ARCHITECTURAL STRUCTURES:
FORM, BEHAVIOR, AND DESIGN

ARCH 331

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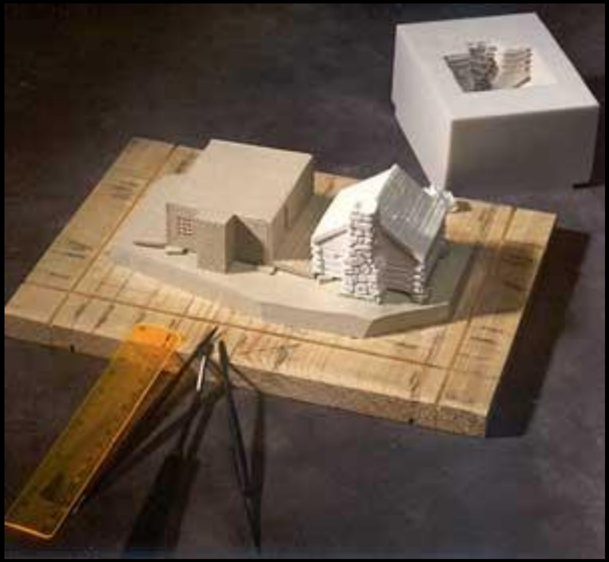
SUMMER 2013

lecture
eleven



design loads, methods, structural codes & tracing

Design

- *factors out of the designer's control*
  - *loads*
  - *occurrence*
- *factors within the designer's control*
  - *choice of material*
  - *"cost" of failure (F.S., probability, location)*
  - *economic design method*
  - *analysis method*

Design Methods

- *different approaches to meeting strength/safety requirements*
  - *allowable stress design (elastic)*
  - *ultimate strength design*
  - *limit state design*
  - *plastic design*
  - *load and resistance factor design*
- *assume a behavior at failure or other threshold and include a margin of safety*

Load Types

- D = dead load
- L = live load
- L_r = live roof load
- W = wind load
- S = snow load
- E = earthquake load
- R = rainwater load or ice water load
- T = effect of material & temperature
- H = hydraulic loads from soil (F from fluids)

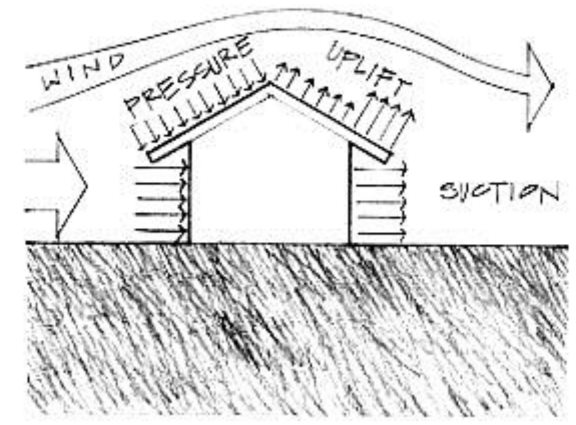
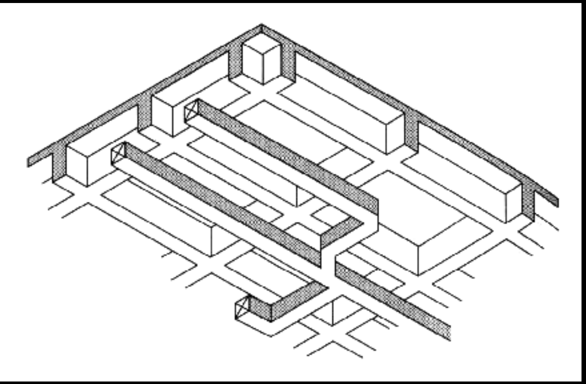


Figure 1.13 Wind loads on a structure.

Dead Loads

- *fixed elements*
  - *structure itself*
  - *internal partitions*
  - *hung ceilings*
  - *all internal and external finishes*
  - *HVAC ductwork and equipment*
  - *permanently mounted equipment*



- *F = mg (GRAVITY)*

Weight of Materials

- *for a volume*
  - $W = \gamma V$ *where γ is weight/volume*
  - $W = \gamma t A$ *for an extruded area with height of t*

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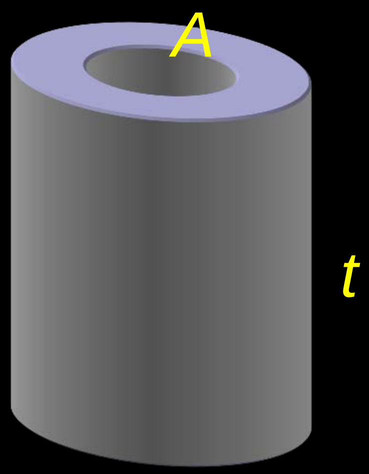
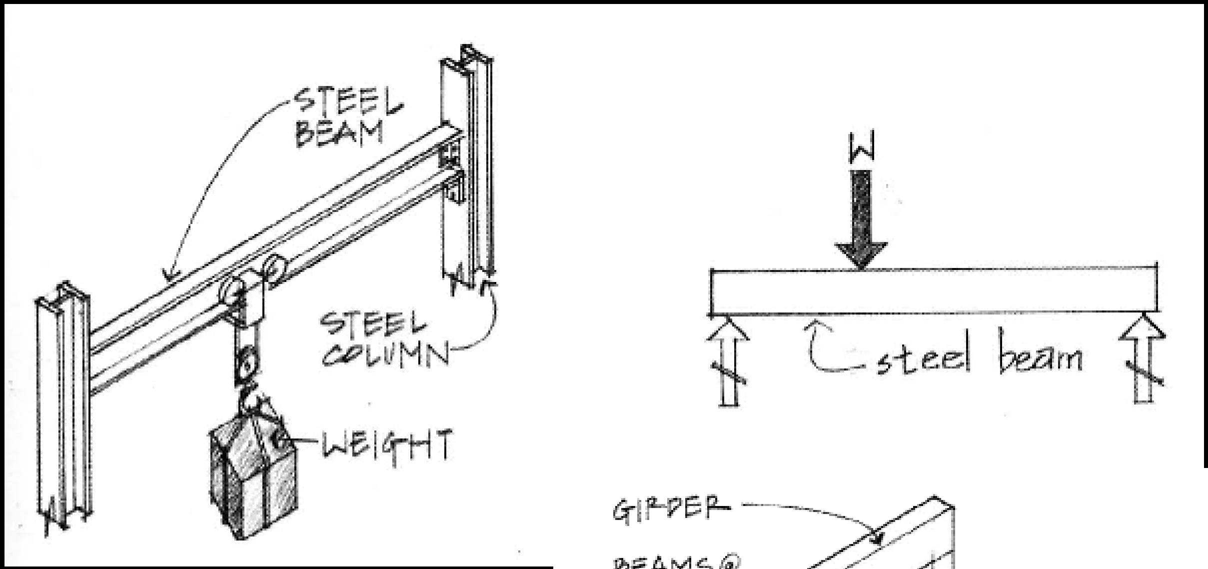
Table 5.1 Selected building material weights.

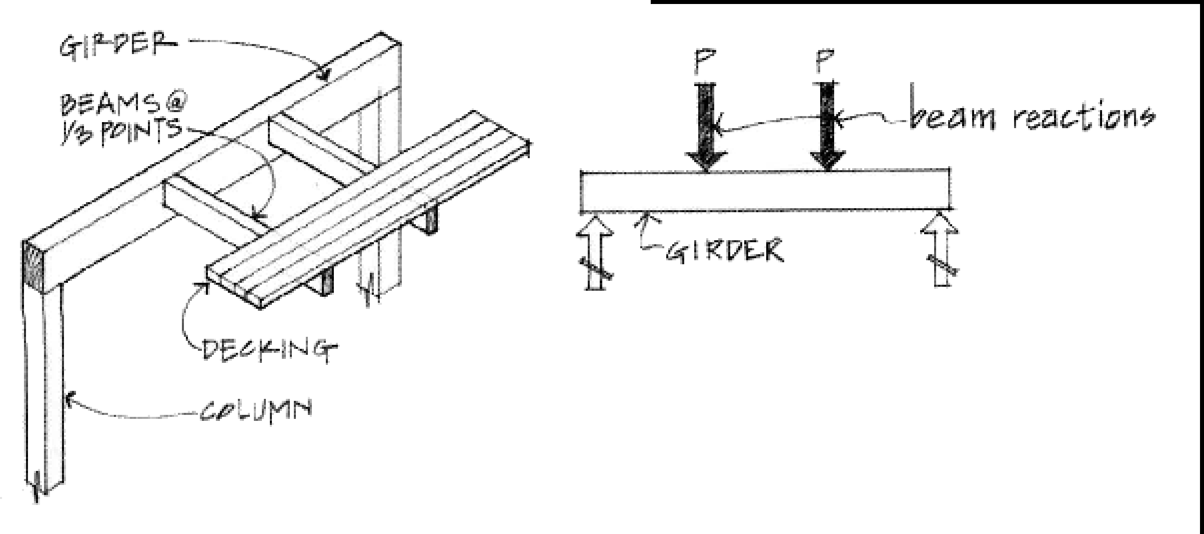
Assembly	lb./ft.²	kN/m²
Roofs:		
3-ply and gravel	5.5	0.26
5-ply and gravel	6.5	0.31
Wood shingles	2	0.10
Asphalt shingles	2	0.10
Corrugated metal	1–2.5	0.05–0.12
Plywood	3/inch	0.0057/mm
Insulation —fiberglass batt	0.5	0.0025
Insulation—rigid	1.5	0.075

Assembly	lb./ft.²	kN/m²
Floors:		
Concrete plank	6.5	0.31
Concrete slab	12.5/in.	0.59/mm
Steel decking w/concrete	35–45	1.68–2.16
Wood joists	2–3.5	0.10–0.17
Hardwood floors	4/in.	0.19/mm
Ceramic tile w/thin set	15	0.71
Lightweight concrete	8/in.	0.38/mm
Timber decking	2.5/in.	0.08/mm

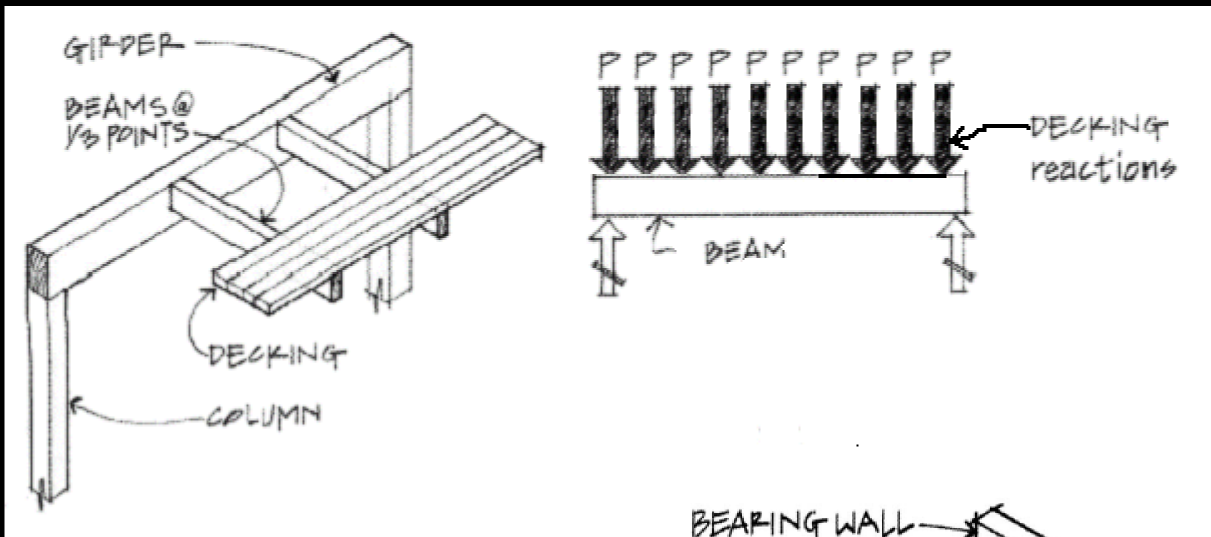


Concentrated Loads



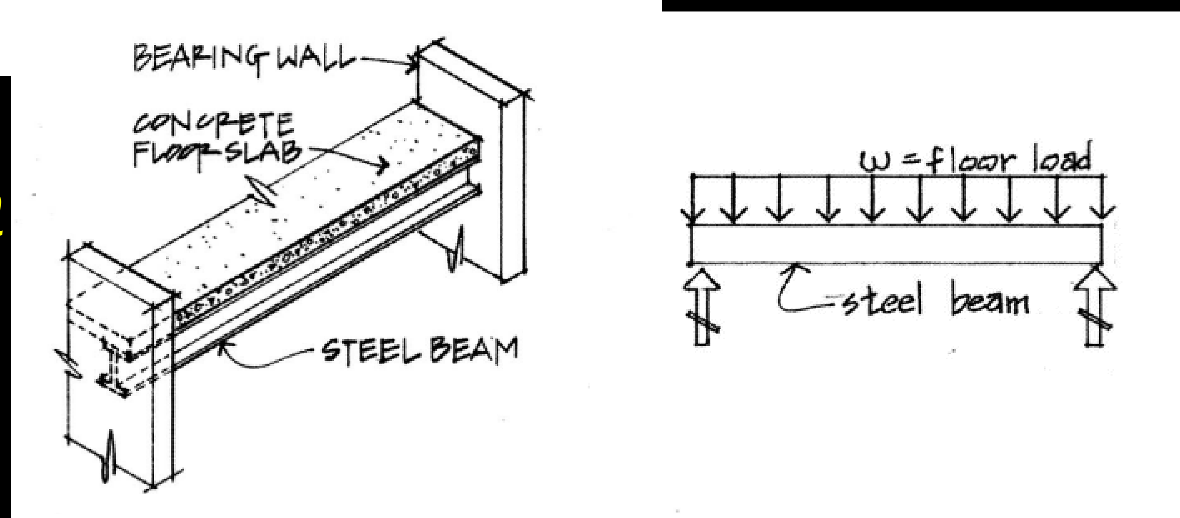


Distributed Loads



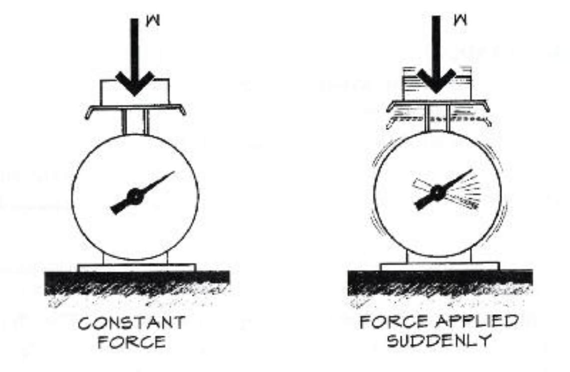
- *for an area*

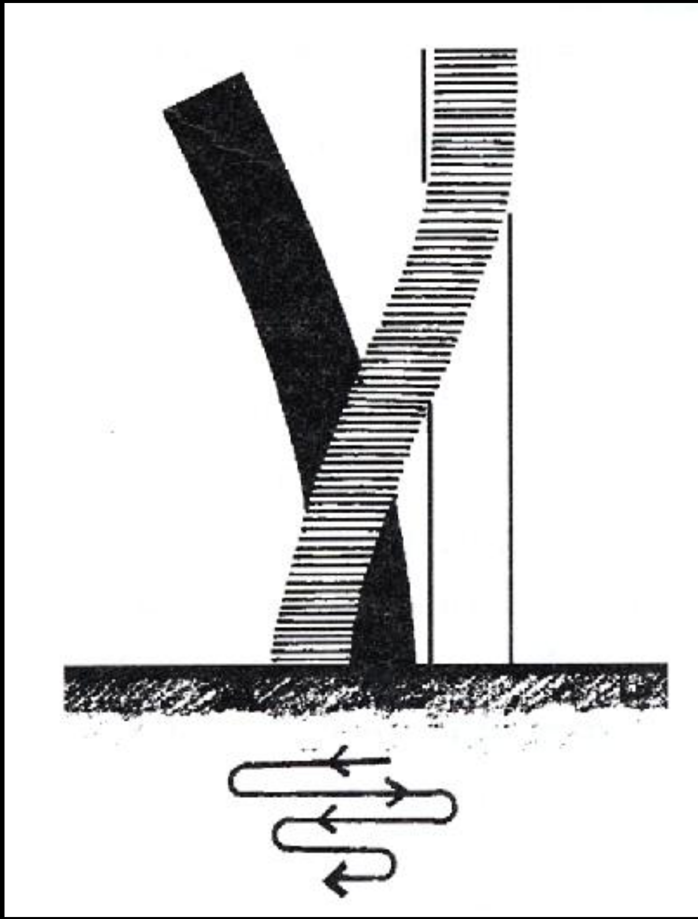
$$w = \gamma A$$



Dynamic Loads

- *time, velocity, acceleration*
- *kinetics*
  - *forces causing motion*
    $W = m \cdot g$
  - *work*
  - *conservation of energy*





Load Locations

- *centric*
- *eccentric*
- *bending or flexural load*
- *torsional load*
- *combined loading*

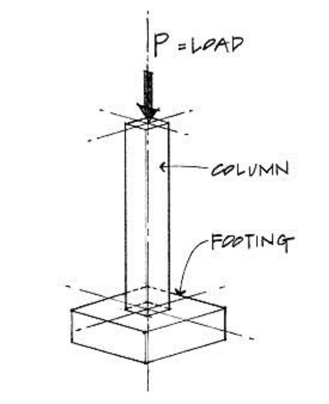
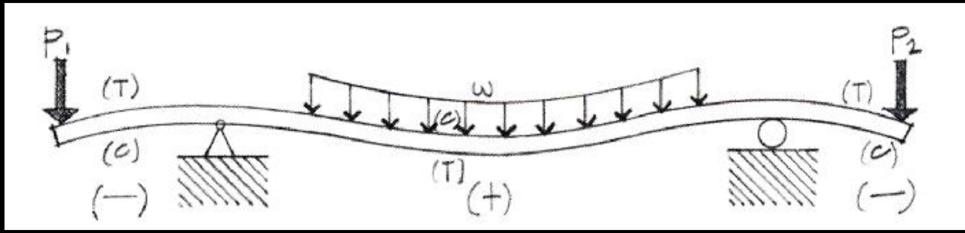
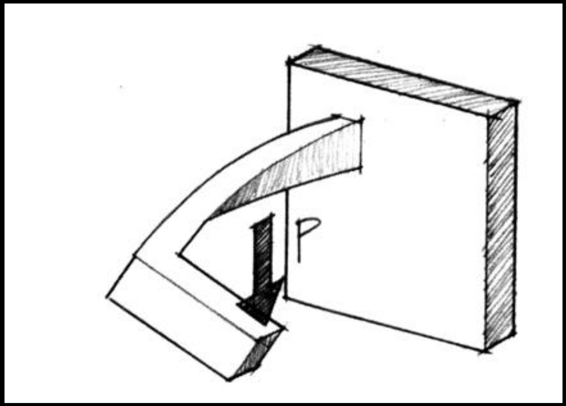


Figure 5.3 Centric loads.





Load Paths

- *tributary areas*
- *transfer*

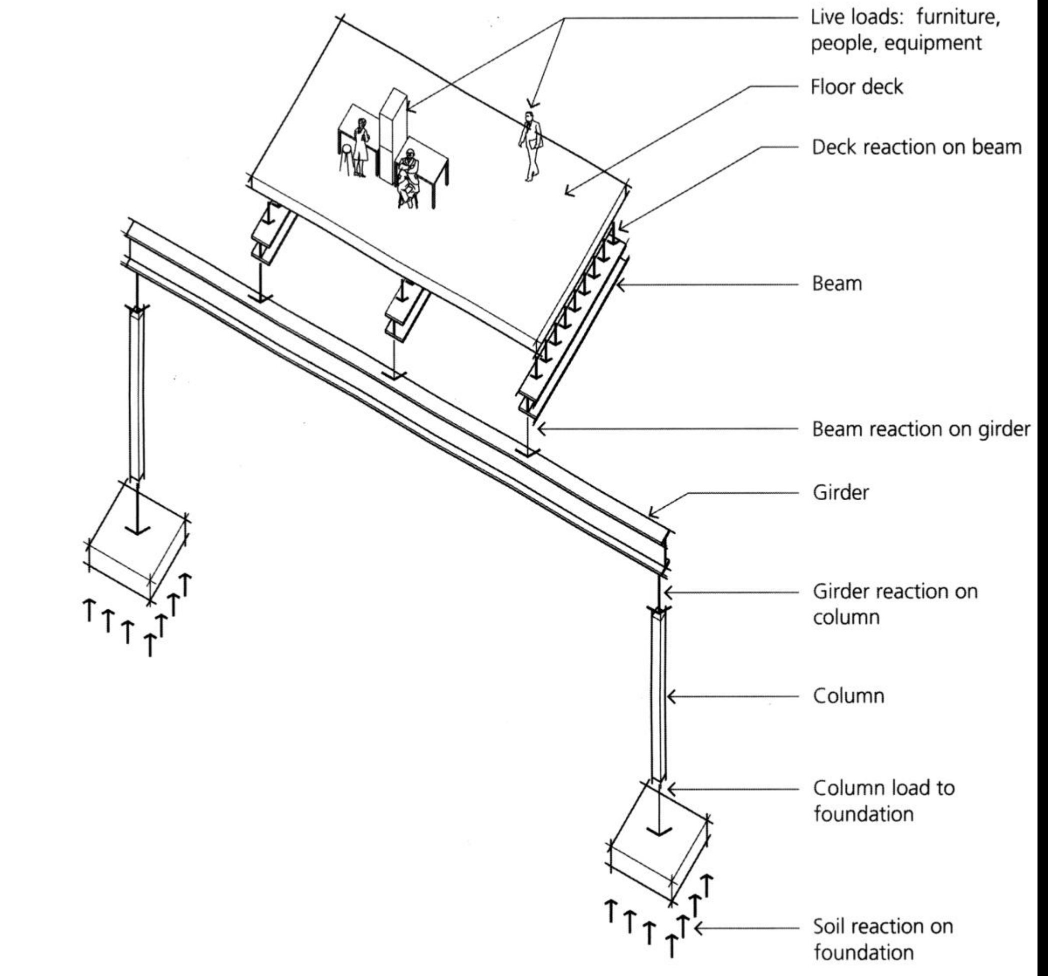
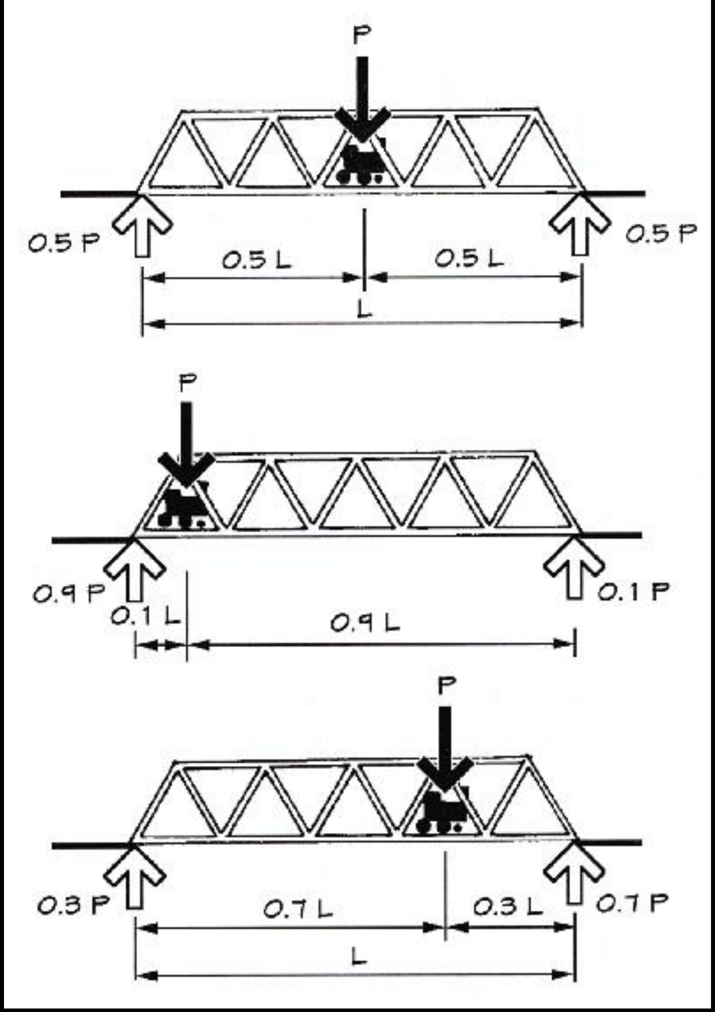


Fig. 1.3 Load paths through structures

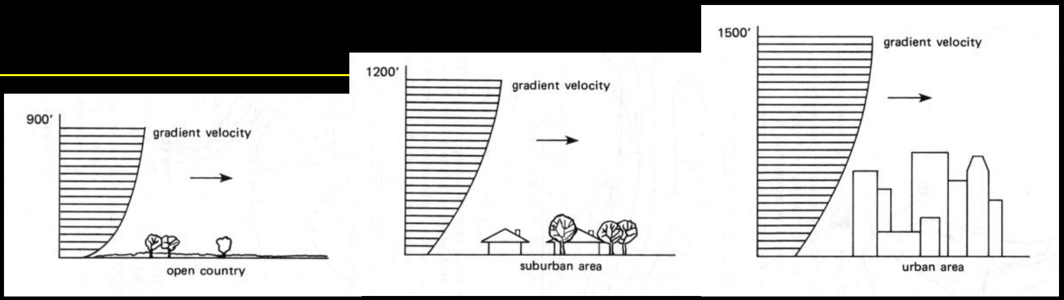
Live Loads

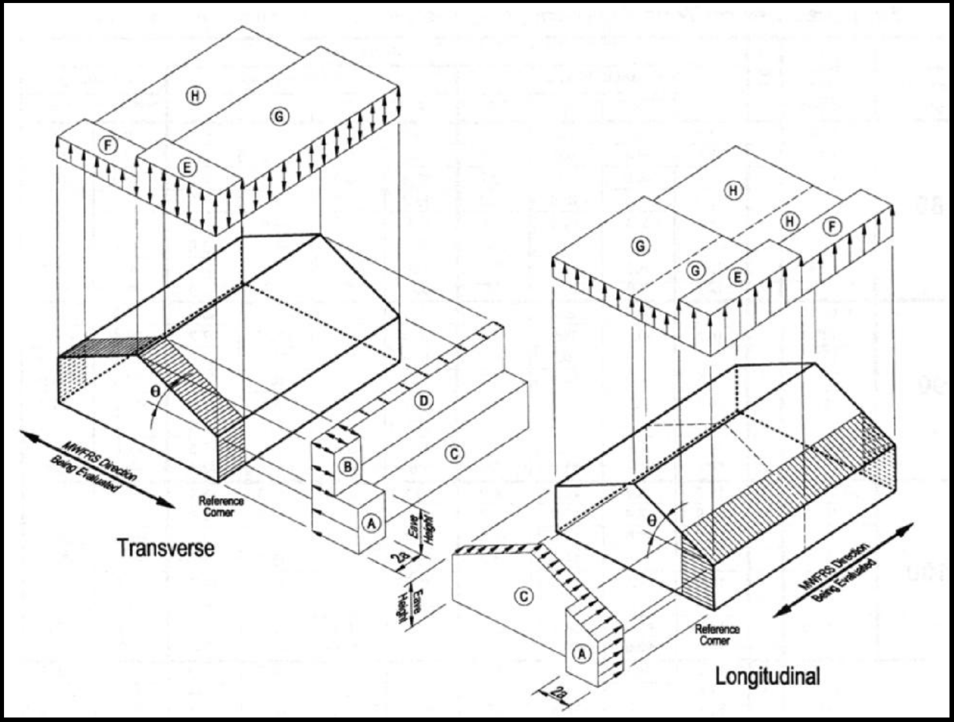
- occupancy
- movable furniture and equipment
- construction / roof traffic – L_r
- minimum values
- reduction allowed as area increases



Wind Load

- *wind speed*
- *gusting*
- *terrain*
- *windward, leeward, up and down!*
- *drag*
- *rocking*
- *harmonic*
- *torsion*





Snow Load

- *latitude*
- *solar exposure*
- *wind speed*
- *roof slope*

Moscow 2006 (BBC News)

Seismic Load

- earthquake acceleration
  - $F = ma$
  - movement of ground (3D)
  - building mass responds
  - static models often used, V is static shear
  - building period, $T \approx 0.1N$, determines C
  - building resistance – R_W
  - Z (zone), I (importance factor)

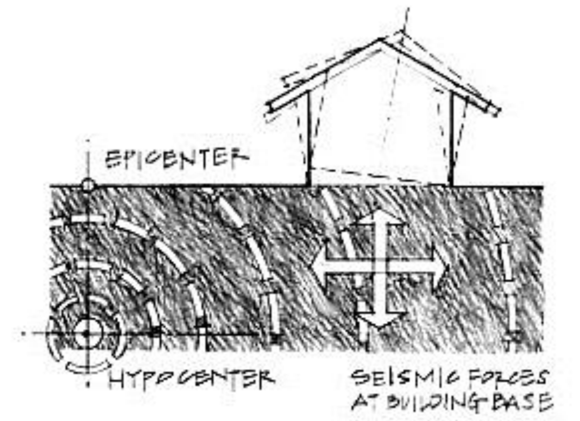
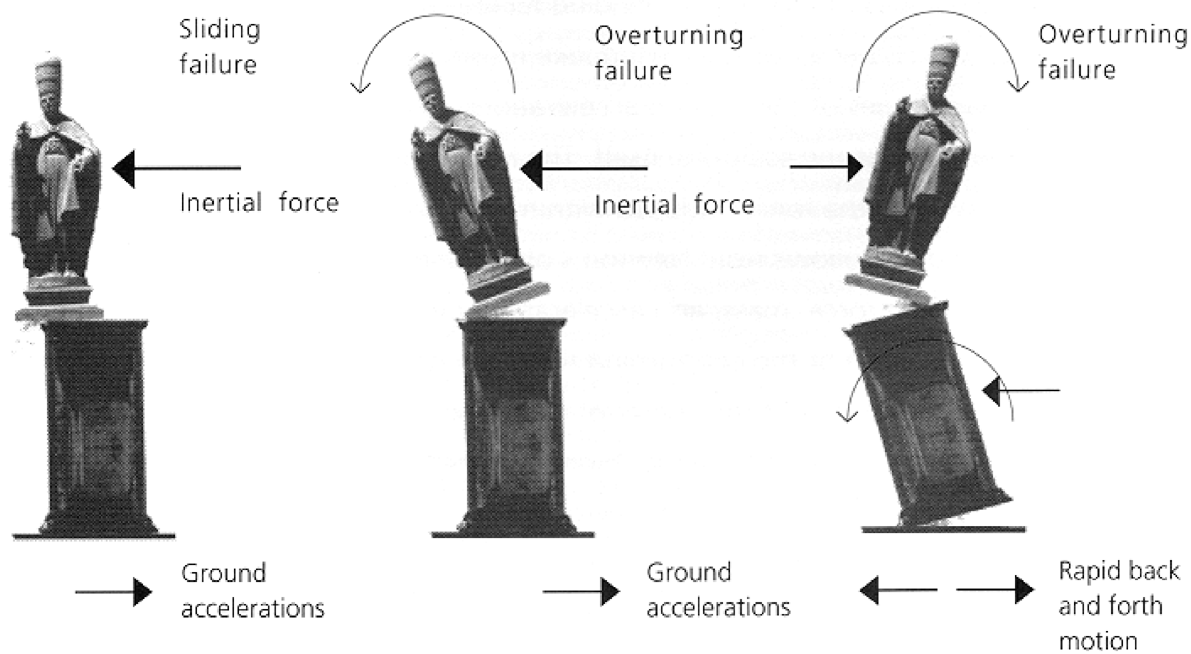


Figure 1.14 Earthquake loads on a structure.

$$V = \frac{ZICW}{R_W}$$

Dynamic Response

Statue in front of the cathedral of Palermo, Sicily



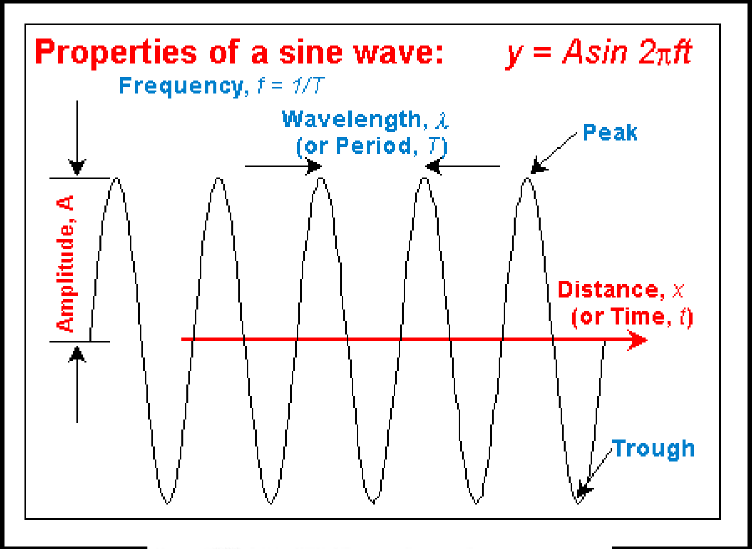
Lateral ground motions associated with earthquakes cause inertial forces to develop that are dependent on the weight of the structure. Sliding failures can occur.

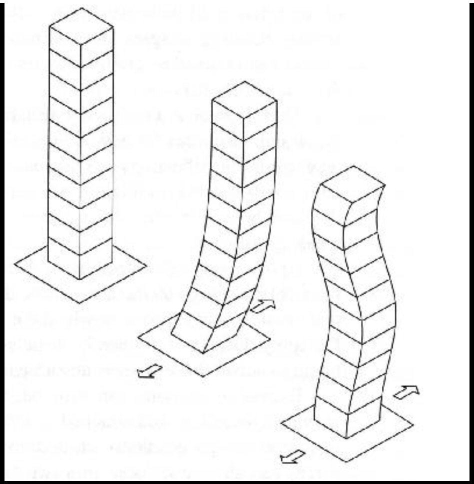
The lateral ground motions can also cause a sculpture to overturn. The magnitude of the overturning effect depends on the weight of the sculpture and its height above the ground.

Back and forth ground motions can cause different parts of the sculpture to move in different directions. Overturning or cracking of elements can consequently occur.

Dynamic Response

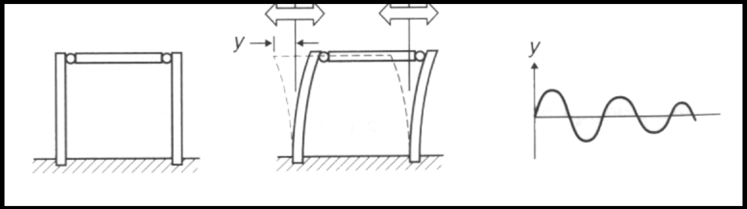
- *period of vibration or frequency*
  - *– wave*
  - *– sway/time period*
- *damping*
  - *– reduction in sway*
- *resonance*
  - *– amplification of sway*



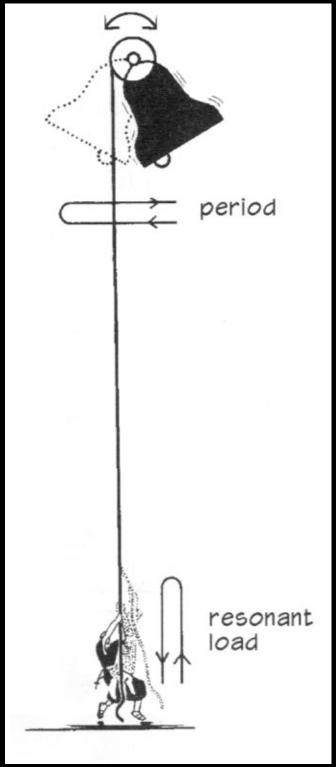


Frequency and Period

- *natural period of vibration*



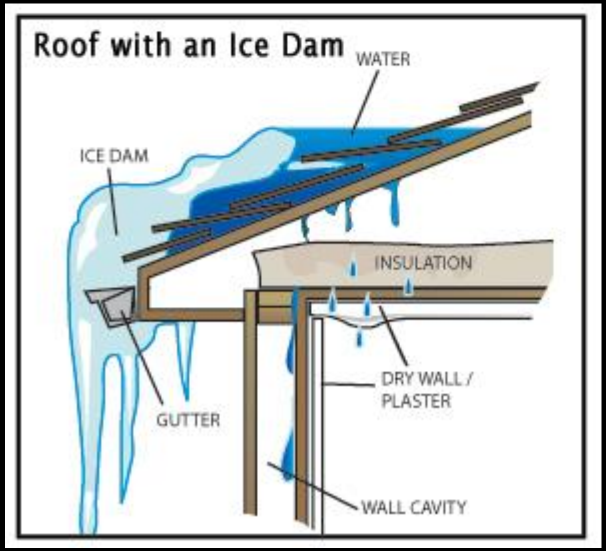
  - *avoid resonance*
  - *hard to predict seismic period*
  - *affected by soil*
  - *short period*
    - *high stiffness*
  - *long period*
    - *low stiffness*



"To ring the bell, the sexton must pull on the downswing of the bell in time with the natural frequency of the bell."

Water Load

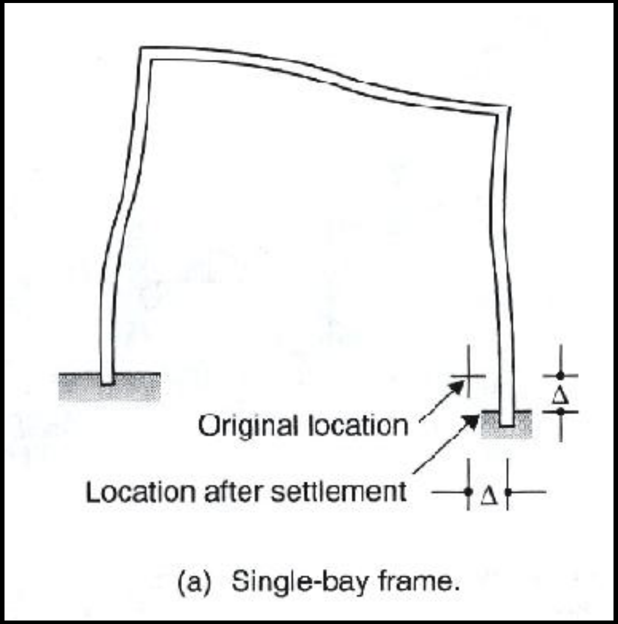
- rainwater – clogged drains
- ponding
- ice formation



mrfussycontracting.com

Thermal Load

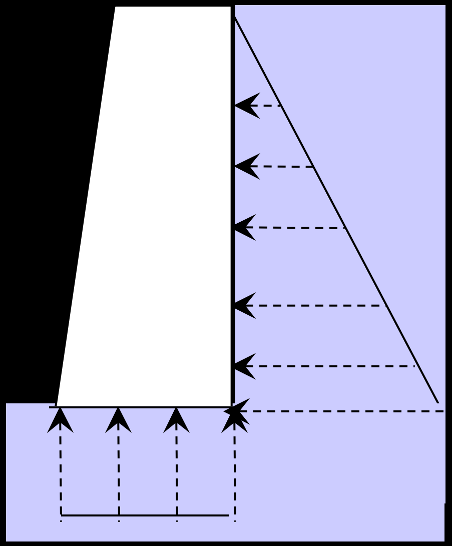
- stress due to strain
- restrained expansion or contraction
- temperature gradients
- composite construction



(a) Single-bay frame.

Hydraulic Loads

- *pressure by water in soil, H*
- *fluid pressure, F*
  - *normal to surface*
- *flood*



Building Codes

- *documentation*
  - *laws that deal with planning, design, construction, and use of buildings*
  - *regulate building construction for*
    - *fire, structural and health safety*
  - *cover <u>all</u> aspect of building design*
  - *references standards*
    - *acceptable minimum criteria*
    - *material & <u>structural</u> codes*

Building Codes

- *occupancy*
- *construction types*
- *structural chapters*
  - *loads, tests, foundations*
- *structural materials, assemblies*
  - *roofs*
  - *concrete*
  - *masonry*
  - *steel*

OCCUPANCY OR USE	UNIFORM (psf)	CONCENTRATED (lbs.)
1. Apartments (see residential)	—	—
2. Access floor systems		
Office use	50	2,000
Computer use	100	2,000
3. Armories and drill rooms	150	—
4. Assembly areas and theaters		—
Fixed seats (fastened to floor)	60	
Lobbies	100	
Movable seats	100	
Stages and platforms	125	
Follow spot, projections and control rooms	50	
Catwalks	40	

Prescribed Loads

- *ASCE-7*
  - *live load (not roof) reductions allowed*
- *International Building Code*
  - *occupancy*
  - *wind: pressure to static load*
  - *seismic: shear load function of mass and response to acceleration*
  - *fire resistance*

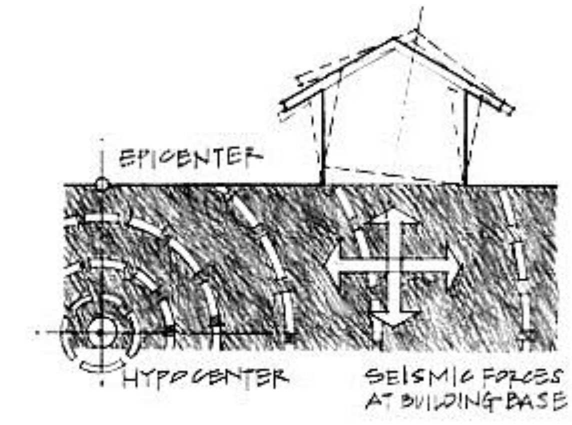


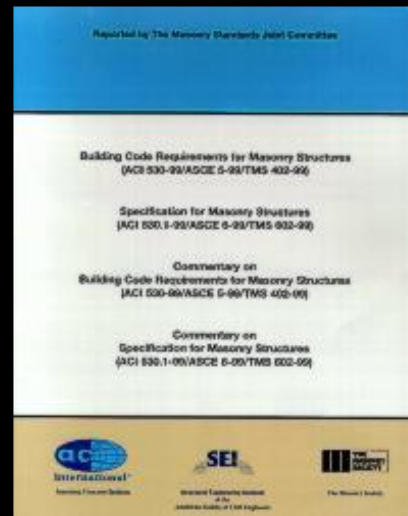
Figure 1.14 Earthquake loads on a structure.

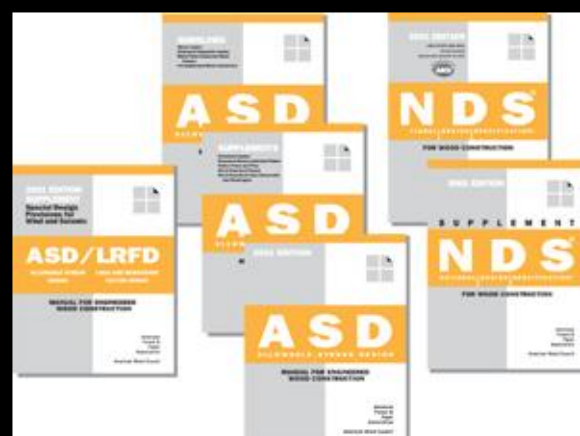
Structural Codes

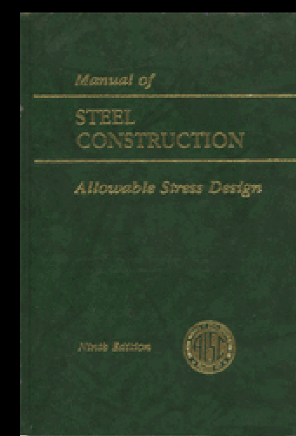
- *prescribe loads and combinations*
- *prescribe design method*
- *prescribe stress and deflection limits*
- *backed by the profession*
- *may require design to meet performance standards*
- *related to material or function*

Structural Codes

- Design Codes
  - Wood
    - NDS
  - Steel
    - AISC
  - Concrete
    - ACI
    - AASHTO
  - Masonry
    - MSJC







Design Methods

- *probability of loads and resistance*
- *material variability*
- *overload, fracture, fatigue, failure*
- *allowable stress design*

$$f_{actual} = \frac{P}{A} \leq f_{allowed} = \frac{f_{capacity}}{F.S.}$$

- *limit state design*
  - *design loads & capacities*

Allowable Stress Design

- *historical method*
- *a.k.a.*
  working stress,
  strength design
- *stresses stay in ELASTIC range*

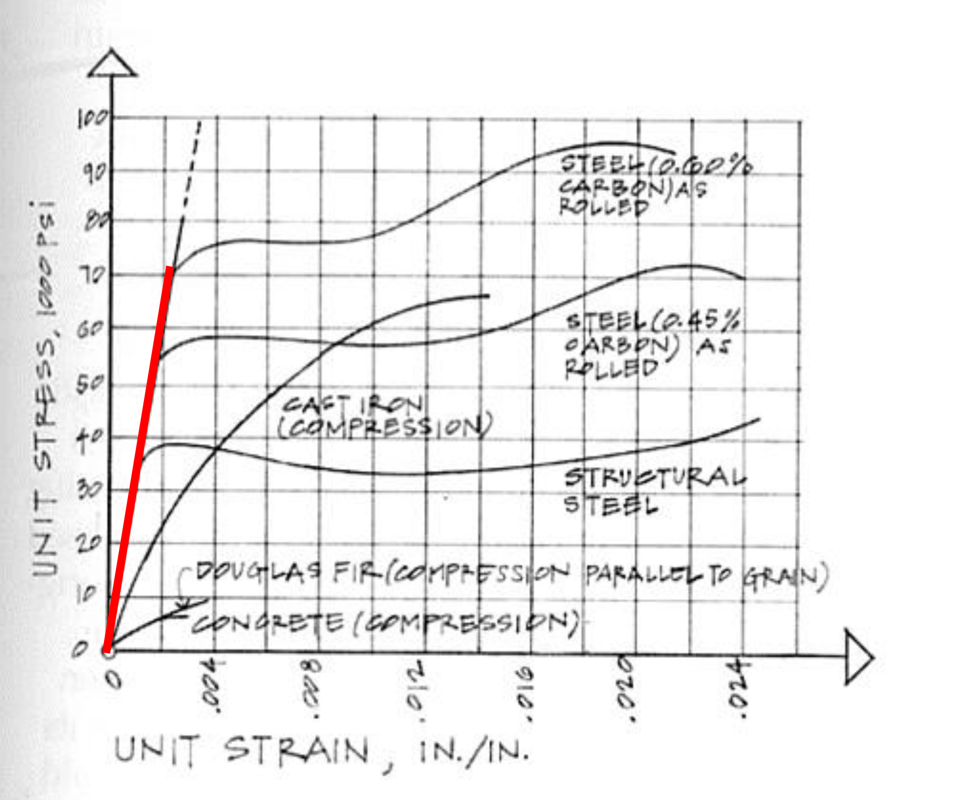


Figure 5.20 Stress-strain diagram for various materials.

ASD Load Combinations

ASCE-7 (2010)

- D
- $D + L$
- $D + 0.75(L_r \text{ or } S \text{ or } R)$
- $D + 0.75L + 0.75(L_r \text{ or } S \text{ or } R)$
- $D + (0.6W \text{ or } 0.7E)$
  - $D + 0.75L + 0.75(0.6W) + 0.75(L_r \text{ or } S \text{ or } R)$
  - $D + 0.75L + 0.75(0.7E) + 0.75S$
- $0.6D + 0.6W$
- $0.6D + 0.7E$

Limit State Design

- *a.k.a. strength design*
- *stresses go to limit (strain outside elastic range)*
- *loads may be factored*
- *resistance or capacity reduced by a factor*
- *based on material behavior*
- *"state of the art"*

Limit State Design

- *load and resistance factor design (LRFD)*
  - *loads:*
    - *not constant,*
    - *possibly more influential on failure*
    - *happen more or less often*
  - *UNCERTAINTY*

$$\gamma_D R_D + \gamma_L R_L \leq \phi R_n$$

ϕ *- Resistance factor*

γ *- Load factor for (D)ead & (L)ive load*

LRFD Load Combinations

ASCE-7 (2010)

- 1.4D
- 1.2D + 1.6L + 0.5(L_r or S or R)
- 1.2D + 1.6(L_r or S or R) + (L or 0.5W)
- 1.2D + 1.0W + L + 0.5(L_r or S or R)
- 1.2D + 1.0E + L + 0.2S
- 0.9D + 1.0W
- 0.9D + 1.0E
  - F has same factor as D in 1-5 and 7
  - H adds with 1.6 and resists with 0.9 (permanent)

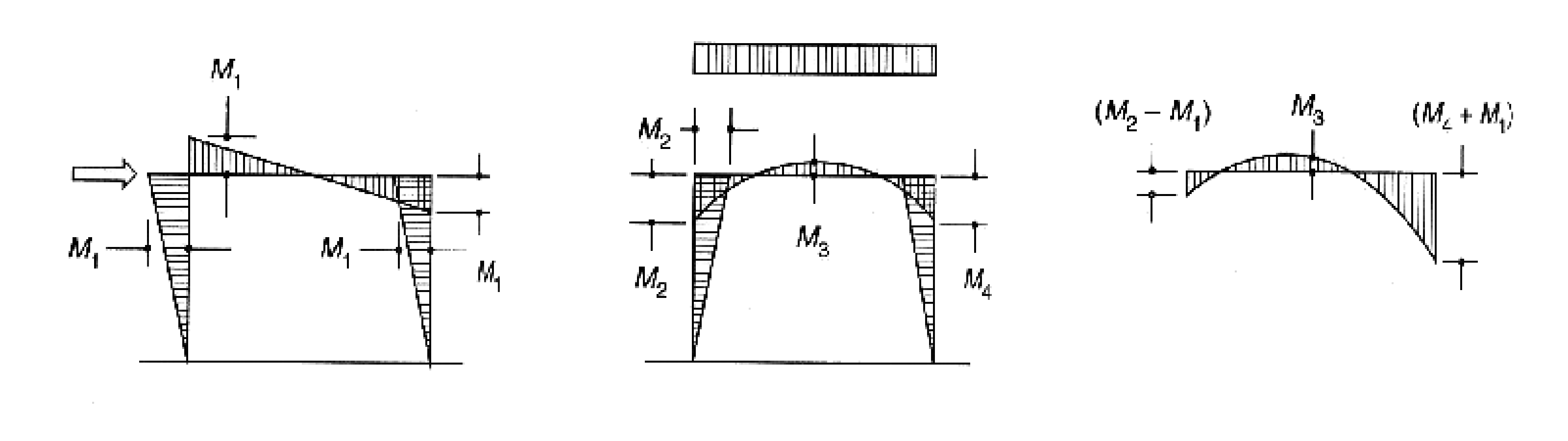
Deflection Limits

- *based on service condition, severity*

Use	*LL only*	*DL+LL*
Roof beams:		
Industrial	*L/180*	*L/120*
Commercial		
plaster ceiling	*L/240*	*L/180*
no plaster	*L/360*	*L/240*
Floor beams:		
Ordinary Usage	*L/360*	*L/240*
Roof or floor (damageable elements)		*L/480*

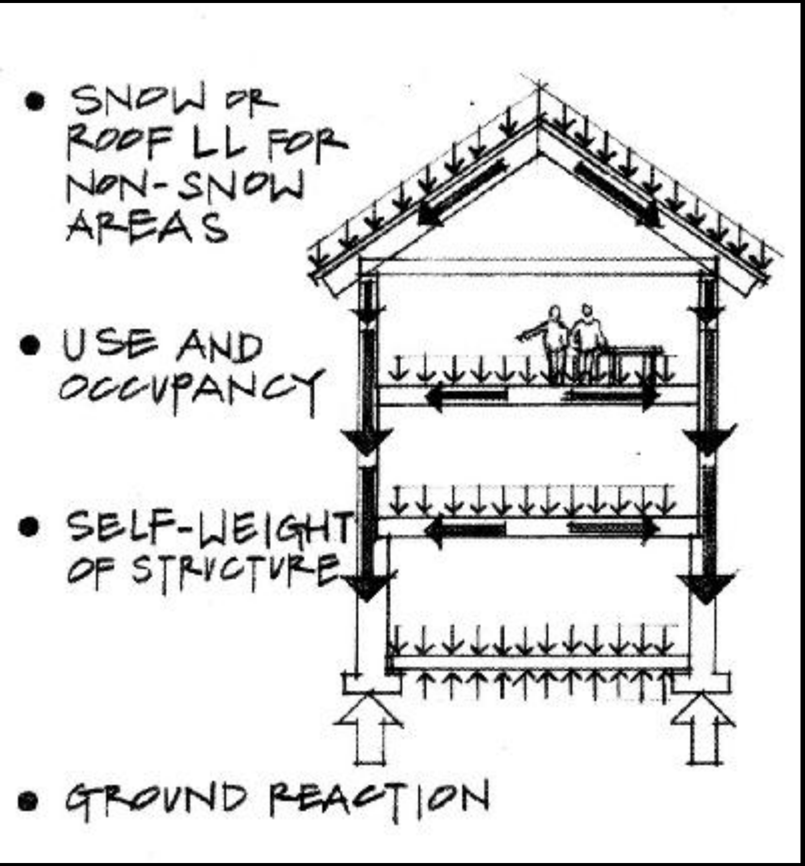
Load Conditions

- *loads, patterns & combinations*
  - *usually uniformly distributed gravity loads*
  - *worst case for largest moments...*
  - *wind direction can increase moments*



Structural Loads

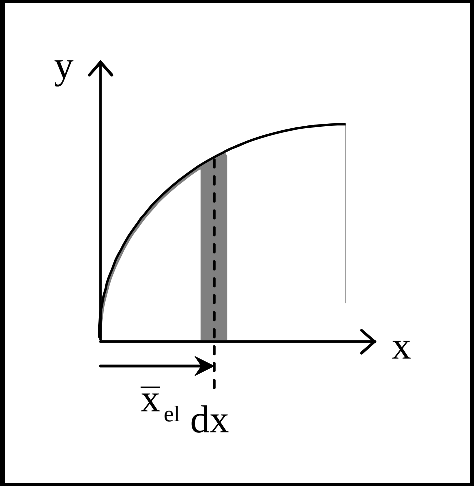
- *gravity acts on mass (F=m*g)*
- *force of mass*
  - *acts at a point*
    - *ie. joist on beam*
  - *acts along a "line"*
    - *ie. floor on a beam*
  - *acts over an area*
    - *ie. people, books, snow on roof or floor*

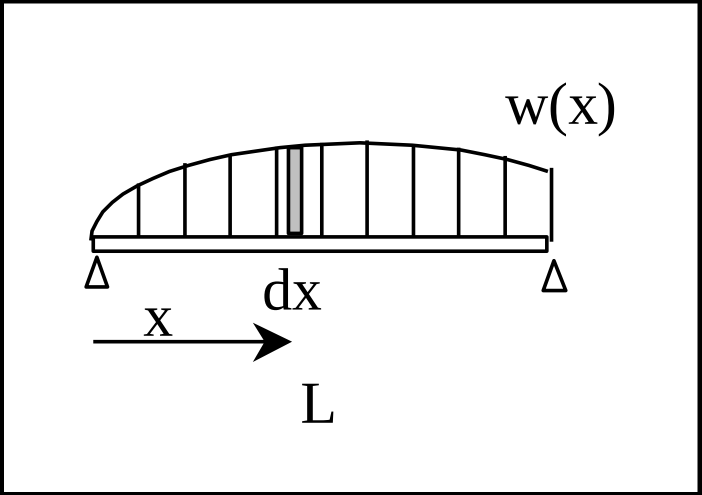


Equivalent Force Systems

- *replace forces by resultant*
- *place resultant where M = 0*
- *using calculus and area centroids*

$$W = \int_0^L w\,dx = \int dA_{loading} = A_{loading}$$

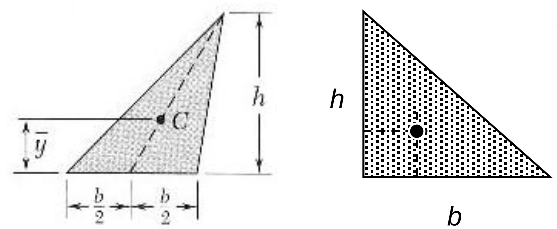
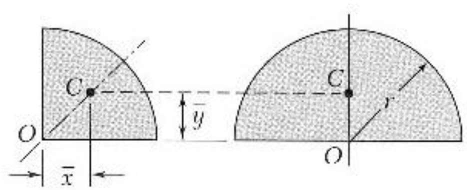
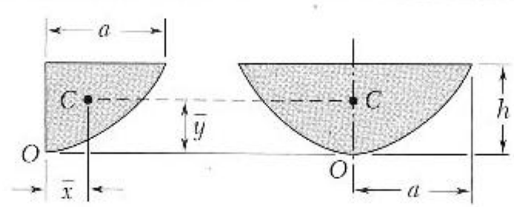




Area Centroids

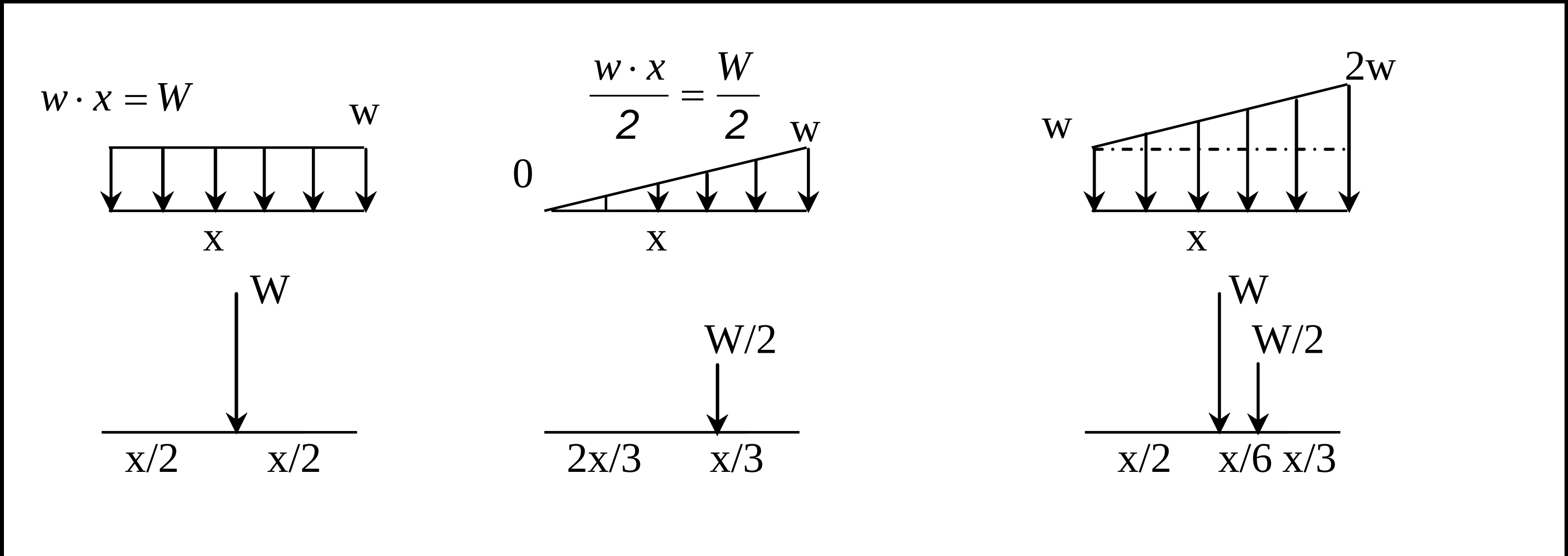
- *Table 7.1 – pg. 242*

Centroids of Common Shapes of Areas and Lines

Shape		$\bar{x}$	$\bar{y}$
Triangular area		$\frac{b}{3}$ *right triangle only*	$\frac{h}{3}$
Quarter-circular area		$\frac{4r}{3\pi}$	$\frac{4r}{3\pi}$
Semicircular area		0	$\frac{4r}{3\pi}$
Semiparabolic area		$\frac{3a}{8}$	$\frac{3h}{5}$
Parabolic area		0	$\frac{3h}{5}$

Equivalent Load Areas

- *area is width x "height" of load*
- *w is load per unit length*
- *W is total load*



Distributed Area Loads

- *w is <u>also</u> load per unit area*

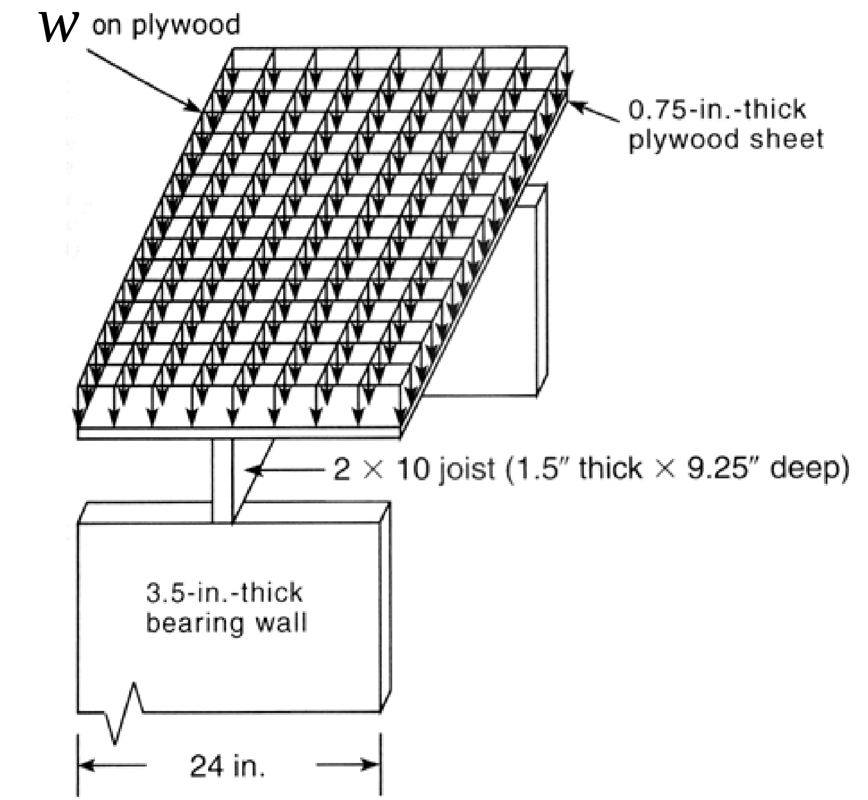
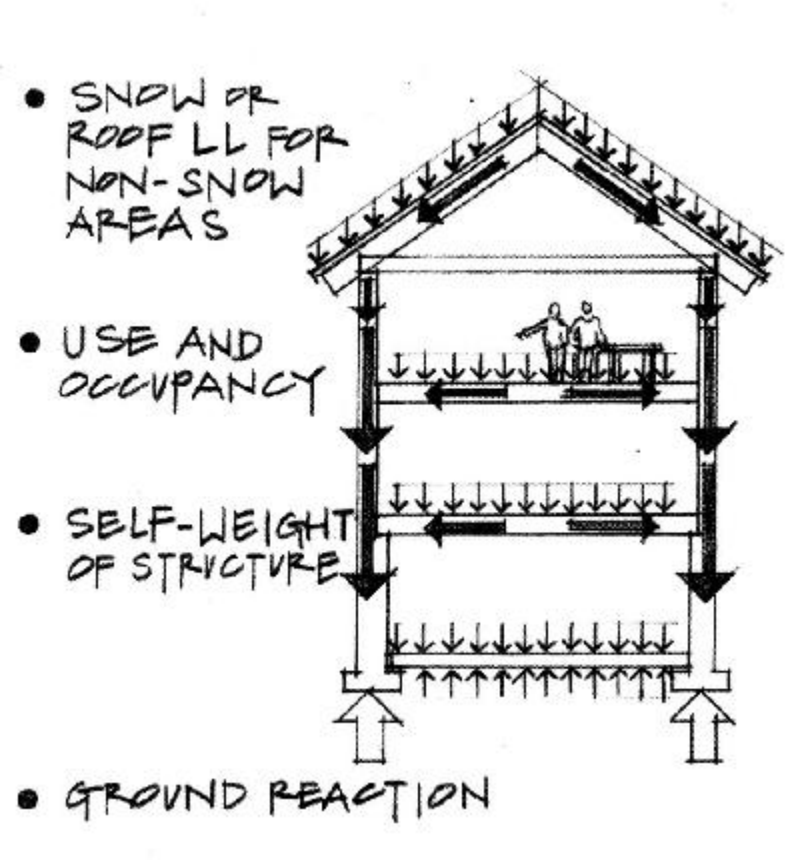


Figure 2.7 Area-distributed load (pressure) on floor decking.

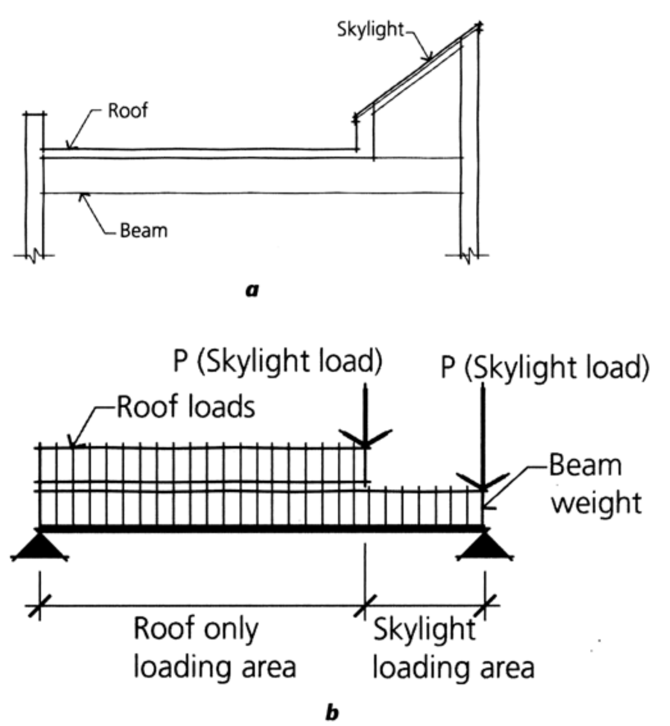
Load Tracing

- *how loads are transferred*
  - *usually starts at top*
  - *distributed by supports as actions*
  - *distributed by tributary areas*



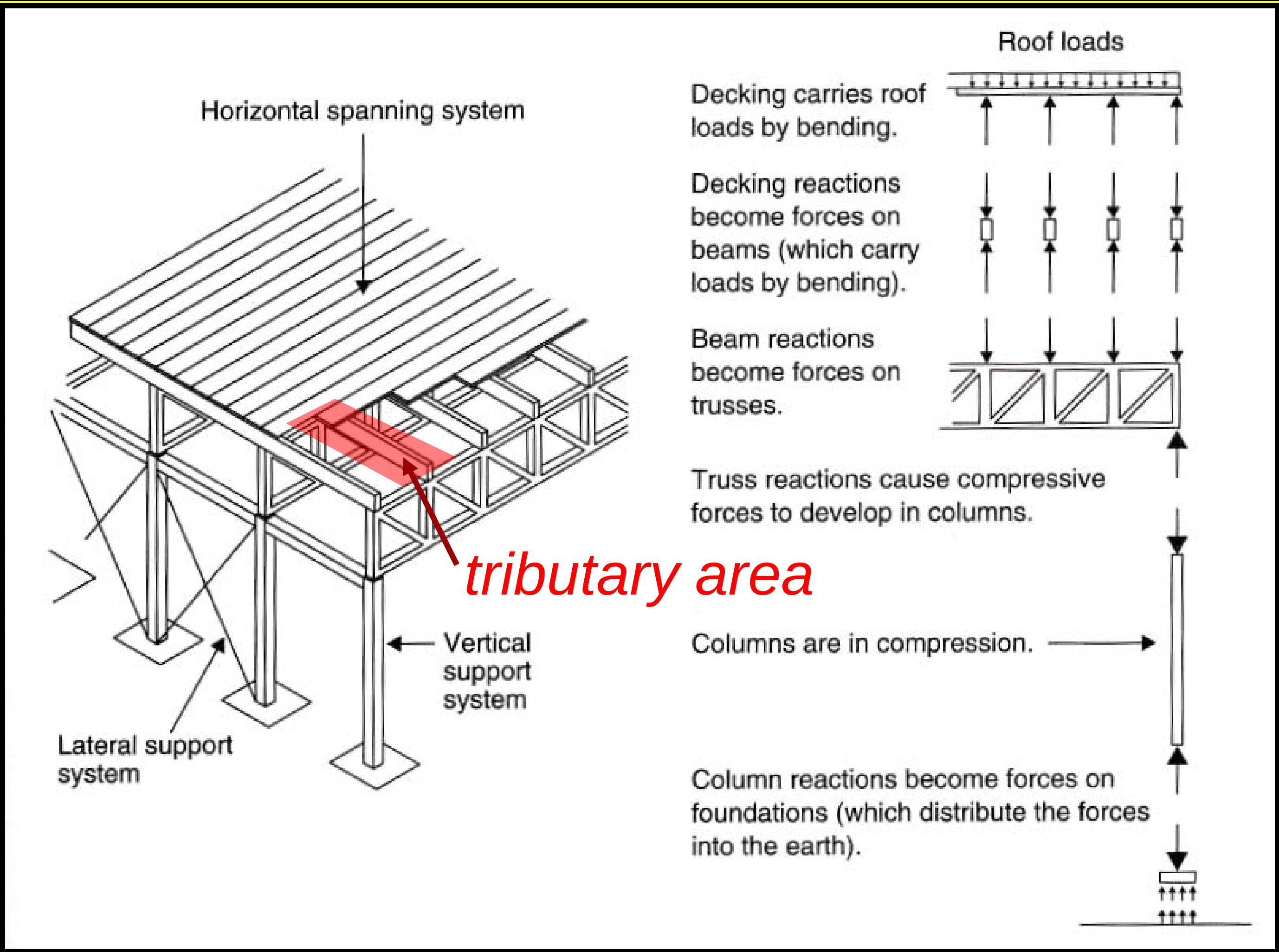
Load Tracing

- *areas see distributed area load*
- *beams or trusses see distributed line loads*
- *"collectors" see forces*
  - *columns*
  - *supports*



Figs. 1.1a, 1.1b Structural loading diagram of an architectural condition

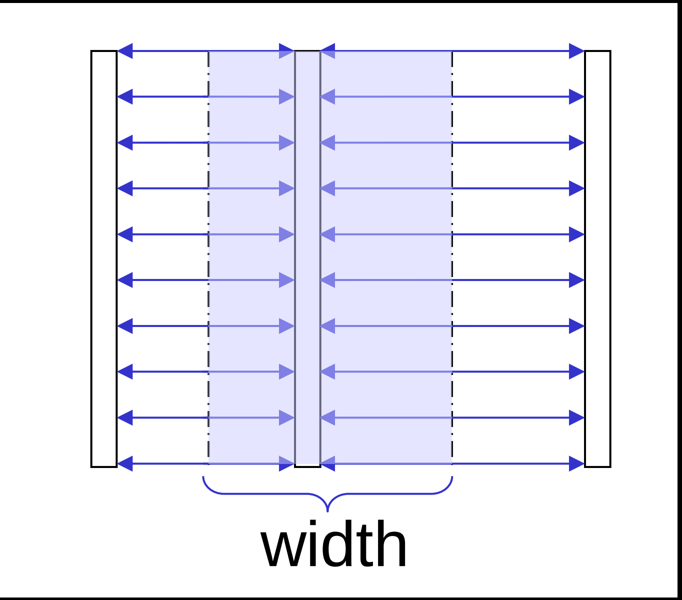
Load Tracing



Load Tracing

- *tributary load*
  - *think of water flow*
  - *"concentrates" load of area into center*

$$w = \left(\frac{load}{area}\right) \times (tributary\ width)$$



Load Tracing

www.columbia.edu

Patcenter
Rogers 1986

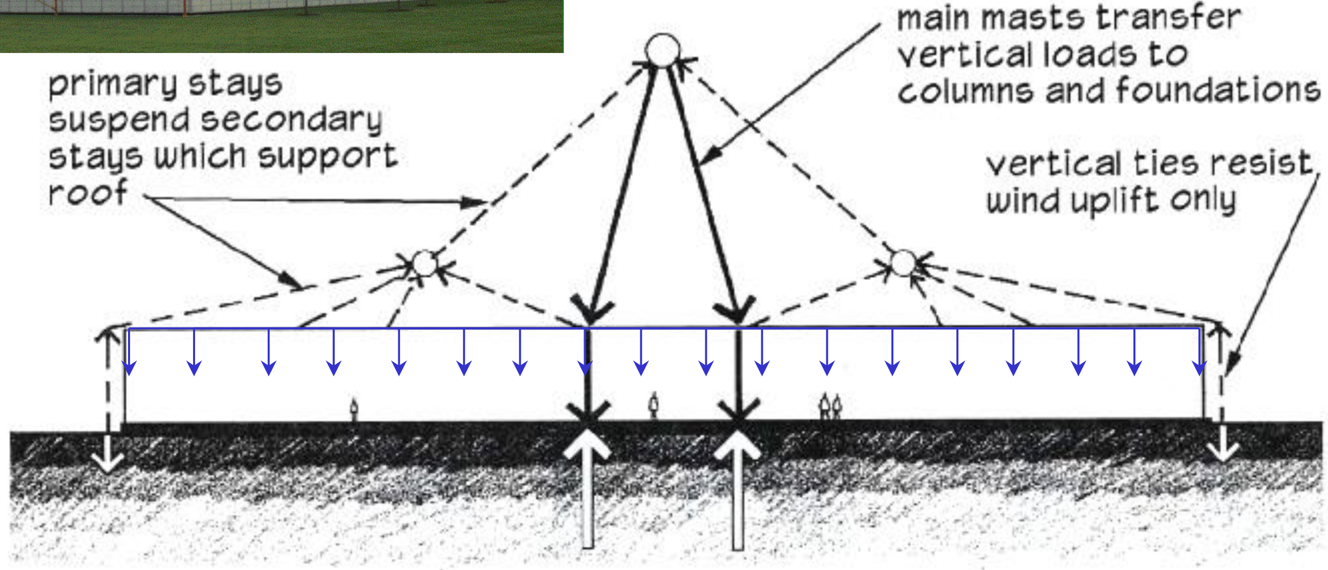


Figure 3.5: Patcenter, load path diagram.

Load Tracing

http://en.structurae.de

Alamillo Bridge
Calatrava 1992

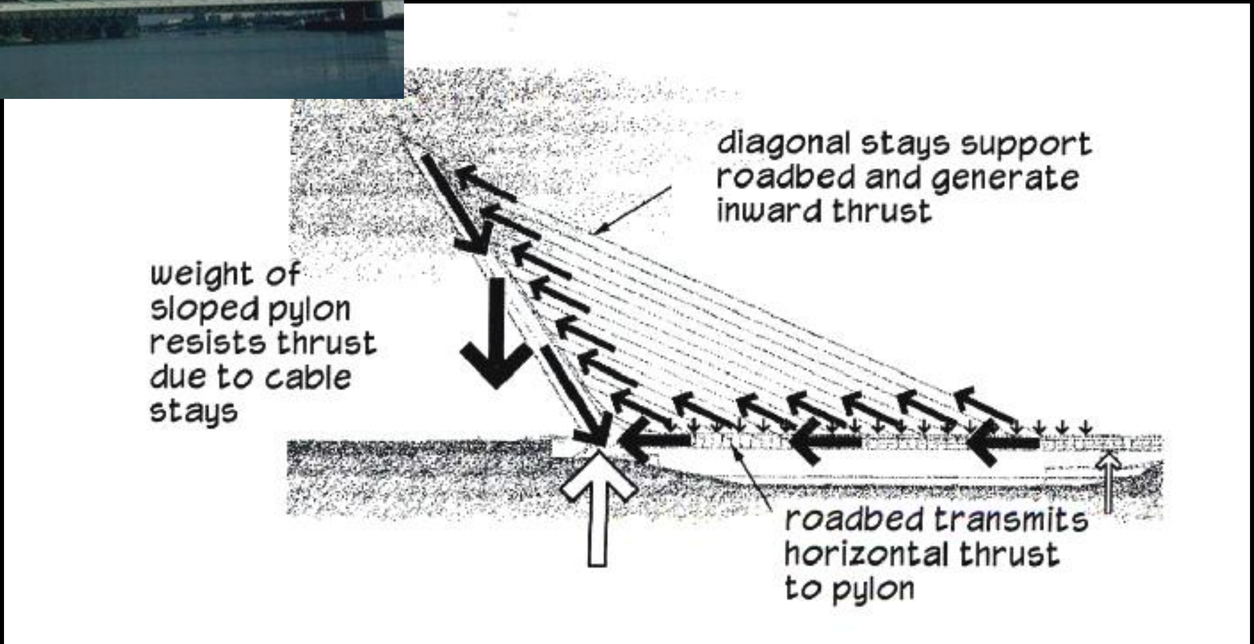
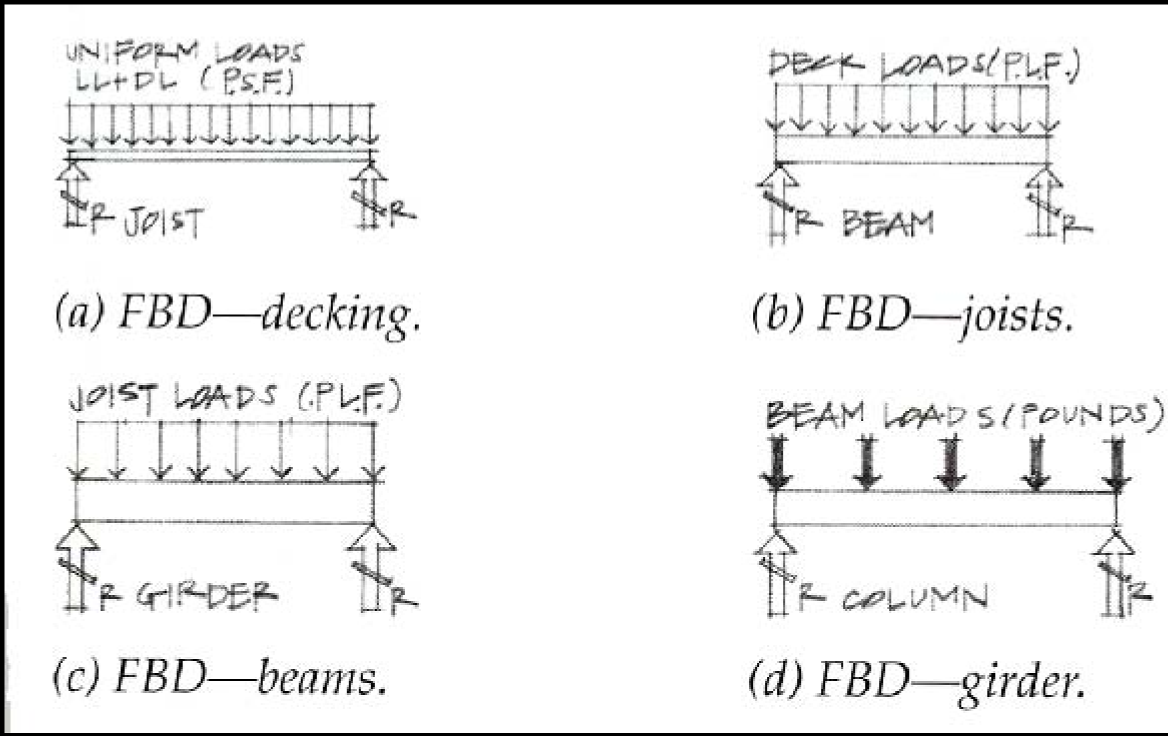


Figure 3.12: Alamillo bridge, load path diagram.

Load Paths

- *floors and framing*

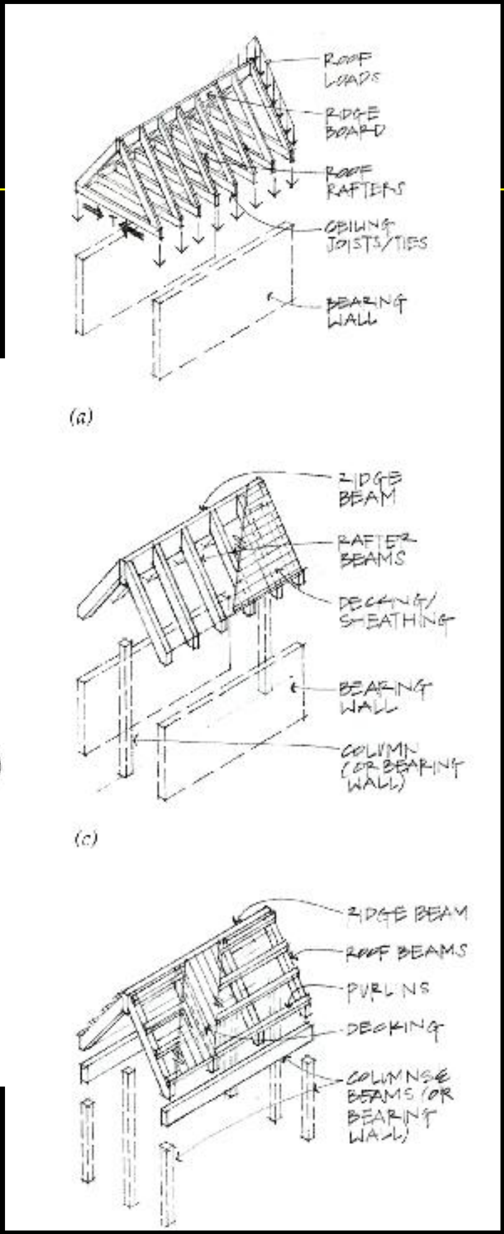


(a) FBD—decking.

(b) FBD—joists.

(c) FBD—beams.

(d) FBD—girder.



Load Paths

- *wall systems*

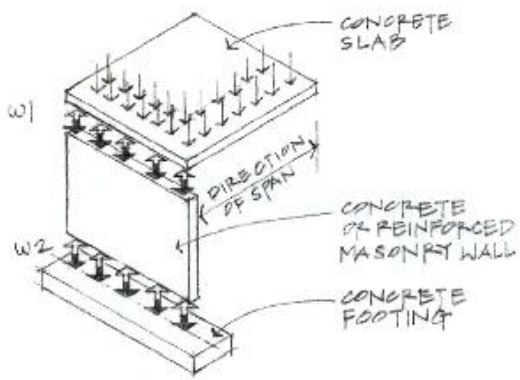


Figure 4.12 Uniform wall load from a slab.

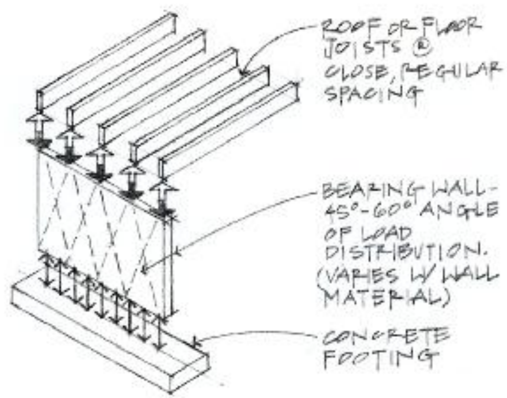


Figure 4.13 Uniform wall load from rafters and joists.

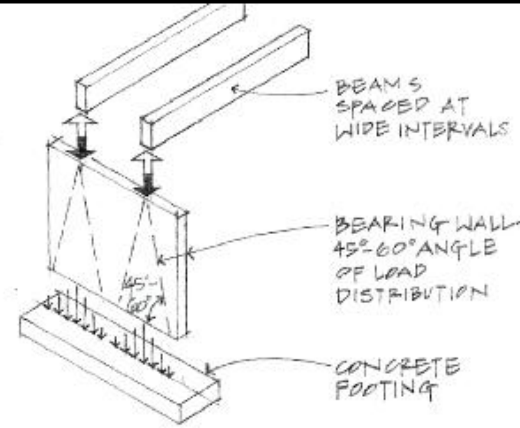


Figure 4.14 Concentrated loads from widely spaced beams.

Load Paths

- *openings & pilasters*

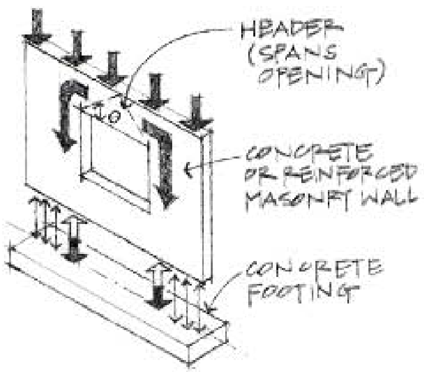


Figure 4.15 Arching over wall openings.

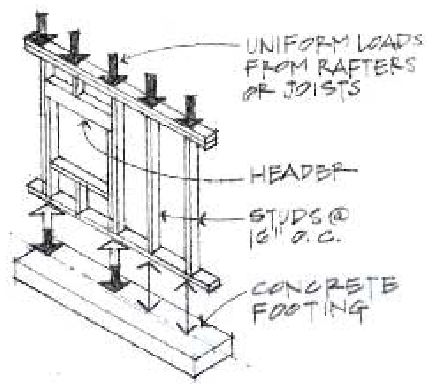


Figure 4.16 Stud wall with a window opening.

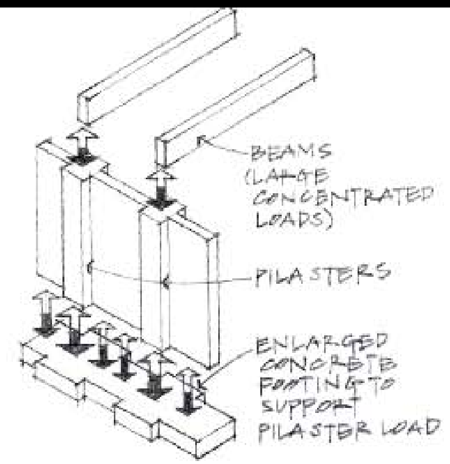


Figure 4.17 Pilasters supporting concentrated beam loads.

Load Paths

- *foundations*

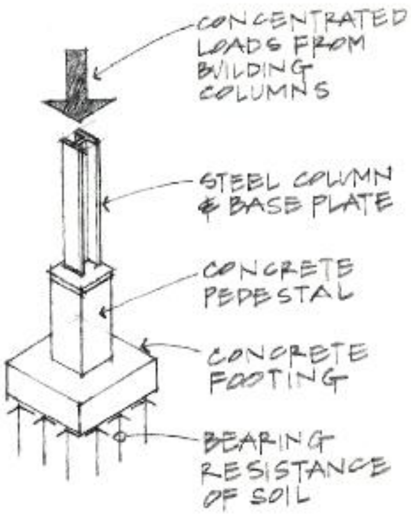


Figure 4.24 Spread footing.

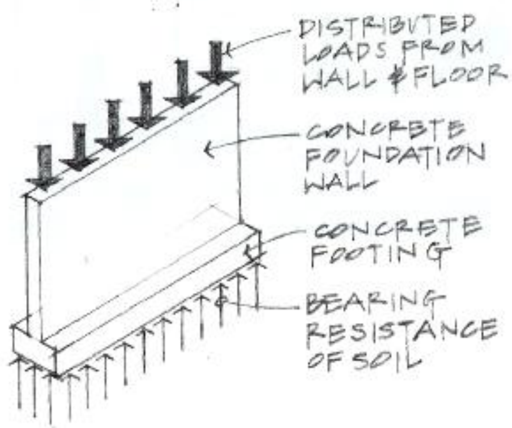


Figure 4.25 Wall footing.

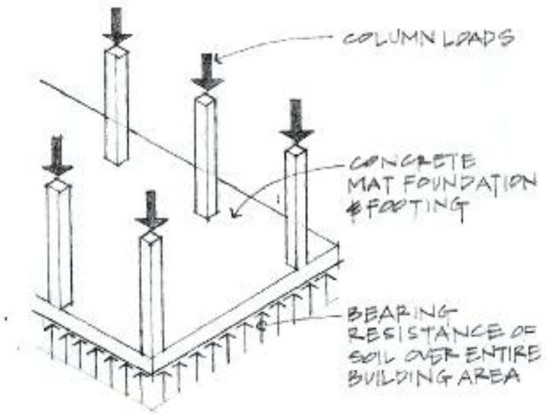


Figure 4.26 Mat or raft foundation.

Load Paths

- *deep foundations*

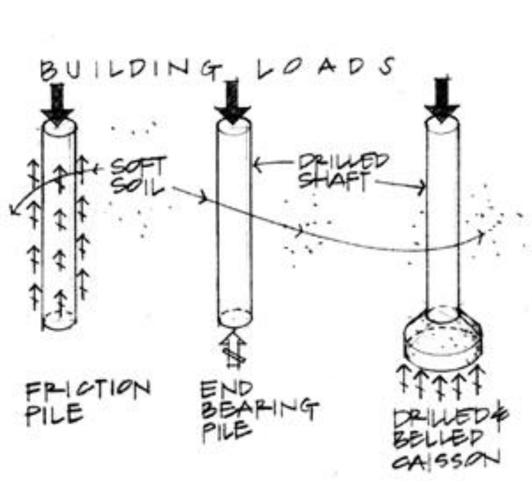


Figure 4.27 *Pile foundations.*

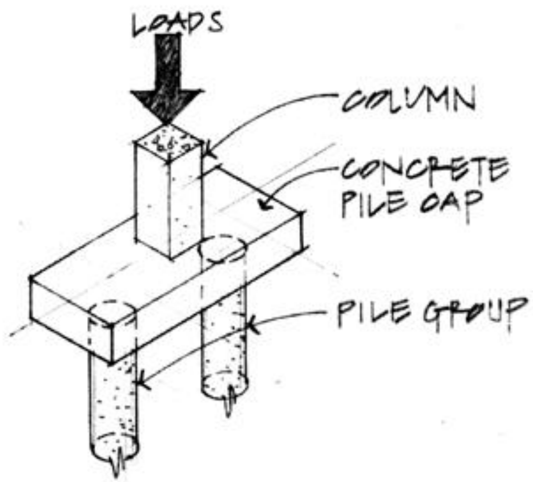


Figure 4.28 *Pile cap on one pile group.*

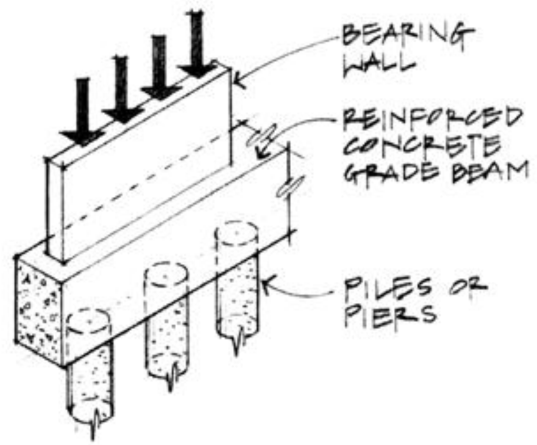
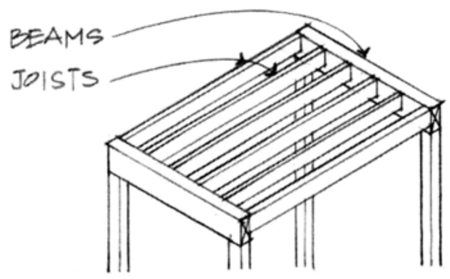


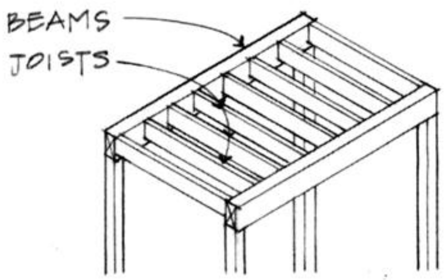
Figure 4.29 *Grade beam supporting a bearing wall.*

Spans

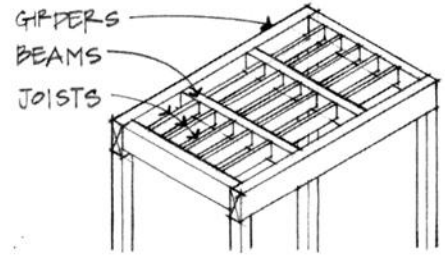
- *direction*
- *depth*



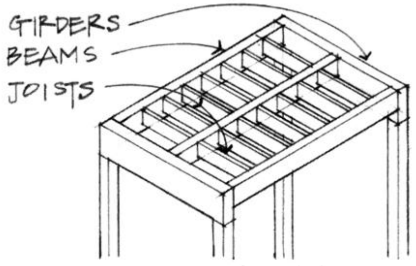
(a) Long, lightly loaded joists bearing on shorter beams create a more uniform structural depth. Space can be conserved if the joists and beams are flush framed.



(b) Short joists loading relatively long beams yield shallow joists and deep beams. The individual structural bays are more clearly expressed.



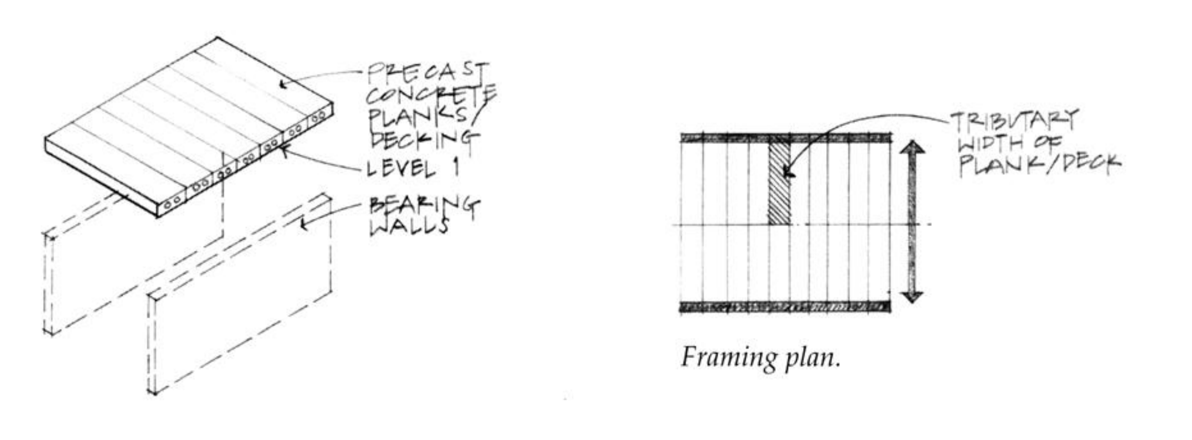
(c) Loads can be reduced on selected beams by introducing intermediate beams.



(d) The span capability of the decking material controls the spacing of the joists, while beam spacing is controlled by the allowable joist span.

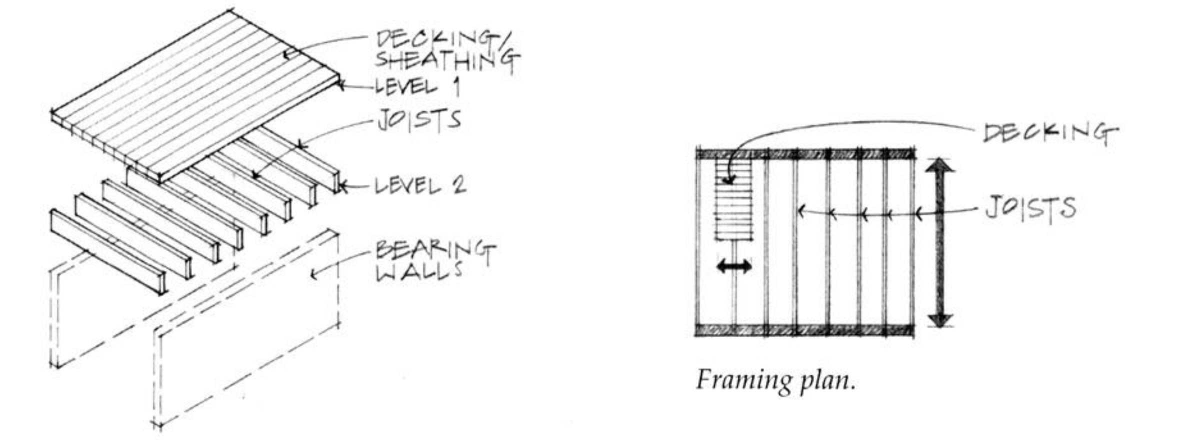
Levels

- *determine span at top level*
- *find half way to next element*
- **include self weight*
- *look for "collectors"*
- *repeat*
- *one:*



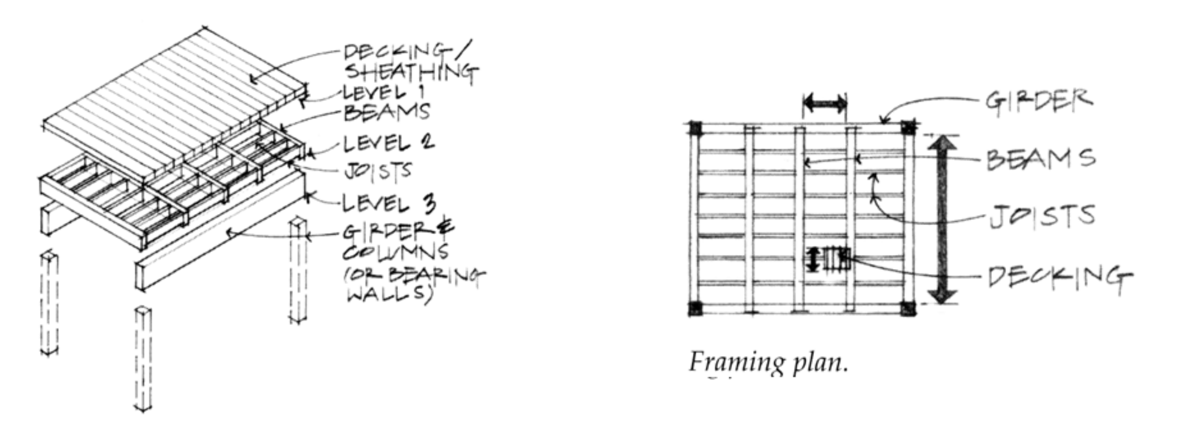
Levels

- *two:*



Framing plan.

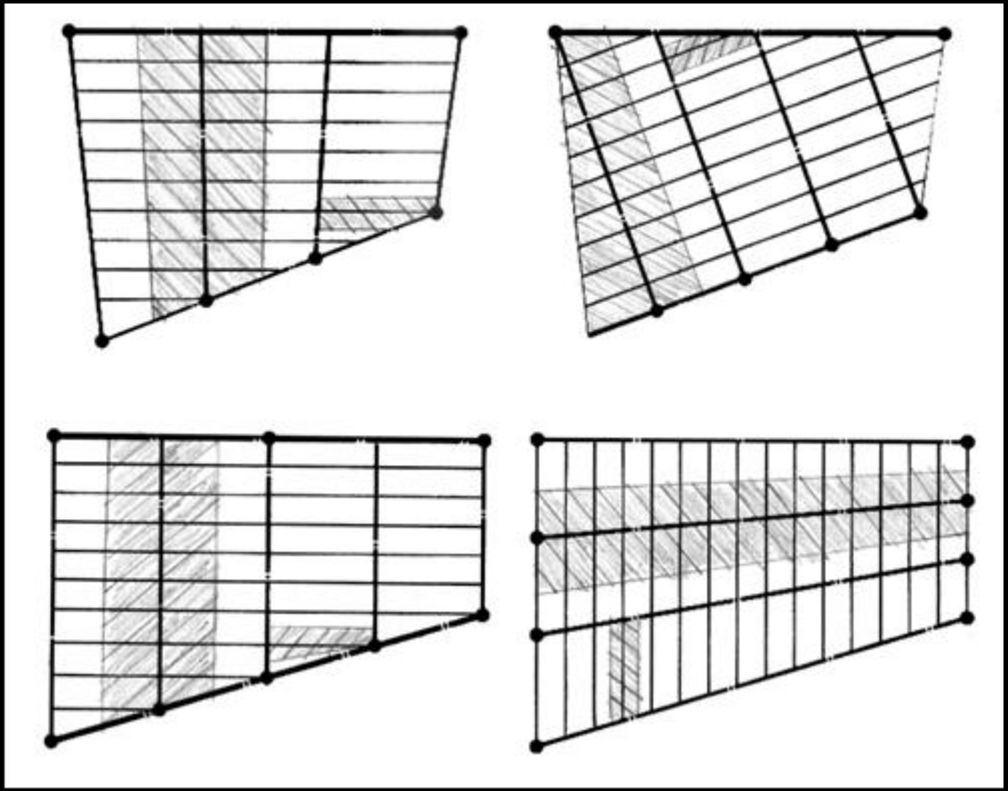
- *three:*

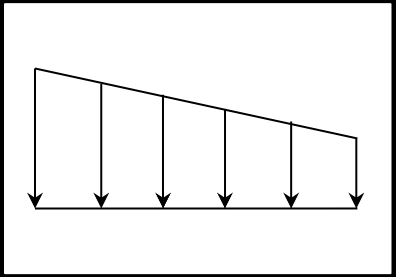


Framing plan.

Irregular Configurations

- tracing still ½ each side





Slabs

- *edge support*

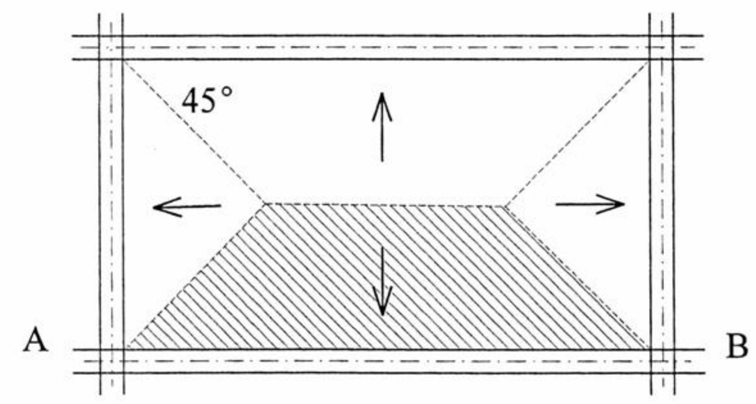


Figure 2-16: Supporting beams' contributing areas for reinforced concrete floor system.

- *linear and uniform distribution*

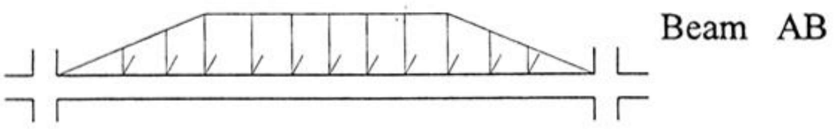


Figure 2-17: Trapezoidal distributed load for Beam AB of Fig. 2-16.

Girders and Transfer

- *openings*
  - *no load & no half way*
- *girder actions at beam supports*

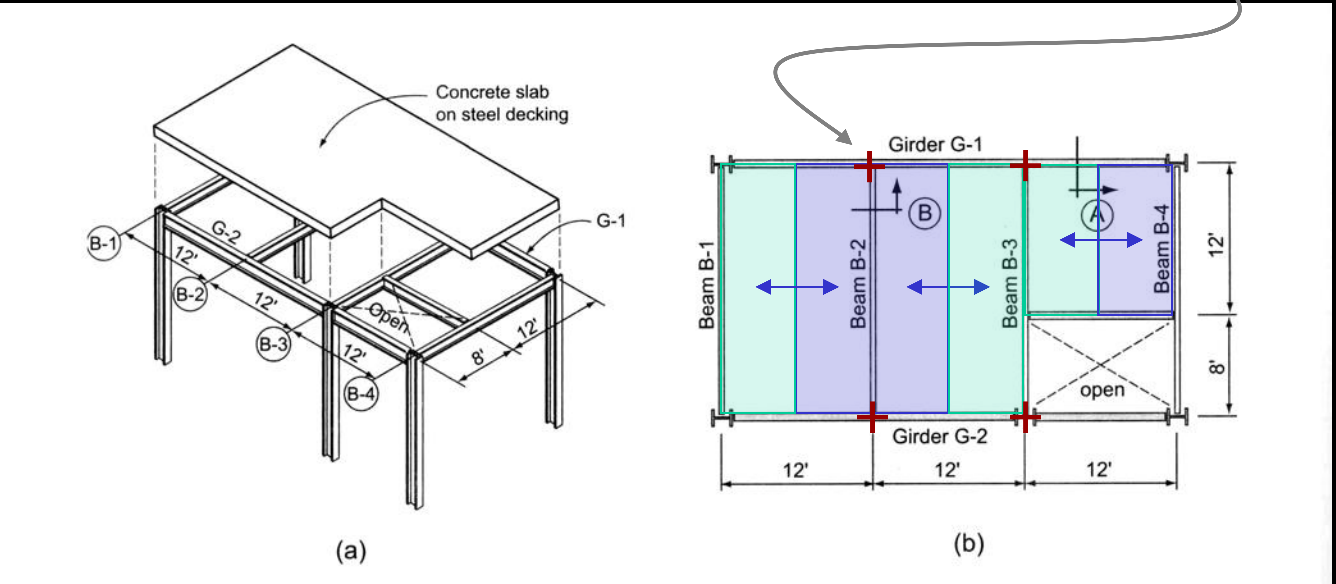
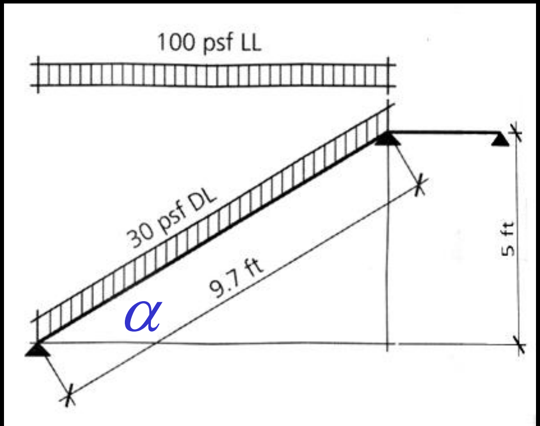


Figure 5.54 (a) Isometric view of partial steel framing arrangement. (b) Partial floor framing—office structure.

Sloped Beams

- *stairs & roofs*
- *projected live load*
- *dead load over length*



- *perpendicular load to beam:*

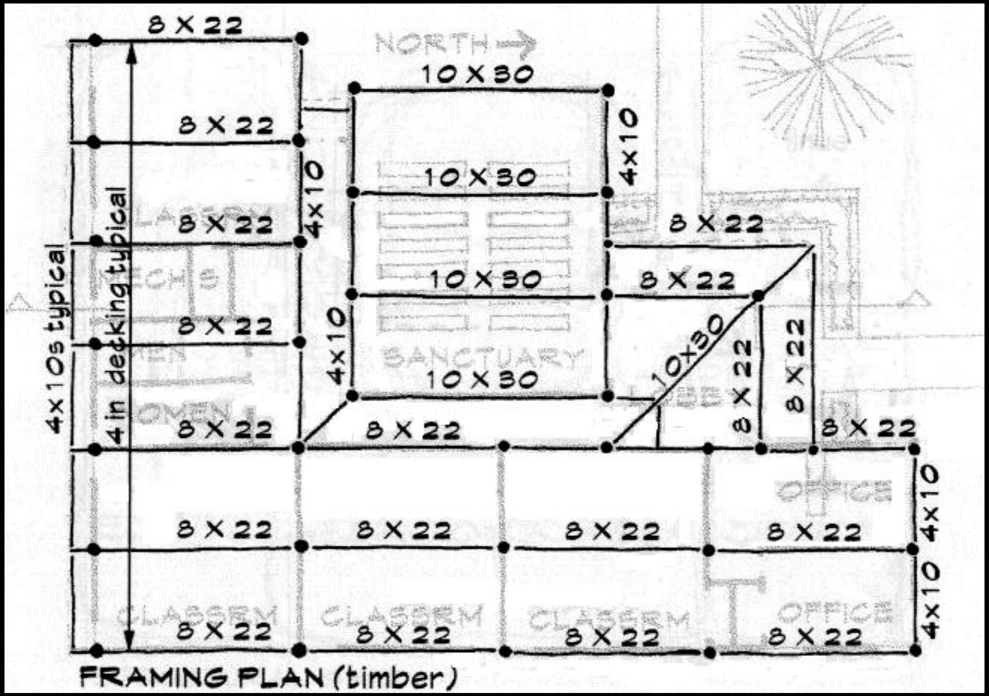
$$w_{\perp} = w \cdot \cos\alpha$$

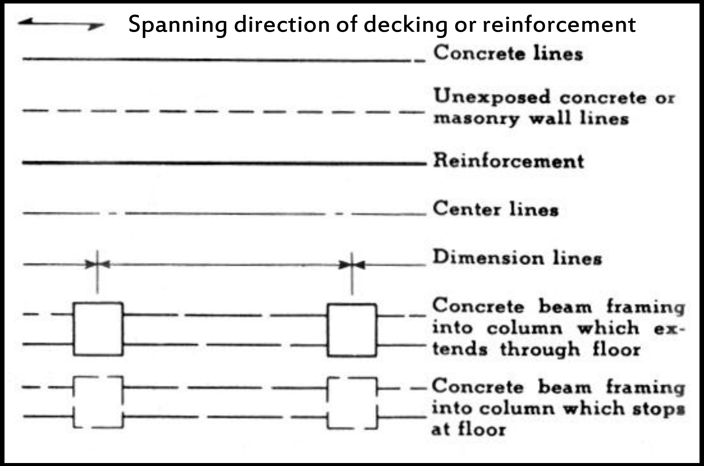
- *equivalent distributed load:*

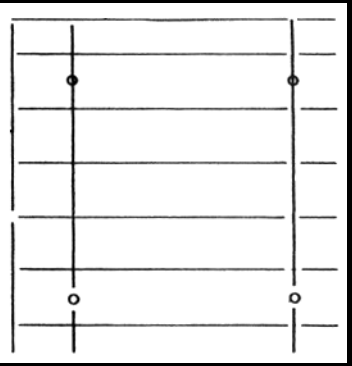
$$w_{adj.} = \frac{w}{\cos\alpha}$$

Framing Diagrams

- *beam lines and "dots"*
- *breaks & ends*

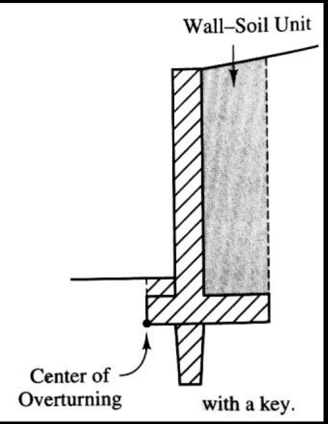


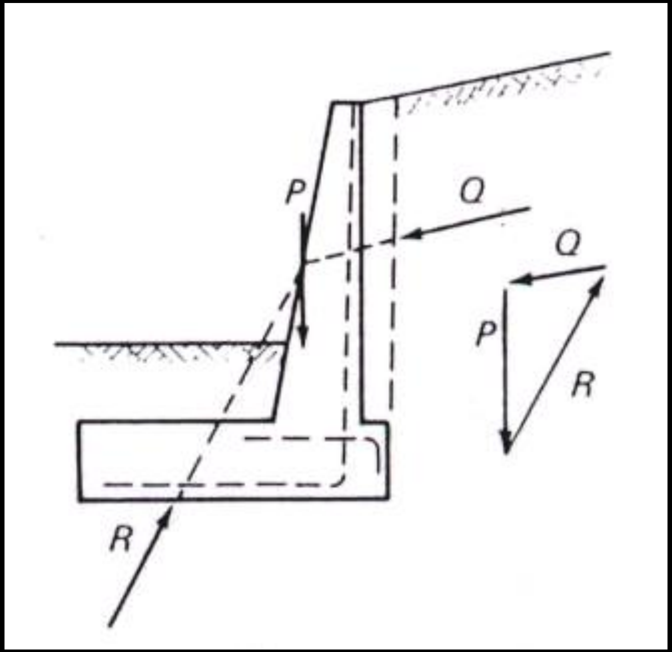




Retaining Walls

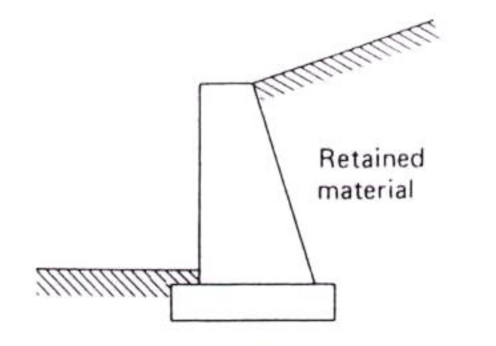
- *purpose*
  - *retain soil or other material*
- *basic parts*
  - *wall & base*
  - *additional parts*
    - *counterfort*
    - *buttress*
    - *key*





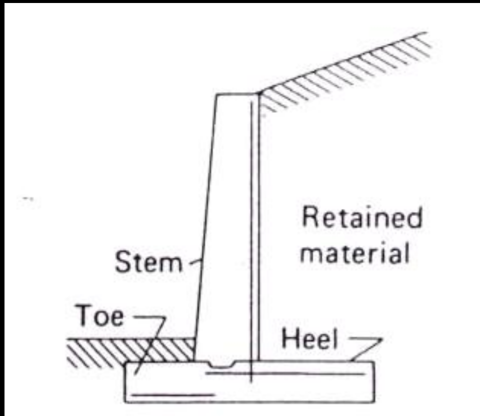
Retaining Wall Types

- “gravity” wall
  - usually unreinforced
  - economical & simple



(a) Gravity wall

- cantilever retaining wall
  - common



(b) Cantilever retaining wall

Retaining Wall Loads

- *gravity*

  $W = \gamma \times V$

- *fluid pressure*

  $p = \omega' \times h$

  $P = ½ \; p \; h$ *at h/3*

- *friction*

  $F = \mu \times N$

- *soil bearing pressure, q*

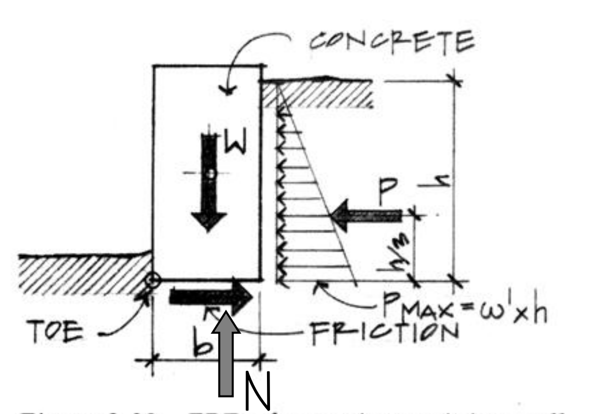


Figure 3.80 FBD of a gravity retaining wall.

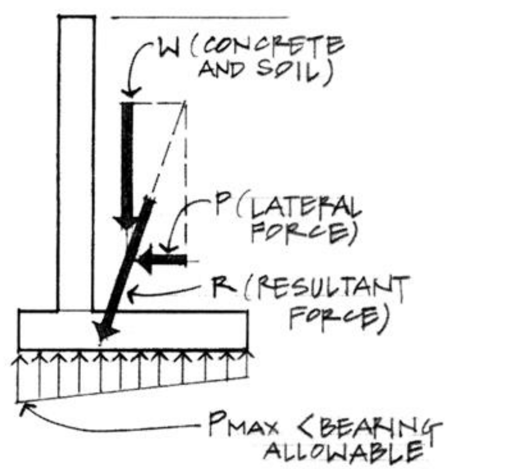
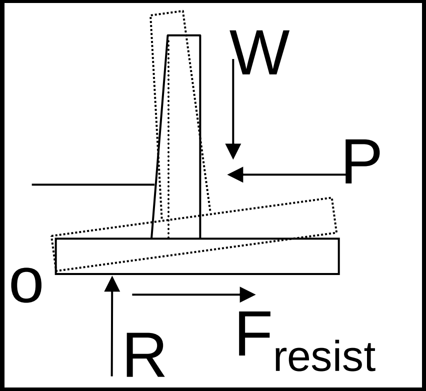


Figure 3.81 Bearing pressure under the wall footing.

Retaining Wall Equilibrium

- *sliding - overcome friction?*
- *overturning at toe (o) - overcome mass?*



$$SF = \frac{M_{resist}}{M_{overturning}} \geq 1.5 - 2$$

$$SF = \frac{F_{horizontal-resist}}{F_{sliding}} \geq 1.25 - 2$$

Pressure Distribution

- *want resultant of load from pressure inside the middle third of base (kern)*
- *triangular stress block with p_{max}*
- *x = 1/3 x width of stress*
- *equivalent force location:*

$$W \cdot x = \frac{p_{max} 3x}{2} \cdot \frac{x}{3}$$

$$p_{max} = \frac{2W}{3x} = \frac{2W}{a}$$ *when a is fully stressed*

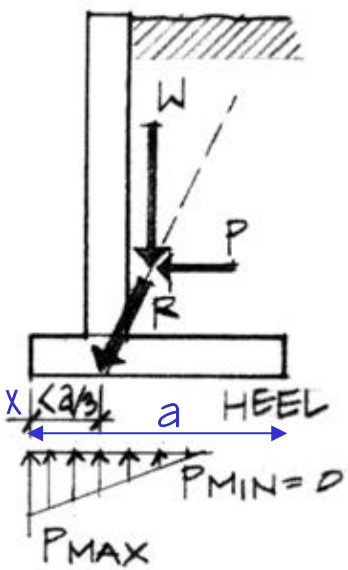


Figure 3.88 Tension possible at the heel.

Wind Pressure

- distributed load
- "collected" into V
- lateral loads must be resisted

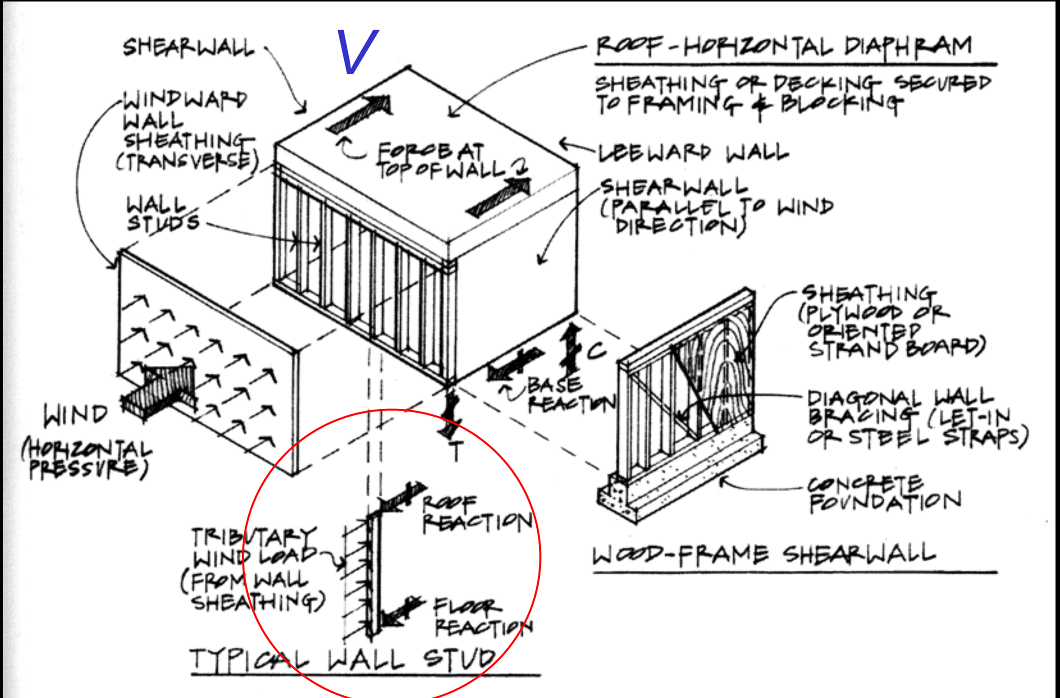


Figure 4.48 Exploded view of a light-framed wood building showing the various lateral resisting components.

Bracing Configurations

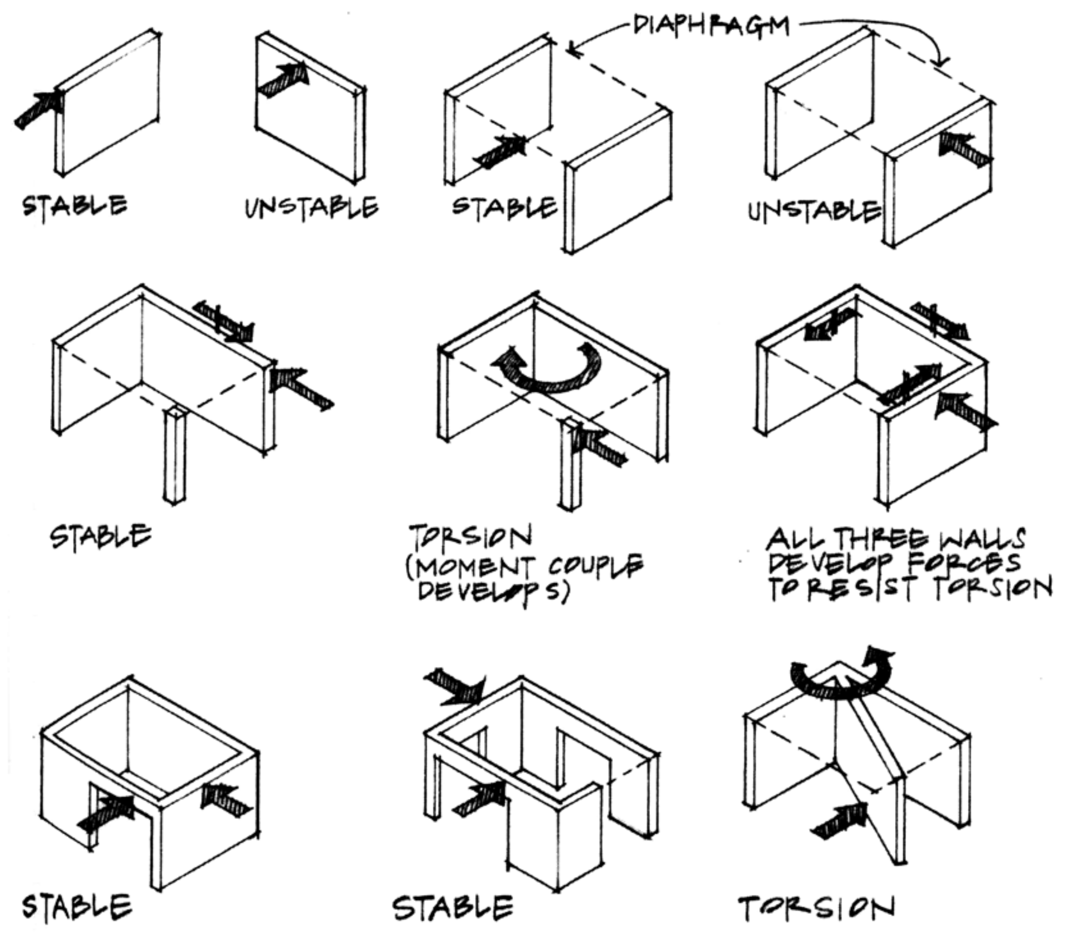


Figure 4.54 Various shearwall arrangements—some stable, others unstable.