Early Multi-story frames

Initiated before the depression:

- Rockefeller Center,
  New York, 1931
- Empire State Building
  New York, 1931
  381 m, 1250’ 102 Stories
  Shreve, Lamb, and Harman
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 $\text{million used to be acceptable}$
- 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
  - there is more steel that a one story building with the same floor area
  - material increase as $\left( \frac{n+1}{2} \right)$ where $n =$ number of floors
- Material (not just columns) for lateral system increase even more dramatically
**Premium for height**

Gravity system:

- Force in column on top floor
- 2nd from top floor = 3g + force in column above
- 3rd from top = 3g + 3g from above
- 4th from top = 4g + 6g from columns
- 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

\[ V_i = \frac{n}{2} \frac{k}{q} \frac{h}{\text{floor}} \]

\[ \Sigma P_{\text{sum}} = \frac{n+1}{2} mq \]

\[ A_{\text{ratio}} = \frac{m}{n} \]

\[ \Sigma V_i \cdot h = \frac{n+1}{2} \frac{q}{a} \frac{k}{\text{floor}} \]

\[ \frac{\Sigma A_{\text{ratio}}}{b} = \frac{V_{\text{max}}}{n} \frac{h}{(n^2b)} \cdot i^2 \]

**Lateral load resisting system:**

\[ V_i = i \cdot V_{\text{max}}/n \text{, where } i \text{ is the story number} \]

\[ M_{\text{at peak}} = \Sigma (V_i \cdot h \cdot i) = \Sigma (i^2 \cdot h \cdot V_{\text{max}}/n) \]

\[ P_{\text{at peak}} \cdot M_{\text{at peak}} / b = V_{\text{max}} \frac{h}{(n^2b)} \cdot i^2 \]
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

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

- 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?
Section 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 the area that is assumed to contribute load to a particular member.

Influence area is the total area upon which the load has a positive 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

\[ L_d \leq 100 \text{ psf} \quad A_t \geq 400 \text{ ft}^2 \]

\[ K_L = \begin{cases} 
K_{A,t} \frac{t}{4} & \text{tributary area for column} \\
0.4 L_d & \text{otherwise} 
\end{cases} \]

\[ K_{A,t} = \frac{L}{A_t} \]

See ASCE 7 Table 4.2 for other values of \( K_{A,t} \)

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. \( L_{10} = 75 \text{ psf} \)

Bay Spacing 40’x40’
Beam \( w_c = 0.75 \text{ k/ft} \)

\[ M_b = (wL)^2/8 \]

\[ = 150 \text{ ft-k} \]

Girder 3 loads of 30 k each

\[ g = (P/4)/2 \]

\[ = 600 \text{ ft-k} \]

Columns: \( 0.075 \times (40’x40’) \)

\[ = 120 \text{ k} \]

\[ P = 120 \text{ k} \]

\[ 3 = 240 \text{ k} \]

\[ 2 = 360 \text{ k} \]

\[ 1 = 480 \text{ k} \]
2. Calculate $A_i$ for each member:

$$A_B^B = 2(10)(40) = 800\text{ft}^2 > 400\text{ft}^2$$

$$A_G^G = 2(40)(40) = 3200\text{ft}^2$$

$$A_C^C = 4(40)(40) = 6400\text{ft}^2$$

(One story only, does not include roof)

$$A_B^{C2} = 4(40)(40)(2) = 12800\text{ft}^2$$

$$A_C^{C2} = 19200\text{ft}^2$$

3. Apply Live Load Reduction:

Beam:

$$0.25 + \frac{15}{\sqrt{400}} = 0.25 + \frac{15}{20} = 0.75$$

$$M_A^B = 0.75(15000 - ft) = 11250\text{ft}$$

Girder:

$$0.25 + \frac{15}{\sqrt{400}} = 0.5$$

$$M_B^G = 0.5(3000 - ft) = 1500\text{ft}$$

Column:

$$0.25 + \frac{15}{\sqrt{3800}} = 0.25 + 0.4 = 0.75$$

$$P_{C1} = 0.3017 + 0.3017 = 0.6034$$

$$P_{C2} = 6(40)(40) = 120 = 246k$$

$$P_{C3} = 0.40(40) = 160 = 256k$$

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
Concentrically-Braced Frame

Buckling-Restrained Braced Frame (BRBF)

BRBF Concept
BRBF Concept

Buckling-Restrained Brace:
Steel Core + Casing

Section A-A

(Briggs, 2007)

BRBF Connections

(Briggs, 2007)

Steel Plate Shear Wall

(Briggs, 2007)
Tall Building Structural Systems (Fazlur Khan)

<table>
<thead>
<tr>
<th>STORIES</th>
<th>LATERAL LOAD RESISTING SYSTEM</th>
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<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>
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</table>

Lateral bracing systems
**Braced bays**

*Diagram showing various bracing systems.*

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

**Plans**

*Diagram showing different bracing plans.*

**Elevations**

*Diagram showing various elevation designs.*
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: costs 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

Spandrel = circles… vs. …… triangles
decor for support

Britannia vs. Saltash

Efficiency: hollow box vs. lenticular
460 foot span vs. 455 foot span
7000 #/foot vs. 4700 #/foot

Economy: £ 198./foot vs. £ 102./foot

Elegance: closed form vs. open form
unexpressive vs. ambiguous

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>
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<th>Bayonne (Ammann)</th>
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<td>span</td>
<td>977 ft</td>
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<tr>
<td>loads</td>
<td>train (24 k/ft)</td>
<td>car (7 k/ft)</td>
</tr>
<tr>
<td>weight</td>
<td>87.8 million lb</td>
<td>37.0 million lb</td>
</tr>
<tr>
<td>arch profile</td>
<td>spreading constant</td>
<td>(unnecessary)</td>
</tr>
<tr>
<td>abutments</td>
<td>stone towers</td>
<td>steel skeleton</td>
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Image: Dave Frieder/Wikipedia commons
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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.*

### Historical context: Structures and Politics

- **Alamillo Bridge** (Calatrava)
- **Barqueta Bridge** (Arenas)
Which bridge is more attractive?
A. Alamillo  
B. Barqueta  
C. Both are equally attractive  
D. Both are equally ugly

<table>
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<th>Barqueta Bridge (Arenas)</th>
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<tr>
<td><strong>Scientific</strong></td>
<td>tied arch (bowstring)</td>
<td>‘incomplete’ cable-stayed</td>
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<tr>
<td><strong>Social</strong></td>
<td>$2,400/m²</td>
<td>$19,800/m²</td>
</tr>
<tr>
<td><strong>Symbolic</strong></td>
<td>quiet, humble</td>
<td>loud, showy</td>
</tr>
</tbody>
</table>

View from Giralda tower…
FREE-D Structures

Turning Torso
Malmo, Sweden
Calatrava

FREE-D Structures

RAK Convention and Exhibit Center, Dubai
OMA

FREE-D Structures

Dancing Towers, Dubai
Zaha Hadid
Arup

(Structure Magazine, 2008)
FREE-D Structures

Infinity Tower, Dubai
SOM

FREE-D Structures

Dubai Towers, Dubai
TVS

FREE-D Structures

Chicago Spire, Chicago
Calatrava
Thornton-Tomasetti