Early Multi-story frames

Initiated before the depression:

- Rockefeller Center, New York, 1931
- Empire State Building, New York, 1931
  \[381 \text{ m, 1250'} 102 \text{ floors}\]
  Shreve, Lamb, and Harmon

Building height (meters) by year

- North America
- Asia
- Australia
- Europe
- Oceania
- Middle East


150 200 250 300 350 400 450
World's Tallest Buildings

It may seem like little progress has been made since 1931.
In fact, significant progress has been made:

- Weight of material required.
  - Optimization
  - Composite construction
- Construction safety
  - 1 man per million used to be acceptable
- Structural reliability, especially for seismic
- Flexibility of architecture with little increased design time

Premium for height

- Floor system weight floor is constant
- Vertical elements must increase towards base to take gravity
  - twice as much steel as one story building with the same floor area
  - material increases as \( \frac{n+1}{2} \) where \( n \) = number of floors
- Structural reliability, especially for seismic
- Flexibility of architecture with little increased design time
**Premium for height**

Gravity system:

- Force in column on top floor: 0g
- Force in column on 2nd from top floor: 3g
- Force in column on 3rd from top floor: 6g
- Force in column on 4th from top floor: 9g
- And so on.

When considering gravity, if you decide to double the number of stories you must also double the strength and weight of the columns.

Because:

If building has \( n \) floors

\[
\sum P_{\text{top}} = \frac{n+1}{2} \times 10g
\]

\[
A_{\text{col}} = \frac{\text{m}}{\text{s}}
\]

\[
\therefore \text{Average force per floor} = \frac{n+1}{2} \times 10g \rightarrow \frac{n+1}{2}
\]

**Lateral load resisting system:**

- Vi = 1 * V_max / n, where i is the story number
- \( M_{\text{cum}} = \sum_i (V_i \times h^2 + i) = \sum_i (i^2 \times h + V_{\text{cum}} / n) \)
- \( P_{\text{cum}} = 0.5 \times M_{\text{cum}} / b = V_{\text{max}} \times h / (n^2 b) \times \sum_i i^2 \)
Constraints of Design of Frames:

a. Architect and owner decide much of the layout and column placement
   e.g. if seismic controls, try to use symmetric plan to minimize twisting
b. Movement: corridors, elevators, stairs
c. Communications equipment
d. Environmental ("mechanical")
   - HVAC, power, lights
e. Safety (e.g. fire)
f. Strength
g. Serviceability
h. Sustainability (minimize energy for construction and use, pollution, waste, use of newly mined raw materials)

Factors leading to decreasing steel weight/square foot of floor area over the years:

a. Innovative structural systems which optimize distribution of material
   e.g. essentially increase moment of inertia of building without increasing its weight: tube, brace to outermost columns, cap truss
b. Composite construction
c. High strength materials for little increase in cost
d. Low weight partitions and utilities
e. Welding (saves 8-15% steel)
f. Enhanced theories of strength and stability
g. Computers
Gravity Systems
- Support all gravity loads
  Dead
  Live (reduced)
  Roof Live
  Snow
  Rain

Gravity Systems
- Four key components
  1. Floor framing
  2. Gravity (leaner) columns
  3. Transfer girders
  4. Foundations
- Typical Systems
  1. Floor system
     - composite steel W-shape beams framing into steel W-shape girders framing into gravity columns (or lateral)

Gravity Systems
  2. Gravity (leaner) columns
  Columns that are framed by beams with shear tabs or similar connections
  Isolates gravity system from lateral-resistance system
  Analysis conducted by gravity load takedown (see live load reduction example)
  Should gravity column be designed for any moment, or to cap axial strength below 1.0?
3. Transfer girders

If columns are terminated, large transfer girders or systems are needed; forces need to be considered from all load combinations for design.

Typical transfer girder system

Influence Area

Tributary area is an area assumed to contribute load to a particular member.

Influence area is the total area upon which the load has an influence on the member, usually larger than the tributary area.

Influence area is a two-dimensional extension of the influence line concept. Use Mueller-Breslau principle.
Live Load Reduction

- ASCE 7 Minimum Design Loads for Buildings

If \( L_o \leq 100 \text{psf} \), \( A_i \geq 400 \text{ft}^2 \)

\[
L = L_o \left[ 0.25 + \frac{15}{A_i \cdot L_o} \right] \geq 0.5 L_o \quad \text{(one floor)}
\]
\[
\geq 0.4 L_o \quad \text{(otherwise)}
\]

\( A_i = A_{tributary \text{ area for column}} \)
\( A_b = A_{tributary \text{ area for beam}} \)

See ASCE 7 Table 4.2 for other values of \( K_o \)

Live Load Reduction

No reduction for roof beams, girders, or top most column.

Also no reduction for:
- public assembly area
- garages
- one way slabs

Example:

1. Analyze for live load e.g. \( L_o = 75 \text{psf} \)

Bay Spacing 40'\times40'

Beam \( w_i = 0.75 \text{k/ft} \)

\[ M_i = \left( w \cdot \frac{L}{2} \right) \]

- Girder 3 loads of 30 k each gives \( M_i = \left( P/I \right)/2 \)
  \[ = 600 \text{ k-ft} \]
- Columns: \( 0.075 \times (40'\times40') \)
  \[ = 120 \text{ k} \]

\( P_o = 120 \text{ k} \)
\( 3 = 240 \text{ k} \)
\( 2 = 360 \text{ k} \)
\( 1 = 480 \text{ k} \)
2. Calculate $A_f$ for each member:

$$A_f^b = 2(10)(40) = 800\, \text{ft}^2 > 400\, \text{ft}^2$$

$$A_f^q = 4(40)(40) = 3200\, \text{ft}^2$$

$$A_f^{c15} = 4(40)(40) = 6400\, \text{ft}^2$$

(One story only, does not include roof)

$$A_f^{c15} = 4(40)(40)(2) = 12800\, \text{ft}^2$$

$$A_f^{col} = 19200\, \text{ft}^2$$

3. Apply Live Load Reduction:

Beam:

$$0.25 + \frac{15}{\sqrt{K_{L_{2f}}}} = 0.25 + \frac{15}{300} = 0.875 \geq 0.5$$

$$M_{fa} = 0.78(0.5) = 0\, \text{ft}$$

Girder:

$$0.25 + \frac{15}{\sqrt{K_{L_{2f}}}} = 0.51 \geq 0.5$$

$$M_{fa} = 0.5(600\, \text{ft}) = 300\, \text{ft}$$

Column:

3: $25 + \frac{15}{\sqrt{K_{L_{2f}}}} = 0.42 \geq 0.8 \Rightarrow \text{use 0.8}$

$$P_{fa} = 0.5(320) = 160\, \text{kips}$$

2: $25 + \frac{15}{\sqrt{K_{L_{2f}}}} = 0.38 \geq 0.4 \Rightarrow \text{use 0.4}$

$$P_{fa} = 0.4(240) = 96\, \text{kips}$$

1: $25 + \frac{15}{\sqrt{K_{L_{2f}}}} = 0.26 \geq 0.4 \Rightarrow \text{use 0.4}$

$$P_{fa} = 0.4(340) = 136\, \text{kips}$$

Floor System Overview

Metal deck on beams and girders with shear studs installed
Open-Web Steel Joists

Open-web steel joists (lightweight trusses) may be used in place of steel beams for lighter loading conditions (AISC, 2008).

Steel Joist Connections

Joists ends typically sit on top of the supporting girders (AISC, 2008).

Steel Joists

(AISC, 2008)
Concentrically-Braced Frame

Buckling-Restrained Braced Frame (BRBF)

BRBF Concept

Buckling-Restrained Brace: Steel Core + Casing

Casing

Steel Core
BRBF Concept

Buckling-Restrained Brace: Steel Core + Casing

Casing
Steel jacket
Mortar
Steel Core
Debonding material

Section A-A

(Brugnoli, 2007)

BRBF Connections

Steel Plate Shear Wall

(Brugnoli and Sabelli, 2007)

(Brugnoli, 2007)
Comparison of Structural Systems

Tall Building Structural Systems (Fazlur Khan)

<table>
<thead>
<tr>
<th>STORIES</th>
<th>LATERAL LOAD RESISTING SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;30</td>
<td>RIGID FRAME</td>
</tr>
<tr>
<td>30 to 40</td>
<td>FRAME - SHEAR WALL</td>
</tr>
<tr>
<td>41 to 60</td>
<td>BELT TRUSS</td>
</tr>
<tr>
<td>61 to 80</td>
<td>FRAMED TUBE</td>
</tr>
<tr>
<td>81 to 100</td>
<td>TRUSS-TUBE W/ INT. COLS</td>
</tr>
<tr>
<td>101 to 110</td>
<td>BUNDLED TUBE</td>
</tr>
</tbody>
</table>

Lateral bracing systems
**Braced bays**

- portal brace
- deep beam brace
- diagonal brace
- K brace
- welded rigid joint
- double height K brace

A braced bay is a line of columns tied together by a bracing system which causes them to act or transverse.

**Plans**

- Beam flanges
- Deep beam flanges
- Hollow tube containing core area
- Solid tube or filled tube of hollow-splayed column
- Tube within a tube

**Elevations**

- Caps, Caps and Mast Tube, Single Tube, Trussed Frame, Tapered Frame
Component 1 (in gray and red) – Stiff braced frame, designed to remain essentially elastic – not tied down to the foundation.

Component 2 (in green) – Post-tensioning strands bring frame back down during rocking.

Component 3 (in gold) – Replaceable energy dissipating fuses take majority of damage

Bumper or Trough (in purple)
Cap Truss

- Keeps plane sections plane
- Building acts like vertical cantilever

COMPARATIVE CRITICAL ANALYSES

Scientific: form and materials
cantilever, column and arch

Social: cost and utility
construction cost, capacity and maintenance

Symbolic: appearance and meaning
form, details and ideas

Iron Bridge vs. Craigellachie

- Efficiency: semi-circular vs. "parabolic"
- 100 foot span vs. 150 foot span
- 1/3 less material

- Economy: many parts vs. mass production
Symbolic:
Iron Bridge vs. Craigellachie
Curve = semi-circular vs. "parabolic" arch
Shape = mutilated... vs. unbroken arch
Span = circles vs. triangles décor for support

Britannia vs. Saltash
Efficiency: hollow box vs. lenticular box
440 ft/yr vs. 455 ft/yr
7000 $/ft vs. 4700 $/ft
Economy: £198./ft vs. £102./ft
Elegance: closed form vs. open form

Pia Maria Bridge (160 m)
1877 – deck merges into the top of arch.

Garabit Viaduct (165 m)
1884 – deck is above the arch.
<table>
<thead>
<tr>
<th>Hell Gate (Lindenthal)</th>
<th>Bayonne (Ammann)</th>
</tr>
</thead>
<tbody>
<tr>
<td>span 977 ft</td>
<td>span 1452 ft</td>
</tr>
<tr>
<td>train: (24 k/ft)</td>
<td>cat: (7 k/ft)</td>
</tr>
<tr>
<td>weight 87.8 million lb</td>
<td>weight 37.0 million lb</td>
</tr>
<tr>
<td>arch profile</td>
<td>arch profile</td>
</tr>
<tr>
<td>spreading constant</td>
<td>spreading constant</td>
</tr>
<tr>
<td>abutments (unnecessary)</td>
<td>abutments (unnecessary)</td>
</tr>
<tr>
<td>stone towers (unnecessary)</td>
<td>stone towers (unnecessary)</td>
</tr>
<tr>
<td>steel skeleton</td>
<td>steel skeleton</td>
</tr>
</tbody>
</table>

_image: Dave Frieder/Wikipedia commons_
Hell Gate (Lindenthal) | Bayonne (Ammann)
---|---
Span | 977 ft | 1,152 ft
Terror (24 k/ft) | 28 k/ft | Cat (7 k/ft)
Weight | 87.8 million lb | 37.0 million lb
Arch | spreading | constant
Supports | stone towers | steel skeleton

Navy's idea!
If the GGB towers had the form of the VNB towers, the GGB bridge would be:

(A) More elegant
(B) Less elegant
(C) Equally elegant
(D) Equally ugly
Both bridges are efficient and economical. Both are elegant (subjective). What are the visual differences between these bridges that could be used to argue that Felsenau is more elegant than the CA bridge?

Take a minute, come to a consensus with your neighbor, and then type/text response.
Which bridge is more attractive?

A. Alamillo
B. Barqueta
C. Both are equally attractive
D. Both are equally ugly

<table>
<thead>
<tr>
<th></th>
<th>SCIENTIFIC (form)</th>
<th>SOCIAL (cost)</th>
<th>SYMBOLIC (aesthetics)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barqueta</td>
<td>incomplete (bowstring) cable-stayed</td>
<td>$2,400/m²</td>
<td>quiet, humble</td>
</tr>
<tr>
<td>Alamillo</td>
<td>complete (towering)</td>
<td>$19,800/m²</td>
<td>loud, showy</td>
</tr>
</tbody>
</table>

View from Giralda tower…
FREE-D Structures

Tallinn Tobacco Plant, Tallinn, Estonia
Calatrava

FREE-D Structures

Bark Cenotaph and Exhibit Center, Dubai
OMA

FREE-D Structures

Dancing Towers, Dubai
Zaha Hadid
Arup