need to understand their properties*
    - *mechanical*
    - *thermal*

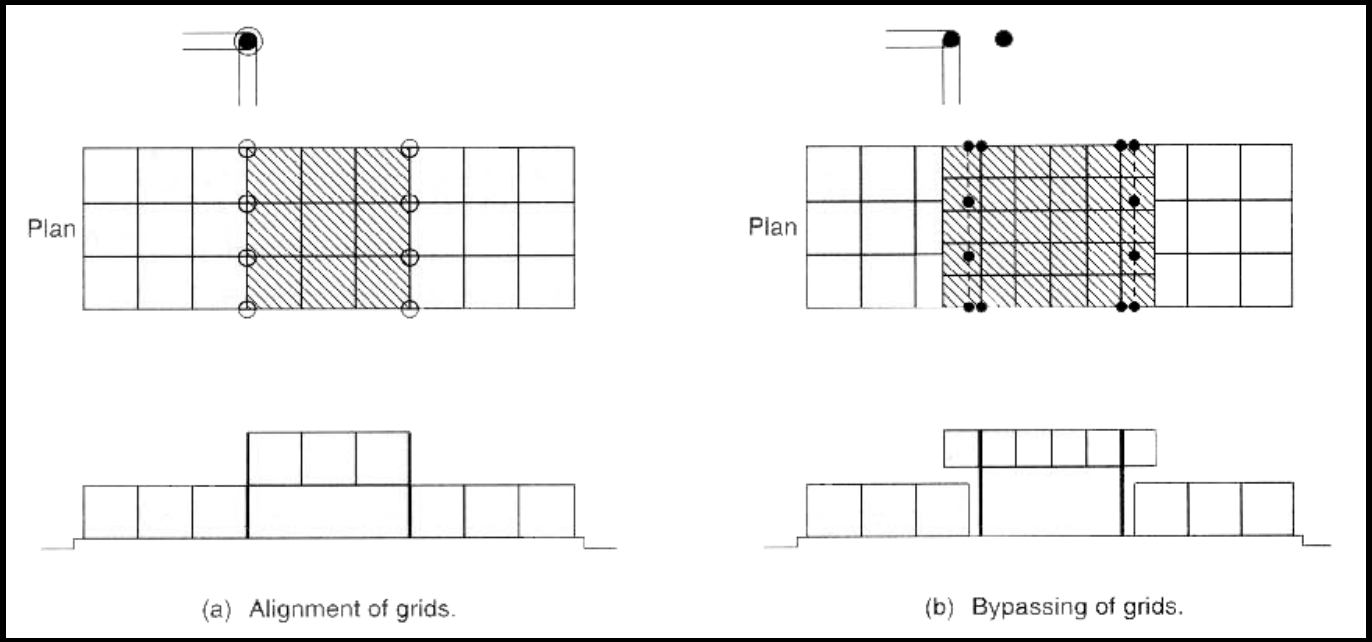
Meeting of Grids

- *horizontal choices*



Meeting of Grids

- *vertical choices*

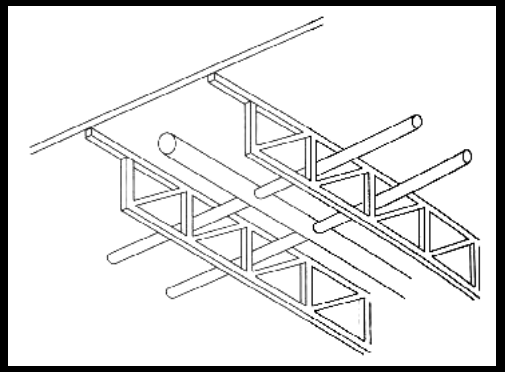


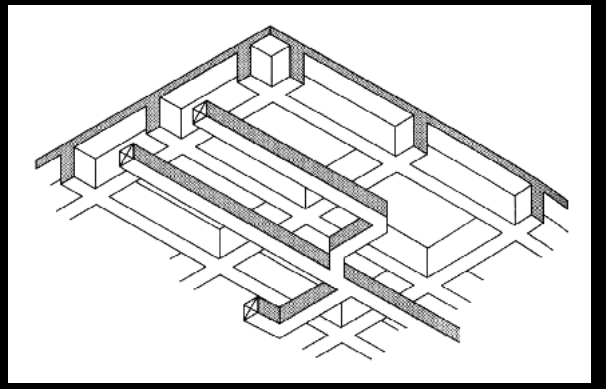
(a) Alignment of grids.

(b) Bypassing of grids.

Other Conditions

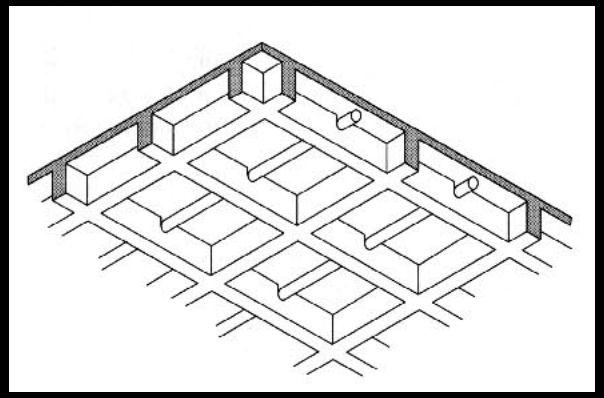
- *circulation*
- *building service systems*
  - *one-way systems have space for parallel runs*
  - *trusses allow for transverse penetration*
  - *pass beneath or interstitial floors*
    - *for complex or extensive services or flexibility*

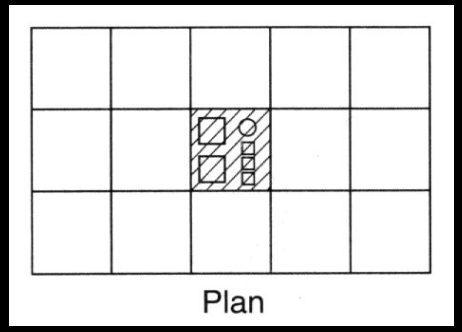




Other Conditions

- poking holes for member services
  - horizontal
    - need to consider area removed, where removed, and importance to shear or bending
  - vertical
    - requires framing at edges
    - can cluster openings to eliminate a bay
  - double systems





Fire Safety & Structures

- *fire safety requirements can impact structural selection*
- *construction types*
  - *light*
    - *residential*
    - *wood-frame or unprotected metal*
  - *medium*
    - *masonry*
  - *heavy*
    - *protected steel or reinforced concrete*

Fire Safety & Structures

- *degree of occupancy hazards*
- *building heights*
- *maximum floor areas between fire wall divisions*
  - *– can impact load bearing wall location*

Fire Safety & Structures

- *resistance ratings by failure type*
  - *transmission failure*
    - *fire or gasses move*
  - *structural failure*
    - *high temperatures reduce strength*
  - *failure when subjected to water spray*
    - *necessary strength*
- *ratings do not pertain to usefulness of structure after a fire*

Project